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Potential Maritime Markets for Marine and Hydrokinetic Technologies:

Draft Report

April 2018

This information is predecisional and is for informational purposes only. No funding is being offered and no proposals are being solicited.

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Executive Summary

This executive summary provides a brief overview of the draft report, *Potential Maritime Markets for Marine and Hydrokinetic Technologies*. This draft report is an initial identification of potential applications for marine energy and information gathered to date.

In fiscal year 2017, the U.S. Department of Energy Water Power Technologies Office (WPTO) Marine and Hydrokinetic Program initiated a project committed to fact-finding and due diligence, identifying and studying the range of potential applications and markets for marine and hydrokinetic technologies. WPTO's intent is to catalog information, perform analyses, and publish a report that identifies and outlines the potential opportunities and challenges for marine renewable energy in a range of different maritime applications and markets. The identified maritime market sectors, which are not traditional WPTO partners, have been engaged to learn about their needs, aspirations, and constraints.

The maritime markets discussed in this draft report are Ocean Observation and Navigation, Underwater Vehicle Charging: AUV, UUV, and ROVs, Desalination, Marine Aquaculture, Marine Algal Biofuels, Seawater Mining: Minerals and Gasses, Data Centers, Constructed Waterways, Shoreline Protection and Replenishment, Disaster Resiliency and Recovery, Isolated Power Systems: Community Scale, Isolated Power Systems: Utility Scale, and other applications: off grid small device consumer and industrial charging, maritime transportation, and ocean cleanup. Each application overview is organized into a summary, a description, a market overview, potential value proposition, and a path to market.

The research conducted to date illuminates the fact that marine renewable energy has some intrinsic strengths and advantages in certain marine and coastal environments. As marine and hydrokinetic technologies meet evolving application and economic requirements, different markets could be realized, and, potentially, even enabled by these marine energy technologies.

1 Introduction

The ocean is a power desert—maybe the largest power desert on earth. While the winds have been harvested for mobility at sea, as a terrestrial desert, other power and needed supplies have historically been brought to sea to achieve desired tasks. Such has been the way of the ocean for all of recorded history. Naturally, the ocean environment contains a tremendous amount of power from the waves, currents, and tides, but this power in its raw form has been difficult to harvest for any economic, research, or defense pursuits—power everywhere and not a watt used.

These unutilized resources present a great opportunity in the evolving "Blue Economy"[1] as the breadth and depth of activities in the ocean expand as never before. Marine renewable energy from waves, tides, and currents have the potential to serve as seeds for energy oases in this ocean desert, supporting new endeavors and enabling the evolution of others. The U.S. Department of Energy (DOE) Water Power Technologies Office (WPTO) supports marine energy research and development for the supply of bulk power and services to the U.S. electric grid. However, marine renewable energy could have intrinsic strengths in supplying power to smaller-scale applications or markets that other power sources simply do not have. DOE's WPTO is looking for near-term opportunities in which marine renewable energy could add value to applications and markets other than large-scale grid power production and address common challenges with larger-scale development.

Marine renewable energy has the potential to enable new markets in the Blue Economy, along with and combined with offshore wind and solar, turning what is currently a desert into a fertile field. WPTO is not alone in examining the potential for marine renewable energy for distributed and alternate applications. In October 2017, the International Energy Agency Technology Collaboration Programme for Ocean Energy Systems published the *Ocean Energy in Insular Conditions Workshop Report*.[2] These near-term applications and markets could increase the number of interested stakeholders and co-development partners, including potential new customer bases, government entities, and supply chain organizations. Technical and other challenges relevant for larger-scale marine energy deployment could be addressed at smaller scales and in less price-sensitive environments, de-risking and accelerating future technology development efforts.

WPTO's intent is to collect information, perform analyses, and publish a report that identifies and outlines the potential opportunities and challenges for marine renewable energy in maritime markets. Fiscal year (FY) 2017 and FY 2018 are devoted to fact-finding and due diligence of marine energy distributed and alternate application opportunities. These industries are not traditional WPTO partners, and we have engaged them to learn more about their wants, needs, and constraints. Numerous activities are highlighted in Figure 1.

[1] The Blue Economy is sustainable use of ocean resources for economic growth and improved livelihoods and jobs, while preserving the health of marine and coastal ecosystems.

[2] https://www.ocean-energy-systems.org/news/report-2017-ocean-energy-in-insular-conditions/

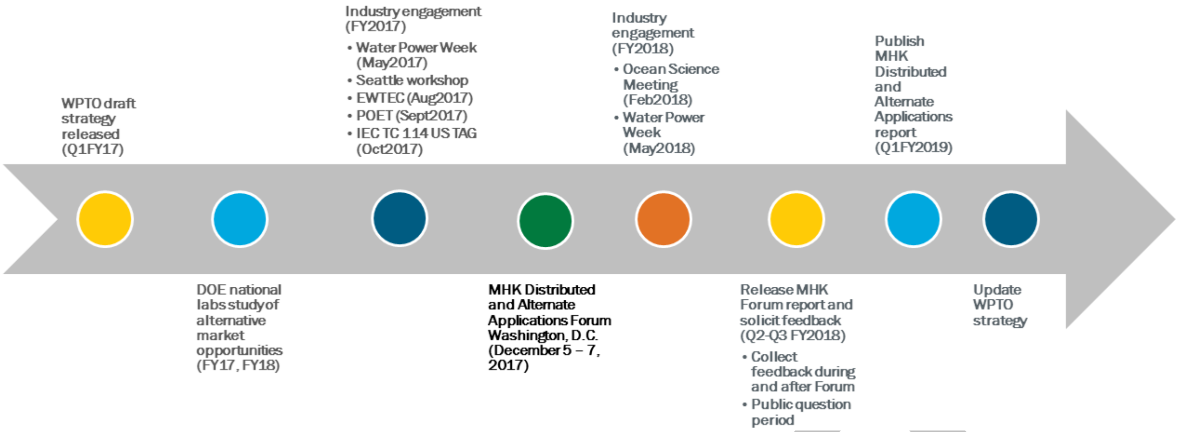


Figure 1. Distributed and alternate applications project overview timeline

The final report and its analyses will be based on information and input from the technical literature, trade and news media, interviews with a diverse set of potential stakeholders, input and feedback from the Distributed and Alternate Applications Forum, and feedback from a Request for Information. This is an initial look at some new potential applications and markets identified to date. Many assumptions are being made, and many information gaps are filled with hypotheses. The DOE WPTO is collecting key relevant information to enable the most informed and rational assumptions and hypotheses and to help identify real opportunities for marine energy.

This draft report includes information and initial assessments of the following potential marine energy applications:

1. Ocean observation and navigation
2. Underwater vehicle charging
3. Desalination, marine aquaculture
4. Marine algal biofuels, seawater mining: minerals and gasses
5. Data centers
6. Constructed waterways
7. Shoreline protection and replenishment
8. Disaster resiliency and recovery
9. Isolated power systems: community scale
10. Isolated power systems: utility scale
11. Other applications.

The chapters on each potential application are organized as follows:

1. Opportunity Summary
2. Application – description of marine energy application, segments, power requirements
3. Markets – customers, power options, geographic relevance
4. MHK Potential Value Proposition – What could marine energy enable or facilitate? How is it complementary with the objectives and requirements of the overall project the MHK technology is providing power for?
5. Path to Market – primary technology hurdles, research and development, potential co-development

Additional information collected will be included in analyses for the final report.

2 Ocean Observation and Navigation

2.1 Opportunity Summary

The use of maritime sensors and navigation aids is widespread and growing rapidly worldwide. Common sensors include surface ocean observation buoys to measure meteorological data, subsurface nodes for tsunami or submarine monitoring, and surface navigation buoys for maritime traffic. Some ocean observation sensors are cabled to shore power, whereas others are powered locally with solar panels or batteries. As the need and capability to measure our oceans advances, more sensors will be deployed with their own unique power needs. Battery life limits the useful duration of most observation and navigation equipment, making locally extracted renewable ocean energy a feasible option for recharging these devices (Ayers and Richter 2016). As an alternative solution to solar, marine and hydrokinetic (MHK) devices could provide longer-term power by taking advantage of the very environment the sensors measure, allowing for nighttime and high-latitude winter charging, areas where some other renewable sources may not be optimal. Some ocean sensors are increasing in size and complexity, requiring additional power. While technological advancements continue to decrease power needs for many individual sensors, there is an overall increase in additional sensors and capabilities and the corresponding need for power for these systems.

2.2 Application

2.2.1 Description of Application

Integrated networks of ocean sensors and navigation aids exist in the United States and international waters to provide monitoring and forecasting of oceanographic and meteorological data and ensure safe navigation, respectively (Figure 2). Oceanographic and meteorological sensors monitor the environment in near real time, improving our ability to understand and predict coastal events, such as hurricanes, waves, sea level changes, and tsunamis. Navigation aids assist commercial and recreational ship traffic, marking areas of danger and established shipping lanes. This improves maritime safety by reducing the risks of collisions, allisions, or groundings.

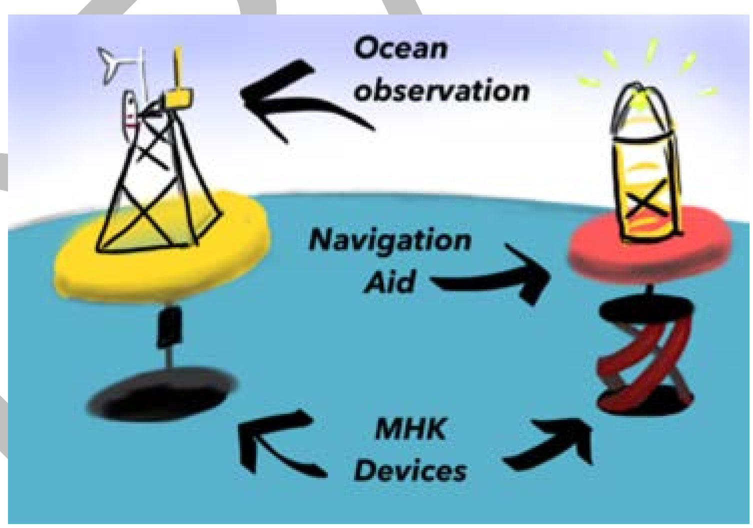


Figure 2. Marine and hydrokinetic application overview for ocean observation. *Image courtesy of Molly Grear, Pacific Northwest National Laboratory (PNNL)*

2.2.2 Power Requirements

The range of power requirements for navigation aids, per installation, is estimated to be 10–600 kilowatts (kW) (Brasseur 2009). There are no accurate power estimates for overall ocean observation systems (Dana Magalang, personal communication, December 2017), as the systems are changing rapidly. It is likely that any additional power that can be generated at sea can and will be used to power additional sensors, nodes, and data communications for ocean observation systems (Ayers and Richter 2016).

A variety of systems and subsystems could use MHK power, including electricity, as outlined in Table 1.

Table 1. Ocean Observation and Navigation Systems and Subsystems and Their Potential Uses for MHK Power

System	Potential Uses
Range of sensors for ambient monitoring (for observation platforms)	Conductivity, temperature, pressure
	Radar
	Meteorological parameters
	Magnetometer
	Acoustic Doppler current profiler, acoustic Doppler velocimetry
	Sonar, other ambient acoustics
	Optical and infrared cameras
	Water quality
	Acoustic tag receivers for sea life
	Military intelligence, surveillance, and reconnaissance
Communications	Satellite (Iridium) links
	Radio signals
	Cell networks
	Safety beacons
	Military navigation network nodes
Computer systems	Data acquisition
	Data storage and backup
	Data upload
Lighting	Required safety lighting for navigation
	Safety lighting on board
	Underwater inspection lights
	Lighting for interior work spaces
Station-keeping (for mobile observation systems)	Propulsion
	Anchoring systems
Onboard maintenance (for fixed navigation and observation systems)	Bilge pumps
	Cathodic protection
Inspection and safety (for industrial installations at sea)	Shut-off valves (e.g., for oil/gas platforms)
	Automated inspection systems

In addition, there will be uses for compressed air, which is generated from mechanical MHK power and could be used in active ballast systems.

Navigation Aids

Navigation aids generally include buoys, floats, air horns, and lights on the surface of navigable waterways (Figure 3). Power is needed for a variety of uses (see Power Requirements section), such as lights, air horns, radar reflectors, air and water sensors, and data transmission (U.S. Coast Guard [USCG] 2017a; 2017b). These navigation aids are found in all major bodies of water and near all ports and shipping lanes. The U.S. Coast Guard manages many of these systems in U.S. waters.

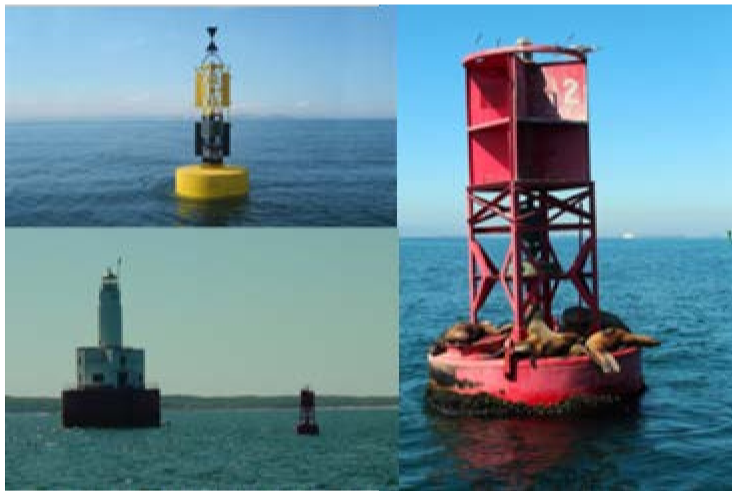


Figure 3. Navigation markers. *Photos courtesy of Polliechrome (bottom left) and Creative Commons (upper left, right)*

Ocean Observation

Ocean observation sites are located along coastlines, on continental shelves, along the margin of oceanic plates, along the equator and other convergence zones, and standing off coastlines for tsunami and storm early warning systems. Most ocean observation devices are subsurface, including oil and gas transmitters and acoustic listening posts, whereas others may be on the surface, including meteorological buoys. Key systems for civilian ocean observation in the United States include the U.S. Integration Ocean Observing System (IOOS) and the related regional system of Ocean Observing Systems (IOOS 2017), including the Neptune array in the Pacific (Interactive Oceans 2017), the Canadian Venus array in the Pacific waters between the United States and Canada (Ocean Works 2017), and the Taos array along the equator and tsunami warning systems off U.S. coastlines (National Oceanic and Atmospheric Administration [NOAA] 2017d, 2017e). Analogous systems operate internationally, with most tied into the Global Ocean Observation System (United Nations Educational, Scientific, and Cultural Organization [UNESCO] 2017) and the European Earth Observation System (UNESCO 2009).

Additionally, military and security uses of ocean observations include systems for surveillance and tracking, such as submarine tracking systems like the decommissioned sound surveillance system array (NOAA 2017c) and the Deep Reliable Acoustic Path Exploitation System under development (The Diplomat 2016).

2.3 Markets

2.3.1 Description of Markets

The world's exports of navigational and survey instruments nearly doubled between 2001 and 2011, from $7.5 billion to $16 billion (Maritime Technology News 2012). Sixty-three percent of the exports ($10.1 billion) in 2011 were for surveying, hydrographic, oceanographic, hydrological, meteorological, or geophysical instruments and appliances, while navigational instruments totaled 37% ($5.8 billion) (Maritime Technology News 2012). These trends indicate that production of navigational and survey instruments has increased substantially in recent years, many of which may be used for ocean observation and navigation purposes. If more of these instruments are being used for maritime-related purposes, more charging power will be needed, and MHK could be used to supplement the power for these instruments.

In 2012, the Duke University Center on Globalization, Governance & Competitiveness completed a study on the global value chains of ocean technologies, including underwater sensors and observation. The study found that technology and manufacturing advances have led to the miniaturization and increased energy efficiency of instruments. Although this would imply reduced energy needs on an individual platform basis, more devices are being integrated and deployed on single platforms to increase functionality and reduce operating costs, which results in a net increase in energy needs (National Academy 2017). In addition, increased activity in the Arctic Ocean and deep sea has increased the demand for sensors that can withstand extreme conditions (Maritime Technology News 2012).

The domestic and international ocean observations and subsea inspections markets are growing, driven largely by increasing needs for early-warning systems for tsunami generation, weather patterns, climate variables, and other scientific questions (National Academy 2017). There are also defense applications for ocean observation sensors and systems, including air, surface, and subsurface intelligence gathering, surveillance, and reconnaissance.

There has been a growing consolidation of the market for ocean observation instruments and equipment, with large firms buying smaller firms in an effort to provide a wide range of products for many different end markets. Recent examples of this consolidation include the purchase of Liquid Robotics by The Boeing Company, the acquisition of Bluefin Robotics by General Dynamics, and the acquisition of Hydroid by Kongsberg Maritime. This market consolidation enables technological acquisition and helps firms attain scales of economy in R&D, marketing, and end-market coverage that may provide a way for large firms to acquire innovative technology (Maritime Technology News 2012).

Governmental and private organizations that develop and support navigation aids and ocean observatories could be likely customers and partners for co-developing systems to provide MHK power. Navigation aids are almost always publicly owned and financed through governments around the world. There is a small market for private surface markers that require power (e.g., lights, radar reflectors, Global Positioning Systems, low power radio), often in conjunction with marinas and ports (U.S. Lighthouse Society 2018). The U.S. Coast Guard is the main authority in the United States that oversees these navigation buoys. However, many ports could also be potential investors and customers for MHK systems to power navigation aids.

Ocean observation systems are commonly financed by government entities (e.g., the National Science Foundation via university consortia in the United States) or by NOAA, the U.S. Department of Defense (DOD), Office of Naval Research, or the U.S. Department of Homeland Security (DHS). Similar governmental organizations in other nations, as well as some private foundations and international aid and finance organizations, presently fund and are expected to continue funding ocean observations.

Offshore manned industrial facilities, such as oil and gas production platforms, require power for a range of operations including lighting, inspection of underwater systems, and the emergency shutdown of valves and other equipment. The need to meet increasingly stringent clean air and water regulations are moving petroleum producers to use alternate sources of power, which could include site-based MHK energy. Similarly, unmanned offshore facilities require power that could be compatible with MHK generation.

2.3.2 Power Options

Navigation aids and (noncabled) ocean observation installations are commonly powered by diesel generators, solar panels, or batteries. At present, wave energy provides only a small contribution to the ocean observation industry from companies such as Ocean Power Technologies and Resen Wave (Naval Today 2018). However, MHK—particularly wave power—could be highly competitive for supplying power to ocean observation instruments and nodes, especially at depth, at night, in high latitudes, and during the winter. The energy density of moving water is much greater than other renewable sources, such as wind or solar, and MHK devices can provide efficient power generation at sea. Solar is likely to have a short-term competitive advantage through photovoltaic (PV) panels used for surface ocean observation and navigation markers, except at high latitudes. PV panels placed close to the sea surface may need more frequent maintenance and cleaning due to corrosion, biofouling, and bird droppings. Large offshore wind is generally location-dependent and provides power outputs that are unnecessarily large for supplying ocean observations and navigation needs. Small buoy or platform-mounted wind turbines could provide an appropriate power source but will be at risk from waves and salt. Diesel generators are impractical in remote locations in the middle of the ocean for many reasons, chief among them the need for refueling and frequent maintenance. Backup storage may be required to match renewable generation with power needs for standalone or hybrid systems.

2.3.3 Geographic Relevance

NOAA's National Data Buoy Center (NDBC) operates and maintains more than 1,300 buoys (Figure 4) that provide ocean and environmental observations to support the understanding of and predictions for changes in weather, climate, oceans, and the coast. These systems collect valuable meteorological and ocean data that support numerous industries, from airlines to fisheries. In the United States, NDBC buoys are located along the coast and offshore of the East Coast, West Coast, Gulf of Mexico, Alaska, and Hawaii. In addition to these NDBC buoys, navigation aids are used along all U.S. coastlines to support vessel traffic, with an increase in these navigation aids most likely congregated around major ports. The top U.S. container ports are Los Angeles, Long Beach, New York, New Jersey, Savannah, Brunswick, Seattle-Tacoma, Virginia, Houston, Charleston, Georgetown, Oakland, and Miami (iContainers 2017). DOE (2013a) estimates the wave energy resources along the East Coast, West Coast, Gulf of Mexico, Alaska, and Hawaii to be 240 terawatt-hours per year (TWh/yr), 590 TWh/yr, 80 TWh/yr, 1,570 TWh/yr, and 130 TWh/yr, respectively. DOE (2013a) also estimates that the magnitude of potential tidal power is significantly less than wave power (250 TWh/yr), with more than 90% of the overall resource located in Alaska. With the significant number of buoys and U.S. container ports located along the East and West Coasts, which makes up approximately 30% of the overall U.S. wave energy resource, MHK power along these coasts could potentially be used to supplement power to these buoys and navigation aids.

Buoys in western boundary currents like the Gulf Stream may offer better pairing potential with ocean current devices. U.S. wave resources are optimal off the coasts of Hawaii and Alaska, the mainland West Coast, and the Northeast, which overlaps well with tsunami nodes. Tidal resources are most common in inland waters, in shallow constrictions where navigation buoys are likely to be most prevalent.

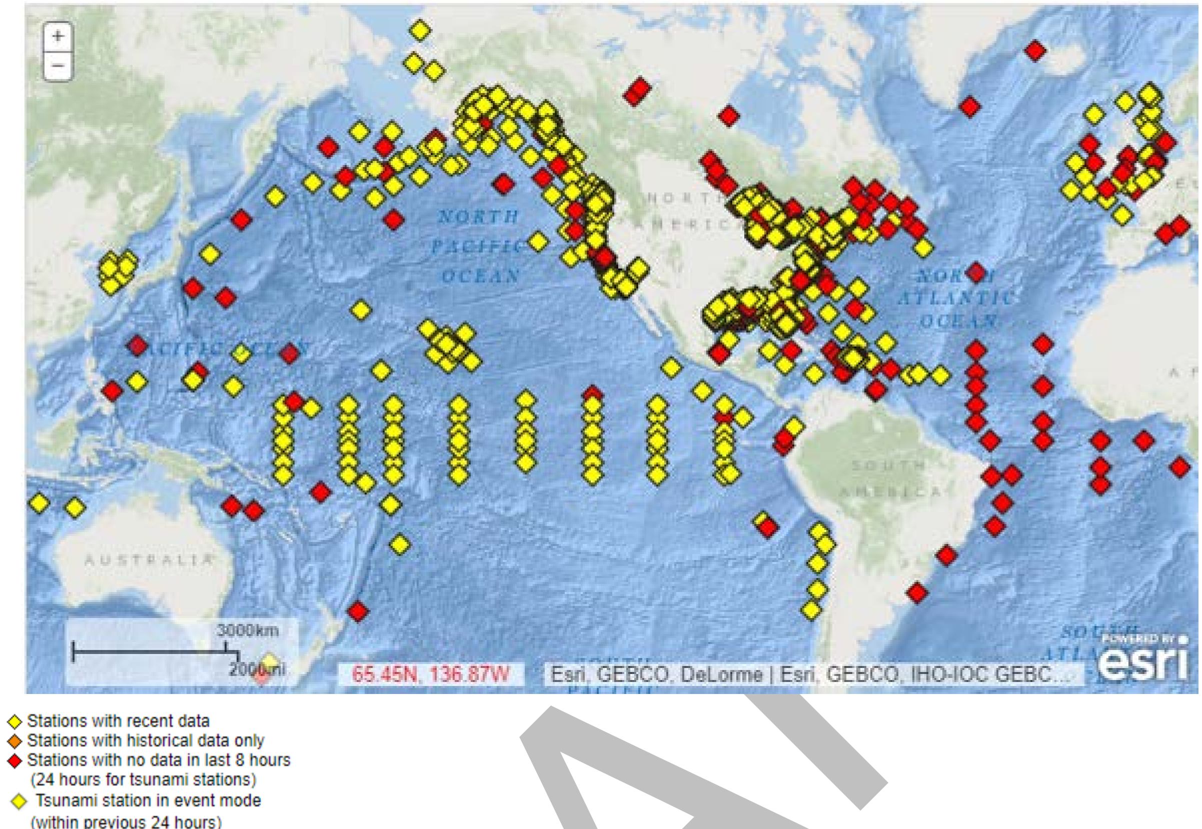


Figure 4. Locations of NOAA buoys. *Map courtesy of NOAA*

2.4 MHK Potential Value Proposition

The large increase in ocean observation and monitoring systems, combined with the desire to record data in real time, adds new power demands. Because many of these systems are in difficult-to-access locations, MHK could reduce costly site visits for maintenance and increase system availability. MHK could meet power needs for surface sensors, especially if integrated with some solar generation and battery storage, whereas undersea needs could be met entirely by MHK and battery energy storage systems. MHK provides unique advantages, including colocation with sensors, markers, and subsea inspection vehicles; continuous power generation; better stealth characteristics; and designs tailored to the marine environment.

Opportunities for powering ocean observation sensors and navigation aids with MHK power occur throughout the coastal area and open ocean, where sufficient wave or tidal resources are present. The DOD—particularly the U.S. Navy—has a presence in these areas and needs a way to power ocean-observation sensors, navigation aids, and systems across the oceans of the world.

Figure 5 highlights the current installed and proposed global seafloor observatories at various stages of development. These observatories are being used for hazard detection and warning, scientific research, coastal/habitat monitoring, or military and security purposes. In the United States, the National Science Foundation's Ocean Observatories Initiative has installed a network of instruments, undersea cables, and instrumented moorings spanning the Western Hemisphere and totaling 759 total sensors (Interactive Oceans 2017).

Figure 5. Installed and proposed seafloor observatories. *Image courtesy of Manalang (2017)*

2.5 Path to Market

2.5.1 Path to Market

Navigation markers and ocean observation systems are a promising point of entry for small wave energy converters (WECs) and tidal devices. The power needs of these devices are smaller than a grid-scale application, which means these smaller devices will have a reduced capital expenditure (CapEx) relative to grid-scale applications, allowing earlier initiation of a viable market for ocean observations.

Additionally, the military funds the continued development of the ocean observation sensors, navigation aids, communications systems, and the necessary power systems (diesel and/or PV + battery, with large potential for MHK to supplant). Working with organizations in this sector may be an expedited path for technology development. Although some of the military observation sensors, for example, may not find their way readily into the marketplace, advances in MHK power systems undoubtedly will.

Ongoing government investments are expected for purchasing and upgrading navigation aids, as well as developing, deploying, maintaining, and expanding/upgrading ocean observation systems. NOAA and the U.S. Coast Guard will typically visit their ocean buoys once a year for maintenance, so developers interested in approaching this market should design their systems to operate around this maintenance schedule. To couple MHK devices and their power output to navigational aids and monitoring systems, government research investment will be needed along with multiple pilot tests. After proving system reliability, it is believed the technology will attract significant private capital. Subsea inspection systems are mostly privately owned; demonstrating a project without government support will require that industry partners be engaged early. These opportunities present significant potential for innovative MHK devices to move forward with this market for MHK companies, including those actively engaged (e.g., Resen Wave, Wave Piston, EC-OG, and Ocean Power Technologies).

Major designs and power needs for navigation aids and markers are relatively well understood. Therefore, R&D in this area should concentrate on the mechanical and electrical integration of MHK devices into navigation markers and monitoring systems. The newer and more rapidly changing ocean-observing markets for power will require similar R&D for linking MHK devices to ocean sensors but will also require further co-development with emerging ocean-observation devices to ensure that they co-evolve.

Potential market synergies exist between applying MHK technologies for ocean observation and navigation aids and applications in underwater recharge, biofuels, and aquaculture, including the need to develop compatible MHK devices and linkages that will operate independently over long periods of time.

To be successful and ensure MHK is considered and integrated as a power source, it will be critical to coordinate with ocean-observation systems in the United States as well as internationally as new systems are brought online. For some applications, MHK devices will need to demonstrate high efficiencies in environments with low resource energy and will need to demonstrate long-term reliability and low maintenance requirements.

2.5.2 Potential Partners

The U.S government has several areas of interest in ocean observing and navigation aids. For ocean observations, these potential mission-driven partners for the MHK industry include NOAA Coastal Survey's NDBC, NOAA Pacific Marine Environmental Laboratory, IOOS, and the regional ocean observing systems (OOSs), the U.S. Coast Guard, and DOD (e.g., the U.S. Navy and the Defense Advanced Research Projects Agency). For navigation aids, additional partners could include the U.S. Coast Guard, U.S. Army Corps of Engineers, and the NOAA Coastal Survey. Coastal ports, which may be governmental entities or public/private partnerships, also have an interest in navigation aids and may be interested in partnering with MHK power generation.

Academic and research partners in the United States are funded for ocean observation by federal agencies and private foundations. Potential partners include major oceanographic university consortia, such as the University-National Oceanographic Laboratory System and, potentially, major research universities, such as the University of California San Diego's Scripps Institute of Oceanography, the Woods Hole Oceanographic Institute (WHOI), the University of Washington, and others. Similar institutions in other nations may have an interest in navigation aids through the Global Ocean Observing System.

Potential industry partners may include subsea and observation original equipment manufacturers (including defense), oil and gas rig undersea inspection services, undersea pipeline and subsea cable inspection services, ocean-observation sensor and equipment companies, and navigation and buoy market manufacturers.

3 Underwater Vehicle Charging: Autonomous Underwater Vehicles, Unmanned Underwater Vehicles, Remotely Operated Vehicles

3.1 Opportunity Summary

Autonomous underwater vehicles (AUVs) and unmanned underwater vehicles (UUVs) are used for surveillance, persistent monitoring, and inspections of subsea infrastructure. Underwater charging and data offloading for AUVs and UUVs could reduce the reliance on expensive surface vessels and extend mission duration. MHK-powered recharge stations could harvest power continuously as the resource allows, and—when paired with battery banks—allow reliable on-demand recharging of vehicles. Underwater recharge stations could also be used as intermediate data repositories, effectively increasing data storage capabilities. The U.S. AUV/UUV market is presently valued at $2.6 billion and is expected to double by 2022 (Research and Markets 2017a).

3.2 Application

3.2.1 Description of Application

AUVs or UUVs include a range of shapes and sizes, such as torpedoes, small submersibles, and less-hydrodynamic cubes. These vehicles are used in the civilian sector for ocean observations, underwater inspections, and monitoring of the seabed and underwater structures. In the military and security sector, they are used for surveillance, underwater monitoring, mine detection and countermeasures, payload delivery, barrier patrol, and inspection and identification.

AUVs/UUVs are performing maritime tasks that once took a fleet of ships months to complete. However, power remains a limiting factor. Missions are limited by battery capacity and typically last less than 24 hours. After the battery is spent, the system must be recovered by a vessel for recharging. Most UUVs use onboard stored electric energy for propulsion, powering sensors, and acquiring data. The energy storage system capacity varies with system type, but roughly 75% of the interior of UUVs are devoted to the energy storage system. Deployment and recovery efforts for recharging AUVs/UUVs are time-sensitive and often limited by weather conditions, which pose a serious hazard to both the crew and the vehicle (Ewachiw 2014). MHK could provide an autonomous power source that would reduce the need to recover the vehicle as frequently, as well as reduce the detectability of operations at sea for security and military purposes (Figure 6). At-sea recharging could also shorten the distance requirement for the energy storage system, enabling more, smaller, and cheaper UUVs.

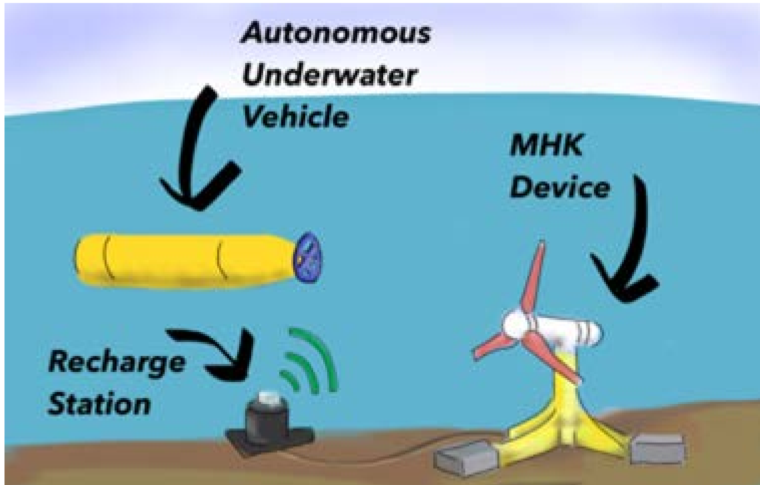


Figure 6. Marine and hydrokinetic application overview for underwater recharge of vehicles. *Image courtesy of Molly Grear, PNNL*

The opportunity to recharge AUVs and UUVs underwater and to offload payload or data is dependent on the availability of robust and efficient recharge technologies. Several such technologies are under development through the U.S. military and its industrial partners, including physical docking stations (Figure 7) that use wireless induction charging or plugged-in connections (Shepard News 2015; Townsend and Shenoi 2013).

Autonomous Underwater Vehicles/Unmanned Underwater Vehicles

AUVs and UUVs (Figure 8) are self-guided and self-powered vehicles that are attractive options for maritime operations because they can reach shallower water than ships and deeper waters than human divers or tethered vehicles. AUVs and UUVs can operate in intertidal waters, and some AUVs can dive up to depths of 6,000 meters (m) (NOAA 2017d). Fully autonomous operations carry power onboard to power propellers or thrusters to move the vehicle through the water. Power is also used to operate sensors on the instrument. Most AUVs and UUVs use specialized batteries, yet some have used fuel cells or rechargeable solar power. AUV/UUV batteries require recharging, but some sensors can run for months at a time before a recharge is needed (NOAA 2017d). The total energy capacity of a smaller AUV may only be a few kilowatt-hours (kWh); the larger 21-inch diameter AUVs may have battery packs with capacities on the order of 10 kWh or more (Dhanak and Xiros 2016).

Figure 7. Underwater Remus docking station. *Photo courtesy of WHOI*

Appendix A of Button et al. (2009) provides an overview of the UUV market, including an inventory of UUVs that demonstrate critical UUV capabilities (e.g., endurance) or attributes (e.g., maturity). As such, this appendix identifies four general classes of AUVs:

- **The man-portable class.** These vehicles displace approximately 25–100 pounds and have an endurance of 10–20 hours. There is no specific hull shape for this class.
- **The lightweight vehicle class.** These vehicles nominally have 12.75-inch diameters and displace approximately 500 pounds. Their payloads are intended to be 6 to 12 times larger than those of the man-portable class. Their endurance is intended to double that provided by the man-portable class.
- **The heavyweight vehicle class.** These vehicles nominally have 21-inch diameters and displace approximately 3,000 pounds. This class is intended to improve capability by a factor of two over the lightweight vehicle class. The heavyweight vehicle class includes submarine-compatible vehicles.
- **The large vehicle class.** These vehicles will displace approximately 10 long-tons and will be compatible for use with both surface ships (i.e., littoral combat ships) and submarines (i.e., attack submarines with a hangar or a plug and guided-missile submarines).

These classes are intended to leverage existing hardware and handling, launcher, and recovery equipment and infrastructure. Characteristics of these four classes are summarized in Appendix A of Button et al. (2009).

Gliders

Gliders are AUVs that use buoyancy propulsion to travel through the ocean to gather data on physical, bio-optical, and chemical properties (e.g., temperature, salinity, chlorophyll, or dissolved oxygen). Glider missions may last up to 3 months and cover distances up to 1,800 kilometers (Figure 8). While traveling, they relay their data to shore via satellite telemetry (WHOI 2017). Although some gliders are self-propelled (Liquid Robotics 2018), others operate on stored energy in battery packs, providing opportunities to extend observation campaigns with recharge at sea by MHK devices operating at sea (NOAA 2017h).

Figure 8. Teledyne Webb Research's Slocum glider. *Image courtesy of WHOI*

Remotely Operated Vehicles

Remotely operated vehicles (ROVs) (Figure 9) are connected to surface ships by cables or tether and are remotely controlled by an operator on the surface vessel. Most ROVs are equipped with a still camera, video camera, and lights, but may also be equipped with a manipulator or cutting arm, water samplers, and other sampling instrumentation. ROVs are used for industrial purposes, such as internal and external inspections of underwater pipelines and the structural testing of offshore platforms and are used for scientific purposes, such as ocean exploration (NOAA 2017e). Recent technological advances have included the development of hybrid ROVs (MODUS 2018) that can be used in traditional tethered mode or disconnected to operate autonomously, like AUVs and UUVs. By disconnecting from the tether, underwater inspection and monitoring ROVs can work in close quarters with cables and other industrial elements that might entangle a tether.

Figure 9. NOAA's Deep Discoverer remotely operated vehicle explores during a 2013 expedition to investigate the U.S. Atlantic canyons. *Photo courtesy of NOAA*

Docking Stations

Docking stations for AUVs and UUVs can be used to extend the mission duration of underwater vehicles by recharging their batteries while at sea. Docking stations provide a secure platform to park vehicles between missions and usually provide power to recharge batteries. Additionally, docking stations may provide a gateway for communications to shore (Monterey Bay Aquarium Research Institute [MBARI] 2017) and improve launch and recovery operations.

Docking stations include sensors that allow the AUV to home on the dock, mechanisms to mechanically connect the vehicle and the dock, and software that controls the overall process. Some docking stations include one or more communication links between the vehicle and the dock, in addition to power transfer systems that power and recharge the vehicle (Dhanak and Xiros 2016).

As described in Dhanak and Xiros (2016), docking systems can be designed to rest on the seafloor and be connected to a cabled observatory. The system shown in Figure 10includes a flared capture cone, which increases the capture aperture of the dock, and a cylindrical housing section, which encloses the docked AUV. A pin containing an inductive coil is inserted into the vehicle, enabling inductive power transfer. An 802.11 link supports short-range communication through seawater. The entire cone assembly is mounted on a gimbal and counterweighted so that the dock will self-level on deployment.

Underwater docking stations have not yet made the transition from demonstration to commercial operations (Dhanak and Xiros 2016), as designs are still undergoing R&D. Factors that have affected the adoption of underwater docking stations include significant investments in infrastructure (moorings with satellite communications and large quantities of batteries); AUV reliability and inherent docking risk; and the comparatively high cost of scientifically equipped AUVs. Another example of a docking station is shown in Figure 11 and 12.

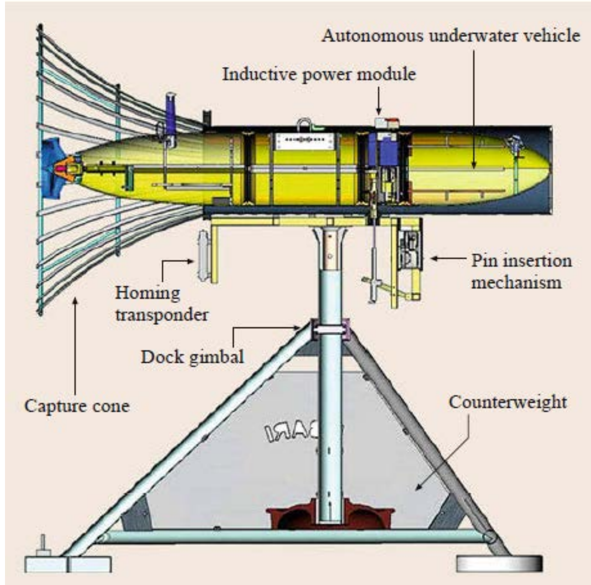


Figure 10. Solid model of a docking station with an AUV captured within the dock. *Image courtesy of Dhanak and Xiros (2016)*

Figure 11. Docking station being recovered after deployment. *Photo courtesy of MBARI (2017)*

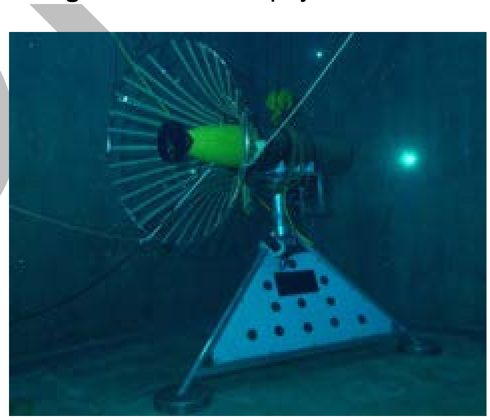


Figure 12. Docking station being tested in MBARI test tank. *Photo courtesy of MBARI (2017)*

3.2.2 Power Requirements

It is expected that AUVs, UUVs, and hybrid ROVs will have similar power requirements. Energy requirements depend on mission requirements and the number of vehicles to service and are estimated to be between 66 kWh and 2.2 megawatt-hours (MWh) per recharge station. Gish and Hughes (2017) cite that 200–500 watts (W) of charging power is required for normal charging, yet faster charge is possible with increased power, which may be more desirable for some applications. A typical AUV recharge takes approximately 4–8 hours (Gish and Hughes 2017).

Ideally, the power source should be able to operate over a wide depth range that is estimated to be between 50 and 1,000 m. The constant harvest of MHK power, coupled with battery backup, would allow recharge on demand.

A variety of systems and subsystems could use MHK power, including electricity, as shown in Table 2.

Table 2. AUVs and UUVs Systems and Subsystems and Their Potential Uses for MHK Power

System	Potential Uses
Range of sensors and payloads for ambient monitoring and underwater manipulation	Conductivity, temperature, pressure
	Radar
	Meteorological parameters
	Magnetometer
	Acoustic Doppler current profiler, acoustic Doppler velocimeter
	Sonar, other ambient acoustics
	Optical and infrared cameras
	Water quality
	Acoustic tag receivers for sea life
	Autonomous sensors for release, capture, data download, and refurbishment
	Robotic/mechanical capture and release mechanisms on vehicle
	Military intelligence, surveillance, and reconnaissance
	Wireless recharging subsystem
	Wireless data transfer subsystem
Communications (generally located on recharge stations)	Satellite links
	Iridium links
	Radio signals
	Cell networks
	Safety beacons
Computer systems (generally located on recharge stations)	Data acquisition
	Data storage and backup
	Data upload
	Safety lighting
	Underwater inspection lights
Station-keeping (for mobile recharge systems)	Propulsion
	Anchoring systems

In addition, there will be uses for compressed air, which is generated from mechanical MHK power, for active ballasting of recharge systems.

3.3 Markets

3.3.1 Description of Markets

Globally, the AUV/UUV market is estimated at $2.6 billion and it is expected to double by 2022 (Research and Markets 2017a). The market for recharging AUVs/UUVs underwater, which includes the charging stations and associated infrastructure, is not developed and has an unknown valuation, but is expected to have a growth rate similar to the greater AUV market, just on a smaller scale.

The AUV/UUV market has been growing over the past several years as a result of the increasing demand in commercial, military, and scientific research applications. New investments in the market have been driven largely by the defense industry (Research and Markets 2017a). The range of applications is broad and includes intelligence, surveillance, and reconnaissance; antisubmarine warfare; inspection and identification; communications; navigation network nodes; payload delivery; barrier patrol for homeland defense and force protection; and seabase support. The tactical and potential cost advantages of deploying swarms of AUVs and UUVs that can cover regions of ocean area are huge relative to comparable services offered by a single ship trying to cover the same area.

The AUV/UUV market is closely coupled with the oil and gas industry and displays similar trends (Markets and Markets 2017). The demand from underwater exploration outfits will likely drive the need for more UUVs and charging capabilities.

The key end users of the AUV/UUV market are the commercial sector, followed by the defense and homeland security sectors (Markets and Markets 2017), as well as scientific uses.

As discussed in Shukla and Karki (2016), the oil and gas industry is making automation a priority due to quickly emerging challenges facing the industry, such as a lower recovery rate, exploration of unconventional reserves, operation in extreme environmental conditions, and profitability of the overall business model. As such, the industry will be relying on robotic solutions (including ROVs) for underwater inspections, welding and manipulation, remote sensing, and oil spill prevention.

Additionally, AUVs and ROVs are used in aquaculture operations for underwater object retrieval, monitoring, and net inspection (The Fish Site 2016). Offshore energy operations also use ROVs to aid in the installation, maintenance, and expansion of energy production (AquaBotix 2017), and ROVs are used for surveillance and inspection of port facilities (Gutierrez et al. 2010). In addition, AUVs, UUVs, and ROVs are heavily used for marine research applications by academia (e.g., WHOI), the federal government (e.g., NOAA), and the military.

DOD has identified nine mission categories for UUVs, including intelligence, surveillance, and reconnaissance; mine countermeasures; antisubmarine warfare; inspection/identification; oceanography; communications/navigation network node; payload delivery; information operations; information operations; and time-critical strike (Button et al. 2009). In 2016, DOD announced that they would be investing $600 million in UUVs over the next 5 years (Pomerleau 2016). Additionally, the DHS Science and Technology Directorate is interested in UUV research and has been supporting funding the development of a UUV called the *BIOSwimmer* that is designed to resemble a tuna and will be used for inspection work in oily or dangerous environments.

Scientific uses of AUVs and UUVs include a variety of monitoring and exploration uses, generally using commercially available or purpose-built devices in cooperation with companies that also supply the military and industrial oil and gas markets.

3.3.2 Power Options

There are few viable options for powering an underwater vehicle recharge station other than MHK (see Figure 13). Diesel generator sets must be surface-based and would require frequent refueling and maintenance, leading to poor stealth characteristics, high costs, and risk of spills. Other renewables, such as solar and wind, are less suitable replacements, as AUV and UUV charging will likely take place underwater, requiring extensive cabling from any surface power source and reducing stealth due to the surface expression. Solar and wind applications must be mounted at the surface. Placing PV solar panels close to the ocean surface will require frequent cleaning of the panels from salt spray and bird droppings. Wind turbines would have to be surface-based on a platform or bottom-mounted on foundations, making them depth-limited for underwater recharge applications.

3.3.3 Geographic Relevance

The evolving need for energy for underwater charging is worldwide, in all bodies of water. Differing energy demands could make the energy in ocean currents, tidal currents, and waves both near to shore and in the open oceans relevant, providing no geographic constraints.

Tidal resources are most common in inland waters and in shallow constrictions where there is less need for long-duration AUV and UUV monitoring. Ocean currents, especially fast-flowing western boundary currents, can approach speeds of 3 to 4 knots in some areas and could be harnessed for underwater vehicle recharge. However, operating these vehicles in fast-flowing ocean currents is problematic. Most tidal and ocean current devices are submerged and may be more useful for stealth or military missions where a surface expression is not preferred.

3.4 MHK Potential Value Proposition

AUVs/UUVs are duration-limited, typically capable of lasting 24 hours before having to surface to offload data via satellite or be recharged by a surface vessel. By surfacing, the AUV is spending time off mission and compromising its stealth. The support vessels that must recover these vehicles are very expensive, charging $30,000 or more per day. Other nonmonetary risks from vessels at sea include additional danger to vessel crews, increased emissions, and the potential for petroleum spills.

If AUVs and UUVs could be recharged and offload data underwater without surfacing, a sizable portion of the operating costs for a typical mission—estimated at hundreds of thousands of dollars—would be eliminated.

The ability to recharge vehicles underwater will lead to cost savings and safety improvements for deployment and retrieval and will increase the amount of time that a deployed vehicle can spend on the mission by eliminating the need to surface, transit, and redeploy from a mother ship (Button et al. 2009).

Underwater recharge stations are currently under development. These stations are presently relying on battery banks for power. Powering these stations with MHK power would provide a locally generated reliable power source, smoothed for intermittency by battery backup. Underwater recharging would reduce the need to recall vehicles to the surface as frequently; save time and resources; improve human safety; increase mission duration, range, and stealth; and reduce carbon emissions. Hybrid ROVs—which can be disconnected from the umbilical cable — could also benefit from MHK power.

Gish and Hughes (2017) presented a hypothetical cost-savings scenario for the development of an underwater docking station for small commercial AUVs.

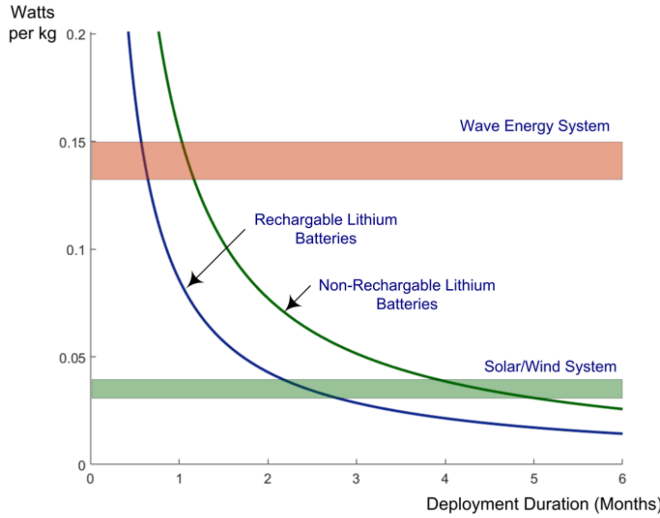


Figure 13. Energy requirements for deployment duration. *Image courtesy of Hamilton (2017)*

Opportunities for underwater recharge occur throughout the coastal area and open oceans where there is a need to survey or monitor with AUVs and UUVs (Figure 14 and Figure 15) and where sufficient wave or tidal resources are available. AUV and UUV operators typically prefer environments with minimal ocean currents when possible as it is easier for the vehicle to navigate and make headway.

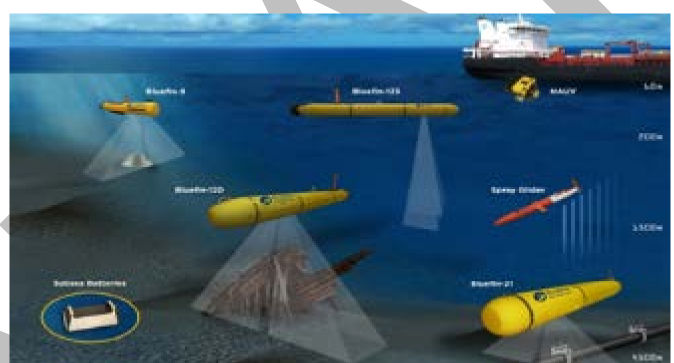


Figure 14. Opportunities for underwater recharge in all oceans, at all depths. *Image courtesy of Bluefin Robotics*

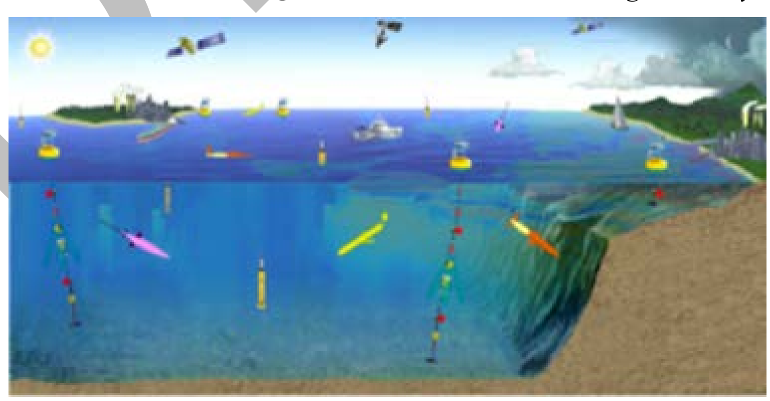


Figure 15. Underwater gliders and profiling arrays. *Image courtesy of ACSA, SeaExplorer, Creative Commons*

Hamilton (2017) estimates that wave energy systems provide a consistent form of energy that will be useful over AUV and UUV instrument deployment cycles. The power provided from wave energy systems is more consistent than that provided by battery power alone and is significantly higher than the solar/wind system, as shown in Figure 13, for a recharge station built into an observation buoy.

An emerging potential market within the DOD sector (Navy and Air Force) supporting the swarm approach over traditional operations at sea are unmanned aerial vehicles or drones in ocean areas. The unmanned aerial vehicles will need recharging, and the ability to recharge stealthily at sea, rather than returning to a land-based recharging station, thereby enhancing mission success, range, and cost.

3.5 Path to Market

3.5.1 Path to Market

Projects will initially be small and bespoke for specific AUVs and UUVs. Defense contractors and laboratories are and will continue to be early adopters of underwater MHK-powered recharge devices. Small-scale WECs and underwater turbines can meet early-development needs for underwater recharge, and there is significant opportunity for the two markets (AUV and UUV recharge and MHK) to co-develop. Permitting MHK use for underwater recharge will have similar time frames and cost estimates as other small, off-grid MHK developments. Security and military uses may allow faster permitting.

R&D in this area should concentrate on the mechanical and electrical coupling of MHK devices to the recharge stations. Specific adaptations to existing MHK designs (WECs in particular) should be developed to eliminate surface expression and to optimize for underwater power generation. Efficient low-speed underwater turbines need to demonstrate high reliability and efficiency. MHK devices need to be reliably demonstrated in deep water with minimal deployment preparation. A potentially large niche within the recharge station arena is a low-visibility, low-surface-expression device that could recharge unmanned aerial vehicles at sea rather than returning to land-based recharge stations.

Efficient underwater charging stations need to be reliably demonstrated. Gish and Hughes (2017) highlight several challenges associated with underwater docking stations for AUV recharge, including reliability and robustness, marine fouling, corrosion, wave and current forces, and deployment and recovery. These are all areas that will benefit from additional research to help advance the market. Standardization of recharge stations to accommodate a variety of AUVs and UUVs will increase adoption and drive down costs. Hamilton (2017) also highlights the need for numerical models for station-keeping system dynamics.

Potential market synergies exist between the application of MHK for underwater vehicle recharge and MHK's application for ocean observation, navigation markers, growing algae at sea, and aquaculture.

Other synergies exist between MHK power and undersea power generation devices. For example, L3 Open Water Power has developed an aluminum-water platform technology for undersea power generation that provides energy storage with extremely high energy density. The aluminum-water chemistry has been shown to be inherently safer and more stable than many other battery and fuel cell chemistries typically found in maritime use. The device promises a significant improvement in the endurance of UUVs and sensors (L3 2017).

3.5.2 Potential Partners

For the development of underwater vehicle recharge, potential U.S. mission-driven partners for the MHK industry include government, academia, and industry.

Within the U.S. government, potential partners include DOD (U.S. Navy, Defense Advanced Research Projects Agency), DHS, and government-funded ocean observatories such as IOOS and regional OOSs.

In academia, potential partners include oceanographic research universities, such as University-National Oceanographic Laboratory System, University of California San Diego's Scripps Institute of Oceanography, WHOI, the University of Washington, and other research institutes, such as MBARI. Oceanographic institutions in other nations are similarly involved with the GOOS and are likely to have interests in underwater recharge of autonomous vehicles as well.

Industry partners could include subsea and observation original equipment manufacturers, defense contractors, oil and gas inspection contractors, pipeline and subsea cable inspection service providers, ocean observation sensor and equipment companies, and navigation and buoy manufacturers.

A number of U.S. and international companies have been identified as interested in the AUV and UUV recharge market including Teledyne Technologies (United States), Subsea 7 (United Kingdom), Kongsberg Maritime (Norway), Saab (Sweden), and Oceaneering International Inc. (United States). Other potential vendors include Searobotics, Boeing, Honeywell, Bluefin Robotics, and wireless charging companies, such as Wiboric and AeroJet Rocketdyne.

4 Desalination

4.1 Opportunity Summary

MHK technology developers have already started developing MHK-powered desalination technologies to find early market opportunities. One reason desalination has already been explored by MHK developers is because the global demand for clean water is well-defined and growing. Therefore, to further understand these technologies, the National Renewable Energy Laboratory (NREL) has performed an initial techno-economic analysis for wave-powered desalination technologies (Yu and Jenne 2017). The analysis leverages existing wave energy technologies from the DOE Reference Model project. NREL designed and modeled a system that directly pressurizes reverse osmosis for clean water production, bypassing the electricity generation process, as proposed by some wave-powered desalination developers. The results suggest that the application of the reference model wave-energy technology to pressurize a reverse-osmosis desalination system would be significantly more cost competitive when producing water than when producing electricity. NREL's initial estimates indicate that the levelized cost of water is around $1.80/m^3 (Yu and Jenne 2017). Using an assumed electricity rate of $0.13/kWh (California average), the levelized cost of water for a traditional reverse-osmosis desalination plant would be slightly less than $1/m^3 before distribution or other added infrastructure is included. These findings signal a near-term market opportunity for wave energy requiring smaller cost reductions before the technology is commercially competitive.

4.2 Application

4.2.1 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 approximately 500,000 m^3/day capacity (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 (U.S. Geological Survey 2014) but there is an anticipated 20% increase in capacity by 2020 (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, there are less price-sensitive market opportunities in regions with few other options, such as isolated communities, disaster relief situations, and, potentially, military applications. MHK technologies (wave and ocean current) can be used to produce drinking water with little to no electricity generation. The ability to produce drinking water with minimal electricity production is appealing in regions where grid-connected electricity is unreliable or costly. In addition to the ability to produce water without electricity consumption, hybrid systems can be designed to produce both electricity and clean water if desired (e.g., Resolute Marine Energy).

The most likely near-term MHK technologies are shallow-water wave and tidal technologies, particularly due to the proximity to shore. Shallow-water technologies allow for more equipment to be located on land, require simpler installation techniques, and have lower maintenance costs. Thus, they reduce the risks associated with a low technology readiness level for WEC technologies. However, environmental and permitting challenges associated with brine discharge and inlet designs (e.g., velocity restrictions) may incentivize deep water technologies as 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 MHK 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 MW will produce an average of 8,100 m^3/day fresh water. This ratio (8,100 m^3/day per MWe-average) is dependent on the cost of both the WEC technology and the reverse-osmosis system. 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^3/day per MWe-avg. A summary of the per-unit costs in both water and electricity production is shown in Table 3.

Table 3. Per-Unit System Cost Summary (NREL 2017)

	\$/$\mathrm{MW_E}$ RATED	\$/$\mathrm{MW_E}$ AVERAGE	\$/$\mathrm{M^3}$ RATED	\$/$\mathrm{M^3}$ AVERAGE
WEC C	$6,254,671	$20,665,117	$1,251	$2,546
WEC oPERATIonal eXPENditure (OPEX)	$109,851	$362,941	$22	$45
Reverse-osmosis CAPEX	-	-	$1,177	$2,395
Reverse-osmosis OPEX	-	-	$38	$77

The deployed MHK system could have minimal surface expression, as shown in Figure 16. 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 and will not require extensive high-cost offshore maintenance. 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 due to reliability constraints.

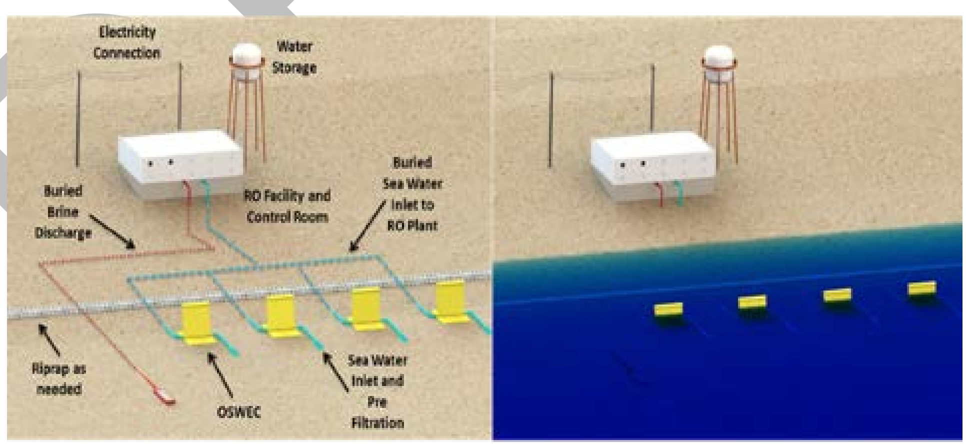


Figure 16. Rendering of a wave-powered desalination plant (RO is reverse osmosis). *Source: NREL*

The rendering in Figure 16is one of many potential application possibilities. There are technology developers designing systems that range from hybrid water and electric systems (Figure 17) to systems designed for easy deployment that have demonstrated the ability to produce water without any electricity (Figure 18).

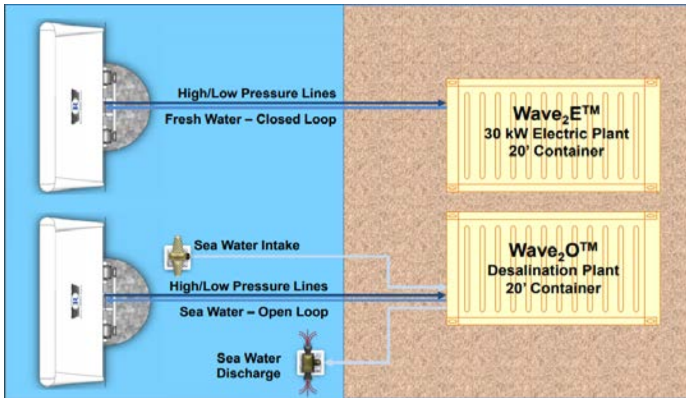


Figure 17. Resolute Marine Energy Wave2E and Wave2O conceptual design.
Image courtesy of Resolute Marine Energy.

Figure 18. SAROS wave-powered desalination demonstration unit.
Source: https://www.digitaltrends.com/cool-tech/saros-buoy/

4.2.2 Power Requirements

Desalination is an energy-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 energy 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 process. 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 (USVI), diesel fuel is commonly used to create the electricity needed to drive pumps. 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 4summarizes the energy consumption for reverse-osmosis systems.

Table 4. 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 kWh/m^3	(Voutchkov 2013)
WEC-powered seawater reverse osmosis	-	24 hour	Critical—performance	2.8 kWh/m^3 equivalent power	(Yu and Jenne 2017)
Distribution	Grid/diesel	24 hour	Critical—performance	Varies with distance and elevation	

4.3 Markets

4.3.1 Description of Markets

For desalination, there are 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, require 100-plus megawatts to run and provide 50 million gallons per day of water supply (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 when other water sources are no longer available. Utilities become interested in desalination to maintain control of the local water supply, provide drought resistance, and diversify their resources (Aquacraft 2011). Because of the high cost of these systems, water utilities expect long-term operation to provide maximum payout.

Operators of isolated systems are likely to tolerate high technology costs if these systems can provide a reliable water supply. Distributed systems, such as those deployed in the USVI, where desalination is the primary source of water, are likely to be competing with the cost of diesel, waste heat, or other renewables, such as solar or wind (Lantz, Olis, and Warren 2011). Island communities that have limited land availability may specifically provide a competitive advantage for MHK 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).

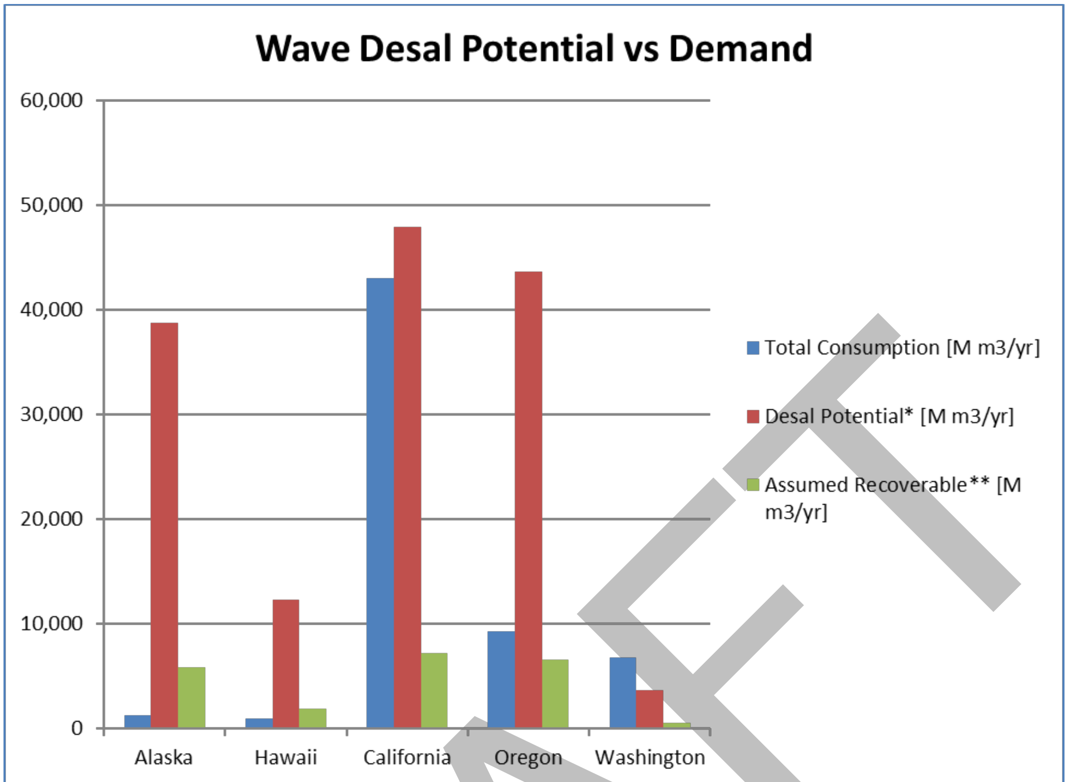
In the United States, the water utility market has the potential for billions of dollars in water sales per year. An initial estimate looked at the wave energy that is available in California, Oregon, Washington, Hawaii, and Alaska, with a practical limit of 15% of the total available resource (assumes 50% unavailable for access, and 30% capacity factor for the other 50%). Using these resource assumptions and water sales of \$1.50/m^3 (approximately the rate sold at the Carlsbad Desalination Plant), the West Coast, Alaska, and Hawaii markets could be worth approximately \$30 billion/yr. This represents approximately 30% of the combined consumption in these states, with most of the consumption in the state of California. The water utility market has the potential to be expanded into the East Coast and the Gulf of Mexico, although these markets have much smaller wave resources and were not considered in the initial analysis. Florida, North Carolina, and Texas have shown interest in desalination technologies and therefore the use of current energy converters, and niche applications (e.g., disaster relief, military bases, isolated water supply) will help expand the technology to the East Coast and the Gulf of Mexico. To understand the magnitude of this opportunity, further analysis is required.

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-kW 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 due to 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 USVI, the volatility of petroleum prices represents a risk that renewable technologies might mitigate.

One of the most significant technical challenges, like other renewable technologies, will be matching the MHK resource with the water demand. Typically, the most significant wave energy resources occur during winter months and the lowest harvestable conditions occur during the summer months. For regions such as southern California, this represents a significant load mismatch between peak (e.g., summer irrigation demand) and maximum wave energy generation. 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 MHK and reverse-osmosis desalination technologies are more widely adopted. This has been shown with other technologies (e.g., wind and geothermal), where 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; 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 due to 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 19. 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.



*Resource knockdown factor of 0.5 (Kilcher 2016)

** Assumes 30% CWR, and 50% of Resource Exploitable for Desal

Figure 19. The total clean water consumption by state compared to what can be produced using local wave energy.

4.3.2 Power Options

The competition for MHK 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 be in competition with MHK. 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.

MHK has some specific advantages compared to other renewables or even diesel-powered systems. Given that MHK 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 MHK 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 safely.

4.3.3 Geographic Relevance

Coastal regions with limited freshwater resources are the potential geographic opportunities for MHK-powered desalination. For WEC technologies, the five U.S. states of California, Oregon, Washington, Alaska, and Hawaii have the most 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 much less significant wave resource, that may suit some small-scale 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.

4.4 MHK Potential Value Proposition

In the near-term, MHK-powered systems can supply significant drinking water for communities with high water supply costs or limited electrical grid availability. MHK 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, more than 50% of the population lives within 50 miles of a coastline in the United States (DOE undated). By locating the energy resource near population centers and directly locating it at the water resource, it enables both water and electricity production where needed. This may be of interest in areas with unreliable grid connection (e.g., island, military, or disaster relief). In the long term, MHK 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-force psi) 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 additional cost, and therefore requires a detailed technoeconomic assessment to understand the most appropriate combination.

When considering economic competitiveness, MHK technologies are currently more expensive than other renewables, although costs are expected to drop as MHK technologies mature. However, the existing estimates suggest that a reverse-osmosis plant CapEx is on the same order of magnitude as the MHK technology that is driving the reverse-osmosis plant. 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^3. This is promising, given that the costs today 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.

4.5 Path to Market

4.5.1 Path to Market

Because of the maturity of existing reverse-osmosis technologies, the path to market will primarily require R&D advancements on the MHK systems and the reverse-osmosis MHK system integration. Specific R&D challenges are listed below. However, once specific technical challenges have been addressed, technologies will need to be demonstrated for both reliability as well as social and environmental acceptability.

The high energy requirements for desalination require very similar, if not identical, MHK technology advancements as we expect with utility-scale MHK. Large-scale water utilities will require water production on a scale that is equivalent to multimegawatt MHK arrays. However, similar to the comparison of isolated power markets and utility-scale power markets, the early MHK desalination opportunities will likely be able to take advantage of much smaller-scale MHK devices. This will provide MHK developers with an opportunity to develop MHK technologies with lower financial risk and reduced installation and maintenance per unit. 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 significantly drive up the cost of the primary pump within the power take-off. This challenge is amplified in scenarios where low pressure (<100 psi) water is delivered to shore and boosted to the required pressure for separation, as suggested by 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 above, 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 devices are not designed to function outside of steady-state operation.

In addition, the Carlsbad Desalination Plant has demonstrated the importance that environmental and permitting changes can have on the commercial viability. Permitting for large facilities can take many years and be significant components of the total CapEx. The Carlsbad plant project cost has been estimated at approximately \$650 million (\$3,400 m^3/day) (Global Water Intelligence 2018), with about half of that cost related to permitting.

System supply chain consists of two major components: the desalination plant and water delivery. The desalination plant consists of the WEC and the 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 design and coordinate the delivery of specialized, often state-of-the-art systems. MHK manufacturers, however, are limited in scope and size, and often are working towards 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 above, 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 significantly 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.

4.5.2 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. The challenge with municipality partners is that they are inherently low-risk, conservative organizations with little appetite for costly innovation. Significant demonstration projects will likely not be of interest to these organizations. At the component level, given the level of hydraulic smoothing that will need to be performed, hydraulic equipment suppliers also provide obvious co-development opportunities.

5 Marine Aquaculture

5.1 Opportunity Summary

Aquaculture can produce high-quality protein with no need for land, fresh water, or fertilizer. In 2014, 73.8 million tons of fish were grown in global aquaculture operations with an estimated first-sale value of $160.2 billion. China continues to be the major producer, providing slightly less than 62% of the world fish production in the past two decades. In 2014, the United States was the seventeenth top producer. Aquaculture requires energy to power monitoring equipment, navigation lighting, and fish feeders to refrigerate the harvested product. These power needs are estimated to range between 4 and 715 MWh per year, depending on the size, location, and purpose of the operation (e.g, shellfish farm, fish farm). This power has historically been provided by diesel generation and only occasionally by renewables. By replacing fossil-fuel power generation with MHK energy, the industry will reduce harm to air and water quality and lower operating expenditures. Marine renewables are believed to be more suited to this task than other renewables because of excellent colocation characteristics, low visual profile, and reduced intermittency. U.S. waters include a large (almost 10 million km^2) exclusive economic zone (EEZ), a significant portion of which could be used for aquaculture development. The advantages of co-locating the energy source with aquaculture operations could potentially favor a MHK power supply for this growing industry.

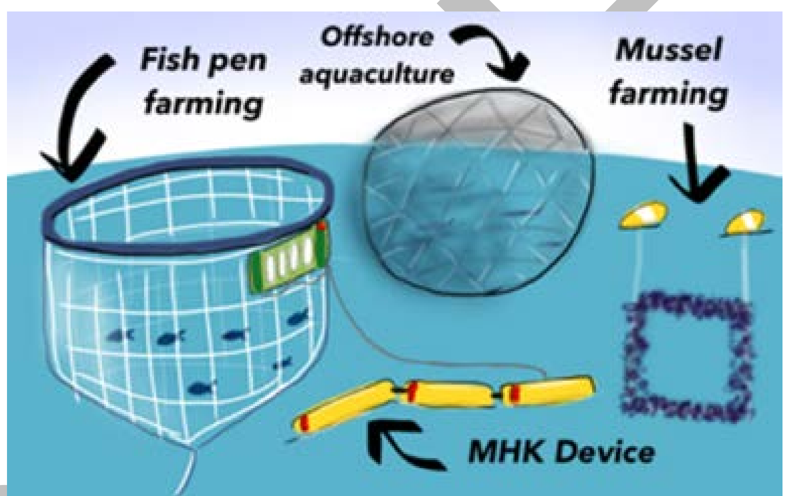


Figure 20. Marine hydrokinetic application overview for marine aquaculture. *Image courtesy of Molly Grear, Pacific Northwest National Laboratory*

5.2 Application

5.2.1 Description of Application

Aquaculture is the cultivation of finfish, shellfish, crustaceans, and seaweeds on land or at sea, primarily for human consumption, with additional markets for animal feed and industrial chemicals (Figure 20). It is a nascent U.S. industry; however, offshore farms are developing worldwide to meet a global market projected to be more than $55 billion by 2020 (Food and Agriculture Organization [FAO] 2016). Small aquaponics operations are under development nearshore on barges in the United States and in Europe (EzGro Garden, 2016; Earth Institute 2011), and many are looking to expand to include additional hydroponic and aquaponic systems. Presently, marine aquaculture operational power needs include navigation lights, compressed air production, nutrient and waste disbursement, fish feeders, and crew support (e.g., lights, heat), all of which are currently met with diesel generators, battery storage, and solar panels.

There is an annual seafood trade gap of approximately $14 billion per year between the United States and its trading partners (NOAA 2015b), which cannot be supplied solely by traditional fisheries. More than 90% of

U.S. seafood is imported, presenting a unique opportunity for offshore and nearshore aquaculture, in addition to economic development and job creation.

Globally, approximately 3 billion people rely on seafood as a primary source of animal protein (NOAA 2015b), yet most capture fisheries[3] worldwide are fully exploited or overexploited (Ye and Gutierrez 2017). In addition to seafood for human consumption, marine products are integral to meeting demands for animal fodder and many industrial chemicals. To ensure a sustainable seafood and marine products supply, growing organisms through aquaculture is needed to meet this demand. In 1974, aquaculture provided only 7% of fish for human consumption, increasing to 26% in 1994 and 39% in 2004 (FAO 2016). The United Nations FAO estimates that the world aquaculture production of fish and plants totaled $165.8 billion in 2014, increasing from approximately $42 billion in 1995 (Figure 21), resulting in a compound annual growth rate[4] of approximately 1.07%.

In addition to seafood for human consumption, aquaculture also supplies fishmeal, fish oil, and animal fodder; chemicals for the food processing, cosmetic, and industrial chemical industry (particularly from seaweeds); small fish and shellfish for aquaculture grow operations and bait; and specialty fish for the ornamentals trade (FAO 2016).

Figure 21. World aquaculture production volume and value of aquatic animals and plants (1995–2014). *Image from FAO (2016)*

Coastal versus Offshore Aquaculture Operations

Aquaculture operations can occur in coastal or nearshore zones and deep water or offshore areas. Coastal aquaculture is the most predominant form of aquaculture, where pens or fish cages are deployed along the coastline (often in a protected area). The majority of crustacean and mollusk farming occurs inshore, where racks are used for breeding (AquaBotix 2016). Other small coastal aquaculture operations are being developed on nearshore barges in the United States and Europe (EzGro Garden, 2016; Earth Institute 2011). These barge operations are typically integrated with both hydrophonics and aquaphonics, often focusing on sustainable urban farming. Offshore aquaculture operations typically employ floating or submersible net pens or cages that are tethered to the seafloor and attached to buoys. Coastal and offshore pens are likely candidates for use of

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[3] Capture fisheries refer to the harvesting of naturally occurring or wild fish populations in their native environment.

[4] The compound annual growth rate for the world aquaculture market between 1995 and 2014 was calculated by dividing the final market value ($165.8 billion) by the initial value ($42 billion) and raising the result to the power of 1 divided by the number of years (1/19 or 0.0526).

MHK power resources; moreover, offshore pens are becoming increasingly large and thus have increasing power needs.

Finfish Aquaculture

Finfish, including anadromous fish, such as salmon, and marine fish, such as halibut, turbot, and black cod, are grown in net pens that are suspended off the seafloor or floating on the surface. These operations can be located in nearshore coastal waters or offshore (Figure 22 and Figure 23).

Figure 22. Open-ocean fish farming. *Photo courtesy of NOAA Fisheries*

Figure 23. Net pens for finfish rearing. *Photo courtesy of Creative Commons*

Shellfish Aquaculture

Most bivalve shellfish aquaculture in the United States is bottom-laid and does not require power except for maintenance or harvest vessels. However, certain shellfish species, notably mussels, require rafting on lines off the seabed, and increasingly, other shellfish are grown on lines or in suspended bags (Figure 24). Other shellfish species, such as shrimp, lobster, and other crustaceans, are generally grown in nearshore ponds that require relatively little power, which is generally supplied from a nearby electrical distribution network. Bivalve shellfish operations currently are mostly nearshore, but there is interest in growing shellfish further offshore, perhaps in conjunction with finfish or seaweed operations. This approach could increase power needs to levels similar to those for finfish.

Figure 24. Shellfish farming. *Photo courtesy of Aquarium of the Pacific*

Seaweed Aquaculture

Seaweeds for human and animal consumption are typically grown nearshore at locations around the world. Like bottom-laid shellfish aquaculture, these operations require little power except for harvesting, monitoring, and transporting. However, there is increasing interest in growing seaweeds offshore in conjunction with finfish or seaweed operations, which could require increased power for shellfish growing operations, similar to those of finfish. Aspects of this market beyond seaweed for food is discussed in more detail in the marine algae chapter of this report.

Multitrophic Aquaculture

Although only in the development phase, there is interest in growing multiple species of organisms together offshore, including finfish, shellfish, and seaweeds. These operations would include pens of different sizes and shapes, including growing surfaces on the seafloor. Using waste from one trophic level to feed the next, these growing operations can increase the product yield to feed ratio dramatically. Power needs for multitrophic grow operations will resemble those for finfish aquaculture.

5.2.2 Power Requirements

Marine aquaculture operations require energy to power standard safety, navigation, and maintenance equipment; automatic fish feeders; refrigeration and ice production; marine sensors; recharging of AUVs; hotel loads for the crew living quarters (if the structures are manned); and for transport vessels.

Large offshore and nearshore salmon operations may include living spaces for the onboard crew or they may be unmanned. Typical power needs for offshore finfish rearing are electricity for automatic fish feeders; living quarters and other amenities for crew; refrigeration of product; compressed air for aerating the pens and scaring away predators; and mechanical or electrical power for operating sensors for water quality monitoring and predator harassment. Other needs include powering maintenance/harvest and supply vessels operating between shore bases and the pens, as well as smaller vessels operating within a pen farm.

Measurements of actual power demands of aquaculture operations are scarce. Toner and Mathies (2002) provide energy load estimates for three land-based aquaculture case studies: a Pacific oyster farm, a rainbow trout farm, and a marine fish farm grown under recirculation. The power loading for the Pacific oyster farm is low and consumption is similar to an average family home. For this operation, the purification system uses the most power (33.6 kWh/week), followed by the holding pond aerator (15.4 kWh/week). For the rainbow trout farm, the aeration system uses the most power (238 kWh/week), and for the marine recirculation farm, the recirculation system uses the most power (13,440 kWh/week).

Aquatera (2014) provides estimated requirements for energy and siting of modern aquaculture units. Although several of the estimates are based on freshwater operations, they are included here to provide a reference and general estimate (Table 5–Table 9).

Table 5. Energy Use for Salmon Hatchery Sites (Aquatera 2014)

Energy Process	Existing Fuel	Use Pattern	Criticality	Average Site Energy Usage
Heating	Kerosene	Potential 24 hr	Critical—Growth/ performance	No data collected
Lighting	Grid electricity with diesel generator backup	Potential 24 hr	Critical—Growth/ performance	433,182 kWh per year
Oxygenation		Potential 24 hr	Critical—Growth/ performance	
Pumping water		Potential 24 hr	Critical—Survival	

Other systems (e.g., monitoring equipment, alarms)		Potential 24 hour	Critical—Survival	

Table 6. Energy Use for Freshwater Salmon Loch Cages (Aquatera 2014)

Energy Process	**Existing Fuel**	**Use Pattern**	**Criticality**	**Average Site Energy Usage**
Feed Systems	Diesel generator (or in some cases, grid electricity)	Potential 24 hr	Critical—Growth/performance; could be down for a short while	74,781 kWh per year
Lighting		Potential 24 hr	Critical—Growth/performance; could be down for a short while	
Other systems (e.g., monitoring, equipment, alarms)		Potential 24 hr	Critical—Survival	

Table 7. Energy Use for Marine Salmon Sites (Aquatera 2014)

Energy Process	**Existing Fuel**	**Use Pattern**	**Criticality**	**Average Site Energy Usage**
Site office and buildings for offshore site (normal shore base)[5]	Grid electricity with possible diesel generator backup	Potential 24 hr		33,070 kWh per year
Feed system	Diesel generator burning marine diesel	Day	Critical—Growth/performance; could be down for a short while	17,136 gallons/yr marine diesel for feed barge This is equivalent to around 229,500 kWh per year
Underwater lighting		At night and seasonal depending on the day length and photoperiod required for the stage of growth	Critical—Growth/performance; could be down for a short while	

[5] A shore base for a land-based feed system would have higher energy requirements (up to three times more) than a normal shore base, but this will be balanced by the fact that there are no more requirements for a feed barge.

Energy Process	Existing Fuel	Use Pattern	Criticality	Average Site Energy Usage
Supplementary aeration		Used during medical treatments and during summer months	Critical—Growth/performance; could be down for a short while	
Acoustic deterrent devices	Battery recharged from diesel generator	Potential 24 hr	Critical—Predator control; could be down for a short while	
Navigational lighting	Usually standalone solar powered with battery	Charging during the day and on at night	Critical—Safety	
Other systems (e.g., monitoring equipment, underwater camera, alarms)	Battery/ uninterruptible power supply backup	Potential 24 hr	Critical—Growth/performance; could be down for a short while	

Table 8. Energy Use for Processing Facilities for Salmon Farming (Aquatera 2014)

Energy Process	Existing Fuel	Use Pattern	Criticality	Average Site Energy Usage
Lighting	Grid electricity	Daily	Critical—No natural light	1,964,705 kWh per year
Cooling/Refrigeration	Grid electricity	24 hr	Critical—Product safety	
Pumping stock	Grid electricity	Daily	Critical	
General equipment	Grid electricity	Daily	Critical	
Waste processing	Grid electricity	24 hr	Critical	

Table 9. Energy Input for Mussel and Oyster Farming (Aquatera 2014)

Input	Mussels	Oysters
Electricity (excluding depuration)	46 kWh per ton	716 kWh per ton
Fuel	28 liters per ton	48 liters per ton
Oil and grease	0.94 liters per ton	1.6 liters per ton

Fish farms typically go through a 2–3-year energy demand cycle, which is closely correlated to the amount of biomass present and the stage in the production cycle that has been reached. These energy demand cycles are not necessarily in sync with MHK resources (Aquatera 2014). The seasonal peaks of energy needs for fish farms may not correspond with the seasonal availability of MHK resources; however, by coupling MHK resources with energy storage systems, these intermittencies can be smoothed.

5.3 Markets

5.3.1 Description of Markets

In 2014, 73.8 million tons of fish were grown in global aquaculture operations with an estimated first-sale value of $160.2 billion, consisting of 49.8 million tons of finfish ($99.2 billion), 16.1 million tons of mollusks ($19 billion), 6.9 million tons of crustaceans ($36.2 billion), and 7.3 million tons of other aquatic animals including frogs ($3.7 billion) (FAO 2016) (Figure 25). World aquaculture production of fish accounted for 44.1% of total production in 2014, up from 31.1% in 2004 (Figure 26). When adding farmed aquatic plants, world aquaculture yield reached 101.1 million tons in live weight in 2014 ($165.8 billion), with farmed aquatic plants contributing 27.3 million tons ($5.6 billion). Although Oceania's (geographic region comprising Melanesia, Micronesia, Polynesia, and Australasia) share of aquaculture production in total fish production has declined in the past 3 years, all continents have shown an increasing trend in the share of aquaculture production, particularly in relation to capture fisheries (Figure 26). Also highlighted in FAO (2016) are the groups of species produced from aquaculture in 2014, and include 362 species of finfishes (including hybrids), 104 mollusks, 62 crustaceans, 6 frogs and reptiles, 9 aquatic invertebrates, and 37 aquatic plants.

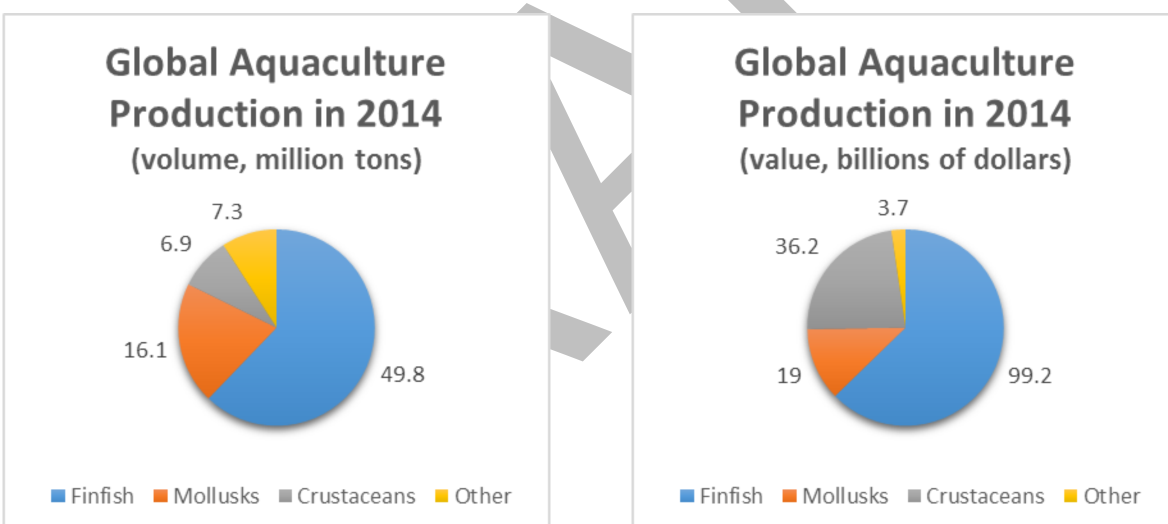

Figure 25. Global aquaculture production in 2014 in million tons (left) and billions of dollars (right). *Data from FAO (2016)*

Also highlighted in FAO (2016), China continues to be the major producer, providing slightly less than 62% of the world fish production in the past two decades. As the top aquaculture producer in 2014, China produced 58,798 thousand tons of total aquaculture. As the 17th top aquaculture producer in 2014, the United States produced 425.9 thousand tons of total aquaculture.

Marine aquaculture products are used as soil amendments as well as seafood, and this market is expected to grow significantly (Markets and Markets 2018). The global soil treatment market was valued at $24 billion in 2015 and is expected to reach $39.5 billion by 2021, growing at a compound annual growth rate of 8% between 2016 and 2021 (GlobalNewswire 2016). This market consists of organic amendments, pH adjusters, and pest and weed controllers (Cision 2013). The Asia-Pacific region is estimated to be the fastest-growing region in the market in terms of revenue and volume. Markets in China, India, and Brazil are also expected to grow due to the rising demand for food caused by population growth (Cision 2013).

FAO (2016) estimates that the growing demand for fish and fishery products will mainly be met by growth in supply from aquaculture, which they estimate to reach 102 million tons by 2025. Asian countries are anticipated to remain the main producers in 2025, with significant increases expected in Latin America and Africa.

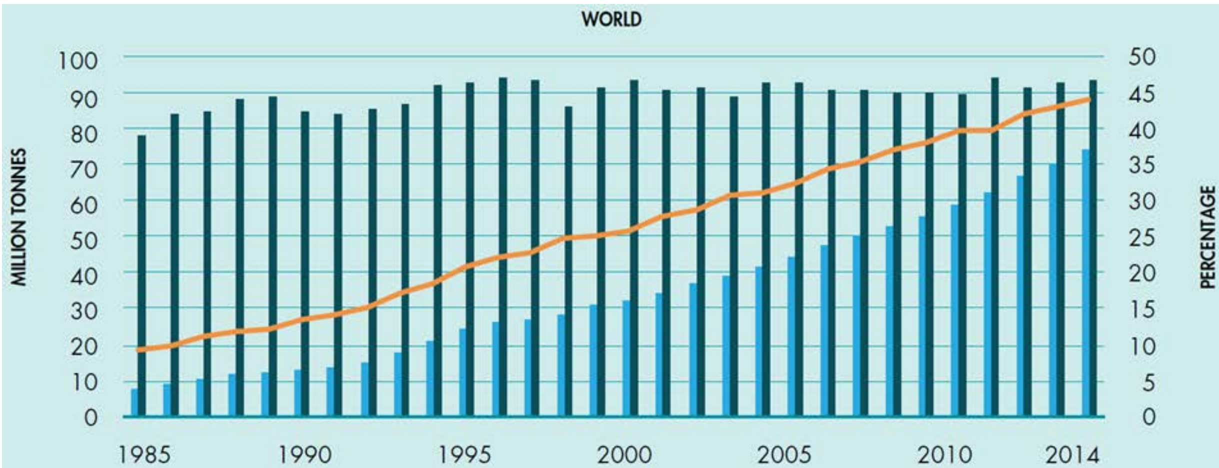

Figure 26. Global share of aquaculture in total production of aquatic animals. *Image from FAO (2016)*

The United States has the world's largest EEZ, which extends 200 nautical miles offshore and encompasses diverse ecosystems and natural resources. The U.S. EEZ spans more than 13,000 miles of coastline and contains 3.4 million square nautical miles of ocean, which is larger than the combined land area of all 50 states (NOAA 2011). Still, the United States imports approximately 90% of all seafood consumed domestically by value (NOAA 2015b), half of which is from aquaculture (NOAA 2017h). The United States would still remain approximately 1 million metric tons short of fulfilling the current domestic demand for seafood if all U.S. fisheries exports were consumed domestically. This deficit results in a $14 billion seafood trade gap between the United States and trade partners. Encouragingly, U.S. marine aquaculture is estimated to increase approximately 19% by 2025, with an approximately 33% increase in exports and 30% increase in imports (FAO 2016).

Market Drivers for Aquaculture and its Effects on MHK Markets

The main drivers for aquaculture production are the increased global supply of fish for human consumption due to population growth (FAO 2016). Aquaculture has been responsible for the growth in supply of fish for human consumption, as capture fishery production has been relatively static since the late 1980s (FAO 2016).

Three billion people rely on seafood as a primary source of protein and other nutrients essential for human health (Mozaffarian and Rimm 2006; NOAA 2015b). The United States Department of Agriculture and Food and Drug Administration) have urged North Americans to significantly increase their seafood consumption from the current level of one meal a week (United States Department of Agriculture and Food and Drug Administration, 2010, adding to the increased demand of fish for human consumption. Fresh seafood reaches only about 55% of American households, whereas one-third of U.S. households make up 80% of the sales (Luening 2017). With appropriate marketing and price points, there is significant room for growth and a further opportunity to augment seafood supplies with aquaculture products. Global fish consumption is expected to increase by 31 million tons to reach 178 million tons in 2025 as a result of rising incomes and urbanization, along with the expansion of fish production and improved distribution channels (FAO 2016). The main drivers affecting world fish prices are believed to be consumer income, population growth, costs of substitutes (e.g., beef, chicken, pork), and production costs (including fish feed and energy) (FAO 2016).

Currently, global aquaculture is dominated by low-trophic level species groups (e.g., seaweeds, carp, and bivalves) that need relatively simple equipment and limited husbandry. With the growing demand for higher-tropic level species (e.g., sea bass, salmonids, catfish, and shrimp), there will be a shift towards more intensive high-technology farming. This shift will drive increased energy needs for producers.

International requirements, pressure to reduce land footprints for food and other agricultural products, competition for scarce freshwater resources, and the expense of artificial fertilizers, the expanding aquaculture industry has strong incentives to seriously consider co-development with MHK resources where possible.

Customers

Shore-based aquaculture operations may be a potential user of MHK technologies as a viable energy source. For example, Fiander et al. (2014) discuss the potential for wave energy to pump water onshore at a low cost, enabling the development of profitable shore-based aquaculture methods. Scale-model and sea-based testing of this concept is currently underway at a shore-based aquaculture site in Lord's Cove, Newfoundland (Fiander et al. 2014). Tidal energy could also be a potential energy source for shore-based and inland aquaculture operations.

Half of U.S. seafood exports by value originate in developing countries; these nations could benefit from the use of MHK technologies to power aquaculture operations.

Small- to medium-sized aquaculture enterprises tend to be highly entrepreneurial and innovative and assume significant financial and technical risks (Agence Française de Développement et al. 2017). Their acceptance of higher-risk opportunities may encourage them to embrace the use of MHK power sources for their operations (Table 10).

Table 10. Simple Classification of Aquaculture Types (adapted from Agence Française de Développement et al. [2017])

	Commercial		**Subsistence-Oriented**	
	Industrial Aquaculture	**Small-to-Medium Aquaculture**	**Small-Scale Commercial Aquaculture**	**Subsistence Aquaculture**
Food and agriculture organization typology	Large-scale commercial	Small- to medium-sized enterprises	Small-scale aquaculture enterprises	
Production systems	Tanks (flow/recirculated), cages, pond arrays	Tanks (flow), ponds, cages	Mainly ponds, lagoons, tanks, small cages/pens	Ponds (rain-filled)
Labor	Salaried employees	Mixed, presence of permanent employees	Mainly family members; activities are integrated into other small-holder farming activities	
Capital	Shared ownership	Family or family groups	Family ownership only	

	Commercial		Subsistence-Oriented	
	Industrial Aquaculture	Small-to-Medium Aquaculture	Small-Scale Commercial Aquaculture	Subsistence Aquaculture
Management	Financial management with on-farm technical support	Mainly family members, with some professional assistance	Mainly family, possibly with some professional assistance	Family only
Market type	100% sales, including export	Mainly sales, both local and regional	Mixed sales and subsistence	Fully subsistence, little or no sales
Legal status	Operated as a limited company	Limited company or association, independent or none	Sole trader/farmer or none	Little or no legal status as operators
Access rights to land and water	Legal concession for use	Land owned by the operator or family or rented	Access to land through customary or family rights	

There are several U.S.-based aquaculture operations that may be interested in supplementing their power needs with MHK. Catalina Sea Ranch is the first offshore aquaculture facility in the United States, with a 100-acre aquaculture facility on the periphery of the San Pedro Shelf. In 2017, Catalina Sea Ranch was awarded funding through the Advanced Research Projects Agency-Energy (ARPA-E) program to conduct macroalgae research. Manna Fish Farms is proposing a 1.5-square-mile facility off the coast of Long Island. The company is planning to build and operate a commercial fish farm and research integrated multitrophic aquaculture with kelp and sea scallops. InnovaSea Systems, Inc. develops aquaculture technologies such as submersible pens. Customers of InnovaSea Systems, Inc. include openblue, Earth Ocean Farms, and Blue Ocean Mariculture.

5.3.2 Power Options

Aquaculture operations that require power have traditionally relied largely on diesel or kerosene generation from onboard generator sets with battery backup. Small shore-based aquaculture operations, particularly in developing countries, generally have little need for power, but in some cases, they may use battery power alone. More recently, some operations have used solar power. For example, low-cost solar thermal aerators are being developed to improve aquaculture in developing countries (Engineering for Change 2017). Additionally, the Lashto Fish Farm in Haiti uses 63 PV solar panels to generate approximately 15,000 watts to oxygenate fish tanks and charge and maintain battery systems (NRG 2018). In the United States, PV panels are being used to power a conventional floating upwelling system (FLUPSY) that is used to force-feed nutrient-rich water to infant shellfish (Energy Smarts 2013).

5.3.3 Geographic Relevance

The United States has the world's largest EEZ (NOAA 2015b), of which a significant portion could be used for aquaculture. Moreover, this vast amount of area shows substantial overlap with excellent MHK resources. Typically, offshore net pens and other aquaculture enclosures are sited in the calmest waters that can provide adequate flow to supply nutrients and clean water while still removing waste. These calmer waters may not coincide with the best wave or current resources. Tidal movement and energy generation is much more predictable than wave energy. Locations where aquaculture power needs and tidal energy generation potential might co-occur are limited, but some nearshore salmon farms (for example, in inlets in British Columbia, Canada) could benefit from replacing diesel power with tidal energy. The emerging industry is focused largely on large devices that operate optimally at tidal currents of 5–7 knots (1.5–3.5 meters per second); however, there are some devices designed to operate in lower current speeds, which could work well with aquaculture needs (Aquatera 2014). Most tidal devices have no surface expression or a low profile, allowing them to survive and compete with offshore wind in a similar manner to WECs. Tidal power, co-located with aquaculture installations, also has similar advantages to solar power for replacing diesel.

In the United States, 47% of aquaculture products are produced along the Pacific Coast, including Alaska and Hawaii; 15% in the Gulf of Mexico; and 38% on the Atlantic Coast (NOAA 2015b). DOE (2016) estimates that the potential wave power in U.S. waters is 2,640 TWh per year (almost 300 gigawatts [GW]) with the largest wave power resources located in Alaska and along the West Coast (Table 11). Although the magnitude of potential tidal power is significantly smaller than wave power (approximately 3 GW), it is concentrated and often in close proximity to major coastal load centers (DOE 2016b).

Table 11. Total Wave Energy Resource Potential by Region (Adapted from DOE 2013)

Total Wave Energy Resource Potential by Region	
Region	**Wave Energy Resource (TWh/yr)**
West Coast	590
East Coast	240
Alaska	1,570
Hawaii	130
Gulf of Mexico	80
Puerto Rico	30
Total	2,640

5.4 MHK Potential Value Proposition

Aquaculture can produce high-quality protein without the need for land, freshwater, or fertilizer. Marine aquaculture requires energy to power equipment like fish feeders and refrigerated product and to transport workers, supplies, and product between the shore and farms. This power is generally provided by diesel generation and occasionally by renewables. Replacing fossil fuels with MHK renewable energy will help the industry reduce harm to air and water quality.

The strongest drivers for moving aquaculture from fossil-fuel sources to renewables are likely to be those that encourage moving towards improving air quality and protecting water quality by avoiding petroleum spills, rather than primarily cost drivers for energy. Price point will be a factor but is less important than for many land-based markets. Although the price point among specific renewables will be a factor in the choice of power sources, factors that could favor MHK include the low profile of wave or tidal energy converters for survivability at sea and their low visual impact compared to offshore wind; the fact that MHK operations are unaffected by waves and spray that would reduce efficiency for other generating sources (e.g., solar); and around-the-clock generation that will be particularly effective at high latitudes (compared to solar). MHK could be a preferred power source for low-profile aquaculture pens in high latitudes relative to solar, because space to accommodate PV panels may not be available because of the low profile of the pens.

Many types of aquaculture facilities could be partially or wholly powered by wave energy. Most WECs aimed at the commercial market require a mean annual significant wave height greater than 1 m (Aquatera 2014). However, there are a number of WEC designs in development that could meet aquaculture needs, including several small devices that are designed to operate in less energetic conditions that may be suitable for fish farming (Aquatera 2014). WECs could be co-located with most aquaculture operations either offshore or nearshore, with devices built into breakwater structures for nearshore operations (Aquatera 2014) or moored offshore. Wave energy is a viable option for coastal-based aquaculture installations and for installations with high energy costs (Toner and Mathies 2002). Given the small power demands for most aquaculture installations, excess power could potentially be sent to the local grid.

There are a number of potential synergistic opportunities for co-location of aquaculture and wave energy devices (Aquatera 2014). Co-locating aquaculture and WEC infrastructure could save on installation and capital costs for both systems. Large-scale wave farms may provide shelter in their lee, which would be beneficial for aquaculture operations (Aquatera 2014). The low profile of most WECs is beneficial because of increased survival at sea, low visual impacts, and easier integration with aquaculture facilities, particularly compared with offshore wind. In competition with solar renewable power, wave energy can offer aquaculture power around the clock and in high latitudes in winter—both areas in which solar traditionally struggles.

5.5 Path to Market

5.5.1 Path to Market

In the United States, DOE and NOAA Aquaculture/Department of Commerce are the most likely sources for collaborative funding. As the process moves forward, private capital will be needed to supplement or replace government funding.

The success of supplying MHK power to aquaculture is tied up in the expansion and commercial success of the aquaculture industry. Finfish aquaculture for human consumption is likely to continue to be the highest-value market. Although great strides have been made in technologies and research for marine fish husbandry, there are still investments needed to improve feeds and survival, particularly for juvenile fish. Other investments are needed to ensure that nonseafood products from marine species can be optimized, including research into high-value uses for fish meal and fish oil, as well as specific chemicals from seaweed, such as alginates, agars, and other organic long-chain compounds.

There have been very few attempts to link MHK power outputs to aquaculture operations. Close coordination with aquaculture researchers and operators will be needed in order for the MHK industry to understand the needs and to establish opportunities for testing MHK devices in conjunction with aquaculture pens or other facilities. In-water tests of net pens and MHK devices will help to hone compatibilities between the systems and may help foster public acceptance of the new hybrid installations.

5.5.2 Potential Partners

Potential mission-driven partners for the MHK industry include those from the government sector as well as the private sector. Examples include NOAA Aquaculture and other U.S. Department of Commerce offices;

U.S. Fish and Wildlife Service (Game) departments; and agriculture departments in coastal states (for example, Alaska Department of Fish and Game, California Department of Fish and Wildlife, Oregon Department of Agriculture, Washington Department of Agriculture, and Hawaii Division of Aquatic Resources, Animal Industry Division).

A number of MHK and aquaculture companies have expressed interest in exploring linkages, whereas others are already engaged. MHK industry players already active in linking MHK to aquaculture, or with strong interests in doing so, include international companies, particularly in Scandinavia and Scotland, such as Wave Dragon, Albatern, and Waves4Power. U.S. companies include Atmocean and Columbia Power Technologies.

There are many aquaculture companies worldwide that are interested in this space, particularly in China, Korea, and the Philippines. U.S. companies with offshore aquaculture interests include Kampachi Farms, Catalina Sea Ranch, Manna Fish Farms, and Innovasea.

Table 12 highlights several projects and initiatives that link aquaculture and MHK resources.

Table 12. Review of Aquaculture and MHK Links

Wave Energy	
Project	Greenius project—Use of AlbaTERN wave energy devices on offshore aquaculture sites
As discussed in	Aquatera (2014)
Location	Scotland
Description	This project aims to identify the power requirements of offshore aquaculture sites, identify the WEC sizes required from the WaveNET modular devices being developed by AlbaTERN to meet these requirements, and provide the necessary technical inputs to allow the physical and electrical incorporation of wave energy devices into an offshore aquaculture site, alongside other elements, such as power storage and backup power, to deal with wave resource variability. The regulatory and environmental impacts will also be investigated, along with the commercial case for deploying such devices, and how the financial risks should be divided between site operators and device developers, with a consideration of the risks associated with such deployments and how appropriate mitigation can be developed to control these risks.
Reference or link	Not available
Status	Feasibility study
Project	Land-Based Multitrophic Aquaculture Research at the Wave Energy Research Centre
As discussed in	Fiander et al. (2014)
Location	Newfoundland

Description	The research project being conducted by College of the North Atlantic in Lord's Cove, Newfoundland, has the overall goal of developing a sustainable land-based aquaculture system using wave energy. Development of the pump is occurring concurrently with the design, installation, and commissioning of a pilot-cascaded Integrated Multitrophic Aquaculture facility in Lord's Cove. In this pilot farm, the effluent from the finfish (the only organisms receiving external feed input) is directed to sea urchin production tanks. From there, water flows to scallop production tanks and, finally, algae culture. The algae produced is fed to the urchins, which consume this and organic sediment coming from the finfish. The suspended organic particulate in the urchin effluent will nourish the sea scallops, and the algae will reduce the dissolved inorganic load before the water is returned to the ocean. Until the wave pump development is complete, water for the farm is being entirely supplied by electric pumping. Scale-model and sea-based prototype testing of the wave driven pump is currently being undertaken.
Reference or link	https://www.cna.nl.ca/Research-And-Innovation/pdfs/WERC-Aquaculture-Facility.pdf
Status	Scale-model and sea-based prototype testing in progress

By developing and adapting MHK devices to provide power for aquaculture operations, the MHK industry will move further along the route to commercial-scale development, while gaining much-needed revenue. Although many of the devices that are most useful for aquaculture adaptation—particularly WECs—are likely to be small, there are likely to be some large aquaculture operations that could use the power from prototype-scale devices. The testing and experience at sea will assist with the pathway to larger devices.

Similar MHK devices to those used for aquaculture will also be useful for powering the growth of very large macroalgae farms used to produce biofuels at sea and devices applicable for powering navigation markers and for recharging underwater vehicles and autonomous ocean observation sites.

6 Marine Algal Biofuels

6.1 Opportunity Summary

Algae refers to a diverse group of organisms including macroalgae, microalgae, and cyanobacteria ("blue-green algae"). Macroalgae (seaweed) and some microalgae can be grown at commercial scale at sea to provide biofuels, animal feed, and other coproducts. Algae have high levels of structural polysaccharides and low concentrations of lignins that can be made into feedstocks for production of liquid biofuels. Many algal species contain organic chemicals that are used in many industrial and agricultural processes ranging from food processing to supplementing animal feed. Current projected costs for marine algae are several times terrestrial biomass, but improvements in yields, scale, and operations could see algae become cost competitive with terrestrial crops (NREL 2017). Seaweed farming has been growing rapidly and is now practiced in about 50 countries (traditionally in Japan, the Republic of Korea, and China). Further, 27.3 million tons of aquatic plants (seaweed included) were harvested in 2014, totaling $5.6 billion (FAO 2016). Although many small algal cultivation sites need little power, the larger marine farms proposed for production of biofuels will need energy for harvesting, drying, monitoring, and maintenance activities, as well as for maneuvering and buoyancy controls for larger farm structures. These power needs could be satisfied wholly or in part by energy generated from MHK devices by designing MHK systems into the growing and harvesting systems to provide off-grid power needs.

6.2 Application

6.2.1 Description of Application

Microalgae and Cyanobacteria

Microalgae consist of unicellular plants that can be grown rapidly under natural or artificial light. Cyanobacteria are unicellular organisms that sit at the junction of bacteria and plants; they can be grown in a manner similar to other microalgae. Most microalgal operations are still under development, favoring growth in raceways or ponds on land. However, there has been some interest in growing microalgae in containers in nearshore waters, likely in conjunction with existing facilities (Roesijadi et al. 2008). Commercial products derived from microalgae and cyanobacteria include products for human and animal nutrition, polyunsaturated fatty acids, antioxidants, coloring substances, fertilizers, soil conditioners, and a variety of specialty products including bioflocculants, biodegradable polymers, cosmetics, pharmaceuticals, polysaccharides, and stable isotopes for research purposes (DOE 2016a).

Microalgae may be grown at sea in semiporous containers nearshore, largely to save space on land, reduce the need for supplemental artificial nutrients, and take advantage of natural sunlight for growth (Hoffman et al. 2017). However, these methods are in a very early stage of R&D and have not yet established the need for an power alternative to the electrical grid or waste energy from other industrial processes (Figure 27).

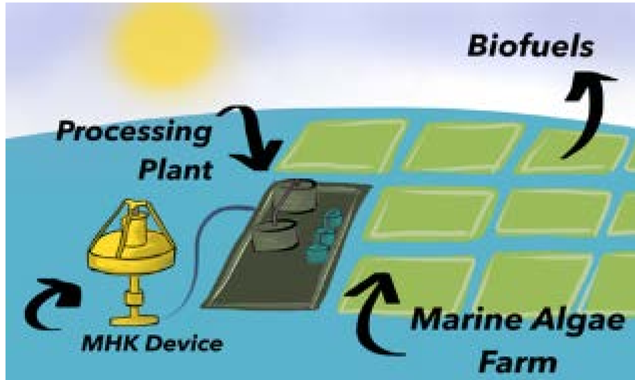

Figure 27. MHK application overview for macroalgae farm.
Image courtesy of Molly Grear, PNNL

Macroalgae

Macroalgae are typically cultivated off-shore or near coastal facilities (DOE 2016a). As described in Titlyanov and Titlyanova (2010), commercial cultivation of seaweeds may be carried out in a seabed, on lines and ropes, and on nets. For seabed cultivation, pieces of thalli are anchored to sandy or muddy bottoms of shallow lagoons and bays and are harvested several months after planting. The crop may be either completely or partially collected, with 10% to 40% of the crop being left to provide material for the next cultivation cycle. Seaweeds may also be grown on the seabed enclosed within fences, without being fixed to the bottom. For line/rope cultivation, plantlets are fixed on ropes suspended at the surface of the water or several meters below the surface. The ropes may be several to hundreds of meters long and are fixed to buoys or rafts, which are anchored to the bottom. The ropes are arranged in parallel rows at intervals from 10 centimeters to 1 meter apart. For net farming, seaweed may be cultivated using nets or racks made of bamboo poles, with ropes attached with algal spores or transplanted sporelings stretched between. Small flat-bottom boats are used to manually insert the sporelings on the ropes on the surface. The ropes sink deeper as the seaweeds grow and become heavier.

Products derived from macroalgae include food for human consumption, algal hydrocolloids (e.g., thickening agents such as agar, alginate, carrageenan), fertilizers and conditioners, animal feed, and macroalgal biofuels (DOE 2016a). Highly cultivated macroalgae (seaweed) crops for human consumption include *nori* (*Porphyra spp.*), *wakame* (*Undaria pinnatifida*), and *kombu* (*Laminaria japonica*) (FAO 2009).

DOE's ARPA-E MARINER program is funding a project in 2018 to develop several alternate means of growing macroalgae at sea in sufficient quantity to create feedstock for biofuels, with the intent of producing other value-added products along the way. In addition to funding a series of technical tools to assist with the growing and harvesting operations (e.g., numerical modeling for siting; autonomous vehicles for hauling product; sensors and AUVs for determining water quality, light, and nutrient availability, and measuring growth; and selective breeding and genomics technologies), APRA-E MARINER expects to move the successful growing and harvesting operations toward commercial viability.

Large macroalgal farms for human and animal consumption are commonplace in Asia, Oceania, and parts of northern Europe (OIST 2016; Seakura 2018; Seaweed Energy Solutions 2018; Zeewaar 2018). Although less common, plans are now underway to cultivate large amounts of macroalgae at sea for biofuel production in the United States and other countries. There are no large operational macroalgae farms for biofuel production, although tests were made at sea during the 1970s off California (ARPA-E 2018). Although still in the early R&D stage, it is clear that macroalgae farms aimed at growing biomass for biofuels at sea will be large (covering hundreds to thousands of hectares) and will require infrastructure and power that resemble large seafood aquaculture operations at sea (ARPA-E 2018). Smaller macroalgae farms may also be created in the open ocean to grow smaller volumes of product for extraction of high-value chemicals and other products (Figure 29).

Biofuels

Growing microalgae and macroalgae can provide several types of biofuels, including biogas produced by anaerobic degradation of biomass; biodiesel produced from lipids accumulated in cells of algae; alcohol; hydrogen from photobiological transformations; or algae biomass that may be used for direct combustion (Dębowski et al. 2013). The average photosynthetic efficiency is 6%–8%, which is much higher than that of terrestrial biomass, which is 1.8%–2.2% (Chen et al. 2015). Additionally, the electricity produced from biogas derived from macroalgae can be cost competitive with solar thermal, solar PV, and biomass-generated electricity (Ghadiryanfar et al. 2016). Algal biomass is compatible with an integrated biorefinery that produces a variety of fuels and valuable coproducts (DOE 2016a). Ethanol, biodiesel, biogas, renewable gasoline, diesel, and jet fuels are all possible products from algal biomass (DOE 2016a). There is a particular need for long-chain hydrocarbons, which are not readily available from land-based biofuels. In addition, the supply of feedstock for biofuels must be of consistent quality and availability to avoid price volatility and attract consumers.

Figure 28. Kelp grown on a longline. *Image courtesy of Creative Commons*

Figure 29. Line cultivation of macroalgae. *Image courtesy of Creative Commons*

Chemicals and Bioplastics

Microalgae contain a wealth of organic compounds that are important for the production of certain antibiotics and pharmacologically active compounds like docosahexanoic acid (Oilgae 2017). The pigments found in algae (e.g., carotenoids, phycobilins, and chlorophylls) can be used as coloring agents in natural dyes for food, cosmetics, and research, or as pigments in animal feed (DOE 2016a). Other products include agar, which can be used as a food ingredient, in pharmaceuticals, and for biological/microbiological purposes; alginate, which can be used in textile printing, as a food additive, in pharmaceuticals, and for medical purposes; and carrageenan, which can be used as a food additive, in pet food, and in toothpaste (DOE 2016a). Microalgae have also been used to produce antioxidants for the health food market, the most prominent being β-carotene from *Dunaliella salina* (DOE 2016a). Algae have also been used to make bioflocculants and biodegradable polymers (DOE 2016a).

Human Food and Animal Fodder

Demand for macroalgae as human food is strong in many countries in Asia and Oceania and is developing in the Americas and Europe. The residual biomass from macroalgae, a result of postprocessing for other uses, can serve as an important animal fodder supplement. Moreover, preliminary tests show promising results on methane reduction from cattle that are fed small additional amounts of specific algal species (Kinley et al. 2016). Algae can also be used in fish feeds as an alternative to fishmeal (The Fish Site 2013).

Other

Other products produced from algae include fertilizers, bioactive compounds, polysaccharides, and stable isotopes for research (DOE 2016a).

6.2.2 Power Requirements

Because the largest operating macroalgae farms are nearshore and rely primarily on human labor for seeding and harvesting, the power requirements for large-scale macroalgae growing and harvesting operations at sea are not known. These could include operations that use alternating-current or direct-current power. However, the requirements for power will likely resemble those for aquaculture operations, including energy to power safety, navigation, and maintenance equipment; automated fish feeders; pumps for nutrients and structure controls; refrigeration and ice production; drying operations; marine sensors; recharging of AUVs; hotel loads for living quarters (if the structures are manned), and transport vessels (Roesijadi et al. 2008). In most cases, there will be a need for on-site energy storage to smooth peaks from intermittent renewable power production and to provide continuous power. Troell et al. (2004) estimate that the energy performance of seaweed farms is comparable to sheep and rangeland beef farming.

Like aquaculture operations, macroalgae grow and harvest operations will not be dependent on consistent, reliable power generation on a daily or monthly basis. Battery or other storage can smooth and provide power on demand to meet the reasonably small power needs of aquaculture operations.

Globally, many small, nearshore algal cultivation sites use human labor and require little power. There is no reason to assume these small operations will not continue in many parts of the world. These nearshore and land-based growing sites for microalgae biofuels are generally co-located with other industrial operations, using waste heat from those operations or power directly from the local electrical distribution network. Large macroalgae farms that are planned for production of biofuels will require energy for seeding, harvesting, drying, monitoring for water quality, and maintenance activities. These power needs can be substantial and could be satisfied wholly or in part by energy generated from MHK devices.

6.3 Markets

6.3.1 Description of Markets

Aquatic plant farming (most of which is seaweed) has been growing rapidly and is now practiced in about 50 countries, with China, Indonesia, Philippines, Republic of Korea, Japan, and Democratic People's Republic of Korea as the dominant producers (FAO 2016; Ghadiryanfar et al. 2016). Indonesia is the major contributor to growth in aquatic plant production in the world, specifically tropical seaweed species. Indonesia's share of the world's farmed seaweed production increased from 6.7% in 2005 to 36.9% in 2014. Globally, approximately 28.5 million tons of seaweeds and other algae were harvested in 2014 for a number of purposes, including human consumption (Table 13; FAO 2016). In 2004, the combined microalgae and macroalgae global market was estimated at a $10–$12 billion (Oilgae 2017). Six macroalgae species and one microalgae species contributed most of the global aquatic plant production in 2014 (Table 14; FAO 2016).

Table 13. Global Macroalgae Production by Nation

Country	2014 Marine Algae Production (thousand tons)
China	13,326
Indonesia	10,077
Philippines	1,549
Republic of Korea	1,087
USA	425[6]

Table 14. Global Macroalgae Production by Aquatic Plant Type

Marine Algae Species	2014 Production (thousand tons)
***Kappaphycus alvarezii* and *Eucheuma* spp.** (red macroalgae)	10,992
Laminaria japonica (kelp)	7,655
***Gracilaria* spp.** (red macroalgae)	3,752
Undaria pinnatifida (kelp)	2,359
***Porphyra* spp.** (red macroalgae)	1,806
Sargassum fusiforme (brown macroalgae)	175
***Spirulina* spp.** (blue-green microalgae)	86

The leading vendors of macroalgal products worldwide in 2016 were Cargill, DuPont, Group Roullier, Irish Seaweeds, and Qingdao Gather Great Ocean, Algae Industry Group (Technavio 2017).

Marine Algae Market Segments

The potential products from macroalgal growth at sea can serve several end markets, including biofuels, industrial chemicals and bioplastics, and human food and animal fodder.

Biofuels

The current worldwide production of biofuels is approximately 1,324 million tons of oil equivalent[7] annually (International Energy Agency 2017); for context, the U.S. goals for natural gas production are 691 million tons of oil equivalent (World Energy Council 2017). In 2016, the global biofuel market was valued at $168.18 billion and is projected to reach $246.52 billion by 2024 at a compound annual growth rate of 4.92% (Biofuels International 2016).

Chemicals and Bioplastics

The global value per annum of algal hydrocolloids, specifically agar, alginate, and carrageenan, is estimated to be $132 million, $213 million, and $240 million, respectively. The antioxidant β-carotene, produced from microalgae, had an estimated $392 million in sales in 2010 (DOE 2016a). The natural food colors market in North America is expected to expand between 2014 and 2020, with a compound annual growth rate of 7.1%,

[6] All aquaculture production.
[7] A tonne of oil equivalent (toe) is a unit of energy defined as the amount of energy released by burning one tonne of crude oil

reaching \$441.4 million by 2020 (DOE 2016a). The global carotenoid market value (in general) was \$1.5 billion in 2014 (DOE 2016a).

Human Food and Animal Fodder

The global value of seaweed per annum for human food is estimated to be \$5 billion, and the global value for animal feed is estimated to be \$5 million (DOE 2016a). DOE (2016a) estimates that the market size for specialty products such as bioactive compounds, polysaccharides, and stable isotopes for research is likely to be very small due to their specialized applications (DOE 2016a).

Other

Growing and harvesting systems for microalgae biomass used for biogas production could be integrated with wastewater treatment facilities (Dębowski et al. 2013). This would allow nutrient-rich wastewater to be used as a culture medium for algal growth, resulting in reduced costs for water and nutrient supplements.

Microalgae could perhaps be harvested from naturally occurring marine algal blooms (DOE 2016a); however, these blooms are unpredictable, and care would need to be taken not to upset the ecological balance in the harvest waters.

The market for marine algae is divided into biomass from microalgae, which will likely also be derived from macroalgae in the future; specialized chemicals for the food products, cosmetics, and pharmaceutical industry; soil additives and fertilizers; animal fodder; and other end products as shown in Table 15 (Nayar and Bott 2014). In each market, there is expected to be significant growth (Transparency Market Research 2018).

The "first generation" biofuels, including ethanol, biodiesel, and pure plant oil, are the most common types of biofuels produced but are considered unsustainable (Ghadiryanfar et al. 2016). As a result, "second generation," or advanced biofuels—made from lignocellulosic biomass and agricultural waste—have been a focus of recent production. These biofuels have the potential to compete with food crops for land and freshwater. Algal biofuels are considered "third generation," and macroalgae grown at sea will not compete with land-based foods and crops. Algal-based biofuels can serve as a viable fuel alternative to petroleum-based fuels. In the United States, the Energy Independence and Security Act of 2007 established the Renewable Fuels Standard, which mandates the blending of 36 billion gallons of renewable fuels by 2022, of which only 15 billion gallons can be produced from corn-based ethanol (DOE 2016a). Only 5% of the fuel used in the transportation sector in 2014 came from biofuels, but that percentage is expected to grow in the future (DOE 2016a). This presents a significant opportunity for biofuels derived from algae to help meet these longer-term needs of the Renewable Fuels Standard and impact the energy supply for transportation fuels.

Table 15. Global Production of Macroalgal Products Was Estimated in 2014 (Nayar and Bott 2014)

Product	**Industry**	**Specific Uses**	**Market Value** (million \$USD)
Carrageenan	Food products	Gelling and thickening agent, specifically for dairy and meat	527
Alginate	Food products	Food thickening agent Substrate	318
	Textiles	Fabric color paste	
	Pharmaceuticals	Tablet compounds	
	Cosmetics	Thickening agent and moisture retainer	
	Metallurgy	Flux binder for welding rods	

Product	Industry	Specific Uses	Market Value (million $USD)
Agar	Food products	Food gelling and thickening agent	173
	Pharmaceutical industry	Laxatives	
	Biomedical industry	Laboratory growth medium	
	Dentistry	Impression material	
Soil additives	Agriculture	Soil conditioning	30
Fertilizer	Agriculture and residential plantings	Soil additive, growth enhancement for plants	10
Seaweed meal	Agriculture and residential plantings	Soil additive	10
Miscellaneous			5
TOTAL			1,073

In the pharmaceutical industry, the significance of marine algae-derived drugs is expected to increase (Transparency Market Research 2018). The increasing preference for veganism and nonanimal-derived products drives the marine algae extracts/products market (Transparency Market Research 2018). Additionally, because of its advancement in healthcare and biotechnology, North America and Europe are likely to present lucrative opportunities in the marine extract/product market (Transparency Market Research 2018).

Linkages between MHK and aquaculture facilities will require government investment to encourage early-stage R&D that can create transformative results. In the United States, DOE and DOD are the most likely sources for collaborative funding. As the process moves forward, private capital will be needed to supplement government funding.

For macroalgae production to become a viable industry, growers will need to improve biomass yields and reduce costs through scaling, reducing labor needs via automation, and optimizing logistics.

Potential Customers

The potential list of customers of marine algae cultivated using MHK is extensive. The potential customers within the biofuels industry include those companies interested in algal-based fuels, such as military, aviation, and commercial transportation enterprises. Within the chemicals and bioplastics industries, potential customers include companies related to pharmaceuticals, cosmetics, health food and supplements, and fertilizers. For seaweed grown for human consumption, potential customers include specialty food manufacturers. For seaweed used in animal fodder, potential customers include animal feed manufacturers.

6.3.2 Power Options

As there are no macroalgae biofuel farms currently in existence, there is no competitive power source to displace; the market is undeveloped, and MHK could have a first-mover advantage. MHK has the advantage compared with solar and offshore wind because biofuel installations require low-profile infrastructure, which will avoid shading the algae from sunlight, provide for more survivability at sea, and reduce visual impacts. With proposals for free-floating biofuel operations, the MHK industry is in a unique position to design devices that can accommodate the farms.

Offshore wind and solar energy could potentially be competitors of MHK for algae-based biofuels, depending on the location of the production site. Offshore and land-based wind and solar installations have been proposed for integration into coastal and inland photoautotrophic microalgae sites (DOE 2016a). These renewable sources could supplant or supplement electrical grid or other industrial sources of energy for drying microalgae (DOE 2016a); however, depending on the location of the site, tidal energy could also be a potential alternative to provide additional energy for the drying process.

6.3.3 Geographic Relevance

Globally, areas of the South Atlantic and Gulf of Mexico, as well as the West Coast, Alaska, and Hawaii and other Pacific Islands have been identified as preferred geographic regions for macroalgal biomass production, with portions of Hawaii, California, Arizona, New Mexico, Texas, Louisiana, Georgia, and Florida as potential areas with adequate sunlight for optimal open cultivation of microalgal biomass within the United States (ARPA-E 2018; DOE 2016a). Additionally, areas of the southwestern United States have been identified as the most suitable for closed systems, such as photobioreactors (Figure 30; Quinn et al. 2011 DOE 2016a). The global seaweed market is projected to reach a value of $17.59 billion by 2021 (Algae World 2016).

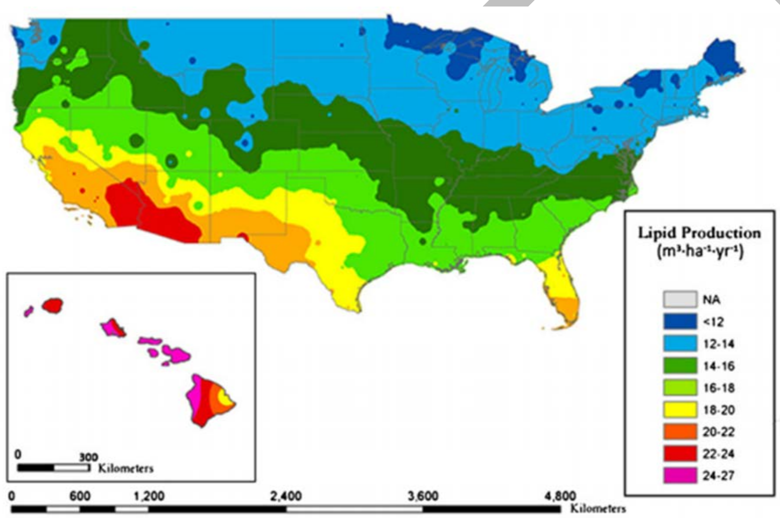

Figure 30. Modeled microalgae lipid productivity potential in the United States. *Image courtesy of Quinn et al. (2011)*

Based on concerns about the potential environmental effects of harvesting natural populations of seaweed nearshore, many countries have developed regulations limiting natural harvests (DOE 2016a). By moving offshore, seaweed farms could alleviate nearshore environmental pressures and establish larger-scale operations, which will greatly expand the market opportunities. In particular, European, Canadian, and Latin American seaweed industries rely on harvesting natural resources (Buschmann et al. 2017).

6.4 MHK Potential Value Proposition

MHK systems can be integrated into growing and harvesting systems to provide off-grid power needs. By replacing fossil fuels with MHK renewable energy, the biofuels industry will reduce harm to air and water quality, reduce supply chain and transport risks, and potentially reduce operational costs. MHK devices at sea will have a durability advantage over other renewable and fossil-fuel sources of power. Biofuels grown at sea will bypass future constraints on terrestrial biomass, such as competition for land and freshwater availability, nitrogen fertilization, and logistics.

MHK has the advantage compared with solar and offshore wind for offshore macroalgae growth because biofuel installations require low-profile infrastructure that avoids shading the algae from sunlight, avoids the detrimental effects of salting of PV panels and corrosion of wind components, provides for more survivability at sea, and reduces visual impacts. With proposals for free-floating biofuel operations, the MHK industry is in a unique position to design devices that can accommodate the farms. The proposed offshore locations for macroalgae farms could benefit most from wave energy.

Coinciding with aquaculture opportunities, macroalgae growing operations could be sited along most coastlines and offshore waters of the United States. Typically, offshore operations would favor waters where there is an abundant nutrient supply and sunlight. These waters could coincide with good wave resources as well as energetic ocean currents. Technologies designed to convert wave or ocean current energy could likely be adapted for both anchored and free-floating growth lines. There are good tidal resources at locations in the United States that coincide with some nearshore operations. Growing seaweeds for food, fibers, and other products requires adequate light and high concentrations of nutrients, so high-latitude growing operations are favored.

With the world's largest EEZ (NOAA 2015b), much of which is viable for growing microalgae and macroalgae, the United States has the potential to become a strong leader in growth at sea for biofuels. Many of these waters overlap with significant MHK resources that could develop systems in conjunction with the growing and harvesting operations.

6.5 Path to Market

6.5.1 Path to Market

Increased demand for cleaner fuels, including air-quality mandates and petroleum spill protections, will spur biofuel markets. High-value coproducts including complex polysaccharides like algin, laminarian, mannitol, fucoidan, and agar can be extracted from macroalgae, leaving the residue for animal feed. The market for these coproducts may spur expansion of macroalgae growth at sea, allowing for early MHK markets.

Although algal biofuels offer great promise as a source of U.S. transportation fuels, the state of technology for production is continuously maturing with ongoing investment. Additional research, development, and demonstration are needed to achieve widespread deployment of affordable, scalable, and sustainable algae-based biofuels (DOE 2016a). For macroalgae specifically, there needs to be considerable scale-up from current activities, improvement in strain selection, and major technological improvements in efficiency of water movements for microalgae to make a substantial contribution to the biofuels marketplace (DOE 2016a).

Ideally, the macroalgae for biofuels and the MHK industries could develop together, but this will require careful attention and collaboration to ensure that the needs of both industries are met, including matching power resources, market needs, growing seasons, and consumer-demand cycles that will drive energy needs. MHK industry and researchers must closely track the design and development of the offshore macroalgae grow and harvest operations underway with ARPA-E MARINER funding to determine power needs and to understand the requirements for integrating MHK devices into the anchored or floating lines and enclosures and the constraints that seaweed growers are operating under for siting locations and deployment timing. Efforts to prove that MHK devices can be adapted for less-energetic areas (e.g., slower currents, reduced sea states) may become important, allowing for additional provision of MHK energy to a broader base of macroalgae growing locations. As the first macroalgae operations are deployed, it would be useful for MHK developers to design and deploy small-scale devices to test the feasibility and interface for providing power. The development of MHK as a power source for offshore aquaculture operations will provide important direction for integration with the biofuels grow operations.

6.5.2 Potential Partners

Potential mission-driven partners for the MHK industry include government funding sources like DOE ARPA-E MARINER, NOAA Fisheries, U.S. Coast Guard, and the DOD—specifically the Defense Advanced Research Projects Agency, the U.S. Air Force, the U.S. Navy, and the U.S. Army.

Private companies and consortia include Sustainable Bioenergy Research Consortium (Boeing). Energy companies include Shell, BP, Exxon-Mobil, and commercial airlines.

Other private companies may also see the expansion of biofuel stocks from the ocean as opportunities for partnerships, including the transportation industry, especially commercial air carriers (e.g., Southwest, Alaska, and South African Airlines); airplane and turbine manufacturers (e.g., Boeing, Airbus, Rolls-Royce, and General Electric); ground and sea transportation companies (e.g., Maersk, Wartsila, Cummings, and CAT); biofuel refineries; chemical manufacturers (e.g., DuPont, Ashland, and Tata Chemicals); food and feed manufacturers (e.g., Whole Foods Cargill, BioProcessAlgae, TerraVia, and Earthrise Nutritionals); and pharmaceutical companies (e.g., Algae to Omega, Florida Algae, and Amgen).

A number of fuel refiners and catalyst developers (e.g., UOP, Chevron, Eni, Statoil, Total, and Neste) have begun to explore converting vegetable oils and waste animal fats into renewable fuels, whereas Neste, UOP, Syntroleum, Eni, Sinopec, AltAir, and Valero/Diamond Green Diesel have built large-scale commercial refineries to produce green diesel (DOE 2016a). These organizations may also serve as potential partners for an algae farm or MHK developer pursuing the market.

By developing and adapting MHK devices to provide power for macroalgae growth for biofuels operations, the MHK industry will move further along the route to commercial-scale development while gaining much-needed revenue. Although MHK devices most useful for macroalgae growth adaptation are likely to be small, there may be some large aquaculture operations that could use the power from full-scale devices. The testing and experience at sea will support progress toward larger devices.

Similar MHK devices to those used for macroalgae growth operations will also be useful for powering the growth of aquaculture farms and devices for powering navigation markers as well as recharging underwater vehicles and autonomous ocean observation sites.

7 Seawater Mining: Minerals and Gasses

7.1 Opportunity Summary

Seawater contains large amounts of minerals, dissolved gases, and specific organic molecules that can play a role as energy sources or in other industrial uses. Some of the most valuable minerals include the 17 rare earth elements (REEs), precious metals, lithium, and uranium. Although land-based minerals are concentrated in specific geologic formations and geographic areas, seawater minerals are generally distributed evenly in seawater with some higher concentrations near continents as a result of terrestrial runoff and interaction with margin sediments. These minerals can be recovered from seawater using adsorption methods that do not require filtering vast amounts of seawater. Extracting minerals from seawater is a more environmentally friendly enterprise than terrestrial mining (Diallo et al. 2015; Parker et al. 2018). Moreover, seawater extraction will not require fresh water for processing nor create volumes of contaminated water and tailings for disposal. Most rare earth elements, as well as uranium and other minerals used in the United States, are imported from other nations, which raises supply chain concerns for both industry and national security. Dissolved gases like hydrogen can become important sources of energy storage and will be used in the future for maritime transportation. An energy source is needed to extract minerals or dissolved gases, preferably one that is locally generated, reasonably consistent, and that does not greatly add to the complexity or maintenance needs of the extraction operation. MHK power harvested at sea has the potential to meet seawater mining needs to power an electrolyzer, perform electrochemical extraction, mechanically drive an active adsorbent exposure system, and power on-site logistical needs (Figure 31).

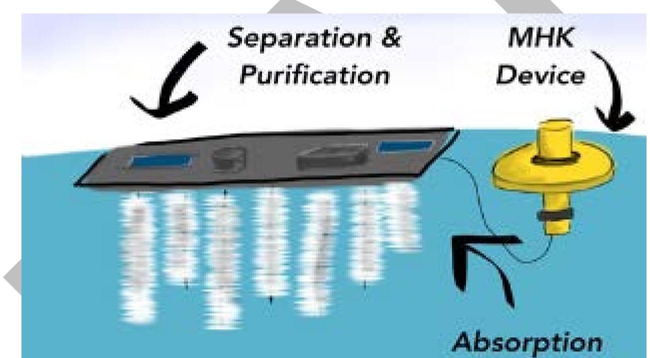

Figure 31. Marine and hydrokinetic application overview for mining seawater. *Image courtesy of Molly Grear, PNNL*

7.2 Application

7.2.1 Description of Application

The total mass of many critically needed elements is greater in seawater than in the Earth's crust, including the 17 REEs and several dissolved gases. Although land-based minerals are concentrated in specific geologic and geographic areas, many seawater minerals are generally distributed evenly in seawater. Exceptions include elevated concentrations of some elements (e.g., Zn, Cd, Cu, Ni, Co, and some REEs) below 500 m, which is caused by interactions of the metals with primary production processes and input from deep-sea hydrothermal vents. Many elements are also elevated near the ocean margins from riverine runoff or interactions between seawater and margin sediments.

Most REEs and valuable minerals used in the United States, including uranium, are imported from other nations (Diallo et al. 2015). This reliance on foreign supply constitutes an industrial and national security concern (Congressional Research Services 2017). Some of these REEs could be extracted from seawater by passive adsorption or electrolysis, decreasing dependence on foreign suppliers and improving industrial supply chain resiliency. Ammonia and hydrogen are other potential products that could be produced through this method (European Marine Energy Center [EMEC] 2017a).

Power will be needed for harvesting minerals from seawater, deploying and retrieving long adsorbent films, extracting elements via electrochemical mechanisms or electrolysis, and powering safety and monitoring equipment, as well as potentially powering the machinery or technology needed to remove elements from adsorbent material. Existing seawater extraction technologies are mostly in the R&D stage but look promising for co-location and pairing with offshore energy technologies.

To extract elements in low concentrations from seawater requires processing large volumes of water, which can be energy-intensive and potentially cost-prohibitive (Bardi 2010). The most economical approaches to date are those that use passive adsorption technology, thereby avoiding the energy needed to process or pump large volumes of seawater (Kim et al. 2013; Diallo et al. 2015). In a passive extraction system, the natural ocean currents deliver fresh seawater to the adsorbent for extraction of the elements of interest. Typical passive adsorbent systems are envisioned as farms resembling a kelp forest, deployed and retrieved by a work vessel (Figure 32).

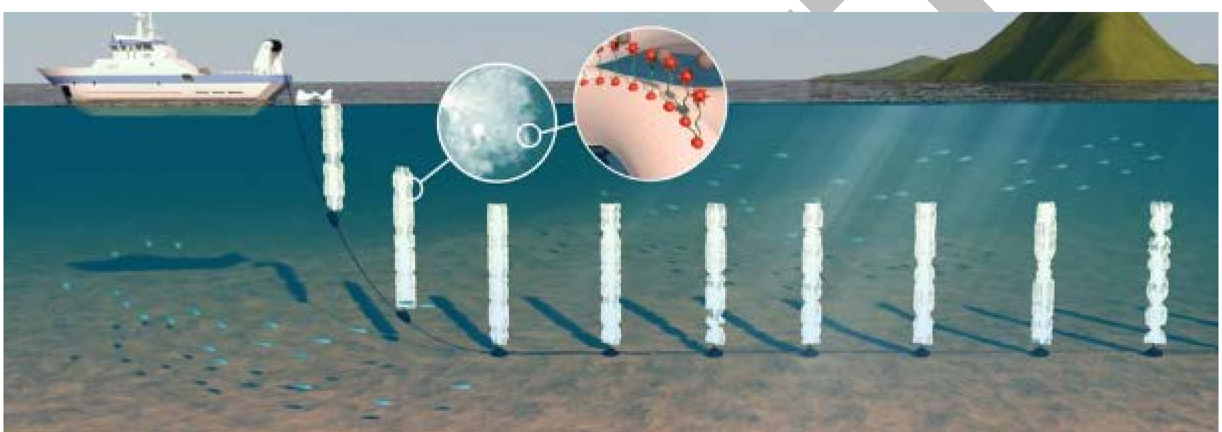

Figure 32. Conceptual deployment of amidoxime-based polymer adsorbent in coastal seawater for the passive extraction of uranium and other elements from seawater. *Source: http://uraniumfromseawater.engr.utexas.edu/*

The cost of performing the extraction process can be significantly reduced by linking the extraction technology to an on-site power source such as marine renewable energy. Three examples of how a local marine power source could be linked to a seawater mineral extraction scheme are described below. These applications are focused around uranium extraction, as this is the technology that has been investigated the most, but the approach could also be applied to a broad suite of other elements.

7.2.2 Power Requirements

Extraction of minerals from seawater requires power to operate mechanical adsorbent exposure mechanisms, pump seawater, and operate the electrochemical cell in electrochemical extraction systems. As no commercial or pilot operations are currently in use, any power requirement assessments are currently based on laboratory-scale operations, as explained in this section, for several processes under development. A variety of systems and subsystems could use MHK power, including electricity (Table 16).

Intermittency of power is acceptable for the extraction of minerals from seawater, as the process is largely passive, allowing operations to slow down or cease for periods of time without damage to the system. Storage backup can help to maintain adequate power for essential parts of at-sea systems like navigation lights and safety gear.

Table 16. Systems and Processes Likely To Require Power To Extract Elements and Dissolved Gases from Seawater, and the Relevant Techniques under Development

System	**Energy Process**	**Type of Seawater Extraction or Material Usage**
Passive extraction process	Electrifying adsorbent materials	Extraction of uranium from seawater using electrochemically enhanced adsorbent approaches
	Electrolysis and electrochemistry	Direct electrochemical extraction of lithium from seawater; extraction of dissolved gases via electrolysis
Mechanical movement of adsorbent materials	Movement of belts or roller chains into and out of seawater and into and out of extraction baths	Mechanically driven adsorbent exposure system
Surface infrastructure and anchoring systems	Floating dynamic positioning systems without vessels needed for deployment or anchoring	Mechanically driven seawater extraction system
Production of dissolved gases	Electrolyzers to separate hydrogen and oxygen from seawater	Energy storage through hydrogen production; hydrogen-powered propulsion systems
	Electrolytic cation exchange process	Synthetic fuel production

Electrochemical Adsorption of Uranium from Seawater

Liu et al. (2017) describe a process that enhances the ability of amidoxime-based[8] adsorbent materials used to extract uranium from seawater through an electrochemical process (Figure 33). Compared to simple passive adsorption processes, applying an electrical field to the adsorption material significantly improves the rate and capacity of the adsorption process (a four-fold and three-fold increase, respectively), while also helping to avoid adsorption of unwanted elements.

[8] The amidoxime functional group, $-C(NH_2)=N-OH$, has a high affinity for sequestering uranium from a solution and can be synthesized as a binding ligand on fibrous polymers to create a uranium-adsorbent material.

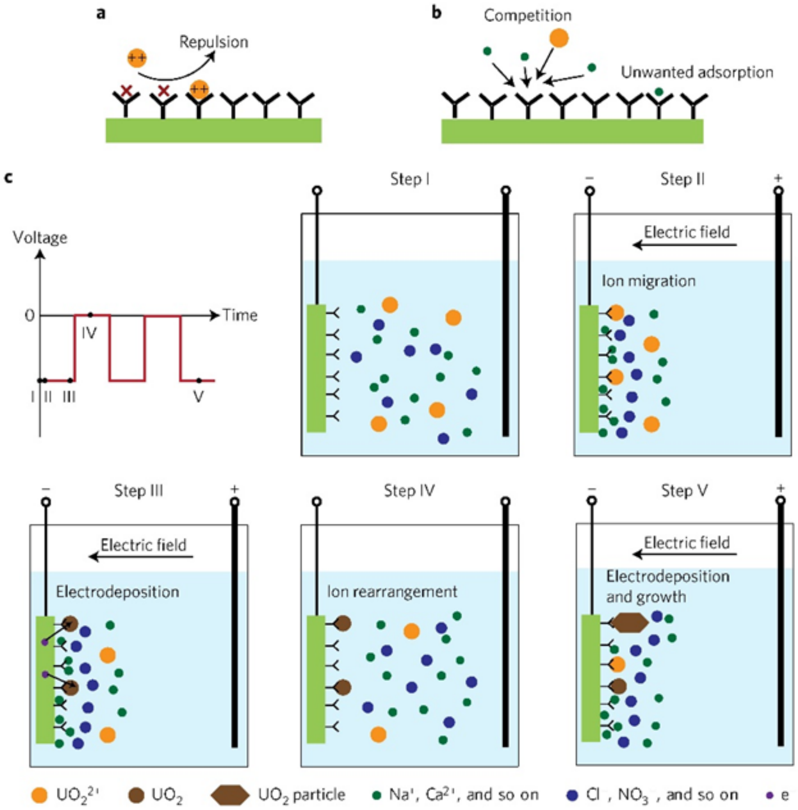

Figure 33. Schematics of physicochemical and half-wave rectified alternating-current electrochemical (HW-ACE) extraction.

Source: Liu (2017)

A Mechanically Driven Seawater Extraction System

A significant reduction in the cost to extract elements from seawater can be achieved by using power generated at sea from an MHK device. Power is needed to extract elements by a mechanically driven system that will expose the adsorbent material to seawater, return it to the surface platform, and allow for extraction of the elements through a solvent bath. This approach achieves cost reductions by eliminating the work vessels needed to anchor the structures to the seabed and the transport vessels needed to continually deploy and retrieve the adsorbents.

Illustrated in Figure 33is a symbiotic system described by Picard et al. (2014) for the extraction of uranium from seawater. The extraction system consists of a continuous belt of adsorbent material 4,000 m in length. The adsorptive belts containing uranium pass through solutions to extract the uranium from the adsorbent, then they are reconditioned in another solution and returned to the sea for another cycle of adsorption. This system was designed to harvest 1.2 tons of uranium per year, enough to power a small (~5- MW) nuclear plant.

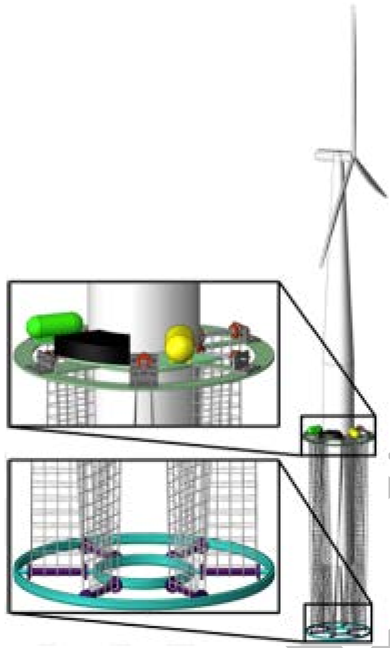

Figure 34. A conceptual model of a continuous seawater adsorbent extraction and elution system for the extraction of uranium from seawater integrated into an offshore wind platform providing the power to drive the system. *Image from Picard et al. (2014)*

Byers et al. (personal communication) compared the cost for the extraction of uranium from seawater using the passive adsorption process (kelp) and the symbiotic system described by Picard et al. (2014) (see Figures 34 and 35). They predicted that by linking the seawater extraction system to a local power source, a 27% reduction in the overall costs to extract uranium from seawater can be achieved.

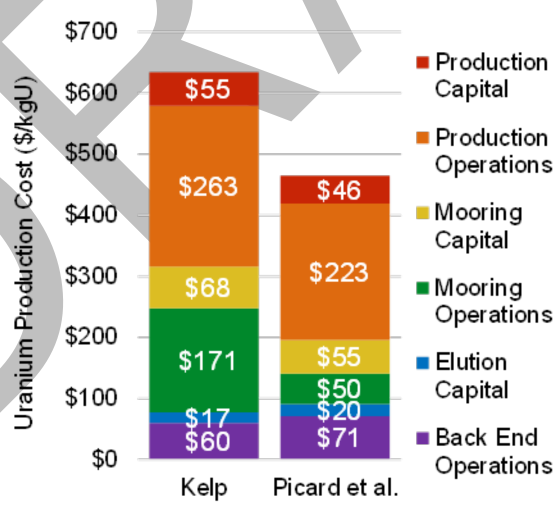

Figure 35. Comparison of the costs to extract uranium from seawater using a passive adsorption technology. *Image courtesy of Margaret Byers, University of Texas at Austin*

Haji et al. (2017a and b) built on the previous systems described by Picard et al. (2014), Haji and Slocum (2016), and Haji et al. (2016) to design a mechanical exposure system they call Symbiotic Machine for Ocean uRanium Extraction (SMORE) that uses adsorbent shells that are incrementally spaced along a continuous moving roller chain (Figure 36). A 1/50 scale model of this concept is depicted in Figure 86.

Figure 36. Adsorbent material encapsulating in a protective sphere (left), and symbiotic machine for ocean uranium extraction (right). *Source: Haji et al. 2017a*

Figure 37 compares the production cost to extract uranium from seawater by passive adsorption (kelp) and the SMORE system described by Haji et al. (2017a and b). Incorporating a SMORE system using on-site power results in a 31% reduction in the production costs to extract uranium from seawater.

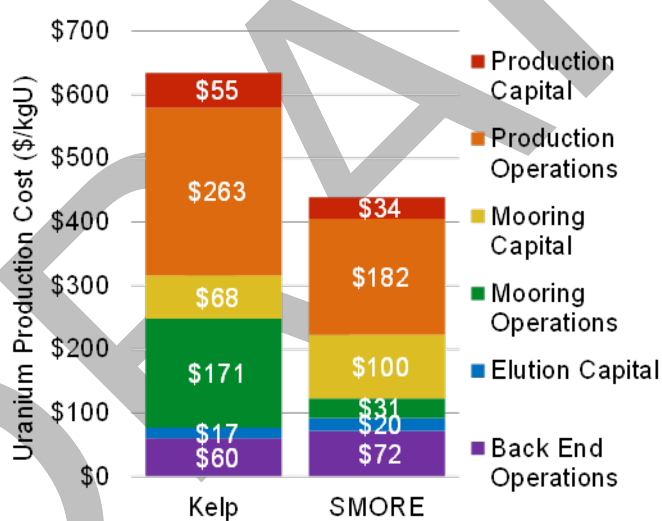

Figure 37. Comparison of the production costs to extract uranium from seawater by passive adsorption (kelp) and the SMORE system. *From Haji et al (2017a)*

Another concept for operating an on-site seawater extraction system is depicted in Figure 38 (Chouyyok et al. 2016), using a free-floating structure. This system is similar to the previous conceptual system in which the adsorbent material is incorporated into a fabric-type belt that rotates into the sea for exposure and then returns to the surface where it passes though tanks containing solutions to strip off the uranium. MHK-derived power could be used to drive the belt deploying the adsorbent material into the water from one end of the barge, move it slowly through the water under the barge, retrieve the belt at the other end of the barge, move the adsorbent material on the belt through extraction bathes on deck, then continue the movement to redeploy the belt and adsorbent materials overboard again.

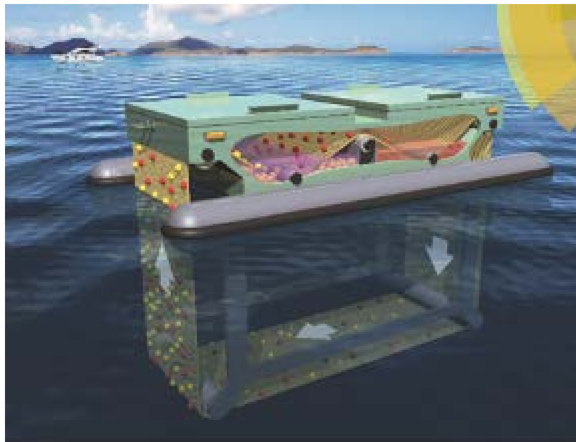

Figure 38. Conceptual process for the continuous collection of uranium from seawater using high-performance thin-film adsorbents coated onto a flexible woven belt structure.
Figure from the cover of Dalton Transactions (July 28, 2016)

Direct Electrochemical Extraction

A promising, but yet unproven, technology for the extraction of elements directly from seawater is electrochemical extraction (Figure 39). Any element that has multiple reduction-oxidation states can potentially be extracted from aqueous solutions, such as seawater, using more traditional electrochemical approaches. Pacific Northwest National Laboratory is currently developing a laboratory-scale system to demonstrate the technology.

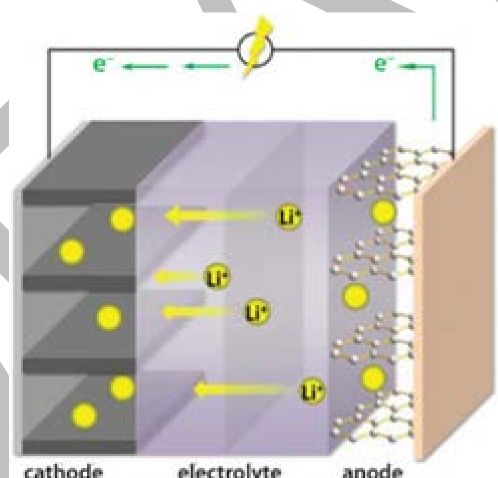

Figure 39. An electrochemical cell for the direct extraction of lithium ions from seawater. The cell is based on lithium-ion battery technology that has a high selectivity for lithium ions. *Source: Matthew Asmussen, PNNL.*

Extraction of Lithium from Seawater

The abundance of lithium in seawater (178 µg/L) is at least 1–2 orders of magnitude higher than most critical elements and has a total mass 17,800 times more than terrestrial reserves (Diallo et al. 2015). The abundance of lithium in seawater could be recoverable, and current estimates of terrestrial lithium reserves could last 371 years, based on current demand projected into the future (Diallo et al. 2015). A preliminary analysis by Dr. Erich Schneider at the University of Texas at Austin has concluded that mining seawater for lithium is feasible from a cost perspective (E. Schneider, personal communication, November 2017). A more comprehensive cost analysis is warranted to assess the potential of mining seawater for lithium.

Extraction of Dissolved Gases

Several dissolved gases (CO_2, H_2, and O_2) can be electrolytically extracted directly from seawater. Two current applications of this technology are production of hydrogen as a means of energy storage and as a fuel source and extraction of carbon dioxide and hydrogen as precursors to synthetic fuel production.

Energy Storage through Hydrogen Production

EMEC is producing H_2 gas directly from seawater as a means of storing unused power being generated by renewable energy (e.g., wind, wave, and tidal) (EMEC 2017b). The H_2 gas is being produced in the outer Orkney islands, off the northeast coast of Scotland, by a 500-kW solid oxide fuel cell (or electrolyzer, for short) that runs in regenerative mode to achieve electrolysis of water and produce both hydrogen and oxygen (Figure 40) The hydrogen is transported to the main Orkney island for use in the intraisland ferry system and land transport. The 500-kW electrolyzer produces up to 220 kg/day of hydrogen, which is compressed and transported to a fuel cell where it is converted back to electricity for local use. Because the hydrogen is produced from a renewable energy source, it is a clean fuel, with no carbon emissions. EMEC is currently exploring a use for the oxygen that is also produced from this process. Applications of this type are most suitable for islands and island communities as well as remote locations where the cost of power is high and there are often remote areas requiring energy.

The electrolyzers used by EMEC to generate hydrogen and oxygen from seawater are 500- and 1,000-kW units, which can produce approximately 2,400 and 4,800 m^3 of hydrogen per day (200 to 400 kg/d). There are units on the market that range from tens of kilowatts to 1,000-kW standalone units to multiunit systems that are greater than 10,000 kW. The typical energy needs of electrolyzer units are around 5 kWh per m^3 of hydrogen.

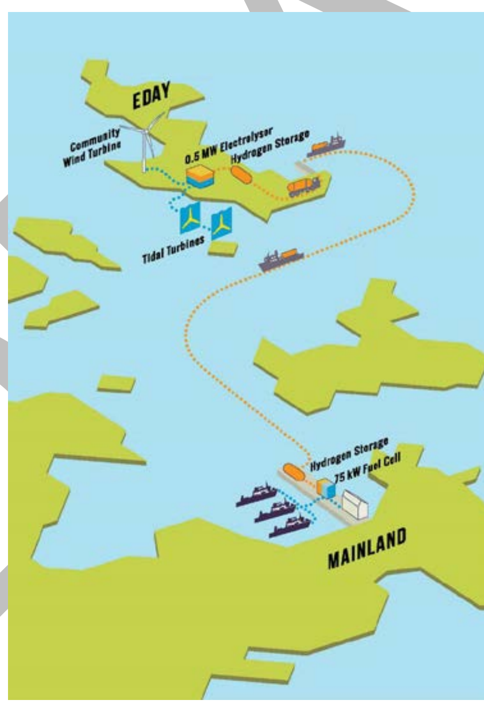

Figure 40. Schematic of production, transport, and storage of hydrogen gas from renewable generation for use in fuel cells at the European Marine Energy Centre, Orkney, United Kingdom.

Source: Elaine Buck, European Marine Energy Center

Synthetic Fuel Production

The U.S. Naval Research Laboratory has developed technology for extraction of CO_2 (g) and H_2 (g) directly from seawater using an electrolytic cation exchange process (Willauer et al. 2017; U.S. Naval Research Laboratory 2016, 2017, 2018). The U.S. Navy has an interest in using these gases as precursors to synthetic fuel production (Willauer et al. 2012). The conversion of CO_2 and H_2 to synthetic fuels is accomplished through a thermochemical conversion process using a catalyst (Dorner et al. 2011; Bradley et al. 2017). The ability to produce synthetic fuels at sea can offer significant logistical and operational advantages to the Navy by reducing their exposure to market volatility and their dependency on at-sea resupply. Key operational parameters for the production of synthetic jet fuel are given in Figure 41.

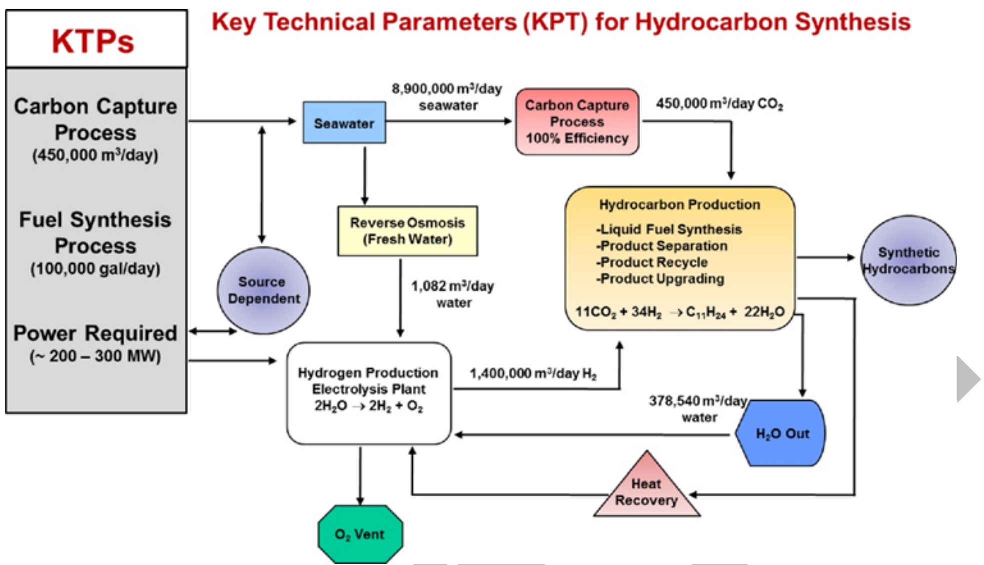

Figure 41. Operational parameters for the synthesis of 100,000 gallons of jet fuel/day.
Image from Willauer et al. (2012)

This technology has the potential to mitigate the effects of CO_2 emissions from fossil fuels. By recycling the carbon captured into energy-rich molecules and fuels, the process is CO_2-neutral, and eliminates the emissions of sulfur and nitrogen compounds that are emitted from the combustion of petroleum-derived fossil fuels.

7.3 Markets

7.3.1 Description of Markets

Critical minerals are often defined as those mineral resources that are essential to the nation's economy or for national defense purposes and for which there is potential for supply disruptions. The target elements are those needed for development and deployment of clean energy technology (DOE 2011), advanced military applications (DOD 2015), and essential civilian and industrial uses. Of particular importance are those elements for which the United States does not have significant domestic resources or for which there is significant risk of supply disruption. Elements that are considered critical include the REEs (e.g., neodymium, dysprosium, europium, yttrium, and terbium), lithium, tellurium, gallium, and indium.

In 2016, the market for REEs was 155,000 tons, dominated by China, whereas U.S. consumption was 20,000 tons (MIT 2017). The current global market for REEs is estimated to be $10 billion and is growing at an estimated compound annual growth rate of 6%. The global market is estimated to be roughly $20 billion by 2030 (Mordor Intelligence 2018. The global uranium market is relatively saturated at the moment due to reduced build-out of nuclear power plants but is expected to recover over the next decade because of increased power needs in the United States and internationally. Global demand for uranium is currently 67,000 tons of uranium per year, or about $8.7 billion (World Nuclear News 2017).

As an example, if initially only 10% of the present worldwide market for minerals could be mined from seawater, the markets would be substantial (Table 17).

Table 17. Estimates of Global Markets for Five Key Minerals That Could Be Mined from Seawater

Element	2017 Price ($/kg)	2017 Global Production (metric tons)	2017 Market Value ($)	Market Value from Seawater Mining* 10% of Global Production from Seawater ($)
Li	$139	43,000	$5,977,000,000	$597,700,000
U	$47	62,027	$2,925,193,320	$292,519,332
V	$59	80,000	$4,744,000,000	$474,400,000
Cu	$6.27	19,700	$123,519,000	$12,351,900
Co	$59	110,000	$6,437,200,000	$643,720,000
Nd	$58	130,000	$7,475,000,000	$747,500,000
Dy	$185	130,000	$24,050,000,000	$2,405,000,000
Tb	$475	130,000	$61,750,000,000	$6,175,000,000
Re	$1,530	52,000	$79,560,000,000	$7,956,000,000
Pd	$27,650	210,000	$5,806,500,000,000	$580,650,000,000

*Assuming 10% of global production could be mined from seawater

The demand for critical minerals is growing, based on likely future scarcities and security concerns for obtaining minerals such as uranium from international sources that may not be readily accessible to the United States. Demand for industrially important minerals such as lithium and REEs will continue to grow with increases in consumer and industrial electronic uses, further stressing terrestrial supplies, particularly from nations that are considered to be security risks. The development of lower-cost domestic extraction of minerals from the ocean will make these sources more economically attractive; help alleviate international supply concerns; and relieve permitting, waste disposal, and public opinion concerns for terrestrial mining operations.

As fuel cell technologies improve, the demand for hydrogen as an energy storage and transport medium will increase; extracting hydrogen from seawater will relieve stress on dwindling freshwater resources and provide a cost-effective alternative to traditional extraction sources.

The early stage of processes to extract minerals from seawater could allow the MHK market to develop in parallel with commercial extraction technologies, providing synergies for both industries. A similar situation exists for the extraction of dissolved gases from seawater, although the market drivers are not scarcity or security concerns as much as cost and potential for introduction of gases into fuel cell and synthetic fuel production pipelines.

Customers

Customers for MHK-connected systems for mineral and gas extraction from seawater are broad. Numerous battery manufacturers (e.g., Tesla, NEC, LG Chem, and Panasonic Sanyo) need lithium, cobalt, and nickel for manufacturing lithium-ion batteries to supply companies making electric vehicles and mobile phones. Need for these materials is rising rapidly and traditional supply sources may not meet demand (Shankleman et al. 2017). Extraction of REEs and uranium could attract customers among many of the large international mining and chemical companies such as Molycorp, Galaxy Resources, Albemarle Corporation, Polymet Mining, Uranium Energy Corporation, and NexGen Energy Ltd.

The U.S. Enrichment Company, a subsidiary of Centrus, is a nuclear fuel enrichment company supplying enriched uranium to the nuclear power industry. In addition, the following companies refine uranium internationally: AREVA (France, United States), China National Nuclear Corporation (China), GE Hitachi Nuclear Energy (Japan, United States), Global Laser Enrichment (United States), Japan Nuclear Fuel Limited (Japan), Tenex (Russia), and URENCO Group (United Kingdom, Germany, Netherlands, United States) (World Nuclear Organization 2018a). The fuel of the future for cruise liners, ferries, and container ships will likely be hydrogen (van Biert et al. 2016; Tullis 2018; MAREX 2017). MHK can supply the power to drive an electrolyzer, using seawater for the hydrogen resource. Domestic and international chemical companies and transport organizations are likely partners for gases, such as hydrogen and ammonia, to power fuel cells or to synthesize fuels at land-based operations as well.

The National Nuclear Security Administration needs a reliable supply of low-enriched uranium for defense purposes. It is unclear if the United States requires highly enriched uranium. There is no current domestic source of low-enriched uranium or highly enriched uranium, but the National Nuclear Security Administration has a stockpile to last until 2038, after which a new plant will be needed for low-enriched uranium production. The United States can only use uranium for defense purposes that has been enriched by U.S.-origin companies. In addition, there is a stockpile of uranium from decommissioned plants operated by the DOE in Oak Ridge, Tennessee; Paducah, Kentucky; and Portsmouth, Ohio (World Nuclear Organization 2018b).

There are no industrial transport companies currently using hydrogen fuel at a commercial scale. There are, however, pilot projects involving towboats, passenger ships and ferries, and short-haul truck routes (Table 18. Pilot Projects Underway Using Hydrogen as a Transportation Fuel (The Verge 2018)).

Table 18. Pilot Projects Underway Using Hydrogen as a Transportation Fuel (The Verge 2018)

Project Name	Project Type	Project Partners
RiverCell – Elektra	Towboat	TU Berlin, BEHALA, DNV GL
ZemShip – Alsterwasser	Small passenger ship	Proton Motors, GL, Alster Touristik GmbH, Linde Group
Nemo H2	Small passenger ship	Rederij Lovers
Hornblower Hybrid	Ferry	Hornblower
Hydrogenesis	Small passenger ship	Bristol Boat Trips
MF Vagen	Small passenger ship	CMR Prototech, ARENA-Project
Class 212A/214 Submarines	Submarine	CMR Prototech, ARENA-Project, ThyssenKrupp Marine Systems, Siemens
SF-BREEZE	Passenger ferry	Sandia National Laboratories, Red and White Fleet
Ports of Los Angeles and Long Beach	Short-haul trucks	Ports of Los Angeles and Long Beach, Toyota
UPS	Short-haul trucks and vans	UPS, General Motors, City of Sacramento

7.3.2 Power Options

As an on-site power generation source, MHK could reduce or avoid the need for diesel generators or cabled connections from shore, which are both costly and not portable if the system needs to be relocated. MHK will reduce offshore installation operating costs, creating a more economically viable installation.

There are no incumbent power sources for seawater mineral extraction; however, in the future, at-sea operations could be satisfied by diesel generators, wind, solar, or MHK power sources. There will be a need for battery backup storage for all renewable sources to smooth generation and provide more reliable power. Warm tropical regions, which are better-suited for seawater mineral extraction, would benefit from solar generation. MHK can produce power at the seawater extraction site without the need to refuel or risk spills from diesel. MHK also has certain advantages over solar and offshore wind for offshore seawater mining operations as low-profile infrastructure is preferred for survivability, removing the detrimental effects of salting of PV panels and corrosion of wind components, and to reduce visual impacts. Seawater mining operations are likely to be in open water. The MHK industry is in a unique position to design devices that can accommodate these operations, particularly with wave energy.

7.3.3 Geographic Relevance

There are many opportunities for mining REEs, uranium, lithium, other minerals, and dissolved gases throughout coastal areas and the open ocean, where sufficient wave or tidal resource is present. U.S. wave resources are optimal off coasts of Hawaii, Alaska, the West Coast, and the Northeast.

Unlike terrestrial sources of elements, the concentration distribution of many elements in the ocean are fairly homogenous. Of course, there are exceptions. Many elements, such as the transition elements and many REEs, exhibit lower concentrations in surface water and are elevated in the deep (greater than 1,000 m) ocean, likely due to emissions from hydrothermal vents and interactions with primary productivity processes. Concentrations of many minor-to-trace elements tend to be higher near the ocean margins due to continental run-off and proximity to margin sediments.

It is unlikely that any seawater extraction technology will occur in the deep ocean, due to the difficulties of developing technologies that work under extremely high pressure. Hence, it is reasonable to assume that any seawater extraction operations will be restricted to the upper few hundred meters of the ocean.

Seawater temperature is another factor that can greatly impact some extraction technologies. For example, the adsorption of uranium onto amidoxime-based adsorbents is approximately four-fold higher in 30°C seawater than at 20°C (Kuo et al. 2018). Hence, warmer seawater locations are likely preferable relative to temperate locations for most elements and technologies.

In the United States, preferred locations for passive mineral extraction that coincide with MHK resources (largely wave resources) include the warmer waters off Hawaii, the Caribbean, and the Pacific islands.

7.4 MHK Potential Value Proposition

MHK power could open up unexploited opportunities in seawater mining, which could further expand mineral and gas markets. Seawater mining would also improve the diversity of the U.S. mineral supply chain, eliminating reliance on any one supplier, and provide a price ceiling on the cost of terrestrially obtained critical materials. Costs for REEs and uranium are likely to be less sensitive to energy costs than other markets and are driven more by security and scarcity concerns.

Linking an MHK power source to a seawater mineral extraction technology could substantially enhance or enable the extraction process. This can occur through providing power to run a mechanical adsorbent exposure system or enabling the use of an electrochemical extraction process. Similarly, MHK power could enable extraction of dissolved gases from seawater directly through catalytic conversion or through an electrolyzer by providing power needed to continuously supply a charge across the electrodes. Auxiliary power needs could be satisfied by MHK, including power for safety, lighting, crew support, and small electric vessels servicing the at-sea installations needed to extract gases.

The extraction of uranium from seawater appears to be the most promising opportunity to link MHK to seawater mining as an adsorption technology and a prototype engineering system has been developed to expose the adsorbent to seawater. The exposure system requires a localized power source to drive it. This promising immediate opportunity to link MHK to seawater mining is likely to coincide with the technology under development by DOE's Office of Nuclear Energy to extract uranium from seawater. The need to find new sustainable supplies of nuclear fuel is driven by predicted scarcities and elevated costs on land by 2035, with terrestrial supplies expected to be exhausted within 60–100 years (DOE 2010; Hall and Coleman 2013; Red Book 2017).

Extraction of Lithium from Seawater

Lithium could be extracted from seawater through electrolytic processes yet to be developed. In addition, there are fibrous adsorbents currently under development for extracting lithium from natural waters (Nishihama et al. 2011; Chung et al. 2004, 2017; Park et al. 2016). If these adsorbents could be made similar in physical format to those described previously for uranium, they could likely be directly substituted into the active-exposure technology requiring linking to an MHK device under development for the extraction of uranium from seawater. Alternatively, MHK could provide the power to actively pump seawater through a flow-through membrane adsorber for recovery of lithium (Park et al. 2016).

Extraction of Multiple Elements with a Common Extraction Technology

The most favorable economic outcome of linking MHK to the extraction of critical elements from seawater will be realized when the technology is adapted to obtain multiple elements of interest from a common extraction technology.

As noted previously, most adsorption technology is targeted at a given element, but will also retain many other elements if they are present. To illustrate this point, consider the uranium adsorption technology. Figure 42 shows the elements that the adsorbent retains after 56 days of exposure in natural seawater. Uranium is the fourth most abundant element retained by this adsorbent in terms of adsorption capacity (g of element/kg adsorbent). Calcium and magnesium are more abundant on the adsorbent than uranium, primarily because their seawater concentrations are six orders of magnitude more concentrated than uranium (Ca = 416,000 ppb; Mg = 1,295,000 ppb; U = 3.3 ppb). Note that the adsorbent retains significant amounts of several other elements, including V, Cu, Ni, Zn, Co, and Cr. The adsorbent also retains rare earth elements at lower relative percentages. Currently, these "nontarget" elements are simply discarded in the uranium extraction process. If the nontarget elements are also of economic value, then the overall cost of obtaining the target element could be reduced. All that would be required is to develop isolation technology to recover the elements of interest from the aqueous solution being discarded from the uranium extraction process. It would be important to explore how much of a cost reduction could be obtained by harvesting the nontarget elements for their economic value.

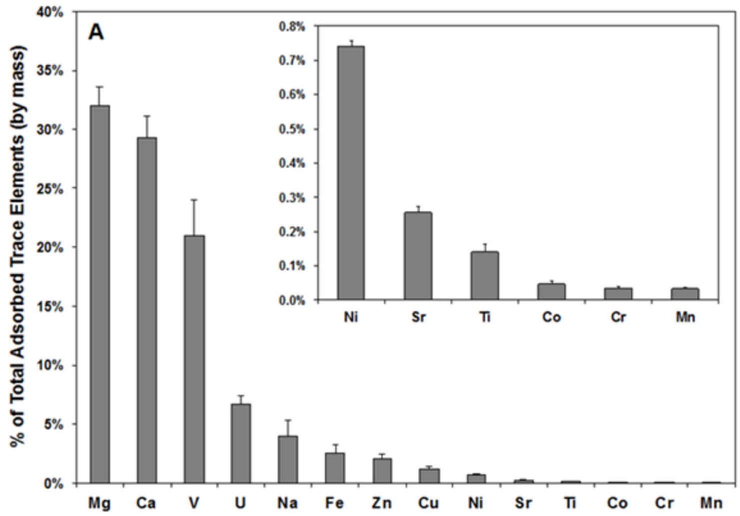

Figure 42. Relative abundance of elements absorbed by the Oak Ridge National Laboratory amidoxime-based polymeric uranium adsorbent AF1 after 56 days of seawater exposure. *Figure from Kuo et al. (2016)*

Extraction of Dissolved Gases from Seawater

Dissolved gases are ubiquitous in seawater, although gases that are mediated by biological activity, such as oxygen and ammonia, are found in higher concentrations in the upper water column and at lower temperatures (many gases are more soluble at lower temperatures). Through electrolysis or catalysis, seawater can be converted into hydrogen and oxygen at any location. Cooler waters that may be preferred for gas extraction that coincide with strong MHK resources can be found off of Alaska, the West Coast, and the Northeast.

7.5 Path to Market

7.5.1 Path to Market

Extraction of minerals and gases from seawater will require extensive R&D to create viable industries. MHK power generation could be an important catalyst to move these technologies from the pilot to full scale. However, the coupling of MHK and seawater extraction technologies will also require extensive development, deployment investigations, and potential design evolutions. Additionally, it is essential to understand the power requirements of the various seawater extraction technologies operating at commercial scale. Currently, there are crude estimates of the power requirements for many technologies at the laboratory bench scale, but the reliability of this information is highly uncertain.

To date, there has been significant focus on the development of technology for the extraction of uranium from seawater, but little attention has been paid to exploring other obtainable critical elements and the cost of their extraction relative to current terrestrial mining operations.

Technoeconomic analyses are needed that identify target elements and costs for extraction from seawater using a variety of extraction approaches. These analyses should include costs associated with extraction of a single target element as well as an investigation into how those costs would change if multiple elements could be recovered with the same technology.

There is a major potential synergy in linking seawater extraction with MHK-driven desalination operations. The brine discharge from a desalination plant has a salinity that is typically 2–3 times that of the original seawater and it is often higher in temperature than the original seawater. These are both favorable features for enhancing adsorption technologies. The potential adsorbent enhancement (in terms of adsorption capacity, i.e., grams of the element per kilograms of adsorbent) is likely to be 4–8 times that of a natural seawater exposure (Sodaye et al. 2009; Kuo et al. 2018; G. A. Gill, personal communication, 2018). Because the desalination plant has its own seawater delivery and disposal system, it should be reasonably simple to integrate a seawater extraction technology. Finally, the power from the MHK system could be used to operate any mechanical or electrochemical systems that the seawater extraction system would require. In this synergy, the waste product from the desalination operation (brine) would become a resource for mineral extraction, thereby lowering the overall cost of the production of fresh water.

7.5.2 Potential Partners

The concept of directly extracting minerals from seawater has been around for centuries, but to date there are no commercial activities in this space, with the exception of extraction of the major salts from seawater (e.g., sodium, potassium, and magnesium). There is, however, a great deal of research interest in this topic within both DOE and DOD as a potential domestic source of critically needed materials.

Within the DOE, the Office of Nuclear Energy's Fuel Cycle Research and Development Program has a subprogram to develop technology for the extraction of uranium from seawater with the goal of addressing future resource availability (DOE 2013a; Gill et al. 2016; Kung 2016; Tsouris 2017; Parker et al. 2018. The DOE Office of Energy Efficiency and Renewable Energy's Geothermal Technologies Program is also exploring extraction of critical elements from hydrothermal systems using advanced adsorption technologies in support of obtaining domestic supplies of critical materials (DOE 2017d). The Advanced Manufacturing Office at DOE will also benefit from development of seawater extraction technology to obtain the critical materials needed for development of clean energy technologies such as structural metal alloys, magnets, light-emitting devices, lasers, catalysts, pigments, batteries, and other high-tech applications (King and Eggert 2017), as well as support for their desalination initiatives. There are likely partnering opportunities with DOD for advanced weapons and warfare manufacturing as well.

Terrestrial mining companies are potential commercial partners that may be looking for additional sources of minerals, including those in abundance in seawater, particularly uranium, lithium, and REEs. The startup company LCW Supercritical Technologies (LCW Supercritical Technologies 2017) has patent-pending technology for the adsorption of uranium and other elements from seawater and other aqueous solutions. This technology has not yet been licensed for commercial application. There is also significant international interest in developing technology for the extraction of uranium and other elements from seawater. Countries that are currently doing research and developing technology include Japan, China, and India (Kavakli et al. 2005, 2007; Tamada 2010; Guo et al. 2015, 2016; Gao et al. 2016; Hara et al. 2016; Zhang et al. 2018

8 Data Centers

8.1 Opportunity Summary

The explosion of cloud computing and internet-based content, from movie streaming to cryptocurrency mining, has created significant growth in the build-out of server centers. These servers have a tremendous electricity demand; in the United States alone it represents 70 Twh/yr, or almost 2% of total U.S. electricity consumption (Shehabi et al. 2016). Customers in this market require uninterrupted power and often have 100% renewable energy targets, but they remain very price sensitive, which limits the type of renewable energy utilized. Data centers need electricity for powering the computer servers and then all auxiliary systems, often referred to as “energy overhead.” Historically, cooling has represented a large proportion of a data center’s energy overhead, but in recent years this portion has decreased due to improved efficiencies in hardware and facility design (Cutler et al. 2017; Microsoft undated). Still, companies look for opportunities to reduce this cost. For example, Google and Microsoft have been experimenting with using ocean water for cooling instead of the more common air cooling method. Evolving small “edge caching” data centers located near coastal population centers increasingly desire rapid paths to deployment, scalability, reduced costs, and access to renewable power (NOAA 2017e). Other applications exist as well: temporary data centers for emergency and military management require extreme ease of deployment and reliability, along with proven integration with storage and other generation sources. MHK has the potential to replace or extend diesel supplies and operational times for these temporary centers. If MHK system reliability and costs improve significantly, they could provide power to the enduring edge nodes through large-scale data centers. Combined, this is a multibillion-dollar market and is only expected to grow as computing needs increase (Jones Lang LaSalle IP, Inc. 2017; RECAP 2017).

8.2 Application

8.2.1 Description of Application

The data center sector is rapidly expanding and evolving, with major players such as Amazon, Google, and Apple utilizing or targeting 100% of electricity from renewable sources. These centers encompass a rapidly evolving range of sizes and purposes, including large hyperscale server centers, in-house or multitenant data centers, edge caching data centers, and temporary data centers (RECAP 2017, Gartner, 2016, Cisco, 2016, IDC 2017.).

Large Hyperscale Data Centers

Large, rapidly scalable “hyperscale” server centers have been defined by International Data Corporation as being “...often architected for a homogeneous scale-out greenfield application portfolio using increasingly disaggregated, high-density, and power-optimized infrastructures. They have a minimum of 5,000 servers and are at least 10,000 sq ft in size but generally much larger.” (www.idc.com/). Many of these data centers are located in areas with inexpensive, reliable electricity, and some are located in northern latitudes to take advantage of lower ambient air temperatures for cooling support. The power load for these data centers may vary from hundreds of kilowatts to hundreds of megawatts.

Edge Caching Data Centers

Data centers located far away from the end user will require long transmission lines to send and receive data packets, but this distance can cause delays or data latency. This can be very disruptive for businesses that conduct rapid transactions, such as electronic traded funds or stream videos. To reduce the disruption of data latency and improve content delivery efficiencies, small local servers are being placed near population centers and will host cached content, called “edge caching.” (Figure 43.) These small centers have tens to hundreds of servers and typically have power loads in the tens to hundreds of kilowatts.

Figure 43: Edge data center from Edge Micro. *Photo from edgemicro.com*

Temporary Data Centers

Off-grid temporary or "pop-up" data centers for events, emergency response, or military operations are now regularly utilized (Figure 44). These are typically mobile truck-based or container-based systems with only a few servers and typically have power needs in the tens to hundreds of kilowatts range. These pop-up data centers value mobility and the ability to deploy quickly with few resources.

Figure 44. Federal Emergency Management Agency mobile data center and operations truck and IBM Mobile Data Center.
Sources: FEMA.gov and IBM.com

Data centers between these extremes also exist. This is a highly dynamic sector that is quickly evolving due to new computing needs and technology trends like cryptocurrency mining. It is envisioned that marine energy combined with storage and potentially other renewable energy sources could provide the power or partial power for these data centers, with ocean or river water providing server cooling to reduce load.

8.2.2 Power Requirements

Large hyperscale centers have a sizable base electrical load, require hundreds of megawatts of power, and are designed for 100% uptime. The preference is to locate server centers where connection to two power grids is possible for redundancy, along with having on-site diesel generators and large battery storage. Many centers are located in northern latitudes to take advantage of cooler ambient air to reduce electrical loads for cooling. The energy overhead that goes to cooling accounts for one of the largest sources of auxiliary power (power not directly going to computing) and can range from 10% to 50% of total overhead depending on the facility and location. In recent years, this cooling overhead has been decreasing due to efficiencies in server and facility design, resulting in significantly improving power usage efficiencies (Shehabi et al. 2016; Rong et al. 2016;

Whitney and Delforge 2014; Google Data Centers undated). For example, Google's power usage efficiency averaged across all their operating data centers has been trending downward since they started measuring (see Figure 48).

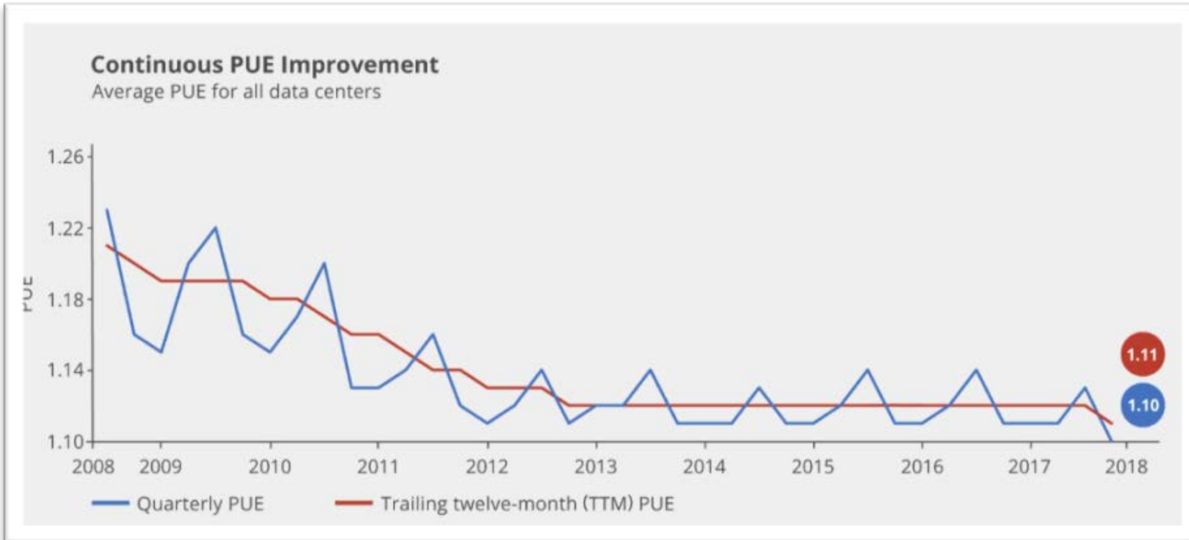

Figure 45. Power usage efficiency data for all large-scale Google data centers. *Source: Google. https://www.google.com/about/datacenters/images/pue-average.png*

Small edge caching data server centers have tens of servers that require tens to hundreds of kilowatts of power. These centers also require 100% availability, are grid connected, and usually employ backup storage.

Temporary data centers with few servers and low power requirements (<100 kW) are either grid connected or powered by diesel generators.

8.3 Markets

8.3.1 Description of Markets

Leaders in the data center sector include Amazon, Apple, Microsoft, and Google, and many of which utilize 100% renewable energy, or close to it. Presently, some power projects are developed on-site adjacent to the data center, but, more commonly, companies purchase renewable energy projects or grid-connected power through power purchase agreements, virtual power purchase agreements or carbon credits from hydropower, wind, and solar projects. However, these companies remain cost sensitive within renewable energy sources.

The Irish Center for Cloud Computing summarized recent analyses by leading information technology market players by noting that:

"Continued growth and adoption of third IT platform technologies i.e. social media, mobile, big data/analytics, IOT and cloud computing are driving data volumes, IP traffic, cloud storage, and processing. This is driving the need for hyperscale data centers and shifting market growth away from enterprise data centers and colocation data centers to the hyperscale segment of the market. By 2020, cloud workloads are forecast to represent 92% of all data center workloads." (RECAP 2017).

The market for providing energy for data centers is immense. Lawrence Berkeley National Laboratory estimates that in 2014, data centers in the United States consumed around 70 billion kWh, representing about 1.8% of total U.S. electricity consumption (Shehabi et al. 2016). Using an average industrial electricity price of 7 cents/kWh means that this is a $4.9 billion annual market in the United States alone. While the number of servers deployed is expected to increase, total electricity demand is not forecast to increase significantly from present levels (Shehabi et al. 2016). However, the recent attraction of cryptocurrency mining and blockchain computing has increased server load noticeably. Data on the energy consumption of these mining farms is speculative at the moment, but some estimates place the global value at close to 33 TWh for 2017.

The evolving edge caching market aims to place servers as near to population centers as possible to reduce data latency for popular content. These edge nodes are presently placed in small buildings that are leased or owned, typically in cities, and are grid connected with some local storage. Rapid scalability is an important factor to companies utilizing these nodes, and companies are looking for ways to enable quick expansion as evolving needs dictate. The evolving edge caching market segment size, nor its total electricity use, is specifically known, but it is thought to be growing and in the hundreds of millions presently.

Customers for MHK power specific to data centers would be any of the large tech firms that build and operate data centers, such as Google, Microsoft, Apple, Amazon, and Cisco. Although these companies are likely to develop larger data centers that have megawatt-scale needs, smaller data center developers may also be potential customers as their energy overhead is often higher than that of the larger facilities. The military, telecommunications firms, and some disaster response groups may also have interests in pop-up data centers that could be powered by MHK. Lastly, groups that have invested in cryptocurrency mining operations would be potential customers as well since their computing needs, and thus energy needs, are only expected to increase as adoption of these electronic currencies continues.

Additionally, servers are an integral part of emergency and military forward operating base management. Local renewable power enables replacing or supplementing diesel-supplied power. Simple and fast setup paired with very high reliability is essential for these markets. The size of this market is unknown.

8.3.2 Power Options

Presently, most hyperscale grid-connected data centers use 100% renewable electricity (or offset their power use through renewable energy virtual power purchase agreements). The sources of this electricity are primarily from hydropower, wind, and solar and their respective prices are competitive with traditional energy fossil-fuel sources like gas and coal. Large offshore data centers would likely be provided by these same power sources due to the fact that if data cables to shore are required, then power cables are not an additional burden. This hinders the value proposition for MHK. Off-grid/temporary data centers for emergency or military management are being powered by diesel generators and battery energy storage, and some are integrated with small solar and wind as well.

8.3.3 Geographic Relevance

South Florida is located near the Gulf Stream current and has a high population base and could be relevant for larger data centers powered by MHK. California has a significant wave energy resource, high coastal population centers, and high concentration of computing needs, making it potentially relevant for edge cache centers. Oregon and Washington have a high wave resource but inexpensive electricity from other sources which hinders the opportunity for MHK. The tidal energy resource in Puget Sound may be viable, though costs for tidal power need to become competitive with other power sources. Hawaii and other U.S. islands have high energy costs and a strong wave resource, sometimes seasonal, which makes these locations good candidates for MHK-powered data centers. Rivers throughout the United States could provide energy to pop-up data centers through run-of-river turbines or similar designs.

8.4 MHK Potential Value Proposition

Marine energy could provide renewable power and "free" water cooling to either ocean-based (e.g., surface to floor and between) or shore-based data centers of all sizes and permanence. However, there are some challenges to overcome: while large data centers have a renewable energy mandate, price sensitivity within renewables makes the case for marine energy difficult in this market. Additionally, efficiencies are resulting in cooling load decreases so the financial incentives of ocean immersion cooling are also decreasing, making it more difficult to recover the costs of operating in the marine environment.

For the edge cache market, developers are looking for ways to rapidly deploy and scale servers near coastal population centers. A goal would be modular submersible server units with low capital costs that could be quickly deployed and scaled as needed, with ambient cooling from the surrounding water and resident power from marine energy technologies. This approach is perceived to be faster, easier, and potentially cheaper than the traditional data center development on shore. The process of building a new data center on shore can take anywhere from 2 to 4 years, whereas, according to studies done by Microsoft for their Project Natick, an underwater data center could be deployed in as little as 3 months.

MHK technologies could provide local power and cooling sources for temporary data centers (e.g., disaster recover, military) to replace or augment diesel supplies and could be integrated into small portable hybrid systems with PV, wind, and batteries.

8.5 Path to Market

8.5.1 Path to Market

Large data centers require reliable cheap power from renewable sources. Marine energy's challenges, time, and investment to market for this application is similar to that of large utility-scale MHK technologies and projects: competitive costs and proven integrated operation with storage and backup power supplies.

Edge caching applications require high ease of deployment so investment into simple, low cost, environmentally compatible deployment methods and mooring and anchoring systems would be valuable. These systems would require integrated storage and, potentially, additional integrated energy sources. Research into design and operation of these hybrid systems would be beneficial.

Temporary data centers require easy-to-deploy autonomous energy systems. They also require proven reliability and integration with energy storage, diesel generators, PV, and small wind. Thresholds of "ease" of deployment and reliability should be established as targets to determine when MHK technologies could commercially play in this space to extend or replace diesel generators and solar panels.

Some companies have been exploring related aspects of marine energy in data centers. For example, a Google data center in Hamina, Finland, utilizes existing water intake infrastructure from the Bay of Finland to look at using water as a heat sink to reduce cooling costs (Figure 46). A Microsoft pilot project in San Louis Obispo, California, called Project Natick submersed a server rack off a pier to look at ocean water cooling and the ability of the servers to run in a watertight vessel under the ocean (Figure 47). This successful pilot was powered from shore by cable, but their desire was to look to ocean-based renewable power, if possible. While local heating of ocean water surrounding a submerged data center is not expected, this is an area of potential concern that also should be addressed.

Common technical challenges with utility-scale marine energy technology development include availability and costs. Smaller power applications, such as edge-nodes or pop-up data centers, would also require systems to be easy to deploy and integrated with storage and other generation sources in hybrid power systems. Effort to these ends would also benefit the remote small market application and larger marine energy technology development. Utilization of marine energy in emergency and military situations for power and desalination of water could also be explored.

8.5.2 Potential Partners

The Federal Emergency Management Agency (FEMA) utilizes and sponsors activities in disaster preparedness and response and could be a potential partner for temporary data center development and deployment. Other partners may include some of the large tech companies mentioned earlier. While these companies have an interest in sourcing their power from renewable energy generation assets, they are not in the business of building these farms themselves. Offshore oil and gas service providers are also potential partners worth investigating if pursuing offshore data center developments.

Figure 46. Google data center with closed-loop water cooling in Hamina, Finland. *Source: Google*

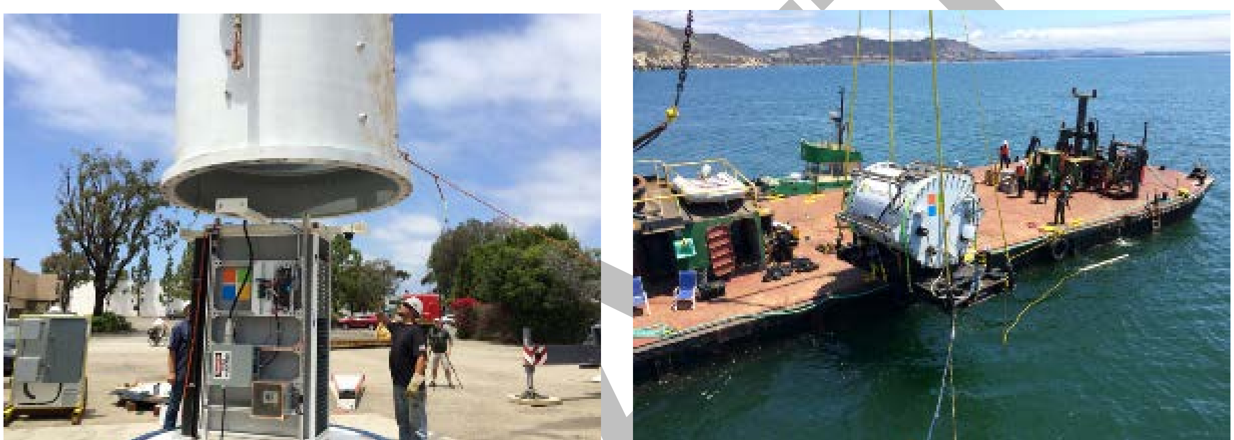

Figure 47. Microsoft Project Natick – modular submersed server with ocean cooling, San Luis Obispo, California. *Source: Microsoft*

9 Constructed Waterways

9.1 Opportunity Summary

The U.S.-constructed waterway system—primarily used to facilitate the flow of water for drinking, irrigation, hydropower generation, and transportation—is believed to encompass tens of thousands of miles. Based on piecemeal studies (e.g., Navigant Consulting, Inc. 2006 and Perkins 2013) and information gleaned from discussions with stakeholders, it has been hypothesized that gigawatts of "excess" energy in water conveyance canals may exist in the United States, mainly in the West, and hundreds of gigawatts globally could potentially be extracted while still meeting the significant delivery requirements for the water being conveyed as this important commodity is tightly managed. Projects could range from 1 kW to 10 MW of networked turbines acting in concert to optimize performance and value and operate within power and water system requirements. Cross-flow and axial flow machines are being developed and deployed globally, with a few projects active in the United States. Proponents of the resource and technology point to short timelines from concept to project installation, low costs through utilization of existing infrastructure, and high value from distributed energy resources. Significant effort is needed to clarify the opportunity, including a resource assessment, levelized cost of energy benchmarking, grid services, and a value potential assessment. Constructed waterway system development and deployment could also benefit the tidal and river current sector through technology optimization and stakeholder education. Aligned interests with powerful organizations such as the U.S. Bureau of Reclamation, the United States Army Corps of Engineers (USACE), and water districts all over the United States provide significant potential co-development partner opportunities.

9.2 Application

9.2.1 Description of Application

This chapter does not include energy from water flow in enclosed pipes but instead focuses on open human-constructed waterways, also known as open-channel or free-surface systems and extracting energy without impoundments or the creation of significant hydraulic head. Owned and managed by federal agencies (e.g., U.S. Bureau of Reclamation), irrigation districts (e.g., Imperial Irrigation District), and municipalities (e.g., Denver) and primarily located in the western United States, these waterways tend to be distributed across the landscape and in rural areas. These waterways are either earthen and unlined or lined with concrete to reduce seepage and changes to waterway profile from scour of walls from turbulent flows, erosion, and vegetation growth. These waterways are characterized by varying cross sections and sizes and subsequently different flow rates (Gunawan et al. 2017).

While some pumping is required to transport water over unfavorable terrain and slopes, stakeholders believe that a significant amount of unused, "excess" energy exists, which could be removed from the system and converted to electricity and provide grid services while still meeting existing and evolving water delivery requirements and operating within waterway constraints. Extraction of energy from existing constructed waterways could take place with turbine systems placed in existing waterway sections, or sections could be modified to be more optimal for turbine installation and operation (Figure 48). Power could be used locally (e.g., an off-grid telecommunications tower) or connected to the grid to provide electricity and grid services from the coordinated control of networks of turbines and utilizing inherent storage in the system (e.g., water storage capacity, flow and volume delivery flexibility). Power and related services could also be used to defer or avoid additional distribution investment.

Like wind and tidal turbines, most machines being developed and deployed in constructed waterways are axial-flow (e.g., SAHT Energy) and cross-flow machines (e.g., Instream Energy Systems, Emrgy Inc.), with other approaches also being utilized with local impoundment (e.g., Natel Energy's linear Pelton-style turbine).

Figure 48. SAHT Energy turbine in the Roza Canal, Oregon. *Source: SAHT Energy http://www.sahtenergy.com/*

9.2.2 Power Requirements

Power from constructed waterways could be used locally or fed into nearby distribution and transmissions systems. Projects could range from less than 1 kW (e.g., for powering remote instrumentation) to multimegawatts of a coordinated network of turbines in a waterway system. System size is dependent upon site characteristics.

9.3 Markets

9.3.1 Description of Markets

It has been hypothesized through conversations with industry stakeholders that there are potentially hundreds of gigawatts of "excess" energy in human-constructed waterways in the United States and many more globally, but this claim has not been verified. This untapped resource could potentially translate into an annual multimillion-dollar market in the United States and an annual global multibillion-dollar market.

Vanguard projects are installed and operational in the United States (Emrgy Inc. and Instream Energy Systems, see Figure 49 and Figure 50). Additionally, some early projects are installed outside of the United States.[9]

Customers for the MHK technology and power generated could be power project developers, asset owners, or water districts. Customers and consumers of the electricity generated could be asset managers (e.g., co-location of energy-intensive process near waterway), farms, rural microgrids, or bulk power markets. Some large firms that have renewable energy goals or targets would also be potential customers. For example, Apple recently partnered with Natel for delivery of a low-head hydro project. However, each customer and their situation is site-specific, and due diligence would be required on the part of the MHK developer before considering any region or area.

[9] Smart Hydropower: https://www.smart-hydro.de/renewable-energy-systems/hydrokinetic-turbines-river-canal/

9.3.2 Power Options

General off-grid power needs are presently met by diesel, solar, and wind in combination with energy storage (depending on requirements and location). Energy costs vary widely by location, so certain regions may represent better market opportunities for MHK technologies than others. Naturally, for grid-connected projects, costs and added value from services would need to be competitive with other (renewable) generation sources.

9.3.3 Geographic Relevance

Water conveyance canals are primarily located in the western United States, with some persistent and seasonal canals and flows throughout the greater United States. These systems also exist globally, with some regions having larger waterways with higher flows.

9.4 MHK Potential Value Proposition

Asset managers seek to maximize the value of their assets. Cost-effective, predictable, renewable energy sources are highly desirable, and the potential to monetize different grid services could be increasing. “Excess” energy in water conveyance channels has the potential to be a cost-effective and base-load electricity source that could have some inherent flexibility and storage and could provide services to interconnected grids when operated in coordinated control. The resource is highly predictable and sometimes constant, depending on season and locale. Few regulatory and permitting hurdles exist in these constructed waterways, and there could be a limited number of decision-makers required to allow a project to advance, resulting in relatively quick project timelines. Existing infrastructure (e.g., civil works) can be utilized, and the technology is easily accessible for maintenance (which could result in relatively inexpensive operating expenditures).

These technologies and projects could provide decentralized, locally produced power to rural and distributed areas that is also locally owned and operated. Projects could provide jobs to these communities. Projects could also add significant value through deferred or avoided distribution investment.

9.5 Path to Market

9.5.1 Path to Market

Early prototype demonstration technologies are being installed presently at some locations in the United States to test designs, validate models, assess effects on constructed waterways and water conveyance systems (see Figures 49, 50, and 51).

Figure 49. Emrgy, Ralston Canal, Colorado.
Source: Emrgy https://emrgy.com/hydropower-in-canal-called-energy-game-changer/

Figure 50. Natel Energy, Monroe Hydro Project, Oregon. *Source: Natel Energy https://www.natelenergy.com/2015/07/20/monroe-hydro-project-photo-tour/*

Figure 51. Energy, Roza Canal, Oregon. *Source: Instream Energy https://www.instreamenergy.com/yakima-washington*

Although companies are pursuing technologies and projects, these efforts could be significantly buoyed by a comprehensive U.S. resource assessment to elucidate opportunities and challenges for each region. The levelized cost of energy from these systems should be baselined and benchmarked to competing technologies, and opportunities for cost reduction should be identified (e.g., performance, reliability, operation and maintenance costs, CapEx). An assessment of the key technology hurdles would be informative and help guide research strategies. Studies should be undertaken to assess the value canal power provides to the grid and ancillary grid services in present and future power markets.

Sandia National Laboratories completed an initial guideline for evaluating turbine performance and flow effects in irrigation canals (Gunawan et al. 2017). Potential concerns identified in this study include water supply disruption (by affecting head-discharge conditions at irrigation canal intakes), spillage and flood risks due to overflowing conditions, increased scour in concrete channels, and reduced hydropower plant generation (by affecting plant inflow, tailwater levels, and net head at hydropower dam or discharge). This study could be expanded to provide greater understanding of potential effects of varying technologies and projects installed in different waterway systems. This additional research would also reduce risk perception and further clarify potential paths forward.

Efforts to advance the constructed waterway current generation industry would also be beneficial to tidal current system development. The development and deployment of small current devices for canal applications would serve as a stepping stone to tidal and river MHK applications. It could enable rapid and cost-effective experimentation and optimization of devices, and cash flows could be re-invested in additional R&D toward cost reduction for larger tidal and river technologies. Constructed waterway deployments could also encourage stakeholder familiarity and risk perception reduction.

9.5.2 Potential Partners

Key potential development partners include the federal, state, and local organizations that own and manage the constructed waterway infrastructure and water rights. This includes the U.S. Bureau of Reclamation (Department of Interior), state agencies (e.g., California Department of Water Resources), municipal water districts (e.g., Denver Water), and irrigation districts (e.g., Imperial Irrigation District). The U.S. Bureau of Reclamation is exploring this potential with pilot deployments in the Roza Canal in Oregon (Instream Energy) and the Ralston Canal in Colorado (Emrgy) and would be a natural partner. The memorandum of understanding on U.S. federal hydropower development, re-established in 2015 among DOE (Office of Energy Efficiency and Renewable Energy), the Department of the Interior (Bureau of Reclamation), and the USACE has an objective to gain a better understanding of the potential for energy extraction from existing canals. This memorandum of understanding is a natural vehicle to further explore potential and could provide a framework for further opportunity exploration.

10 Shoreline Protection and Replenishment

10.1 Opportunity Summary

Increases in extreme weather events along with the threat of future sea level rise has prompted the need for increased shore protection in the form of beach nourishment and the construction of coastal structures to reduce shoreline impacts (NOAA 2017i, 2018b; National Climate Assessment. 2014.). Simultaneously, there is growing interest in local renewable energy sources, including marine renewable energy. Integrating MHK devices with shore protection structures could be a two-pronged solution to help solve energy-security and coastal protection concerns facing many coastal communities. WECs and tidal turbines can be designed and constructed into coastal structures, such as breakwaters and storm surge barriers, with the energy generated from these devices used to power local communities, marinas and ports, or other shore protection activities, such as beach nourishment. Additionally, the sale of electricity from such integrated infrastructure could defray the long-term cost of installing coastal protection.

10.2 Application

10.2.1 Description of Application

Shoreline protection and coastal defense of coastal environments is a growing necessity in the face of sea level rise and more intense storm impacts. The development of breakwaters, berms, groins, storm surge barriers, and other similar coastal structures will increase globally, presenting the opportunity for the integration of WECs and turbines, as well as retrofitting into existing structures (Figure 10). The power generated could be delivered to marinas, ports, local communities, or even aid in sand replenishment from offshore to beaches.

As discussed in Gorton et al. (2018), shore protection solutions can be classified as either hard or soft approaches. Hard approaches include groins, breakwaters, jetties, seawalls, and revetments. Soft approaches include beach nourishment, living shorelines, and sand-filled geotextiles. There has been a recent shift away from hard shore protection structures toward softer alternatives (Goudas et al. 2001) as a result of environmental impacts, such as shoreline erosion and impacts to longshore sediment transport. The following sections describe various types of shore protection projects, including beach nourishment, living shorelines, shore protection structures, and storm surge barriers.

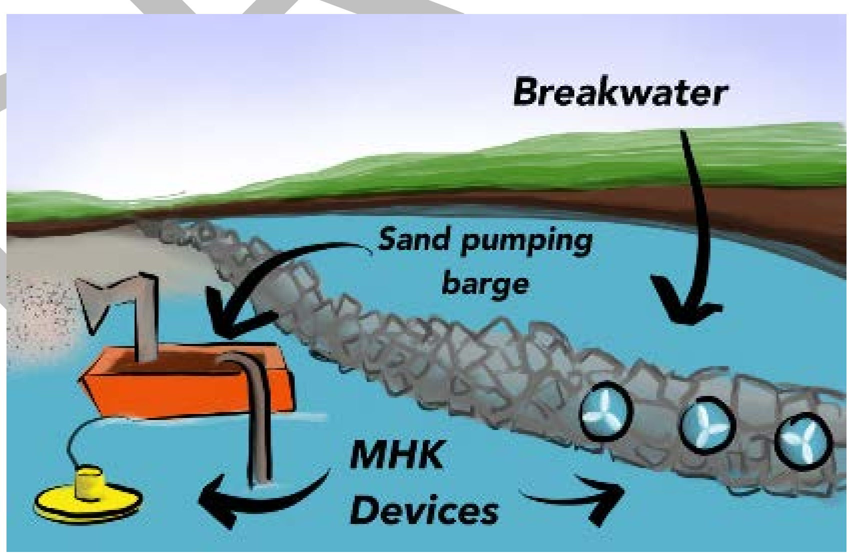

Figure 52. MHK application overview for shoreline protection. *Image courtesy of Molly Grear, PNNL*

Beach Nourishment

Beach nourishment (or replenishment) is USACE's preferred approach to shore protection for beaches and shorelines with open wave exposure as it does not harden the shoreline and is the only protection approach that adds sediment to the existing coastal system (USACE 2018a). Sand placement is designed and engineered to be naturally distributed over time. Once the new engineered beach profile reaches equilibrium, the wider beach gently slopes offshore, assuming a more natural form. The longevity of a beach nourishment is a function on the geometry of the project, the nature of the fill material, and the wave climate to which the project will be exposed during its lifetime (Dean and Dalrymple 2002). As a result, many sites may need to be renourished periodically; the resulting shoreline impacts of sea level rise may also require beaches to be renourished more frequently.

As discussed by Great Lakes Dredge and Dock (2018b), the selection of equipment for nourishment projects is a function of the location and character of the sediment borrow area.[10] If the borrow area is within 20,000 ft of the beach site, then the most economical dredging method generally entails use of cutter suction dredges that pump material through pipelines. For borrow areas farther away from the beach site, trailing suction hopper dredges mine the sediment, travel to a hook-up point, and discharge the material onto the beach via pipelines, sometimes using boosters to augment the power of the hopper dredge.

Typically, nourishment activities take place as part of a scheduled project or in response to a coastal storm. The nourishment project in Long Branch, New Jersey (discussed earlier), was a scheduled nourishment as part of the USACE Sea Bright to Manasquan Coastal Storm Risk Management and Erosion Control Project (USACE 2018d). The project consists of 21 miles of shoreline between Sea Bright and Manasquan, New Jersey. Initial construction of the project was completed in 1994, and the project has been in a renourishment phase since original completion. The nourishment in Long Branch that included the feeder beach took 3 months to complete. In 2017, South Island in Hilton Head, South Carolina, completed an emergency nourishment project (300,000 yds^3) to restore its shoreline to pre-Hurricane Matthew conditions, which took approximately 3 months to complete (Hilton Head Island 2018).

Living Shorelines

A living shoreline is a protected and stabilized shoreline that is made of natural materials such as plants, sand, or rock (NOAA 2017d). As discussed in the New Jersey Resilient Coastlines Initiative (2016), a living shoreline is a shoreline management practice that addresses the loss of vegetated shoreline and beach by providing for the protection, restoration, or enhancement of these habitats through the strategic placement of plants, stone, sand, or other living and nonliving materials. Living shorelines simulate natural coastal processes (such as the collection of mud, sand, and nutrients), which results in regrowth of vegetation. Living shorelines help maintain the health and characteristics of coastal habitats and ecosystems, which are key to improving water quality, providing opportunities for recreational activities (e.g., kayaking, sport fishing, bird watching), and supporting key commercial and recreational fish species.

Shore Protection Structures

Hard shore protection structures are designed and constructed to prevent further erosion of a beach or to impede the motion of sediment along a shoreline (Dean and Dalrymple 2002). Examples of hard shore protection structures include groins, breakwaters, artificial headlands, revetments, seawalls, bulkheads, and jetties. Common construction materials include concrete, steel, timber, stone (quarried and armor units), and geotextiles (USACE 1984).

Shore protection structures provide a means for integration with renewable energy devices. Mustapa et al. (2017) provides a review of the integration of wave energy devices with marine facilities. A main driver for integrating WECs with shore protection structures is better economic viability through cost sharing on construction, installation, maintenance, and operation. In addition, the integration of WECs into shoreline

[10] A sediment borrow area is the location of the offshore source of beach fill material. For a typical beach nourishment project, an investigation takes place that identifies potential sediment borrow areas that have sediment of a suitable grain size, sufficient volume, and are within a reasonable distance from the nourishment site.

protection structures may increase social acceptance of these projects. Integrated devices are beneficial for remote locations as they help to reduce the use of diesel fuel for electricity production and protect the shore through wave dissipation.

Several types of WEC concepts have been adapted for integration purposes, including overtopping, oscillating water column (OWC), and piston type, as shown in Table 6. The table shows that the OWC concept is the most used concept in breakwater-WEC integration.

Table 19. Characteristics of WEC-Wave Breaking Devices (Modified from Mustapa et al. 2017)

WEC-Wake breaker device	Construction Date		Type	Water Depth (m)	Mean Wave Power (kW/m)	Output Power (kW)	Comment
Sakata Port breakwater	1989–1995		OWC	18	18–67	27.3	
Stellenbosch wave energy converter	-		OWC	14	30	5,000	Designed, not constructed
Shore wave energy converter	-		OWC	14	2.3	6	Designed, not constructed
Mutriku wave energy plant	2011		OWC	5	26	68.5	
Siadar wave energy project	-		OWC				Proposed, not constructed
Siadar 1	-			8	60–70	4,000	Proposed, not constructed
Siadar 2	-			8	60–70	30,000	Proposed, not constructed
Land-installed marine power energy transmitter	2000		OWC	6	20	113	
PICO	1999		OWC	8	37.9	31.7	
Trivandrum (India)	1990		OWC	12	15	125	
Sea Slot cone generator)	-		Overtopping	6–8	14–16	49–62	No construction
Overtopping breakwater for	2015		Overtopping	25	2–8	-	

WEC-Wake breaker device	Construction Date		Type	Water Depth (m)	Mean Wave Power (kW/m)	Output Power (kW)	Comment
energy conversion							
Piston-type porous wave energy converter			Piston	-	-	-	Concept/theory

As discussed in Mustapa et al. (2017), OWC devices consist of two elements: the reinforced concrete structure that acts as an oscillating chamber and a group of turbine generators. The first integrated OWC-breakwater was constructed at Sakata Port, Japan (Figure 53). In 2008, the first multiturbine facility consisting of 16 chambers integrated with vertical breakwaters was successfully constructed at the port of Mutriku, Spain (Figure 54). In 2012, construction began on the biggest OWC-breakwater integration project, the Resonant Wave Energy Converter 3, in the harbor of Civitavecchia, Italy (Figure 55). Currently, only eight of 17 caissons are constructed.

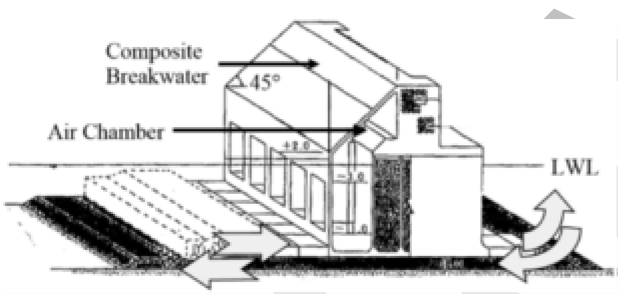

Figure 53. Integration of Sakata Port breakwater and OWC.
Image from Mustapa et al. (2017)

Figure 54. Mutriku, Spain, breakwater-OWC integration.
Photo from TidalEnergy Today

Figure 55. The Resonant Wave Energy Converter 3 Device in Civitavecchia Port, Italy. *Photos from Maestrale*

As discussed in Contestabile et al. (2017), an overtopping breakwater for energy conversion prototype has been constructed in Naples, Italy (Figure 32). The prototype hosts up to five turbines, three of which have already been installed as of March 2018.

Figure 56. Overtopping breakwater for energy conversion prototype in Naples, Italy. *Photo from Contestabile et al. (2017)*

Storm Surge Barriers

Storm surge barriers (flood barriers) are another form of coastal protection designed to prevent storm surge from flooding the protected area behind the barrier. In most cases, the barrier consists of a series of movable gates that remain open under normal conditions to let the flow pass but are closed when storm surges are expected to exceed a certain level (USACE 2018c). During normal conditions, these barriers are typically opened to allow for navigation and saltwater exchange with the estuarine areas landward of the barrier (USACE 2018c). These structures are often chosen as a preferred alternative to close off estuaries and reduce the required length of flood protection measures behind the barrier (USACE 2018c).

The largest flood protection project in the world is Delta Works in the Netherlands. Delta Works consists of a number of surge barriers, including Oosterscheldekering (Figure 57), the largest storm surge barrier in the world (5.6 miles long). Oosterscheldekering, also called the Eastern Scheldt, has also been equipped with five tidal turbines (Figure 58) with a total capacity of 1.2 MW, enough generation to power 1,000 Dutch households (M Power 2018).

Figure 57. Oosterscheldekering storm surge barrier in the Netherlands. *Photo from Amazing Planet*

Figure 58. Five tidal turbines integrated with the Oosterscheldekering storm surge barrier in the Netherlands. *Photo from HydroWorld.com*

In the United Kingdom, the Thames Barrier protects 48 square miles of central London from storm surges. The Thames Barrier (Figure 37) was built in 1982 and is made up of 10 steel gates, reaching 520 meters across the river (de Castella 2014). The gates lie flat on the river floor when they are open and close by being rotated upward until they block the river (Figure 39).

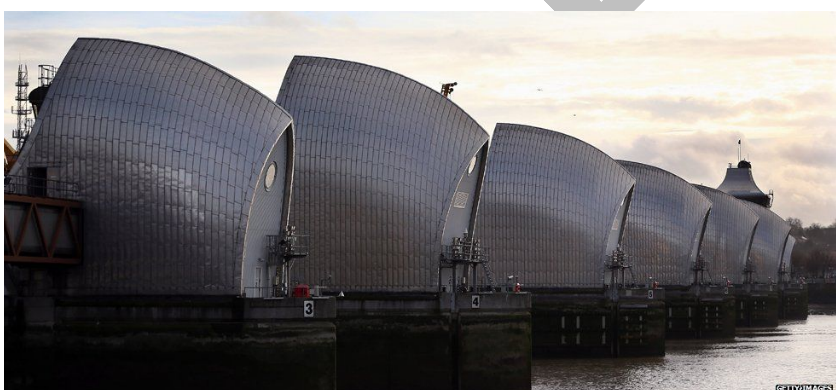

Figure 59. Thames Barrier, United Kingdom. *Photo from BBC*

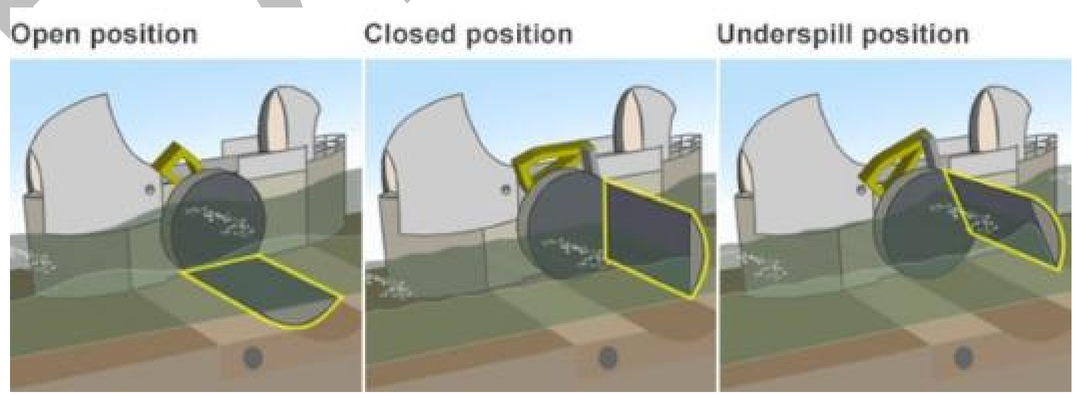

Figure 60. Thames Barrier operational positions. *Illustration from BBC*

A number of storm surge barriers have also been proposed and constructed in the United States, including the Inner Harbor Navigation Canal-Lake Borgne Surge Barrier for southeast Louisiana (Figure 40), which is the longest design-build civil works project in the history of the Army Corps. This barrier is located at the confluence of the Gulf Intracoastal Waterway and the Mississippi River Gulf Outlet, approximately 12 miles east of downtown New Orleans.

Figure 61. IHNC-Lake Borgne Surge Barrier for southeast Louisiana. *Photo from USACE*

In the wake of several hurricanes that have devastated parts of the northeastern U.S. coast, including Hurricanes Irene and Sandy, there have been several proposals to construct a storm surge barrier across the entrance to the New York/New Jersey harbor, protecting New York City from storm surge damages. The proposed Outer Harbor Gateway, conceptually designed by CH2M (Figure 62), estimated in 2009 at $5.9 billion, would cross the entrance from Sandy Hook in New Jersey to the Rockaway Peninsula in New York at 30 feet above water level (CH2M 2017). The design calls for two pairs of large radius sector gates that would each block a 600-ft clear channel, a 300-ft lifting gate, a smaller navigation opening for local vessels, and 50 sluice gates (each 80 ft wide) (CH2M 2017). Critical design considerations including maintenance, environmental impacts, water depth, currents, and geotechnical conditions need to be further evaluated to validate moving forward with design and construction (CH2M 2017).

Figure 62. Conceptual design of Outer Harbor Gateway by CH2M. *Illustration from CH2M*

10.2.2 Power Requirements

Beach Nourishment

As discussed earlier, energy generated from integrating MHK with shore protection structures could potentially be used to supplement power needed for beach nourishment projects. Being that nourishment activities take place both offshore (e.g., pumping sediment from the borrow area) and nearshore (e.g., pumping sediment onto the beach), MHK devices may need to be easily mobilized so that power can be used in either location. Table 20presents the estimated power consumption for various offshore vessels used for beach nourishment projects. All estimations are based on equipment owned by Great Lakes Dredge and Dock.

Table 20. Estimated Power Requirements for Beach Nourishment Vessels

Beach Nourishment Vessels	Estimated Power Consumption
Trailing suction hopper dredge [1]	Propulsion power: 3,000 hp–13,404 hp (2,238 kW–9,995.4 kW) Dredge pump power: 1,700 hp–10,000 hp (1,268 kW–7,457 kW) Total installed power: 9,395 hp–28,625 hp (7,009 hp–21,345.7 kW)
Cutter section dredge [2]	Cutter power: 250 hp–4,500 hp (187 kW–3,357 kW) Total installed power: 1,665 hp–21,380 hp (1,242 kW–15,949 kW)
Booster pump [3]	Main pump power: 3,600 hp–14,400 hp (2,686 kW–10,742 kW)
Hydraulic unloader [3]	Total installed power: 6,800 hp (5,073 kW)
[1] https://www.gldd.com/equipment/trailing-suction-hopper-dredges/	
[2] https://www.gldd.com/equipment/cutter-suction-dredges/	
[3] https://www.gldd.com/equipment/auxiliary-equipment/	

10.3 Markets

10.3.1 Description of Markets

With the threats from sea level rise and increases in coastal storm intensity and frequency, communities are protecting their shorelines and coastal infrastructure through the development and construction of shore protection strategies. USACE is the nation's leading agency responsible for protecting America's infrastructure, including coastal infrastructure, with specific priorities to serve mandated functions. The USACE FY 19 budget (USACE 2018b) includes $1.930 billion for the study, design, construction, operation, and maintenance of inland and coastal navigation projects. The Flood Risk Management Program is funded at $1.491 billion, which is a collaborative effort that integrates and synchronizes the flood risk management projects, programs, and authorities of USACE with those of other federal, state, regional, and local agencies. The program helps to reduce the risk of loss of life and property damage from riverine and coastal flooding and to increase the resilience of local communities through structural and nonstructural measures.

As discussed in USACE (2003), USACE projects follow legislation, which follows public demands after devastating coastal storms. USACE shore protection projects are constructed only where public access to the beach is assured, adequate parking is provided, and only after thorough studies have determined a positive benefit-to-cost ratio. The majority of USACE's shore protection projects are located on the Atlantic Coast, with the rest distributed fairly evenly along the remainder of the coastal areas. Between 1950 and 2000, USACE has constructed 71 specifically authorized shore protection projects at just more than $1.2 billion (Table 21). Of this $1.2 billion, about 43% is attributed to initial beach restoration, another 43% to periodic nourishment, 12% to structures, and 2% to emergency costs (see Table 21).

Table 21. Total Actual Construction Cost, USACE Shore Protection Program (1950–2002). Source: USACE (2003)

Type of Measure	Total Cost ($000)
Initial beach restoration	522,193
Periodic nourishment	524,297
Structures	146,576
Emergency	22,095
Total	1,215,161

As a steward of the U.S. Outer Continental Shelf energy and mineral resources, the Bureau of Ocean Energy Management (BOEM) also plays a critical role in providing access to offshore borrow areas wherein material is used for beach nourishment projects. As of July 2015, BOEM has executed 48 leases and agreements for coastal restoration projects and conveyed more than 109 million cy of sediment to restore more than 269 miles of coastline in seven states (New Jersey, Maryland, Virginia, North Carolina, South Carolina, Florida, and Louisiana) (BOEM 2016). Additionally, BOEM is engaged in new negotiated noncompetitive agreements for offshore sand resources for projects along the Atlantic Coast and in the Gulf of Mexico (BOEM 2016).

The American Shore and Beach Preservation Association, partnering with APTIM (consulting company) and the USACE Regional Sediment Management Program, has developed a geodatabase of U.S. beach nourishment projects.[11] The beach nourishment projects represented in the database include those with "captured" sand (e.g., inlet, offshore or upland) that was placed on the beach. Three kinds of projects are included:

- Federally funded beach nourishment projects (typically USACE or FEMA), called Known Federal
- Beach sand placement from navigation channel dredging (also known as beneficial use, regional sediment management, or sand bypassing), called Known Regional Sediment Management
- Beach nourishment projects sponsored by the private sector or local or state governments, called Known Other; this component also includes projects with unknown funding sources or placement type.

Table 22 provides a summary of U.S. beach nourishment statistics. Nationally, there have been 2,910 nourishment events spanning 447 projects, utilizing approximately 1.5 billion cy of nourishment material along 790 miles of coast, totaling almost $6 billion. Table 22 also presents the total wave energy resource potential by region. The majority of the wave power potential exists in Alaska and along the West Coast, whereas the majority of the beach nourishment projects are constructed along the East Coast. As described in DOE (2013), the magnitude of potential tidal power is 250 TWh per year (significantly less than wave power potential), more than 90% of which is located in Alaska.

[11] National Beach Nourishment Database: https://gim2.aptim.com/ASBPANationwideRenourishment/

Table 22. U.S. Beach Nourishment Statistics by State. Source: National Beach Nourishment Database

State	Number of Projects	Number of Nourish-ment Events	Oldest Event	Newest Event	Known Total Cost	Total Volume (cy)	Known Length (Miles)	Total Wave Energy Resource Potential (TWh/yr) [1]
AK	2	7	2010	2016	$9,871,702	331,271		1,570
HI	19	27	1939	2015		239,760	1.4	130
WEST COAST								590
CA	42	435	1927	2016	$75,028,778	394,107,701	13.7	
OR	2	8	1998	2014		206,297		
EAST COAST								240
CT	28	40	1955	2014	$15,161,135	6,234,672	13.9	
DE	16	199	1953	2017	$180,798,329	35,255,203	19.7	
FL [2]					$818,339,760	175,806,536		
GA	2	10	1964	2008	$37,808,234	10,939,000	5	
MA	39	224	1936	2017	$44,437,772	8,332,358	20.9	
MD	2	18	1963	2016	$95,881,206	13,248,792	14.2	
ME	5	14	1956	2015	$12,258,683	1,063,538	3.6	
NC	27	284	1939	2017	$737,701,178	137,446,828	79.4	
NH	2	9	1935	2013	$6,244,948	2,123,971	1.4	
NJ	36	269	1936	2015	$1,032,319,489	171,592,376	101.6	
NY	21	139	1923	2016	$550,505,445	158,563,969	76.9	
RI	6	10	1959	2014	$4,668,855	501,590	1.8	
SC	17	74	1954	2018	$356,331,521	53,971,313	63	
GULF COAST								80
AL	5	15	1986	2016	$60,757,977	17,675,692	16.7	
FL [2]					$522,086,146	125,710,107		
LA	19	56	1955	2017	$602,772,576	85,655,776	43.6	

State	Number of Projects	Number of Nourish-ment Events	Oldest Event	Newest Event	Known Total Cost	Total Volume (cy)	Known Length (Miles)	Total Wave Energy Resource Potential (TWh/yr) [1]
MS	3	17	1952	2017	$328,139,793	37,662,870	28.8	
TX	20	96	1956	2017	$134,359,567	30,525,596	27.8	
GREAT LAKES								
IL	1	9	1999	2015	$6,080,483	560,215		
IN	2	8	1990	2013	$16,855,518	665,959		
MI	30	286	1990	2016	$68,688,318	8,507,479		
OH	2	2	2002	2004	$839,230	126,846		
TOTAL	**447**	**2910**			**$5,917,906,946**	**1,513,960,368**	**789.7**	

[1] DOE (2013)

[2] The National Beach Nourishment Database provides Florida statistics on a project-by-project basis. The author geospatially investigated each nourishment in Florida to determine if the project was on the East Coast of the state or on the Gulf Coast.

Global and Domestic Trends in Shoreline Protection

Hard approaches often result in severe environmental impacts, such as down-drift erosion.[12] Specifically related to groins, attempts have been made to reduce the erosion down-drift of these structures by shortening, notching, or removing the entire groin to increase the bypassing of sediment to the down-drift beaches (Rankin et al. 2004). As a result, there is a shift away from hard shore protection structures toward soft protection measures (Goudas et al. 2001), with beach nourishment being the preferred approach in the United States.

Globally, there has been a trend toward using "integrated coastal management" or "ecosystem-based management" approaches. As discussed in Dell'Apa et al. (2015), management of marine and coastal resources in the United States has moved toward ecosystem-based management as a comprehensive strategy to address multiple pressures exerted by human activities on the state of natural resources and ecosystems. The European Commission has also adopted integrated coastal management that contributes to sustainable development of coastal zones by the application of an approach that respects the limits of natural resources and ecosystems (European Commission 2016).

As discussed in Manasseh et al. (2017), there are several factors that favor the use of marine renewable energy for shoreline protection, with the greatest potential at the local community scale, including (1) isolated island or coastal communities that are largely dependent on imported fossil fuels, combined with a need for shoreline

[12] Down-drift erosion is the erosion of a shoreline located in the direction of longshore transport.

stabilization; and (2) low-lying coastal communities that are at the greatest risk of inundation from sea level rise (NOAA 2017i).

Potential MHK Customers

Potential customers of MHK power generated by integrating MHK devices with coastal protection structures include local communities (e.g., residential, commercial), ports and marinas, and local shore protection projects (e.g., beach nourishment, channel dredging).

Many ports have adopted sustainability and environmental programs to conserve resources and reduce energy consumption. For example, the Port of San Diego has a Green Port Program[13] to "achieve long-term environmental, societal, and economic benefits through resource conservation, waste reduction, and pollution prevention." As part of the program, port officials intend to investigate opportunities to participate in renewable energy projects. Pier 69 in the Port of Seattle has an energy conservation program,[14] which has saved more than 2.38 million kWh annually, equaling $160,000 in annual savings.

[13] https://www.portofsandiego.org/environment/green-port.html
[14] https://www.portseattle.org/Environmental/Air/Energy-Efficiency/Pages/default.aspx

Table 23. Average Energy Usage for Businesses Based on Size by Employees. Source: U Switch for Business 2018

Business Size by Employees	Average Business Electricity Consumption	Average Business Gas Consumption
0–10	5,000–15,000 kWh	5,000–15,000 kWh
11–50	15,000–25,000 kWh	15,000–30,000 kWh
51–250	30,000–50,000 kWh	30,000–65,000 kWh
251+	50,000 kWh+	65,000 kWh+

Estimating the power requirements of marinas is highly dependent on the size of the marina and types of vessels berthed at the marina. For example, electrical power requirements of some yachts are quite significant. Infrastructure components in a marina that require power include: power distribution pillars on the docks; lighting; fueling stations; boatyard and maintenance facilities; pumping capacity; cranes; boat lifts; dry stack storage; clubhouse; offices; and other potential infrastructure, such as a restaurant (Heron and Juju 2012).

As discussed in United Nations Economic Commission for Latin America and the Caribbean (2014), for ports and common container terminals in South America, electricity consumption is on average distributed as follows: (a) reefer containers (i.e., refrigerated containers carrying deep-frozen or chilled cargo) (40%), (b) ship-to-shore cranes (40%), (c) terminal lighting (12%), and (d) administration buildings and workshops (8%). Fossil-fuel consumption (diesel or gas) is distributed, on average, as follows: (a) stacking operations (68%), (b) horizontal transport of boxes (e.g., by tractor) (40%), and (c) other vehicle and equipment operations such as those using terminal cards and forklifts (2%).

As discussed in the U.S. Environmental Protection Agency (EPA) (2017), the power consumed while vessels are berthed in ports is typically generated by diesel auxiliary engines. However, shore power can be used by vessels to plug into the local electricity grid and turn off auxiliary engines while berthed. Vessel systems, such as lighting, air conditioning, and crew berths, use energy from the local grid when using shore power. The power generating plant that supplies electricity to shore power applications may not be within the port confines. Land-based power supply systems fall into two main categories: high-capacity systems that typically service large cruise, container, and reefer vessels (> 6.6 kV), and low-capacity systems that typically service smaller vessels, such as fishing vessels and tugs (220-480 V) (EPA 2017). The locations of these land-based power supply systems are shown in Figure 63.

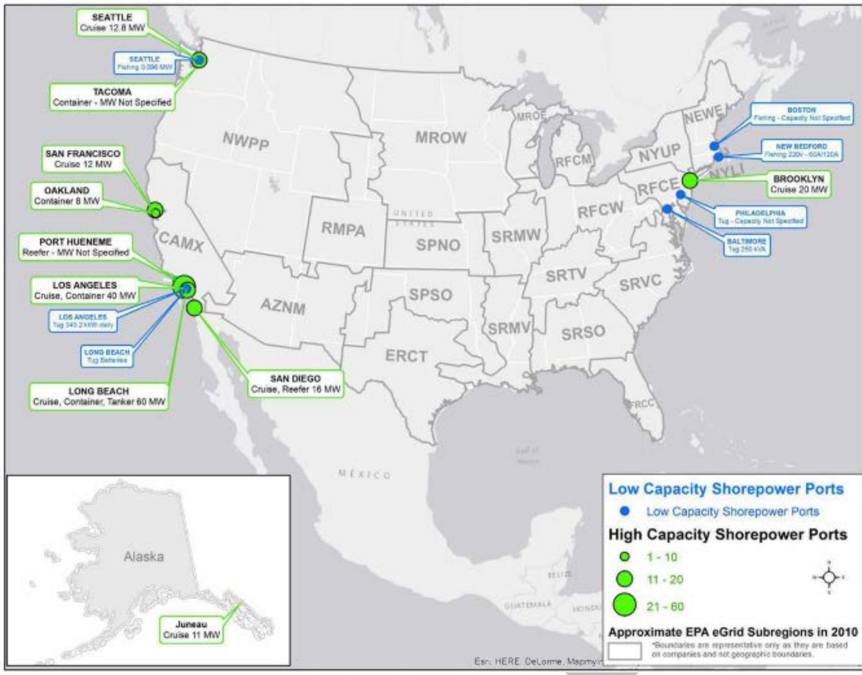

Figure 63. Existing shore power installations at U.S. ports and U.S. EPA eGRID subregions. *Illustration from U.S. EPA*

The EPA conducted a Shore Power Technology Assessment in 2017, and included the following relevant key findings:

- Shore power may be most effective when applied at terminals and ports with a high percentage of frequently returning vessels, typically cruise ships and container ships.
- Application of shore power for commercial marine vessels in the United States is relatively new and not commonly available, at present.
    - Though the technology is relatively new in the commercial sector, shore power has been successfully used by the U.S. Navy for decades and is included in the Navy's Incentivized Shipboard Energy Conservation program.
- Vessels that frequently call on the same ports and remain at berth for longer times are potentially the best applications for shore power.
- Many ports do not have the appropriate infrastructure to connect to vessels with shore power components.
- Barriers to shore power installation include infrastructure and electricity costs. Shore power requires landside infrastructure, electrical grid improvements, and vessel modifications.
    - The relative cost of using shore power instead of a vessel's own fuel sources is more attractive when fuel costs are greater than electricity costs.

10.3.2 Power Options

Currently, power supplied to shore communities and ports and marinas is typically supported by grid power and/or diesel generation. Shore protection projects, such as beach nourishment, are typically powered by offshore vessels and construction equipment that use diesel fuel.

Port officials globally have indicated their interest in renewable energy by integrating solar energy into their infrastructure, as well as drawing from nearby wind energy installations. The Port of Helinski in Finland has installed 72 solar panels, with plans for more installations. In 2016, the Port of Long Beach, the second-busiest port in the United States, installed a 904.75-kW photovoltaic solar panel system (SoCore Energy 2016). The system has the potential to generate approximately 1,547 MWh of energy per year. In India, there is currently a push to convert all 12 of its major domestic ports to renewable energy by 2019, including solar and wind energy (Tenndulkar 2017). The initial goal is to install about 200 MW of solar and wind energy projects, with a plan to reach 500 MW over the coming years.

10.3.3 Geographic Relevance

This application of marine energy is potentially relevant in all ocean, great lake, and river coastal locations.

10.4 MHK Potential Value Proposition

WECs and tidal turbines could be integrated with coastal protection structures, such as breakwaters, groins, revetments, and storm surge barriers to provide energy to local areas with little additional infrastructure cost. Due to threats of sea level rise and increase in frequency and intensity of coastal storms, many new coastal structures will be constructed or improved, providing an opportunity for MHK integration. Power from integrated MHK devices could be used to power local communities, marinas and ports (e.g., navigation lights, powering electric boats), or to supplement power for beach nourishment activities.

As discussed in Mustapa et al. (2017), the benefits obtained from the integration of breakwater and wave energy devices over the stand-alone wave energy device are as follows:

- Offers cost-sharing benefits including construction, installation, and maintenance; in 2011, the installation cost for single commercial prototype of wave and marine current energy conversion technologies ranged between $11 million and $15 million
- Provides energy extraction and coast protection services
- Limits potential environmental impacts thought to be associated with marine renewable energy installations by using existing breakwater structure as an integrated platform
- Improves WEC device reliability, allowing energy extraction to occur during heavy wave conditions; this is different compared to stand-alone offshore wave energy devices that need to be retracted for safety reasons
- Improves ease of maintenance and device lifetime; access to the device for routine and emergency maintenance will be improved compared to turbines or WECs deployed at sea
- Provides additional strength for the wave energy device to operate and withstand high wind and wave conditions.

10.5 Path to Market

10.5.1 Path to Market

The path to market for integrating MHK devices with shore protection structures includes early engagement with public and private agencies to identify opportunities to co-locate MHK devices with coastal infrastructure. These opportunities may arise during the design phase of new construction or the redesign of existing structures for improvements and upgrades. As discussed earlier, integrating MHK power into strategic planning documents would also add to coastal and grid resiliency of many shore communities.

Potential mission-driven partners include USACE, state environmental management agencies, municipal public works departments, and port authorities. For example, Port of Los Angeles officials have instituted a renewable energy program as part of their Energy Management Action Plan. Regarding wave energy, the program states:

> Offshore Wind and Wave Generation Feasibility: The Harbor Department could initiate feasibility studies for offshore wind and wave farm projects in partnership with federal, state, and regional agencies and other stakeholders. The studies could assess the technical and economic feasibility of various technologies for the Southern California offshore environment, as well as the potential impacts of the projects on the environment and human uses, including commercial shipping and recreational boating. If feasible offshore wind or wave opportunities are identified, the Harbor Department could begin the process of engineering, design, and demonstration of a test system (Port of Los Angeles 2014).

As a result of sea level rise and an increase in storm intensity and frequency, coastal communities are developing mitigation and adaptation strategies to address coastal resiliency. Many of these strategies will most likely include shore protection alternatives in the form of beach nourishment, living shorelines, and/or hard structures. Integrating MHK power into the development of these strategies would provide an added layer of coastal and grid resiliency that communities can rely on when needed.

Studies predict an increase in the transportation of goods by ship and increases in shipboard passengers, which calls for an appropriate adaptation of the existing marina and port infrastructure to meet these needs (Siemens 2017). There is also movement toward electricity as a source of energy in port operations (Siemens 2017). Port operators are aiming to reduce CO_2 emissions significantly (Siemens 2017). Regulations in Europe stipulate that the European Union's CO_2 emissions from maritime transport must be reduced by at least 40% by 2050, or even 50% if possible, as compared to 2005 levels. This could provide an opportunity to supplement electrical power with energy generated from MHK devices integrated into coastal protection structures in the vicinity of a port or harbor.

While many turbine and WEC designs may be readily adapted for placement in breakwaters and other coastal protection structures, there is a need to refine and test devices to ensure their robust operation and survivability, as well as to optimize energy production to meet coastal community and port/marina needs. Challenges including establishing the perfect compromise among storm resistance, technical reliability, environmental friendliness, and cost effectiveness need to be addressed (de Almeida 2017). de Almeida (2017) suggests that new WEC concepts should rely on some already existing scaled-up technologies to reduce future costs and time to market, as well as to increase reliability.

Several novel concepts are currently under development and being tested. For example, the REEFS concept developed by de Almeida (2017) consists of a nearshore fixed submerged caisson placed on the seafloor at low depth. Due to the design and porosity of the structure, the water flow inside the structure drives a low head hydropower turbine inside the device. The structure can also contribute to shore protection by dissipating waves. A series of scaled model experimental tests were conducted in a wave flume, and researchers concluded that the REEFS model captured about 1/5 to 2/5 of the power that it would capture if it were installed in a small-scale river dam. The model demonstrated evidence that the REEFS structure was successful at breaking/dissipating waves. Another novel concept is being developed by Zyba, a British wave energy start-up, which integrates a new curved wave energy device (CCell) with artificial coral reefs to provide both renewable energy and coastal protection for islands (Lempriere 2017).

In 2015, SINN Power installed a WEC module at the Port of Heraklion in Greece to measure generated electricity and evaluate long-term functionality of components with the aim of using wave energy to power the port's facilities (Balkan Green Energy News 2016). SINN Power received a $1.2 million grant in 2017 from the German Federal Ministry for Economic Affairs and Energy to install other WECs on a breakwater in the Port (Harris 2017). Results from tests conducted from the grant will be used to inform an 18-module array that may soon be located near the port.

Power generated from MHK devices integrated with coastal protection structures could also supplement grid resiliency efforts, in addition to being used to support water desalination (Manasseh et al. 2017), coastal/nearshore aquaculture operations, or emergency response efforts. For more discussion on grid resiliency and emergency response, please see the chapter on *Emergency Response and Disaster Recovery*.

10.5.2 Potential Partners

As noted in the chapter sections above, various coastal management and engineering organizations could be relevant partners. This includes Federal Agencies such as NOAA, BOEM and USACE, FEMA; state and local coastal and port/harbor planning and management organizations; international organizations with relevant pilot projects; and offshore supply chain members such as engineering design and build firms and dredging companies.

11 Disaster Resiliency and Recovery

11.1 Opportunity Summary

Following coastal disasters, such as hurricanes, flooding events, earthquakes, or tsunamis, there may be an immediate need for emergency power, as well as safe drinking water and process water for essential services, such as heating and fire suppression systems. Isolated portions of a coastal grid may be susceptible to extended loss of power and could require a boost for grid restart, referred to as a “black start.” Typically, FEMA and/or state or community emergency services provide diesel generators for emergency power sources. As of 2014, FEMA had 1,012 generators in its fleet comprised of 103 generator sizes, ranging from 1.5 kW to 1.825 MW (Danjczek 2014), requiring that shipments of diesel be continually delivered into disaster zones. MHK power could be used to augment or replace power from diesel generators, as well as provide “black start” capability to isolated portions of the grid. All coastal areas are at risk from these natural disasters and could benefit from MHK power. Isolated grids (e.g., coastal Alaska) have less resiliency than areas with neighboring grids and could benefit the most from having an independent source of power from the sea. FEMA’s Disaster Relief Fund is one of the main funding sources for emergency response and disaster recovery, receiving base funding of $615 million in FY 17 and an additional $6.7 billion for major declarations (PolitiFact 2017).

11.2 Application

11.2.1 Description of Application

Power generated from MHK devices could be used to supplement other energy sources during emergency response and disaster relief activities, offsetting the heavy reliance on diesel generators (Figure 64). The reliance on diesel requires it to be shipped to areas ravaged by disaster, creating logistical and financial challenges. Further, using diesel generation close to communities creates environmental health and safety issues, as a result of storing and burning diesel in those areas. Medium to large MHK devices could be used to aid in grid restart, whereas smaller devices could improve the resiliency of isolated grids in response to severe storms or other disrupting events.

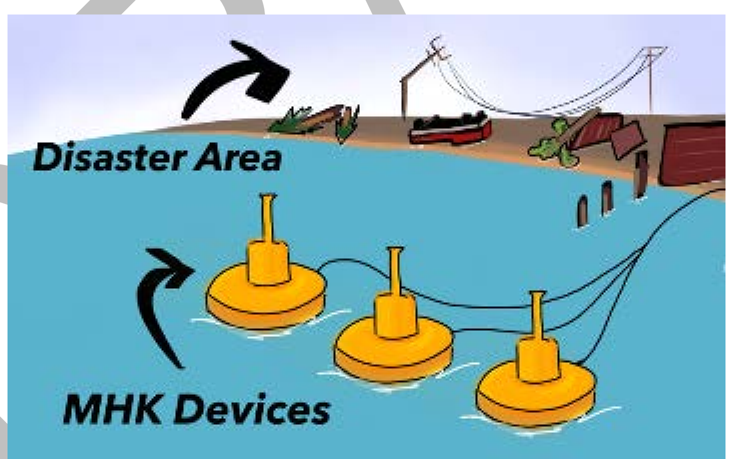

Figure 64. MHK application overview for emergency response. *Image courtesy of Molly Grear, PNNL.*

In 2016, DHS published the *National Response Framework* (DHS 2016), which provides a guide to how the nation responds to disasters and emergencies. The framework describes specific authorities and best practices for managing incidents that range from serious, local events to large-scale terrorist attacks or catastrophic natural disasters.

As discussed in the framework, once an incident occurs, efforts focus on saving lives; protecting property and the environment; and preserving the social, economic, cultural, and political structure of the jurisdiction.

Depending on the size, scope, and magnitude of an incident, local, state, tribal, territorial, and insular area governments (and in some cases, the federal government) may be called to action. The response core capabilities are the activities that generally must be accomplished in incident response regardless of which levels of government are involved. Table 24 provides a summary of each response core capability and the critical tasks to achieve its objective.

Table 24. Overview of Response Core Capabilities in the National Preparedness Goal (DHS 2016) and Requirements for MHK Power

Task	Objective	Power Needs
Planning	Conduct a systematic process engaging the whole community as appropriate in the development of executable strategic, operational, and/or tactical-level approaches to meet defined objectives	No power required; tasks carried out in advance of disasters
Public information and warning	Deliver coordinated, prompt, reliable, and actionable information to the whole community through the use of clear, consistent, accessible, and culturally and linguistically appropriate methods to effectively relay information regarding any threat or hazard and, as appropriate, the actions being taken and the assistance being made available	Electricity needed for communications systems, radio systems, and cell towers to equip personnel to provide ongoing information to community
Operational coordination	Establish and maintain a unified and coordinated operational structure and process that appropriately integrate all critical stakeholders and support the execution of core capabilities	Electricity needed for emergency management centers, including lighting, heating/cooling, communications
Infrastructure systems	Stabilize critical infrastructure functions, minimize health and safety threats, and efficiently restore and revitalize systems and services to support a viable, resilient community	Electricity needed to augment fuel for hybrid and electric vehicles, communications, debris removal equipment, communications, debris disposal
Critical transportation	Provide transportation (including infrastructure access and accessible transportation services) for response priority objectives, including the evacuation of people and animals and the delivery of vital response personnel, equipment, and services into the affected areas	Augment fuels for vehicles and other means of evacuation, including boats; delivery of vital supplies; heating/cooling, lighting for evacuees; processing drinking water; communications
Environmental response/health and safety	Conduct appropriate measures to ensure the health and safety of the public, workers, and the environment while supporting responder operations and the affected communities	Supply electricity and clean water for medical assistance, lighting, heating/cooling, communications

Task	Objective	Power Needs
Fatality management services	Provide fatality management services, including decedent remains recovery and victim identification, work with local, state, tribal, territorial, insular area and federal authorities to provide mortuary processes and temporary storage or permanent internment solutions, share information with mass care services for the purpose of reunifying family members and caregivers with missing persons/remains, and provide counseling to the bereaved	Provide refrigeration for morgues, transportation for medical personnel and bodies, and communications
Fire management and suppression	Provide structural, wildland, and specialized firefighting capabilities to manage and suppress fires of all types, kinds, and complexities while protecting the lives, property, and the environment in the affected area	Provide power for water pressure and pumping, lighting, and communications for fire crews
Mass care services	Provide life-sustaining and human services to the affected population, including hydration, feeding, sheltering, temporary housing, evacuee support, reunification, and distribution of emergency supplies	Provide power for constructing temporary shelters, processing clean drinking water, distributing food and services, heating/cooling, lighting, and providing emergency first aid
Mass search and rescue operations	Deliver traditional and atypical search and rescue capabilities, including personnel, services, animals, and assets to survivors in need, with the goal of saving the greatest number of endangered lives in the shortest time possible	Augment fuel for search and rescue vehicles, lighting, and communications
On-scene security, protection, and law enforcement	Ensure a safe and secure environment through law enforcement and related security and protection operations for people and communities located within affected areas and response personnel engaged in lifesaving and life-sustaining operations	Provide power for emergency equipment, including lighting, communications, and medical care
Operational communications	Ensure the capacity for timely communications in support of security, situational awareness, and operations by any and all means available, among affected communities in the impact area and all response forces	Provide power for communications among rescue personnel, field crews, emergency centers, and local and regional authorities; provide power for tools to rebuild communications infrastructure

Task	Objective	Power Needs
Logistics and supply chain management	Deliver essential commodities, equipment, and services to impacted communities and survivors, to include emergency power and fuel support; coordinate access to community staples; synchronize logistics capabilities and restore impacted supply chains	Augment fuel for vehicles to deliver supplies, transport the injured or ill; provide power for communications equipment and lighting
Public health, healthcare, and emergency medical services	Provide lifesaving medical treatment via emergency medical services and related operations and avoid additional disease and injury by providing targeted public health, medical, and behavioral health support and products to all affected populations	Provide power for essential medical equipment, lighting, heating/cooling, and communications; provide power to produce clean drinking water and process water for sterilization
Situational assessment	Provide all decision-makers with relevant information regarding the nature and extent of the hazard, any cascading effects, and the status of the response	Provide power for communications and lighting

Electrical Grid Black Start

As described in Feltes and Grande-Moran (2008), electrical grids are designed to be resilient and to maintain operations and consistent voltages over time. However, system power outages occasionally occur due to human error or natural occurrences, such as lightning strikes, hurricanes, or electromagnetic pulses.[15] When a portion of the grid goes down, the grid is restored with assistance from a neighboring area of the grid. In circumstances where an isolated portion of the grid, or when a widespread blackout occurs and there is no neighbor to assist, a situation known as a black start becomes necessary. A black start involves restoring the system from a preselected, reliable generating asset. For large grid operations, these black-start generators might be isolated coal-fired plants or other power sources. In more isolated grids, black-start generators might include fuel cells, microturbines, wind generators, or photovoltaic panels (Lopes et al. 2005).

As outlined by Federal Energy Regulatory Commission (FERC) (2016), electric utility companies develop their own bulk power system recovery and restoration plans that would be implemented following a widespread outage or blackout. In 2014, FERC, in partnership with the North American Electric Reliability Corporation, reviewed these plans for restoration and recovery of nine registered entities with significant bulk power grid responsibilities. The findings of the review are presented in FERC (2016).

In the United States, the 2003 blackout that left close to 50 million people across the Great Lakes Region without power was the most devastating of its kind to hit the U.S. industrial complex (DOE 2015). The blackout was so widespread and severe that black-start procedures were required to bootstrap the affected electrical grid. Outages spread northeast from the Great Lakes through Pennsylvania, New York, and into Ontario. The event contributed to at least 11 deaths and cost an estimated $6 billion (Minkel 2008). Table 2 summarizes nine of the worst power outages in U.S. history, almost all of which were a result of natural disasters.

[15] Due to the concern about the potential impacts to the grid from a high-altitude electromagnetic pulse, DOE developed an *Electromagnetic Pulse Resilience Action Plan* (DOE 2017e). The action plan discusses the federal government's ability to clarify and communicate electromagnetic pulse threats and impacts, reduce high-altitude electromagnetic pulse (HEMP) vulnerabilities, and facilitate the energy sector's response and recovery from high-altitude electromagnetic pulse events (DOE 2017e).

To increase grid resiliency and prepare for potential black-start operations in the event of a blackout, several U.S. states and other countries are instituting black-start power alternatives. In 2016, the utility Imperial Irrigation District demonstrated the use of a 33-MW lithium-ion battery energy storage system in California to provide a black start to a combined-cycle natural gas turbine from an idle state (Colthorpe 2017). Also, in 2016, a 5-MW utility-scale battery park in Germany was able to restore power to the local grid (Colthorpe 2017).

Microgrids

As discussed in International Electrotechnical Commission (IEC) (2014), a microgrid is a system of geographically grouped, distinct distributed resources, such as generators or loads, that represent a single generator or load to the wider electricity system. Microgrids may be connected to the wider electricity grid. Microgrids that are not connected to the utility grid and are distinct islands for which no connection point between the utility grid and microgrid exists are called isolated microgrids.

Microgrids are inherently suitable for maintaining electricity needs during or after a disaster, as described in IEC (2014). For example, microgrids can dramatically improve the reliability of centralized power systems; isolated microgrids can continue operation, maintaining local power supply autonomously. Microgrids can also reduce the load on the wider grid or export power from the microgrid to a broader area, in addition to helping with voltage and frequency control in such situations.

Power and energy storage technologies associated with microgrids include microturbines, batteries, flywheels/supercapacitors, fuel cells, renewable generators, and combined heat and power systems (IEC 2014). Figure 65 indicates that wind turbines are the most utilized renewable energy generation technology in microgrids around the world. As indicated in Figure 65(B), there is a reasonable distribution of microgrid sizes, ranging from microgrids that generate less than 20 kW to those that produce more than 60 MW. North America has become the dominant player in microgrid research, which is a partial response to renewed government interest after a series of crippling blackouts (IEC 2014). MHK technologies could become a significant player in microgrids associated with recovery of generation in coastal areas.

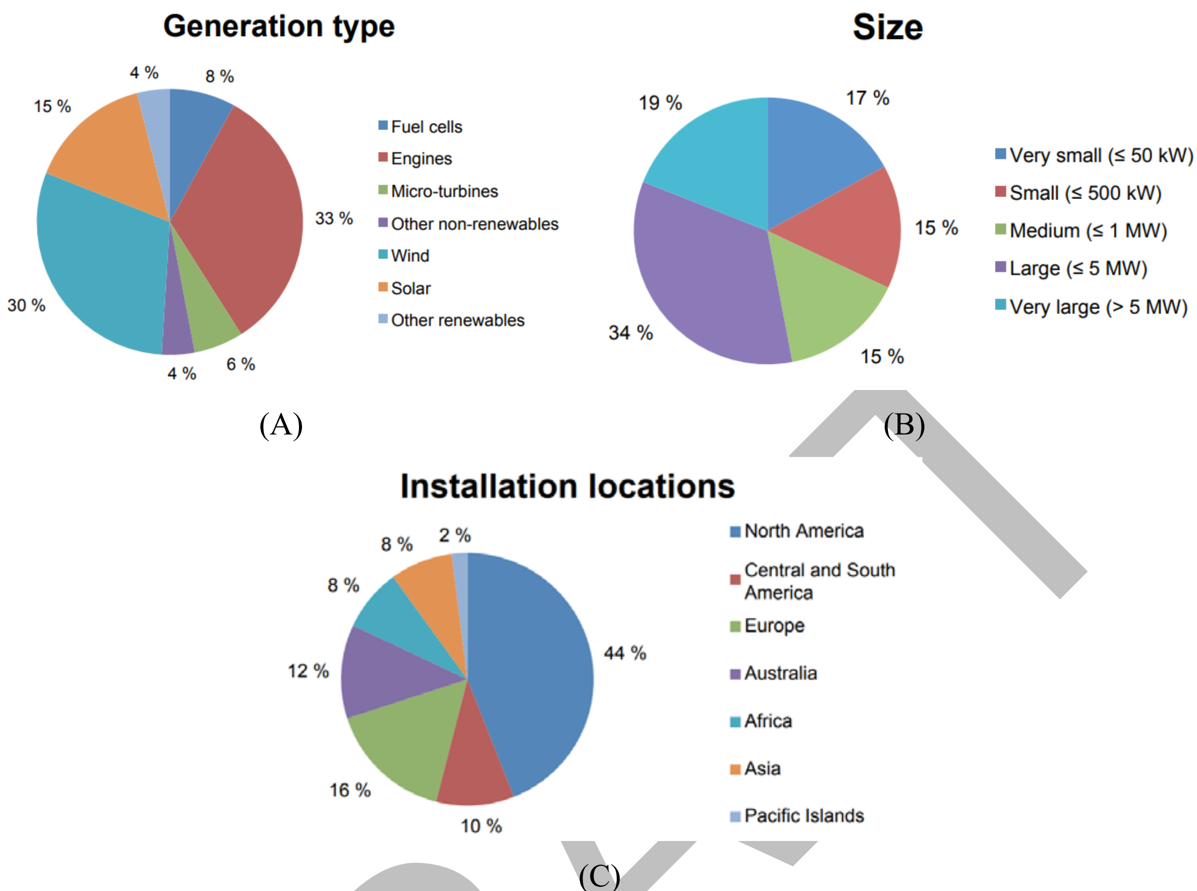

Figure 65. Microgrids around the world: (A) composition/generation type; (B) size; (C) installation locations.
Image from IEC 2014

11.2.2 Power Requirements

Each of the critical tasks outlined by DHS for emergency response will require power to run medical equipment, communication networks and devices, lighting, heating/air conditioning, refrigeration, and many other necessary services. As discussed in IEC (2014), when power is constrained (as in after a disaster), low-priority loads may be shed to maintain supply to critical infrastructure. Following an emergency, there will also be extensive needs for energy to power communities, including the needs identified in Table 25; for shoreline communities, this power could be supplied by MHK devices off the coast. For communities along sizable rivers, riverine devices could supply power in the same manner.

Table 25. Power Needs After a Disaster

• Air traffic control **• Communications (e.g., cellular, internet)** **• Emergency lighting** **• Emergency response operations and activities**	**• Refrigeration (e.g, food, ice, medicine)** **• Residences and businesses** **• Sewage and sanitation systems** **• Shelters**

The U.S. Energy Information Administration estimates that in 2016, the average annual electricity consumption for a U.S. residential utility customer was 10,755 kWh, an average of 897 kWh per month (EIA 2017). U Switch for Business (2018) provides the following estimates of average energy usage for businesses as a function of business size by employees (Table 26). The energy consumption information presented is included to provide a sense of scale for the power needs of a community. MHK resources in coastal communities could provide at least a portion of this power.

Table 26. Average Energy Usage for Businesses Based on Size by Employees. Source: U Switch for Business (2018)

Business Size by Employees	**Average Business Electricity Consumption**	**Average Business Gas Consumption**
0–10	5,000-15,000 kWh	5,000-15,000 kWh
11–50	15,000-25,000 kWh	15,000-30,000 kWh
51–250	30,000-50,000 kWh	30,000-65,000 kWh
251+	50,000 kWh+	65,000 kWh+

11.3 Markets

11.3.1 Description of Markets

While multiple agencies play a part in the nation's disaster recovery, FEMA's Disaster Relief Fund often gets the most attention. As summarized by PolitiFact (2017) each year, Congress sends two distinct portions of funds to the Disaster Relief Fund. The first portion is the fund's base funding for FEMA operations and routine events. In FY 17, base funding was $615 million. The second portion is for major declarations, and in FY 17, that appropriation was $6.7 billion. When disaster recovery outstrips FEMA's available funds, as in the case of Hurricane Harvey, Congress can release more funds in the form of supplemental appropriations. Following Hurricane Harvey, Congress approved more than $15 billion for additional relief, of which $7.4 billion was appropriated for the Disaster Relief Fund. MHK power could be associated with operations as well as with major declarations. If MHK were to be integrated and used by FEMA during emergency response activities, there would have to be significant planning and coordination, as part of operations/planning with base funding. However, when a major disaster declaration occurs, federal funds may be needed to deploy MHK devices that are not prestaged and distribute the power to the critical consumers, supported from the major declarations fund.

Figure 66 summarizes the amount of federal funds spent on hurricane disaster relief in the United States in relation to the total economic damage. Note that this figure was generated before economic data from Hurricanes Harvey and Irma were made available. Since Hurricane Katrina, federal recovery spending has covered 62% of estimated damages on average, peaking at 72% of Katrina's damages and 80% of Sandy's damages (Struyck 2017). Additionally, Congress made 14 supplemental appropriations from 2004 to 2013, totaling $89.6 billion, which included $43 billion in 2005 alone, the year that Hurricanes Katrina, Wilma, and Rita hit the United States (PolitiFact 2017).

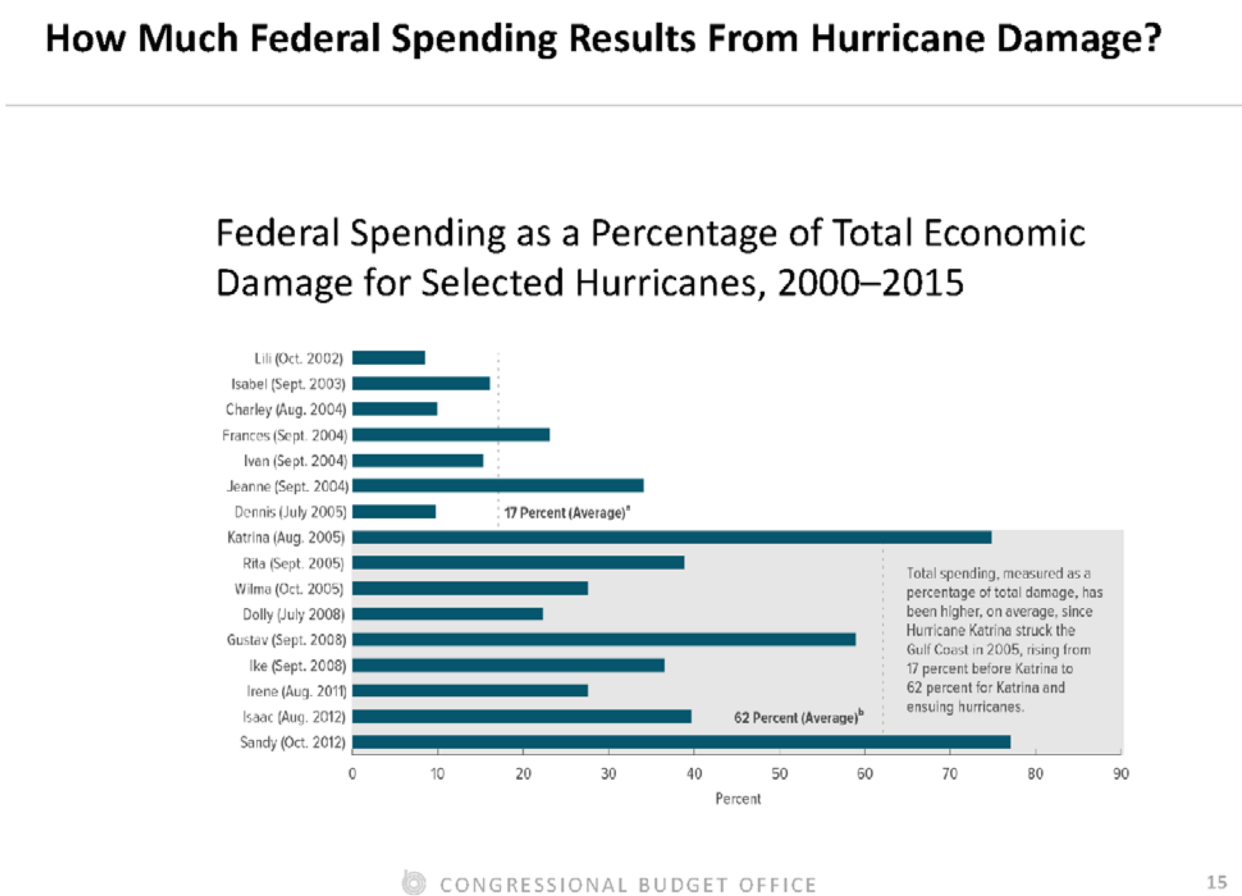

Figure 66. Federal government hurricane recovery dollars. *Image from Struyck 2017*

Increases in extreme weather events and sea level rise (NOAA 2017i, 2018b; National Climate Assessment. 2014.) are affecting the resilience of local communities and the operational demands placed on emergency management systems. This can affect core emergency management mission areas and reduce physical and economic loss from disasters in three ways: (1) impacts on mitigation, preparedness, response, and recovery operations; (2) resiliency of critical infrastructure and various emergency assets; and (3) triggering indirect impacts—population displacement, migration, public health risks —that increase mission risks and will have far-reaching effects on emergency response and disaster relief efforts. In 2010, 39% of the Nation's population lived in counties directly on the coastline; this population is expected to increase by 8% from 2010 to 2020 (NOAA 2017g). These extreme events, in combination with budget constraints and increased coastal populations, may force emergency response and disaster relief efforts to push the limits of government funding, driving communities to rely more heavily on local relief and adjust how is valued emergency response is valued in the future. Communities need to understand all the potential risks and look ahead to become more resilient (McKay 2014). Facing future events, and perhaps anthropogenic disasters like terrorist attacks on the electrical grid or other essential services, local relief efforts may become the front line for recovery. MHK technologies could provide valuable supplemental power to businesses, residences, and government facilities to improve recovery time and grid resiliency.

11.3.2 Power Options

Diesel generators, solar energy, and battery energy storage systems are the main sources of competition to MHK for disaster recovery. For example, Tesla has provided solar panels to deliver power to some areas of Puerto Rico that were still without power after Hurricane Maria in 2017 (BBC 2017). Tesla also installed a new solar-powered microgrid on the American Samoan island of Ta'u, shifting the entire island's energy generation from 100% diesel fuel to 100% solar (Lin 2017). The system was built with the capability of withstanding a Category 5 hurricane. If MHK will compete, it needs to prove reliability equal to or greater than these technologies.

11.3.3 Geographic Relevance

Potentially relevant for all ocean, river, and great lake adjacent emergency response activities in the U.S. and globally.

11.4 MHK Potential Value Proposition

MHK devices on standby could be configured to contribute to the power needs for emergency recovery and grid restart along coastlines prone to natural disasters, such as large storms (hurricanes), seismic activity, tsunamis, and flooding. A mix of renewable energy sources has the potential to replace diesel generation traditionally used to respond to emergency power needs and to restart isolated portions of coastal grids from a black start. MHK power can also contribute to coastal microgrids or a more diversified macrogrid to increase resiliency.

Rising sea levels and extreme weather events have challenged communities to become more resilient and rely more heavily on locally available, alternative energy sources. MHK power can help coastal communities respond immediately to emergencies and provide the necessary power to keep critical infrastructure running. In addition to critical electrical systems needing power, MHK could be used to support other emergency needs, such as water treatment and supply (e.g., emergency desalination).

An obvious example of the potential for MHK to support power needs in coastal communities can be found in Puerto Rico following Hurricanes Irma and Maria in 2017. In addition to the fragility of the electrical grid and the need for power in this coastal island, the lack of black-start grid capability continues to plague the island's utility and people as of April 2018.

Depending on the constraints of the location and needs of the community or grid, MHK devices could be hardened or prestaged for quick deployment postdisaster. Hardened MHK devices would need to be designed to withstand intense climates, including severe precipitation, wind, wave height, and currents. Prestaged MHK devices would need to be designed to be deployed in a very short amount of time to supply power to critical infrastructure as quickly as possible.

Coastal communities would be a direct customer of the MHK power during emergency response. Federal agencies such as FEMA, USACE, and the Department of Homeland Security could also use the energy harvested by MHK devices to supplement emergency power during their response efforts. Additionally, civilian and volunteer organizations, such as the American Red Cross, could use MHK power to aid their response efforts as well.

Isolated coastal grids are often dependent on opportunistic availability of generation sources (Lopes et al. 2005), which may include small coal or natural gas plants, solar, wind, fuel cells, or biomass digesters. Local and regional utilities would have an interest in MHK power for black start of isolated coastal grids, allowing for investment in ready standby wave devices in strategic locations near shore. For example, Oregon passed legislation that increased Oregon's renewable portfolio standard to 50% renewables by 2040, which includes wave, tidal, and ocean thermal energy (Oregon Department of Energy 2018), with explicit reliance on MHK and other renewables to assist in coastal recovery and grid black start (Oregon Department of Energy 2011).

11.5 Path to Market

11.5.1 Path to Market

Emergency managers and officials at the federal, state, and local levels need to be made aware of the potential for MHK to contribute to the mix of power sources they might call upon for emergency response. This awareness can be accomplished through education and outreach as well as demonstration projects at relevant locations susceptible to frequent outages or disasters. Tests are needed to ensure that the power from MHK devices can be conditioned and made available on a reliable basis, in conjunction with storage solutions, to pave the way for adding MHK power to the emergency management toolkit.

Following Oregon's lead, coastal states could examine the potential for explicitly adding MHK to the list of renewables and other energy sources to be used in the case of emergency response and grid restart. Additionally, there will need to be coordination among local communities, FEMA, and state emergency managers to ensure that MHK is available as a disaster recovery energy option.

The drivers and dynamics affecting emergency management (discussed earlier) will drive demand for new, augmented, or otherwise different capabilities. Several essential capabilities were identified in FEMA's *Crisis Response and Disaster Resilience 2030: Forging Strategic Action in an Age of Uncertainty* (FEMA 2012). One of the identified capabilities states:

- Plan and coordinate around shared interests and interdependencies to exercise the entire range of emergency management capabilities. This will require effective leadership, which can come from multiple sources, aligning strategies and operations across sectors, and using tools such as models, scenarios, and simulations as learning opportunities to tease out stress points and gaps.
- Why this need? The future may challenge our community with chronic resource constraints at times of rising demands for emergency management services. Current regional approaches are limited. Planners need to be motivated and empowered to look beyond short-term concerns and narrow stovepipes and recognize opportunities for collaboration around shared interests (FEMA 2012).

The utilization of MHK power for emergency response and disaster relief can be considered a "shared interest" and collaboration opportunity with shore communities and emergency response organizations.

Planning and testing the placement of standby-ready MHK devices in strategic locations would be needed to ensure that deployment, operation, delivery to the grid, retrieval, and refurbishment of the devices is feasible. Significant development and testing would need to be conducted to ensure that the power or freshwater generated by MHK devices will be efficiently distributed to the grid or other relevant consumers in the event supplemental power is needed.

When the MHK power (generated by permanent MHK devices, as opposed to maneuverable devices) is not being used for emergency response and disaster relief efforts, the power can be distributed to the local grid, used for coastal/nearshore aquaculture operations, desalination operations, or stored for future emergency response uses.

Isolated coastal grids, such as that found in southwest Oregon, are presently designated for black start using solar or wind power. The Oregon Office of Emergency Management and other state and local agencies in Oregon are planning for disasters, including the possibilities for power loss to extensive sections of the grid (Oregon Department of Energy 2011). For example, following a major disaster like a Cascadia subduction zone earthquake event of magnitude 9 and resultant tsunamis, Pacific Northwest coastal cities are likely to be without power and drinking water for extended periods. In addition, the electrical grid on the Oregon coast is considered to be fragile, with all power coming over the coast mountain range on Bonneville Power Administration transmission lines. This fragility suggests that grid outages are likely to happen with major wind storms and flooding.

A coastal disaster resilience field experiment is being planned at Camp Rilea in the spring of 2019. This experiment will use MHK to provide electricity and desalinized water to a field hospital (Oregon National Guard 2013).

11.5.2 Potential Partners

Potential partners for MHK power for emergency response include federal and state emergency response and disaster relief organizations, including FEMA, USACE, United States Agency for International Development, and the Department of Homeland Security. Other potential partners include civilian and volunteer organizations, such as the American Red Cross.

Regional and state-level utilities might invest in MHK power to ensure that small isolated coastal grids have the restart ability. As previously discussed, microgrids are inherently suitable for maintaining power supply during or after a disaster (IEC 2014) and integrating MHK as a potential power source would improve grid resiliency. MHK devices could be used in bigeneration microgrid setups alongside diesel.

12 Isolated Power Systems: Community Scale

12.1 Opportunity Summary

There are hundreds of isolated communities in the United States, primarily in Alaska and island territories, that have microgrid power systems from 200 kW to 5 MW. All are currently dependent on diesel generators for some or all of their power. The energy cost is high, sometimes more than $1/kWh, and the cost varies with the ever-fluctuating price of oil. Transporting diesel is difficult, expensive, and, in many cases, requires extensive storage capacity. Any commercial endeavor faces investment risk because of the uncertainty of future oil prices and the resulting unpredictable energy costs for remote locations. The DOD has dozens of permanent bases that operate in these same regions with similar electricity supply conditions and significant pressures to "…dramatically change energy consumption at an installation or joint base, implement renewable energy technologies, and generate and store energy to improve supply resilience for critical loads…" (Energy Resilience & Conservation Investment Program). The DOD also has numerous forward-operating bases that are often more remote from fuel sources and operate with higher cost profiles (Defense Science Board Ad Hoc Committee (Task Force) on Energy Systems for Forward/Remote Operating Bases August 1, 2016). For the DOD, transporting diesel fuel to forward-operating bases and remote-operating bases takes on a significant added element of risk exposure due to the potential for loss of human life with fuel transport. Isolated resorts are another category of microgrid consumer. In Alaska these are often fishing resorts, some of which have been around for generations. In both Alaska and the warmer island regions there is a growing ecoresort sector and some of them are remote. They all have the same incentives as the isolated communities for reducing or replacing diesel generation of power and the ecoresorts have the added incentive of needing to maintain a green footprint as much as possible while continuing to provide the amenities expected by tourists.

Most of these isolated communities have access to harvestable MHK resources: wave energy or tidal current for coastal and island communities and river current for inland locations (Alaska Energy Authority, 2017. Kilcher, 2016a and b). The desire to reduce energy costs and keep remote communities viable has motivated subsidized energy for many communities. Alaska provides support to all remote communities to reduce electric utility prices for residential users to a rate that is close to the larger grid-connected communities. This practice gives the state an incentive to support the development and use of renewable technologies that have no fuel cost and the state support could provide impetus for MHK deployment as costs decrease over time.

If MHK technologies costs become significantly lower than diesel costs, MHK technologies could improve the financial viability of remote communities by reducing dependency on the state subsidy which is at risk. If further cost reduction allows costs to fall below subsidized rate it could reduce the cost of living and allowing more money to circulate in the local economy.

12.2 Application

12.2.1 Description of Application

In remote communities, bases and resorts, electric power is essential for lighting, water pumping, and running services, such as waste water treatment. As show in Figure 67, many remote communities are currently powered by diesel generation, some with a wind turbine complement. Although diesel fuel is power dense and allows for on-demand power, it presents operational and logistical challenges. Inland river, northern, northwestern, and western region communities in Alaska depend on a few bulk deliveries by barge when weather conditions permit. Sometimes fuel must be flown in if supplies run short. While barge delivery of fuel to remote locations is expensive, air freight is far more expensive (Alaska Fuel Price Report 2016). In Bethel, Alaska, the last barge of fall tops off the tanks, leaving the community with almost 13 million gallons of fuel to use over the next 8 months or so (Demer 2016). When stored for long periods of time, diesel grows mold and requires additional treatment before use, which adds to the cost of storage.

Figure 67. Wind generators with oil storage tanks in foreground. *Image by Ian Baring-Gould, NREL 16097*

MHK technologies, operating individually or in combination with other local renewables, could provide critical electrical generation, replacing current day dependence on diesel fuel. For riverine communities, the first level of development that could provide operational experience is river current generators that provide sufficient daily energy to offset a small community's entire load during the summer. Igiuggig, Alaska, has been exploring the utilization of a river current generator that provides about half of the community's power. A community generating all its energy in this way would only need enough storage to respond to the variations in load because the river current generator provides continuous power. These communities cannot use small hydro as an alternative due to the size of the rivers and spring ice flow that make dams not a feasible answer for a small community.

For some coastal communities, developing a tidal current system is similar to developing a river current system (but slightly more challenging due to corrosion and varying current velocity and direction). Tidal currents, while predictable, vary hour by hour and day to day. Greater storage capacity is needed to transfer energy produced during peak tidal flow to the slack tide period and to respond to load variation during the day. There are also variations in the tidal range and current (Spring and Neap tides) that depend on the alignment of the sun and moon, and the system must be designed to compensate for that with additional storage or other forms of generation. Tidal generation has locations where ice will be less of an impact than it is for interior rivers and northern Bearing Sea locations, specifically in the Gulf of Alaska and Aleutian Islands. The Bering Sea freezes over, and many locations in the Bering Sea and Arctic Ocean could be impacted; however, the phenomena of frazil ice and breakup seen in river current applications are not present. Frazil ice is a phenomenon in which the water reaches freezing temperature and forms ice crystals but is too turbulent to freeze solid. The icy river is slushy on top and very abrasive. Therefore, operating tidal current generators under the ice is feasible. Doing maintenance during ice-covered times of the year might not be economically viable or even possible.

Coastal communities with a WEC resource must account for variability in their system designs, but wave energy resource variability is not as sudden as PV or wind energy variability, along with inherent seasonal reductions in solar irradiance at higher latitudes (NREL Solar Atlas). The variability implicit in the typical wave period is on the order of a few seconds, and these variations are smoothed out in the collection of WECs in a farm. While the wave height varies from wave to wave, the embodied energy in the usable vertical column has less cyclic variability. The wave resource is predictable in most locations a couple of days in advance, so managing complementary generation sources can be planned. The available energy varies significantly throughout the year and through periods of stormy and calm weather, so a WEC farm may not be a good solo candidate for a 100% renewable system. However, in combination with solar PV, which is good in the summer in the Gulf of Alaska and many places with a winter wave resource, a hybrid WEC and PV farm with storage could be designed to provide all the energy for many days in the year. Areas where the seas freeze over are not viable during the ice-covered period even if the WEC device is bottom mounted because the ice suppresses the waves. Ice cover is diminishing in the Bering Sea and some villages are being eroded out of existence due to the lack of an ice barrier during winter storms so the latitude limits for WEC devices in the Bering Seas appears to be shifting.

For DOD, the energy resiliency afforded by having on-site/near-site renewable energy generation (tidal or wave) enhances operations, and any reduction in transported fuel adds to the value proposition of MHK technologies. Bases always have backup generation on-site for necessary resilience, so the focus will be integrating MHK generation with existing power sources and/or backup generation establishing effective microgrid capability. The requirements for MHK technologies will be the same for all generation capabilities; i.e., to ensure available, reliable, and quality power is available continuously to accomplish DOD missions.

12.2.2 Power Requirements

Remote communities typically have microgrid power systems from 200 kW to 5 MW with high reliability a key objective. Remote resorts will span the spectrum from a few kilowatts to megawatts and, in some cases, are part of an isolated community grid. Remote DOD bases will have electric power needs comparable to remote villages, though load size will generally be at the upper end of the load spectrum and bases will often have greater fuel storage capacity.

12.3 Markets

12.3.1 Description of Markets

Many isolated communities are not connected to a major utility grid. These communities are isolated either by water (islands) or being remote from population centers (for example, more than 300 communities in interior and coastal Alaska). In this report, we will only discuss communities with a load less than 5 MW that are not connected to a major regional grid. Utilities with a load greater than 5 MW have scale advantages that can lower their costs. These utilities also have larger populations that correlate with better transport connections.

Isolated U.S. communities with a load less than 5 MW have a combined market of more than 70 MW, which is $350 million in MHK technologies installed cost (assuming $5 per Watt installed). The U.S. market includes approximately 175 to 300 small communities in Alaska, the two smaller Hawaiian islands of Lanai and Molokai, a couple of dozen islands mostly off the Maine coast, four inhabited islands in the Northern Mariana Islands, and some islands in American Samoa (Kilcher 2016a). Other major island territories, such as Guam, have larger utilities and are covered in the Isolated Power Systems Utility Scale chapter.

There is a growing number of remote and ecotourist resorts. Some are included in the power systems of the isolated communities above and some are independent. No database of remote resorts and their electrical loads has been identified.

DOD operates numerous Pacific Island facilities in the Marshall Islands, Guam, and Okinawa, as well as Diego Garcia in the Indian Ocean. Some of these bases will have loads larger than the 5-MW target, but the basic market and benefits of MHK technologies will still apply. DOD has nine bases in Alaska; about half are coastal and could benefit from MHK technologies.

The international market is much larger, comprised of thousands of small island and remote coastal communities. Indonesia alone has 13,000 rural communities without utility power services (GE Reports Staff

2017). A competitive MHK system will have a large global market space to develop. DOD has nine bases in Alaska; about half are coastal and could benefit from MHK technologies.

12.3.2 Power Options

The established source of power generation in isolated communities is primarily diesel generators. Any new generation must be competitive with diesel-generated power. While diesel fuel is inexpensive today, the price has been much higher in the past. Even at today's prices, the cost range of diesel-generated power for most of the remote Alaska communities is more than $0.50 and sometimes exceeds $1 per kWh (Power Cost Equalization Program 2016). For larger and less remote locations, costs can be in the $0.19-$0.37/kWh range with higher costs associated with degree of remoteness and seasonal limits to access. Diesel generation is flexible and is set up to follow load, with technology and controls that are familiar and reliable. Any new generation must be integrated with the existing diesel system.

Over the past 20 years, an increasing number of community grids in Alaska have incorporated wind energy. There are 27 communities with wind installations in rural Alaska (REAA 2016). In Wales, Alaska, two 60-kW wind generators provide up to 150% penetration at times. In other words, the wind generators can at times produce 1.5 times the electric load. They have a battery system and heat loads to balance the utility system while making use of excess electricity generation. For high-latitude locations, wind is the established competitor for diesel replacement. The installed cost of wind generators in remote locations (especially Alaska) is high (up to four times the cost of continental U.S. installations), and maintenance is very challenging because cranes are not available. Due to logistics constraints and grid size wind generators installed are smaller than typical utility wind generators, which means they are more expensive and offer fewer options. So wind installations are vulnerable to competition from MHK technologies if they can reduce project cost and demonstrate reliability.

For midlatitude and tropic communities, the number of solar PV installations is increasing rapidly with the decline in the cost of PV and storage. Islands off the coast of Maine are reducing energy loads with energy efficiency programs and by adding large ground-mounted PV systems and battery energy storage systems. The coastal islands off Maine are a good fit for PV due to having peak summer loads from tourism that align with peak summer performance from PV. This niche market will likely be filled in the short term by PV and storage before MHK technologies are available at competitive prices. However, MHK provides power at night and could complement PV.

For DOD, the competition in these markets will be diesel, PV, wind, and storage, but with greater emphasis on the reliability and resiliency that MHK technologies afford; cost will be an important but secondary factor.

12.3.3 Geographic Relevance

U.S. markets are coastal and interior Alaska, islands off the Maine coast, smaller Hawaiian Islands, and smaller territorial islands. Remote resorts are present from Bering Seas fishing lodges to Caribbean diving retreats. DOD has bases in Alaska, Puerto Rico, the Bahamas, U.S. Virgin Islands, Cuba, and other remote areas. The interior Alaska communities have river current potential, and the coastal and island communities usually have wave and tidal current resources. High-latitude locations with winter ice covering most rivers will only be generating power during half the year unless river/tidal generators are developed for use under the ice. Even if generators are developed that can operate under the ice, they must be able to survive the annual freeze and break up. The freezing in some rivers includes formation of fazil ice and during breakup, the ice, which is several feet thick, breaks into chunks that can be larger than a bus and can pile up, even forming momentary dams.

In high-latitude locations like Alaska, electrical power consumption is greatest in the winter and lowest in the summer. While much of the heating load is provided by burning diesel directly and diesel's thermal efficiencies are much higher than its electrical efficiencies, the electric load is significant due to 20 or more hours of daily dark. The river currents are high in the summer and low in the winter; even if the challenge of operating in an ice-covered river can be overcome, there is a resource-seasonal mismatch to the load. The only reason that river current is a valuable consideration is that it produces steady and consistent power, which means a higher energy delivery per installed kilowatt and minimal integration needs, such as storage. The wave energy resource in the Gulf of Alaska is higher in the winter, so the seasonal distribution of wave energy correlates well with the energy consumption pattern of the communities. For tropical island locations, electricity use is less seasonal.

12.4 MHK Potential Value Proposition

MHK technologies offer price certainty, relief from transport logistics, and reduced pollution risk. MHK devices do not have a fuel cost and are therefore not subject to the energy cost variations that diesel generators have due to oil market volatility. While currently more expensive than other renewable energy technologies, MHK devices typically have less variability in the short and long terms, making integration into hybrid systems easier (as well as diminishing storage or demand response requirements). The availability and reliability vary by resource: river current has an integration advantage due to the near-continuous power generation, and tidal current is predictable and available for most of every day. Average wave energy can be forecasted days in advance and varies on a slower timescale (when averaged over multiple devices) than wind energy and solar PV. In remote applications, the logistics costs and resource variation will have a major impact on the competitive advantage and value of the MHK technologies in complex hybrid systems.

Like all renewable energy, if MHK technologies begin to comprise a large share of the generation in a small utility (have high penetration), maintaining grid stability could be challenging. In a diesel generator grid system, the diesel generators are typically operated in the range of 50% to 80% of their capacity. The inertia of the rotating engine an generator provide stability to short-lived disruptions, such as a shorted feeder. The reserve “head room” in generating capacity supports meeting sudden load increases within seconds. At low penetration levels of variable generation sources, such as MHK and other renewables, the variability of the generation is a minor addition to the load variation. The diesel generators can still provide the needed response to compensate. As variable generation penetration levels increase, there is less diesel generation capacity on the system and therefore less ability to rapidly increase or decrease power to maintain stability. It is not possible to have unloaded diesel generators running on standby. A diesel generator must be loaded to a minimum of 40% or 50% to avoid accelerated degradation. The penetration levels for variable generation are limited in a diesel hybrid system by the need to operate the diesel generators within their acceptable operating range while still maintaining the ability to respond to the largest combined variation in load and variable generation sources (Power and Water Corporation, Austrailia, Solar/Diesel Mini-grid Handbook.)

Beyond this penetration level, storage or demand response is required (Defense Advanced Research Projects Agency). With river and tidal current generators, the short-term variation is minimal and does not add to load variation; therefore, higher penetration will be possible with current generators than with wind or PV. If the cost of river current generators decreases enough, these generation sources could be managed like a diesel generator in that they could be run at less than maximum output so they provide reserve capacity to handle load variation. The value and cost compared to adding storage and demand response require a complex system analysis.

Some configurations of WEC devices need to be fairly large (about 1 MW) to be efficient and therefore may not fit into a community grid of much less than a megawatt. They will be more difficult to integrate in any isolated community microgrid. Other types of WECs scale well and can be built in the 100-kW range or even smaller.

12.5 Path to Market

12.5.1 Path to Market

The advantage of this market for the developing MHK technologies is that the cost of generated electricity is high; therefore, the cost and performance requirements the MHK technology must meet are less difficult than in the general utility market. While it will be more expensive to install and maintain MHK devices in remote locations, all competitors have similar or greater challenges. For instance, in permafrost areas, heavy construction is planned for when the ground is frozen and installing a wind generator requires moving a crane to the site by barge in the summer. The crane remains over the winter; it cannot be returned until the river opens the following spring. There are river current demonstration projects in several locations, including Igiuggig and Eagle in Alaska. Tidal current and wave projects have been proposed in Alaska.

Devices using river or tidal current to produce power need more prototype demonstrations to show effectiveness and improve reliability, ease of deployment, and understanding of servicing requirements. Better approaches to avoiding damage from debris need to be developed and tested for river and tidal current installations. The feasibility of operating current devices under the ice must be studied to identify the benefit and cost reduction of year-round production. River systems in Alaska are mostly frozen for approximately half of the year. While most river current devices being tested in Alaska are floating devices, bottom-mounted devices are being tested in other locations. A bottom-mounted device in a deep location would be less vulnerable to ice and would be exposed to less floating debris. Little published technical study is available on the formation of frazil ice and ice breakup phenomena. So even if a current generator can operate under the ice, there may be additional challenges during the transitions from ice-covered to free of ice in spring and back to ice-covered in the fall.

Wave devices need prototype testing to determine the effectiveness of the various WEC configurations that have been designed. Some are bottom mounted and some float, and researchers must determine which will be better for this market and environment. Some scale and others (especially floating point absorbers) may not scale well due to resonant wave period response requirements. The survival of WEC devices in this environment needs to be demonstrated. The successful devices then need to be installed in demonstration projects that will allow cost, installation, and operation procedures and costs to be developed and validated. The ability to maintain WEC devices in a location like the Gulf of Alaska, which has high energy waves for long periods especially in the winter, must be demonstrated. The smaller the maximum wave height for safe maintenance, the more reliable the WEC device must be to be viable. A bottom-mounted flapping WEC has been proposed for Yakutat on the Gulf of Alaska. This type of WEC scales well and can be deployed in the size range that fits Yakutat’s small load. That project has not been funded.

All types of MHK devices need better integration management controls for microgrids so developers can incorporate MHK technologies as pilot projects without designing a new control system for each installation. These controls need to be simple and reliable. They need to integrate easily into existing diesel systems that are transitioning to complex integrated systems that have multiple generation options, along with load control and storage assets. The integrated energy cost, including installation and operation, must be lower than imported diesel generation (in many areas less than $0.50/kWh). Depending on the MHK device type and configuration, it may or may not have inertia (resistance to rapid changes in frequency) like the diesel generators have due to their spinning mass being electrically directly coupled to the electrical grid. Technology for synthetic inertia in generation connected through inverters has been developed and has been commercially deployed with large wind power plants in Quebec, Canada.

12.5.2 Potential Partners

This market can serve as a development step for MHK technologies in that it serves a market niche with high energy costs so it is easier to be competitive. The customers have relatively small power requirements that may make projects easier to finance for the early high-risk demonstrations of the technology.

Planning and financing early projects in Alaska will require cooperation between the state government and the local utility. Both have a financial stake in the energy system. The state provides a fuel subsidy for power generation in high-cost remote communities. The drawback is that because the state pays approximately half of the cost of electricity in these remote communities, if it does not provide much of the capital cost for a renewable energy system there is less incentive for the small local utility to fund a project. Remote resorts do not get subsidies, so they have the full incentive to offset fuel cost and many have an ecotourist branding to maintain so reducing or eliminating diesel use supports their branding.

Although DOD requires extremely high reliability for their bases and operations, the agency also offers testing and validation programs that help move technologies toward market readiness. DOD has several programs in technology and energy development that target different technology readiness levels and can be effective partners in new technology development, including the Defense Advanced Research Projects Agency, which is focused on making pivotal investments in breakthrough technologies for national security; the Environmental Security Technology Certification Program[16] and Strategic Environmental Research and Development Program,[17] which target prototype test projects and early market entrance projects; and the Energy Resilience and Conservation Investment Program,[18] which targets commercially viable energy technologies that enhance base energy, security, and resilience.

[16] https://serdp-estcp.org/About-SERDP-and-ESTCP/About-ESTCP
[17] https://serdp-estcp.org/About-SERDP-and-ESTCP/About-SERDP
[18] http://www.hnc.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-View/Article/490653/energy-division-energy-conservation-investment-program-ecip-validation/

13 Isolated Power Systems: Utility Scale

13.1 Opportunity Summary

U.S. isolated power system markets are the Hawaiian Islands, the U.S. Virgin Islands, Puerto Rico, and Pacific Island territories. There are eight utilities with more than 5 MW of load in Hawaii and U.S. island territories, such as Guam and the U.S. Virgin Islands, that rely on expensive imported fuel to make most or all their electricity (Hawaii State Energy Office 2016). The Alaska railbelt grid (Fairbanks to Homer) is not included in this group. It meets the size requirements, but local coal, natural gas, and hydro generation take it out of the high cost range. The imported fuel is mostly diesel, but the larger utilities, such as Puerto Rico, import a little coal and natural gas for some of their generation. The total load for these eight utilities is over 1,300 MW. Assuming 25% of that could be converted to MHK generation at an installed cost of $4 million a megawatt, the market value is approximately $1.3 billion. In addition, the U.S. Virgin Islands uses diesel generators that consume 11 million gallons of fuel a year to drive desalinization plants that purify 2 billion gallons of water annually (NREL 2011). Use of diesel generators for these high-cost utility markets causes energy price volatility due to fluctuating oil prices, as well as other negative impacts, such as high greenhouse gas emissions and localized air pollution. However, most island utilities have wave and/or tidal current resources, and early MHK projects could significantly reduce reliance on diesel fuel. There are plenty of multimegawatt opportunities for MHK projects with an avoided cost that is more than $0.30/kWh (Kilcher 2016a, 2016b). DOD has permanent bases around the world in coastal and island locations. These bases usually have independent power systems and are able to maintain operational capability under any condition.

13.2 Application

13.2.1 Description of Application

MHK projects in combination with other local renewable energy sources could provide electrical generation that would replace some or all of the diesel fuel currently used to provide electricity and desalinate seawater (NREL 2011). These island locations have wave and tidal current resources as well as solar PV and wind resources. Any MHK generation would be integrated into complex systems that could potentially include diesel generators, solar PV, wind, and energy storage systems. The existing large utilities, which are already present on these islands, have the resources to develop controls and management infrastructure to support complex systems. For example, Hawaii is already producing 25% of its electricity from wind, solar PV, hydroelectric, geothermal, waste burning, and biomass sources (Hawaiian Electric Company Inc. 2018), and the U.S. Virgin Islands has a program to reduce fossil fuel use in generating electricity by 60% by 2025 (NREL 2011).

13.2.2 Power Requirements

This market is defined as isolated or islanded utility markets with greater than 5 MW of load and high costs.

13.3 Markets

13.3.1 Description of Markets

Hawaii, the U.S. Virgin Islands, and Puerto Rico account for $750 million in electricity sales every year. Energy efficiency programs are underway in many of these locations, which should help to reduce electricity demand, but a growing transition to electric vehicles will add to the demand. Though net impact on load growth and timing is not yet defined, the cost of energy and the price uncertainty are major incentives to explore and develop alternatives to diesel generation. For many islands—especially those that are densely populated, like Puerto Rico and some of the Hawaiian Islands—an additional incentive to reduce fossil-fuel use is to mitigate carbon emissions and localized pollution from sulfur oxides and nitrogen oxides. The population on these islands exhibits stable to slow growth of less than 1%.

13.3.2 Power Options

Due to the significant cost decrease of many nonfossil-fuel generation technologies, utilities have increasingly turned to them as cheaper alternatives to diesel generation. The solar PV sector has experienced large growth in utility-scale plants and distributed customer-based systems (DOE 2017a, 2020 Utility-Scale Solar Goal Acheived), and the number of utility-scale wind energy installations has also increased, largely due to the decreased manufacturing cost and efficiency gains in both sectors. Though these competitors will likely compete with MHK projects as a viable alternative to fossil fuels, many island locations do not have sufficient land for wind and solar PV installations to meet their energy needs, along with inherent seasonal reductions in solar irradiance at higher latitudes (NREL Solar Map). The recent reduction in the cost of offshore wind energy generation is anticipated to compete with the MHK sector but only in locations where conditions are right for offshore wind. Favorable conditions are not found in all locations; for example, Hawaii has limited areas with suitable water depth for offshore wind installations, so the offshore wind potential is limited. The MHK sector is also limited by the same issues and could end up sharing the same limited development areas in Hawaii.

The competitive dynamics of MHK with other renewable energy technologies will vary depending on a complex mix of factors, including the future costs of each technology, the quality of the resource, the availability of land with good resource, and the importance of energy diversity in balancing generation timing. While the ability to predict wind power plant performance is improving, there can be significant minute-to-minute variations in power (Burman et al. 2011). Solar PV can be highly variable due to sporadic cloud cover. In large utility systems on the mainland, the geographic distribution of PV and wind projects diminishes the impact of renewable energy generation variability by averaging down the rate of change in generation for the whole system from local moment-to-moment variations. On a grid that is small in both power capacity and geographic area, the rate of change can be more difficult to manage while maintaining grid stability. On a different timescale, the sun goes down on all solar PV at nearly the same time even if it is spread out over many miles. This creates a rapid reduction in solar PV generation and requires alternate sources to ramp up quickly. This dynamic increases the value of a diverse mix of generation sources, which have different timelines and timescales (ramp rates) of variation.

Different types of marine renewable energy offer different benefits, especially in predictability, reliability, and variability. Tidal current is predictable decades in advance and provides roughly the same magnitude of power every day. Average wave energy can be forecasted days in advance and, in some cases, is less variable than wind and PV. Comparative ease of integration and management in a utility system of all these renewable resources varies significantly by location, and an analysis of each location is necessary to ensure a well-balanced mix. Storage and demand management can be used to manage the variations in generation. The increasing availability and reduced storage cost will have a significant impact on the cost of designing, building, and operating high-penetration mixed renewable energy systems.

13.3.3 Geographic Relevance

U.S. isolated power system markets are the larger Hawaiian Islands, the U.S. Virgin Islands, Puerto Rico, and Pacific Island territories. There are eight utilities (the U.S. Virgin Islands includes two separate grids but one utility) with more than 5 MW of load each in Hawaii and U.S. island territories, such as Guam and the U.S. Virgin Islands. There are many isolated utility-scale power systems globally.

13.4 MHK Potential Value Proposition

As a diesel replacement, MHK projects like all renewable energy generation offer price certainty, relief from transport logistics, and respite from local air pollution. Currently, compared to other renewable energy generation, all MHK technologies are more expensive. However, MHK technologies have some advantages, especially as the penetration levels of other renewable energy generation increase (see the Competitors section). Like all renewable power sources, MHK has no marginal fuel costs and generating equipment could outlive capital cost payback. The addition of WECs and tidal current generation offers diversity that provides a different timeline for generation and generally lowers ramp rates, and MHK technologies have little land use impact which, on some islands, will be critical. In remote applications like this, the logistics costs and resource variation will have a major impact on the competitive advantage and value of the MHK technologies in complex hybrid systems.

13.5 Path to Market

13.5.1 Path to Market

The advantage of the high-cost utility market for the developing MHK technologies is that the established energy generation source is mostly diesel generators. Diesel generators are expensive to operate, the energy produced is subject to cost variations with oil prices, they impact air quality, and are noisy. To some extent, MHK technologies will compete with and complement the other renewable energy technologies (see the Competitors section) Manufacturing in volume will be necessary for MHK technologies to become cost competitive with PV and wind technologies; initial projects will likely be primarily justified by resource diversification needs or limits on available land to develop solar PV and wind generation. To reach significant market penetration and volume production, the integrated energy cost of MHK technologies, including installation and operation, must be lower than imported diesel generation and must add value to systems with PV and wind generation. Some of the required development experience can come from applications in the isolated community-scale power system market, wherein higher costs are acceptable and projects will be smaller.

All types of MHK technologies need demonstration projects to show effectiveness, improve reliability, demonstrate ease of deployment, and enable understanding of servicing requirements before they are accepted for large utility projects. International standards are being developed through IEC Technical Committee 114 to provide a minimum common baseline for designing and validating MHK systems. There are some differences in the challenges of WEC devices versus current devices. WEC devices come in many configurations, and no clear winner has emerged at this point.

Although a few designs have been deployed, many others are only preliminary designs. Prototype testing is needed to confirm the effectiveness of the design configurations and to validate software modeling programs. Then, demonstration projects are needed to develop and confirm maintenance costs and reliability. Certification standards are being developed to provide a minimum common baseline for designing, testing, and rating WEC devices.

Some current-based generators are being tested in rivers, especially in Alaska (see section 10). As a result of these test installations, the debris problem has been well documented for river current applications (Alaska Center for Energy and Power 2018). This problem will no doubt be present in tidal and ocean current applications as well.

Depending on the MHK device type and configuration, it may or may not contribute inertia (resistance to rapid changes in frequency) to the system. Diesel generators contribute inertia due to their spinning mass being electrically directly coupled to the electrical grid. Technology for synthetic inertia in generation connected through inverters has been developed and commercially deployed with large wind power plants in Quebec. It is not currently available with small inverters.

13.5.2 Potential Partners

Projects that meet the needs of isolated community-scale power systems can serve as demonstration projects (see Chapter 10. The cost of energy and the scale of projects needed could make these demonstration projects economically viable or needing little subsidy. There is also growing pressure to convert many island nations to 100% renewable energy (e.g., Hawaii). These programs will be looking for alternatives to wind and solar PV, which are the established renewable energy technologies. The value of integrating MHK technologies into the renewable energy mix is covered in the Competitors section in this chapter. The Carbon War Room at the

Rocky Mountain Institute is supporting island countries in developing and implementing plans for 100% renewable energy systems. They currently have projects with 13 island countries in the Caribbean.

14 Other Applications

Additional applications for marine energy include off-grid charging for industrial and consumer applications, marine transportation, and ocean pollution cleanup. This chapter aims to identify opportunities for future exploration that were not studied in-depth for this report.

14.1 Off-Grid Small Device Consumer and Industrial Charging

14.1.1 Potential MHK Application and Market

The rapid adoption of portable electronic devices has created a global market for charging technologies, especially in areas without access to grid power (Genesis 2018, Research Nester, 2017). At present, the two primary off-grid charging solutions are portable battery packs and small transportable solar PV panels. The majority of off-grid charging of small personal electronic devices is presently accomplished with portable battery packs, typically in the 5,000–50,000 mAh range (see Figure 68). Larger-scale battery packs are also available, serving applications like buildings or townships. Personal use battery packs are now inexpensive, reliable, convenient to carry, easy to use, and can operate independent of local resources. They are available commercially at around $4/Ah, or about $40 for a battery that can charge three smartphones with a single charge.

Figure 68. Portable lithium-ion battery (Belkin Pocket Power 10K Power Bank, $40, 10,000 mAh) and solar PV charger (GoalZero Nomad 14 $150, 14-W Peak). *Sources: Belkin and GoalZero.*

However, these personal chargers are not sufficient for all applications. For extended or higher energy use off-grid personal, industrial, or military activities, portable consumer solar PV panel systems in the 5–50 W range are more suitable. These PV-battery systems have seen increased adoption as prices have decreased significantly within recent years (Wu et al. 2017; World Bank 2018). These smaller PV systems are now available commercially around $12 per W or $80 for a 7-W peak panel that can charge a single phone in a few hours with decent solar irradiance. Panels are also becoming more flexible and able to be incorporated into clothing, packs, and other equipment (Wu et al. 2017).

New portable consumer wind generators are also commercially available, including the MiniWiz HYmini, which has a capacity of 1-W peak with a 1,500-mAh battery at a price of around $50. These wind systems are naturally dependent on wind speeds and can reliably generate power in 9–40 mph winds.

Recently, the flexible Waterlily wind and water turbine system has been released, which generates a 15-W peak and operates in winds of 7–55 mph and current speeds of 0.5–3 meters per second. The turbine is anchored with a supplied cord in the current and a power cable is run to shore to charge devices directly or

Figure 69. Waterlilly water current and wind turbine generator. *Source: Waterlilly*

included 2,600-mAh battery pack. This system is available for $199. If it is assumed that the 2,600-mAh battery is about $15, this system is comparable to the PV systems at $12/W.

Turbine systems for charging batteries on boats have been available commercially for some time (e.g., Watt and Sea Hydrogenerators, Eclectic Energy Sail-Gen, Save Marine Hydrogenerator). For example, the Watt and Sea Hydrogenerator 300-W 12-V Cruising 24", which operates off the side of a boat at boat (or current) speeds of 1-10 meters per second is around $4,000, or $13/W.

Figure 70. Watt and Sea Hydrogenerator 300-W 12-V Cruising 24". *Source: Watt and Sea*

This technology would probably be more costly per watt at smaller capacities. While this generator system has been commercially available, utilization in smaller capacities in portable nonboat mounted applications is unknown.

14.1.2 Going Forward

Charging of small electronic devices from river and other water currents may be a small subset of the off-grid personal charging sector. Adoption of the new Waterlily turbine system should be followed closely to assess the potential of the personal charging market (e.g., reliability, market traction). A cheap, easily deployed, marine renewable energy charger would likely be of use to hikers, recreational boaters, and off-grid coastal communities.

14.2 Marine Transportation: Charging Electric Boats and Aircraft

14.2.1 Potential MHK Application and Market

Similar to providing energy to a storage system for charging underwater vehicles, marine energy could provide energy to charging stations for electric boats and aircraft. If charging stations are grid connected, the opportunities and challenges for marine energy are similar to remote electricity markets or high-cost electricity markets, as noted in those respective chapters. However, opportunities could exist off grid, such as charging stations in remote terrestrial locations or locations without grid accessibility, or at-sea (moored, station kept or floating-unmoored) for water surface and airborne craft to utilize for recharging to "hop" and extend useful ranges.

Global pressures to reduce greenhouse gas emissions and increase local air quality are causing significant changes to the shipping sector. The Paris Climate Accord and other international agreements with goals to cut greenhouse gas emissions, including a 2020 global 0.5% Sulphur cap affecting up to 70,000 ships, has created significant pressures for adaptation and innovation. Some strict emissions limits are already in place in specific emission control areas, partially in response to local air and noise pollution, along with evolving global requirements. To comply with these evolving objectives and requirements, companies are adapting or retrofitting engine systems to run with cleaner burning fuels (e.g., Liquid Natural Gas) and using diesel-electric hybrids.

A ramp-up of research, development, and implementation of electrification and automation in global shipping fleets is occurring, but significantly lags behind terrestrial transportation, and is focused on short distance trips. Some companies are now developing and customers using fully electric vessels for passenger ferries and short haul cargo transport in canals and rivers, along with recreational craft, as shown in Figure 71 and Figure 72 (DNV GL 2017a, 2017b, Guarnieri 2018). Electric ferries are presently in operation, an example of which is shown in Figure 71.

Figure 71. MF Ampere, Norway. *Source: Corvus Energy*

Bloomberg reports that the world's first fully electric and potentially autonomous container barges will be operating in the Netherlands the summer of 2018. It is noted that five barges able to carry twenty-four 20-ft containers weighing up to 425 tonnes for 15 hours will be in operation, with six larger 110-m-long barges, carrying 270 containers capable of running for 35 hours in development (Holter and Hodges 2018). DNV GL reports that 185 battery-powered ships are in operation or scheduled for delivery worldwide in 2018, most in Norway and France (DNV GL 2017b). Bloomberg expects Europe's 7,300 inland ships to eventually be electric (Holter and Hodges 2018).

Figure 72. Port-Liner canal cargo vessel in development, capable of autonomous operation. *Source: Port-Liner*

DNV GL forecasts that a significant number of electric vessels could be in operation by 2040 and 2050. The analysis assumes that batteries will only be capable of powering small vessels for short haul operations, presumably because of energy density and battery costs (Figures 73 and 74).

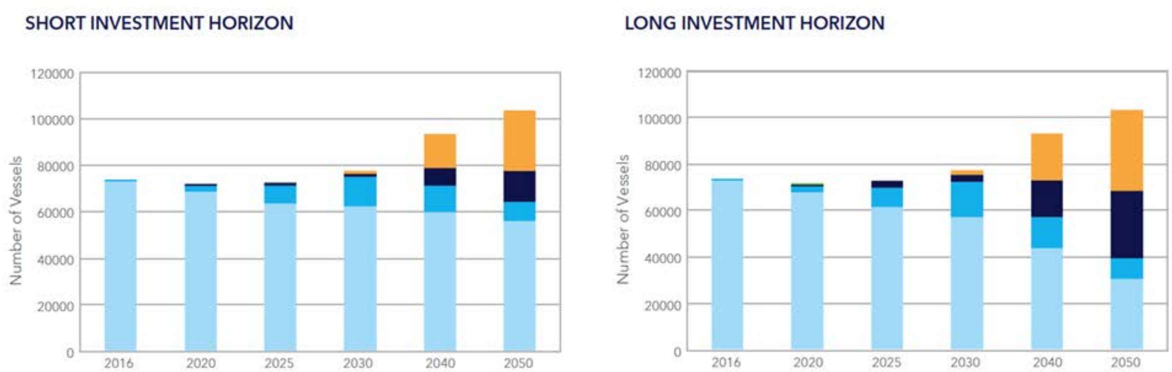

Figure 73. Forecasted growth in deployment of electric vessels, assuming only capable for small, short haul craft.
Source: DNV GL Reference 1

Short sea shipping will use 37% of the total energy, or 4.3 EJ, and in these segments electricity can constitute a significant share (9%) of energy use (DNV GL 2017a), comprising 0.4 EJ. Assumptions for this limitation are not known.

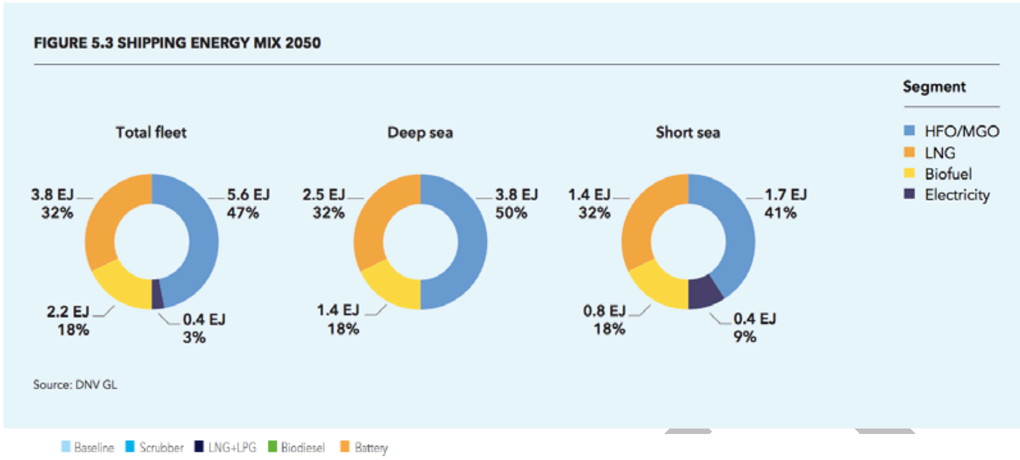

Figure 74. DNV GL forecasts that 37% of total shipping energy use (4.3 EJ) will be in short sea shipping, with electricity possible to contribute 9% of total shipping energy use, at 0.9 EJ. *Source: DNV-GL*

14.2.2 Aircraft

Autonomous and remotely operated electric-propelled aircraft are rapidly growing in utilization for commercial purposes, emergency management, military operations, and environmental monitoring. Fully electric passenger aircraft are presently in development, including autonomous vertical take-off or landing crafts, such as "Cora" from Kitty Hawk, with stated speeds of over 150 kph and a range of over 100 km (Kitty Hawk 2018). The National Aeronautics and Space Administration has an active program, X-57, developing an electric aircraft with a speed of 172 mph, 140 kW continuous, 300 kW max., 69.1 kWh (47 kWh usable) as shown in figure 75 (NASA 2017).

Figure 75. The National Aeronautics and Space Administration X-57 aircraft.
Source: NASA https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-109.html

Numerous companies are developing short transport "air-taxis," including Joby Aviation, who are designing an aircraft to hold five people with a range of over 150 miles on a single charge and is "100 times more quiet during takeoff and landing than a helicopter and near-silent during flyovers" (Vance and Stone 2018).

In the future, it is possible that strategically located landing platforms with integrated charging ports and batteries could enable extended travel over large bodies of water and extended utilization of both autonomous craft, for scientific, weather monitoring, military and homeland security, and for passenger travel. These charge stations could be combined with underwater vehicle charge stations.

14.2.3 Going Forward

Opportunities could exist off grid, such as charging stations in remote terrestrial locations or locations without grid accessibility, or at-sea (moored, station kept or floating-unmoored) for craft to utilize recharge and extend ranges. The requirements of these recharge stations should be compared to the costs and value of appropriate marine energy, wind, and/or PV energized charging stations, or hybrid systems inclusive of multiple renewable energy technologies, depending on planned ship volume, timing, and loads to be serviced. Extended usage of electric vessels will depend on evolving regulations, fuel costs, battery energy densities, and costs. System lifecycle cost and value analyses should be conducted for different shipping use cases to assess the utility, limitations, and key hurdles for electrified water transport across areas without feasible grid connection. Marine energy's relative or collaborative potential contribution to charging station power can then be assessed from this perspective.

It is thought that batteries' energy densities will limit larger electric air transportation for the foreseeable future. Smaller electric planes could be feasible, however. Similar to shipping, system life cycle cost and value analyses should be conducted for different use cases to assess the utility, limitations, and key hurdles for electrified water transport across areas without feasible grid connection. Marine energy's relative or collaborative potential contribution to charging station power can then be assessed from this perspective.

14.3 Ocean Plastic Cleanup

14.3.1 Potential MHK Application and Market

Plastic debris in the ocean is pervasive and physically harmful to wildlife and the environment. Marine plastic has even been found in seafood destined for human consumption (Rochman et al. 2013b; Browne et al. 2008; Lithner, Larsson, and Dave 2011; Teuten et al. 2009; Rochman et al. 2013a). No one knows exactly how much plastic is currently in the ocean today, but best estimates place the amount around 150 million tons. If we continue with business as usual, by 2025 the amount will increase to the point that for every 3 tons of fish in the sea there will be one ton of plastic. By 2050, the ratio will be one to one (GOV.UK 2018; Rochman et al. 2013b). The scale and complexity of ocean plastic pollution is not well understood, but it is of growing concern to many nations. It is likely that as true scale and impacts of marine pollution are realized we will see more solutions proposed.

Most debris that makes it to the ocean will eventually wind up in an ocean gyre, which is a large circular current near the center of ocean basins. These gyres have become known as maritime "garbage patches" due to prevalence of trash found within them, see Figure 101. There are five major gyres in the world oceans, and each contains plastic debris. When it comes to clean-up efforts, the best solutions are those that prevent trash from ever reaching the ocean. However, there is currently an immense amount of plastic already in the ocean and it needs to be removed before it degrades into dangerous microplastics.

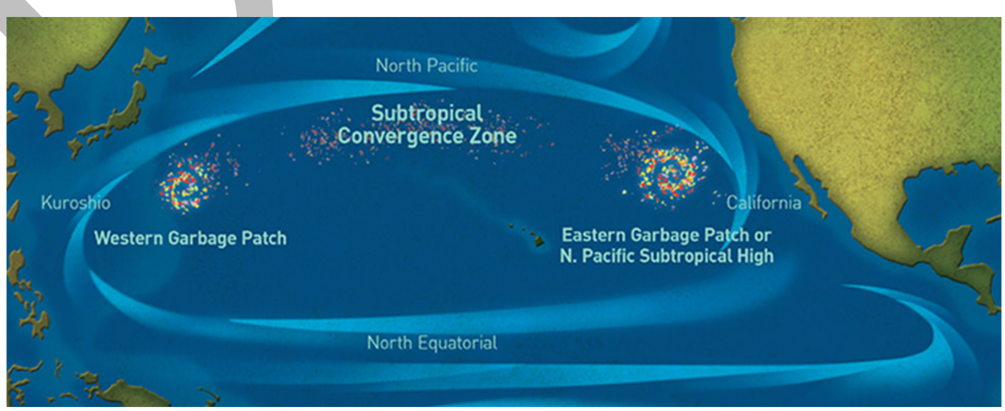

Figure 76. Ocean "garbage patches." *Image from https://oceanservice.noaa.gov/facts/garbagepatch.html*

At the moment, there are three popular, yet different, in-water clean-up solutions for ocean plastic pollution:

1. The Seabin Project to passively collect floating debris (Seabin Project)
2. The Waterfront Partnership of Baltimore's Trash Wheel powered by currents and solar PV (The Waterfront Partnership of Baltimore's Mr. Trash Wheel)
3. The passive moored Ocean Cleanup Project.

The Seabin and the Trash Wheel are examples of coastal clean-up efforts; they attempt to remove trash and debris from the water before it reaches a major body of water. Although these devices are generally within easy access of a grid connection, there is still potential to use marine energy for power applications. For example, the Trash Wheel converts river currents into mechanical energy to power its conveyor belt for trash collection.

The Ocean Clean-Up Project device is designed to use solar energy to power its sensors and navigation lights. However, given the limitations of solar in maritime applications, especially in ultraremote locations far out at sea, this device may be an excellent candidate for marine renewable energy. Moreover, if the pilot device proves successful, the intent is to build dozens of these clean-up devices for each of the major gyres. This would certainly be a market opportunity.

14.3.2 Going Forward

Removing plastic debris from the ocean is costly and unregulated. Should clean-up efforts to remove ocean plastic from remote or at-sea locations gain traction and funding, the requirements of clean-up systems should be compared to the costs and value of appropriate marine energy, wind, and/or PV energized charging stations, or hybrid systems inclusive of multiple renewable energy technologies.

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