U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

POWERING the BLUE ECONOMY™

Exploring Opportunities for Marine Renewable Energy in Maritime Markets

April 2019

This report is being disseminated by the U.S. Department of Energy (DOE). As such, this document was prepared in compliance with Section 515 of the Treasury and General Government Appropriations Act for fiscal year 2001 (Public Law 106-554) and information quality guidelines issued by DOE. Though this report does not constitute "influential" information, as that term is defined in DOE's information quality guidelines or the Office of Management and Budget's Information Quality Bulletin for Peer Review, the study was reviewed both internally and externally prior to publication. For purposes of external review, the study benefited from the advice and comments of nine energy industry stakeholders, U.S. Government employees, and national laboratory staff.

NOTICE

Available electronically at OSTI.gov http:/www.osti.gov

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
OSTI http://www.osti.gov
Phone: 865.576.8401
Fax: 865.576.5728
Email: reports@osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312
NTIS http://www.ntis.gov
Phone: 800.553.6847 or 703.605.6000
Fax: 703.605.6900
Email: orders@ntis.gov

How to cite this report:

LiVecchi, A., A. Copping, D. Jenne, A. Gorton, R. Preus, G. Gill, R. Robichaud, R. Green, S. Geerlofs, S. Gore, D. Hume, W. McShane, C. Schmaus, H. Spence. 2019. *Powering the Blue Economy; Exploring Opportunities for Marine Renewable Energy in Maritime Markets*. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. Washington, D.C.

Powering the Blue Economy

Exploring Opportunities for Marine Renewable Energy in Maritime Markets

Table of Contents

Acknowledgments

The U.S. Department of Energy Water Power Technologies Office would like to express our appreciation to everyone who has contributed to this fact-finding effort, including leadership and staff; the national laboratories; our partners in the U.S. Department of Defense and U.S. Navy and other federal agencies; our affiliated universities; representatives from companies in the marine energy community; and our new friends representing industries and opportunities associated with the dynamic blue economy. The research was carried out and the technical chapters written by teams at the National Renewable Energy Laboratory (Al LiVecchi, Scott Jenne, Robert Preus, Robi Robichaud, and Rebecca Green) and Pacific Northwest National Laboratory (Andrea Copping, Alicia Gorton, and Gary Gill). We are grateful to the more than 100 individuals who participated in the 2017 Marine Energy Technologies Forum and provided feedback on emerging opportunities for marine energy technologies. We thank the many reviewers from government, industry, and academia for their time and thoughtfulness in responding to the Request for Information on the draft report, which lead to a much-improved final product. Significant direction and input at all stages of the project were provided by Water Power Technologies Office Project Lead William McShane, and team members, including Simon Geerlofs, Simon Gore, David Hume, Carrie Schmaus, and Heather Spence. A summary graphic for each thematic chapter was developed by Pacific Northwest National Laboratory Intern, Molly Grear. The final version of the report was strengthened through detailed reviews provided by Robert Thresher and Jochem Weber of the National Renewable Energy Laboratory. We also thank the National Renewable Energy Laboratory Communications team for detailed report editing and graphics development, including Sheri Anstedt, Kiki Carpenter, and John Frenzl.

Abstract

The blue economy is an emerging sector that will require energy to allow many scientific and commercial endeavors to reach their potential. The U.S. Department of Energy's Water Power Technologies Office seeks to understand marine and coastal opportunities for which marine energy could fulfill those energy needs. This report documents the material gathered during a year-long fact-finding effort engaging users and developers, through literature review, workshops, interviews, and national lab analyses, as well as a Request for Information process. Each market was assessed by a set of common analyses: opportunity summary; application description and power requirements; market description, power options, and geographic relevance; marine energy potential value proposition; and path forward including research and development needs and potential partners. The major finding is that there are more markets with potential than anticipated, both for Power at Sea (including ocean observation and navigation, underwater vehicle charging, marine aquaculture, marine algae, and seawater mining), and Resilient Coastal Communities (including desalination, coastal resiliency and disaster recovery, and community-scale isolated power systems). The enabling attributes of marine energy resources include that they are abundant, geographically diverse, energy dense, predictable, and complementary to other energy sources. This report can help direct analysis and research and development efforts by government, scientists, developers, and other stakeholders to more deeply understand and meet specific technical and economic requirements to power emerging opportunities in the blue economy.

Executive Summary

Introduction

Expanding demand for ocean-derived food, materials, energy, and knowledge is driving rapid growth in the emerging "blue economy."[1] Traditional ocean sectors, such as shipping, fisheries, and ports, are undergoing rapid change in response to new technologies, competition, and regulation that reflect an increasing focus on environmental sustainability. At the same time, technology innovation is fueling high-growth industries including marine aquaculture, ocean observing, marine robotics, biofuels, and seawater mineral extraction.

Marine energy could play a unique role within each of these applications, enabling new capabilities and economic development. While marine energy (along with offshore wind) is a dynamic and rapidly growing sector of the blue economy, it's also true that other sectors rely on access to consistent, reliable power to achieve their needs. Aligning innovation in the blue economy with recent advances in marine energy technology could provide solutions for both legacy and emerging industries that meet economic, social, and environmental goals.

Many technologies and industries are looking to take advantage of the scale of the ocean, moving further from shore and away from conflicts with other sectors and ocean users. This requires access to consistent, reliable power untethered to land-based power grids, demanding new approaches to onboard energy generation and storage as well as reliable remote recharging. Closer to shore, remote coastal and island communities are exploring options to reduce reliance on single sources of fuel and water that limit their ability to realize energy independence and sustainability. This transition necessitates new forms of energy generation using local and naturally renewable resources.

This report is a high-level analysis of potential market opportunities where marine energy may hold a unique value proposition to meet the energy needs of the blue economy. It was commissioned by the U.S. Department of Energy Water Power Technologies Office (WPTO) and authored by the National Renewable Energy Laboratory and the Pacific Northwest National Laboratory. The information in this report was collected through a variety of methods, including a workshop, interviews, literature reviews, and public comments. It represents a starting point—an initial understanding of opportunities to inform further detailed analyses and a long-term program strategy for WPTO.

WPTO supports foundational science and early-stage research to improve performance and reduce costs of marine energy generation technologies. Since its formation in 2008, WPTO has primarily focused its funding and research priorities toward regional grid-scale power markets.

Developing and selling new technologies for integration into the grid is challenging, especially for marine energy. The time it takes to fully develop, test, and refine any design takes multiple iterations; when working in the ocean with large devices and long permitting cycles, a single design cycle can take years. These long design cycles create challenges for technology advancement.

In late 2016, WPTO began exploring potential markets for marine energy technologies beyond the grid. This exploration focused on markets, end users, and partners with a faster path to market, higher risk tolerance, reduced price sensitivities, and lower power needs to allow for smaller designs and faster design iteration cycles. WPTO is particularly interested in opportunities in which existing energy technologies are a factor limiting market growth and where marine energy could remove constraints and enable new capabilities.

---

[1] See, for example: Economist Intelligence Unit. 2015. "The Blue Economy: Growth, Opportunity and a Sustainable Ocean Economy." http://www.greengrowthknowledge.org/resource/blue-economy-growth-opportunity-and-sustainable-ocean-economy.

This investigation began with informal information gathering through conversations and literature review and then matured into a formal research project leading to the development of this report. Through this process, WPTO has gained a better understanding of the diverse set of markets that represent development pathways for marine energy, both near term and into the future. This report and subsequent programmatic activities have started to illuminate the compelling need for energy innovation in the blue economy as a potentially critical element underlying the success of multiple sectors across scientific, economic, and security domains.

Marine Energy and the Blue Economy

The term "blue economy" is gaining traction among government, industry, and nonprofits as an organizing principle that captures the interplay between economic, social, and ecological sustainability of the ocean. This interest is fueling investment in next-generation maritime or "blue" technologies. The blue economy is generally considered to be comprised of sectors and activities that span commerce and trade; living resources; renewable energy; minerals, materials, freshwater; and ocean health and data.[2] According to the Organization for Economic Co-operation and Development's 2016 report, *The Ocean Economy in 2030*, ocean-related industries contribute more than $1.5 trillion in value added to the overall economy each year and that value is expected to double by 2030.[3] Given the tremendous value of the ocean, our ability to contribute to the blue economy sustainably has important implications with a wide range of societal and environmental benefits.

In most definitions of the blue economy, marine energy is characterized as an emerging sector and often grouped together with offshore wind under names such as 'offshore renewables.' Marine energy technologies convert energy from ocean waves, tides, and ocean currents into electricity or other forms of usable energy.[4] Marine energy resources are geographically diverse, making them applicable to the entire United States and its territories. The energy contained within these resources is sizable, predictable, reliable, and can be developed in an environmentally responsible manner.

Market Themes

A diverse range of potential applications for marine energy were explored for this report, naturally falling within two thematic areas:

1. Providing power at sea to support offshore industries, science, and security activities, fitting the theme of **Power at Sea**

2. Meeting the energy and water needs of rural coastal and island stakeholders, fitting the theme of **Resilient Coastal Communities**.

Five of the applications identified in this report are focused on providing power at sea in off-grid and offshore locations. Three are concerned with meeting energy and water needs of remote, island, and rural communities (and military bases), on or close to land. For each market within these themes, a dedicated chapter investigates power requirements, market trends, incumbent technologies, geographic relevance, the value proposition for marine energy, and further research needs.

---

[2] Economist Intelligence Unit. 2015. "The Blue Economy: Growth, Opportunity and a Sustainable Ocean Economy." http://www.greengrowthknowledge.org/resource/blue-economy-growth-opportunity-and-sustainable-ocean-economy.

[3] Organisation for Economic Co-operation and Development. 2016. *The Ocean Economy in 2030*. https://doi.org/10.1787/9789264251724-en.

[4] Marine energy also includes technologies that extract power from thermal and salinity gradients. Marine energy as a whole is an emerging technology, but thermal and salinity gradient technologies are especially nascent and were not included in this report because of the challenges in understanding their value proposition for alternative applications.

Power at Sea

Within the Power at Sea theme, chapters are presented on ocean observation and navigation, charging underwater vehicles, marine aquaculture, marine algae farming, and seawater mining. Although all of these markets are potentially viable, some are more near term than others. Chapters are presented in the order of perceived relevance to marine energy as a viable near-term market.

Ocean Observation and Navigation

Integrated networks of ocean sensors and aids to navigation exist to monitor oceanographic conditions and promote safe navigation. Oceanographic and meteorological instruments monitor the ocean environment in near real time and help meteorologists improve weather forecasts. These sensors also improve our ability to provide early warning of more extreme coastal events, such as hurricanes, rip currents, and tsunamis. Aids to navigation assist sailors and mariners by marking areas of safe passage and danger, and by protecting the environment and vessels from significant damage. To persistently monitor the ocean or mark areas of interest requires electrical equipment, such as sensors, transceivers, and lighting, all of which require power.

The world's sales of navigational and survey instruments nearly doubled between 2001 and 2011, from $7.5 billion to $16 billion (Maritime Technology News 2012). While only a portion of these instruments will be used on offshore monitoring systems or navigation aids, it remains a sizeable opportunity. This demand for ocean data is driven largely by customers in the U.S. Department of Defense, oil and gas, and research communities that wish to better understand ocean environments and their interaction with manmade systems. As we move into the age of digitalization and the need for data accelerates, it is expected more powerful sensors and instruments in the ocean will increase as well.

The large increase in ocean observation and monitoring systems, combined with the desire to record data in real time, leads to larger power demands. Because of their remote location, these systems typically rely on in-situ energy generation or energy storage to power their instruments and equipment. Renewable energy can meet many of these needs, but some technologies are better suited than others. Marine energy could power ocean observation instruments and nodes at depth, in high latitudes, and during the winter or at night, all areas or applications where other renewable energy technologies are limited. In this way, marine energy could be uniquely suited to certain mission profiles and could enable a level of data collection never before possible.

Underwater Vehicle Recharging

Autonomous underwater vehicles (AUVs) and unmanned underwater vehicles (UUVs) are used for a variety of underwater applications. In the civilian sector, these vehicles are used for ocean observations, underwater inspections, monitoring the seabed and underwater structures, and scientific studies. For defense and security applications, they are used for persistent surveillance, underwater monitoring, mine detection and countermeasures, and payload delivery, among many other tasks. These vehicles come in a variety of shapes and sizes, from torpedo-like designs as small as a football to others as large as a school bus weighing several tons.

In most cases, these vehicles rely on an internal power source, such as a battery, to provide power for all the electrical systems on board, including sensors, navigation, propulsion, and communication. Because of battery capacity, underwater vehicles are generally limited in range and duration. Over the last several years, there have been a number of designs for underwater docking stations that could be used to recharge an underwater vehicle, yet a persistent power source is still needed.

Globally, the AUV/UUV market is estimated at $2.6 billion and is expected to double by 2022 (Research and Markets 2017). The market for recharging underwater vehicles, 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 but smaller in scale than the greater AUV market. 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, but the oil and gas industry also drives growth.

Underwater recharge stations are currently under development and lack standardization. As these designs mature, marine energy could provide reliable, locally generated power. As a result, it could reduce the need to recall vehicles to the surface as frequently; reduce reliance on support vessels and crew; improve human safety; increase mission duration, range, and data collection; and reduce carbon emissions.

Marine Aquaculture

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. The method of cultivation and harvest varies depending on the species—finfish may be raised in large net pens offshore, whereas oysters might be reared on hanging lines in estuaries. The type of aquaculture will determine the power needs for these systems. Marine aquaculture power needs include navigation lights, compressed air production, nutrient and waste disbursement, refrigeration, fish feeders, and potentially even crew support (e.g., lights, heat) for larger aquaculture farms. The desire to move aquaculture facilities offshore is an important industry trend, which could represent opportunities for marine energy.

At present, more than 90% of U.S. seafood is imported and there is an annual seafood trade gap of approximately $14 billion per year between the United States and its trading partners (National Oceanic and Atmospheric Administration 2015). Closing this gap solely by traditional fisheries is unlikely, and traditional nearshore aquaculture is limited by siting challenges. For this reason, offshore aquaculture is expected to grow rapidly to meet rising seafood demand. Offshore aquaculture is a nascent industry here in the United States, but offshore farms are developing worldwide and the market is projected to be more than $55 billion by 2020 (Food and Agriculture Organization 2016). Much of this growth will be witnessed in the Asia-Pacific region by countries like China and India, but markets in other countries like Brazil are also expected to grow as a result of the rising demand for food caused by population growth.

Power for marine aquaculture is generally provided by diesel generation and occasionally by renewables, such as solar with battery storage. By replacing fossil fuels with marine renewable energy, the aquaculture industry could become more sustainable and reduce the likelihood of potential harm to air and water quality via emissions and oil spills. There are a number of potential synergistic opportunities for co-location of aquaculture and wave energy devices (e.g., wave farms could provide shelter in their lee to an offshore aquaculture facility). Although the ideal environment for offshore aquaculture does not always present the best resource for a marine energy conversion system, in order to meet the expected demand there are likely many locations suitable for a combined marine energy and aquaculture farm.

Marine Algae

Marine algae refers to a diverse group of organisms including macroalgae, microalgae, and cyanobacteria ("blue-green algae"). Macroalgae, commonly known as seaweed, and some microalgae can be grown at commercial scale at sea to provide biofuels, animal feed, and other co-products. Micro and macroalgae have high levels of structural polysaccharides and low concentrations of lignins that can be made into feedstocks for the 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. Although many existing small cultivation sites need little power, 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 farm structures.

Seaweed farming has been growing rapidly and is now practiced in about 50 countries (Food and Agriculture Organization 2016; Ghadiryanfar et al. 2017). With the world's largest Exclusive Economic Zone, much of which is viable for growing microalgae and macroalgae, the United States has the potential to become a leader in algae production. Algae grown at sea could bypass future constraints on terrestrial biomass, such as competition for land and freshwater availability. Geopolitical pressures to use less carbon-intensive fuels, as well as algae's benefit of being an effective means to sequester carbon, will likely drive more interest in marine algae in the coming years.

Marine energy could be integrated into growing and harvesting systems of marine algae farms to provide off-grid power needs. Not only does much of the U.S. Exclusive Economic Zone overlap with areas of marine resources, but marine energy devices at sea could have a durability advantage over other renewable and fossil-fuel sources of power because of their marinized design. With proposals for free-floating biofuel operations, marine energy, especially wave energy, is in a unique position to accommodate farming activities.

Seawater Mining

Seawater contains large amounts of minerals, dissolved gases, and specific organic molecules. These elements and compounds are more evenly distributed throughout the ocean, albeit at lower concentrations, than in terrestrial locations. Lithium, uranium, and hydrogen are of particular interest and have been extracted or produced from seawater in several laboratory tests. For mineral and element extraction from seawater, there are two proposed methods: passive adsorption and the less common electrochemical process. Gases, such as carbon dioxide, hydrogen, and oxygen, can be electrolytically produced directly from seawater.

The power required for each method varies. Passive adsorption methods will likely require significantly less power than an electrolytic process, for example. Potential uses for power in these applications include deploying and retrieving long adsorbent films, extracting elements via electrochemical mechanisms or electrolysis, pumping seawater, powering safety and monitoring equipment, as well as potentially powering the machinery or technology needed to remove elements from adsorbent material.

Most systems that could extract minerals from seawater are in early stages of development, but a strong market demand exists for many of the end products. 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 rare-earth minerals, will continue to grow with increases in consumer and industrial electronic use, further stressing terrestrial supplies, particularly from nations that are considered to be security risks.

As this market is still nascent, it is unclear exactly how marine energy might best provide value. However, there are no incumbent power sources that must be displaced, perhaps presenting an opportunity for marine energy technologies to co-develop with these new technologies and secure a first-mover advantage. Marine energy may have some unique advantages over solar and offshore wind for offshore seawater mining operations, such as low-profile infrastructure for improved survivability and reduced visual impacts.

Resilient Coastal Communities

Within the theme of Resilient Coastal Communities, chapters are presented on seawater desalination, coastal resiliency and disaster recovery, and community-scale isolated power systems: community microgrids. Although all of these markets are potentially viable, some are more near term than others. Chapters are presented in the order of perceived relevance to marine energy as a viable near-term market.

Desalination

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

There are two primary market segments for desalination: water utilities and isolated or small-scale distributed systems. Large-scale desalination systems require tens of megawatts to run and provide tens of millions of gallons of desalinated water per day. Small-scale systems vary in size, from tens to hundreds of kilowatts and provide hundreds to thousands of gallons of water per day. In the United States, the existing market capacity for reverse-osmosis systems is approximately 500,000 m^3/day, translating to approximately $45 million–$65 million per year in electricity costs (National Research Council 2008). Changing weather patterns can create drought, and population growth is placing increasing stress on existing water supplies; both will contribute to more interest in seawater desalination to address the shortfall.

Wave- or tidal-powered technologies could be used to directly pressurize seawater for a reverse-osmosis system, eliminating the need for electricity, one of the largest cost drivers for the production of desalinated water. Marine energy resources are inherently located near potential desalination water supplies and population concentrations along the coast, therefore areas that have unreliable grid connections or water infrastructure may receive both electricity and water benefits from marine energy systems. In the long term, marine energy could provide low-cost, emission-free, drought-resistant drinking water to larger municipalities.

Coastal Resiliency and Disaster Recovery

Coastal areas are prone to extreme events, such as tsunamis, tropical storms, and flooding. Before a disaster strikes, it is possible to fortify coastal communities both by augmenting natural defenses, like beaches and marshes, and creating microgrids with distributed power generation sources. These actions mitigate damage and improve resilience.

Disasters can disrupt freshwater and electricity supplies, limiting access to essential services for days, weeks, or sometimes months. This disruption creates a need to provide humanitarian relief and emergency supplies of clean water and electricity until regular utility services are restored. There are also damages to shorelines through erosion and sediment transport after a major storm, often putting waterfront homes at risk.

Extreme weather events and sea level rise are driving coastal community response in three ways: focusing efforts on mitigation, preparedness, response, and recovery operations; improving the resilience of critical infrastructure and various emergency assets; and triggering indirect impacts, such as population displacement, migration, and public health risks. In the United States, spending on disaster preparedness and recovery has been increasing. Since 2005, average federal spending on recovery as a percentage of total damage caused per hurricane has increased 62% (PolitiFact 2017).

Marine energy could contribute to extreme event preparedness and recovery. When building new coastal fortifications, such as breakwaters or seawalls, marine energy devices can be integrated into the design. This approach could enhance infrastructure benefits by providing both shelter from the sea and power production. In some areas, it might be possible to use marine energy systems to transport sand or sediment to replenish beaches and mitigate erosion. As a distributed energy resource, numerous marine energy systems could contribute to a coastal microgrid, adding greater diversification in generation assets and reducing the likelihood of a complete blackout in the event of wide-scale grid outages. Postdisaster, marine energy technologies could be used to provide desalinated water or electricity in remote coastal areas not easily serviced by emergency responders.

Community-Scale Isolated Power Systems

Not every community has access to reliable electrical grid infrastructure. In many remote areas, communities are isolated entirely from the grid and must find other ways to generate power. There are hundreds of isolated communities in the United States, primarily in Alaska and island territories, that have microgrids with capacities with as little as 200 kilowatts to as high as 5 megawatts or more (Alaska Energy Authority 2016a). Internationally, there are many more such communities.

Nearly all of these isolated systems depend on diesel generators for some or all of their power. Although diesel fuel is energy dense and provides on-demand power, it presents operational and logistical challenges. For example, many remote communities in Alaska depend on a few bulk fuel deliveries each year that are susceptible to supply chain disruptions and fuel price volatility. This results in energy costs higher than the national average, sometimes more than $1/kilowatt-hour.

For this investigation, only those communities with load requirements below 5 megawatts and that are not connected to a major regional grid were considered. With this threshold, isolated U.S. communities represent a combined market of more than 70 megawatts (Alaska Energy Authority 2016a). The U.S. market includes approximately 175 to 300 small communities in Alaska, and then dozens of islands in the South Pacific and New England areas. Additionally, the U.S. Department of Defense operates multiple military facilities and outposts in the Pacific Ocean and Indian Ocean. Internationally, the market is much larger, comprising thousands of small-island and remote coastal communities. Indonesia alone has 13,000 rural communities without utility power services (GE Reports Staff 2017).

Marine energy technologies could benefit isolated community microgrids with marine or riverine resources in close proximity. Marine energy technologies might provide long-term energy price stability, relief from fuel transport logistics, and reduced risk of pollution. Moreover, marine energy devices typically have less variability in their generation profiles over the short and long terms, allowing for easier integration with other systems. Lastly, marine energy diversifies the generation resources and creates a more reliable system, improving the resiliency of isolated communities when threatened by extreme events.

Other Applications

An additional chapter provides information on other applications that were not considered in depth, but which may still hold opportunities for marine energy, including marine transportation, personal charging, ocean pollution cleanup, offshore communications, and offshore data centers.

Marine Transportation

Global pressures to reduce greenhouse gas emissions and increase local air quality are driving shipping companies to modify vessel engine systems to use cleaner-burning fuels, or modify vessels to operate as diesel-electric hybrids, fully electric, or with hydrogen fuel cells. Demand for these technologies, as well as the fuel and energy to power and charge them, respectively, will increase in the coming years. Marine energy's obvious colocation benefits near ports and harbors may make them well-suited to this task. However, marine energy may not present a distinct advantage initially, as vessels are likely to charge using connection to the existing power grid. In the future, marine energy could serve charging needs in remote locations or potentially offshore charging stations.

Personal Charging

Portable electronic devices, such as mobile phones, have created a global market for charging technologies, especially in areas without access to grid power. At present, the two primary off-grid charging solutions are portable battery packs and small transportable solar photovoltaic panels. Opportunities exist for marine energy to develop small charging systems using river or ocean resources, providing small amounts of power for hikers, sailors, remote coastal communities, or defense applications.

Ocean Pollution Cleanup

The ocean environment is being affected by a number of stressors. Oil and plastic pollution, ocean acidification, coral bleaching, and illegal fishing are a few of the major issues gaining increasing attention as major threats to ocean health. Within each of these areas, there are technologies or other solutions under development to help mitigate or address the threats. Some of these are energy intensive and could be paired with marine energy.

Offshore Data Centers

Data centers, in aggregate, are becoming one of the largest consumers of electricity in the world. As space for data centers becomes more difficult to find in congested population areas, some companies will look to deploy server farms offshore. Google has started using seawater cooling and Microsoft has even begun submerging data centers underwater entirely in watertight containers. The ocean provides free cooling, historically one of the greatest costs in operating a data center, as well as the potential to be powered by locally sourced power from marine energy.

Although these various applications were not included as complete chapters in this report, they are worthy of further investigation and could benefit from marine energy.

Discussion

The marine energy resources considered in this report include ocean waves, tidal, river, and ocean currents. The wide range of potential applications for marine energy include coastal and offshore locations, mechanical and electrical energy outputs, and milliwatts to megawatts in power needs. Each application has unique load profiles for energy consumption that may vary over timescales of days, weeks, months, or years.

Depending on the application, marine energy generation could serve as a sole energy source, or be integrated into hybrid systems that might include wind, solar, diesel, and energy storage to meet the application requirements. Incumbent technologies vary; in markets such as underwater vehicle charging, there are presently no existing power solutions, but for markets such as remote coastal communities, diesel generator sets are common. Solar, diesel generators, and battery energy storage systems are the most common incumbent technologies in the established markets.

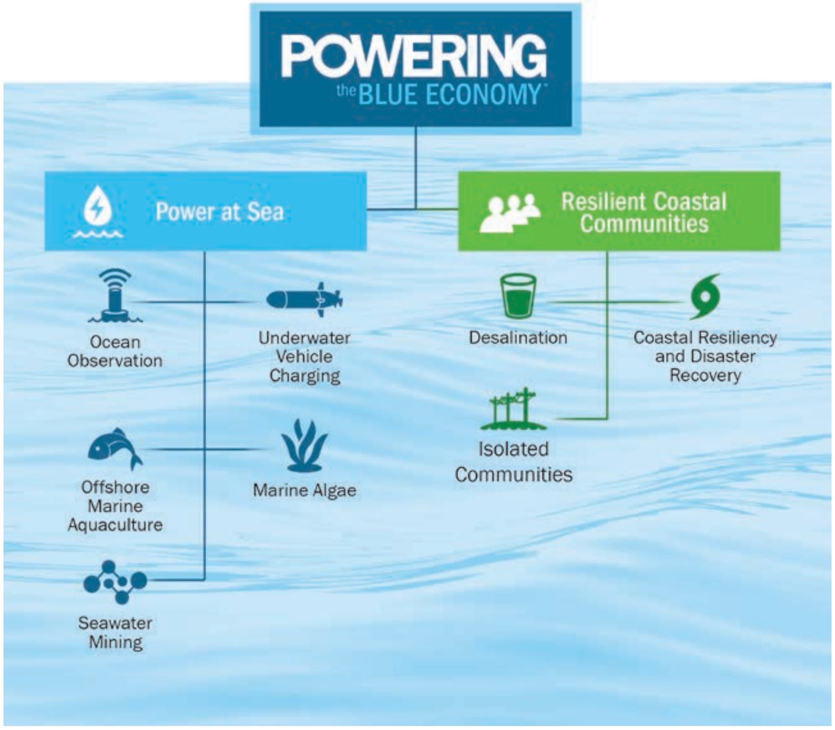


Figure ES.1. Potential marine power applications explored in this *Powering the Blue Economy*™ report. The eight applications are broken out into two areas: Power at Sea and Resilient Costal Communities

All of the markets considered are to some degree growth limited by their need for energy, whether it is watts or megawatts. Given the maturity of some of these markets, the opportunity exists to innovate and develop entirely new marine energy technologies that are tailored to their specific needs, addressing energy limitations and potentially creating new development opportunities.

There are numerous technology-focused attributes of marine energy that could be beneficial to many blue economy markets. Attributes include the ability to provide both electrical and mechanical power; minimal surface expression improving storm survivability; opportunities for co-design and integration with other infrastructures; the ability to leverage existing maritime supply chains; and the fact that marine energy devices are inherently designed to remove energy from ocean resources instead of fight against them.

Potential stakeholders in these markets are as varied as the markets themselves. For established blue-economy markets, stakeholders and customers would typically be larger companies or government organizations. For example, within ocean observation, critical stakeholders include the National Oceanic and Atmospheric Administration, the National Science Foundation, and the U.S. Department of Defense. For emerging markets, it is unclear who the major players are in some cases and in others they are characterized by large numbers of startups and small businesses. For example, within the offshore aquaculture and marine algae industry in the United States there are only a handful of small businesses that have, or are seeking, permitting for projects in federal waters within the Exclusive Economic Zone. Future markets are uncertain, and the same is true of their key stakeholders. These markets are still largely constrained to conceptual plans or lab research projects in academia and there are few, if any companies pursuing them at the moment.

Conclusion

This report addresses nongrid market opportunities and applications potentially suitable for marine energy technologies. Expansion into these markets could benefit the marine energy industry by opening new development pathways and establishing partnerships with a diverse set of end users operating in the rapidly growing blue economy. Beyond benefits to the marine energy sector, there are many co-benefits to U.S. interests that could be enabled by these applications. For example:

- U.S. national security could be enhanced through the development of advanced ocean sensors and charging stations for underwater vehicles. With the ability to stay on mission longer or increased range and duration for underwater vehicles, marine energy could indirectly provide better surveillance on contested sea areas while keeping more military personnel out of harm's way.
- Marine-energy-enabled ocean-sensing technologies could also advance our fundamental understanding of ocean processes and resources, providing foundational knowledge to pursue conservation and sustainable use strategies.
- In economic terms, America's seafood trade gap could be reduced if offshore aquaculture or marine algae industries expand offshore. This expansion into the U.S. Exclusive Economic Zone, enabled in part by marine energy technologies, could create new economic development opportunities in coastal towns and cities.
- Marine energy could be a key element of a set of technologies that support production of hydrogen directly from seawater; liquid fuels from biomass; and a secure supply of energy critical materials, such as uranium, cobalt, and lithium, contributing to a diverse U.S. energy economy.
- Marine energy technologies could contribute to national goals to improve water security for drinking and agricultural use, as well as provide local power options to remote island and coastal communities, contributing to higher standards of living and disaster preparedness.

This report informs WPTO's Powering the Blue Economy™ initiative. By seeking to understand the value proposition for marine energy in markets beyond the grid, the initiative complements and supports WPTO's existing marine energy strategy. Future analyses and reports will build off this research to provide more quantifiable and specific details on each market opportunity and develop specific research and development pathways that align with the strategy. The vision for Powering the Blue Economy is to unlock opportunities for ocean science, security, and maritime industries by exploring new applications for marine renewable energy. Through the Powering the Blue Economy initiative, WPTO will partner with stakeholders in industry, government, and academia to understand how marine energy could be uniquely suited to meet energy innovation needs to power growth in the blue economy.

References

Alaska Energy Authority. 2016a. Power Cost Equalization Program: Statistical Data by Community (obtained spreadsheet of the data). http://www.akenergyauthority.org/Portals/0/DNNGalleryPro/uploads/2017/2/28/FY16PCEAnnualCommunity.pdf

Food and Agriculture Organization of the United Nations. 2016. *The State of World Fisheries and Aquaculture 2016: Contributing to Food Security and Nutrition for All*. Rome. 200 pp. http://www.fao.org/3/a-i5555e.pdf.

GE Reports Staff. 2017. "Power and Light for 13,000 Indonesian Villages." Accessed April 1, 2018. https://www.ge.com/reports/power-light-13000-indonesian-villages/.

Ghadiryanfar Hoffman, Justin, Ronald C. Pate, Thomas Drennen, and Jason C. Quinn. 2017. "Techno-economic assessment of open microalgae production systems." *Algal Research*, 23: 51–57. https://www.sciencedirect.com/science/article/pii/S2211926416303046.

Global Water Intelligence. Desalination Markets. 2016. Global Perspective and Opportunities for Growth. Oxford: Media Analytics.

Maritime Technology News. 2012. *Market and Technology Trends in Underwater Sensors & Instrumentation*. https://www.researchgate.net/publication/292981347_Market_and_Technology_Trends_in_Sensors_and_Instrumentation.

National Oceanic and Atmospheric Association. 2015. *Marine Aquaculture Strategic Plan: FY 2016-2020*. U.S. Department of Commerce. 34 pp. https://www.afdf.org/wp-content/uploads/8h-NOAA-Marine-Aquaculture-Strategic-Plan-FY-2016-2020.pdf.

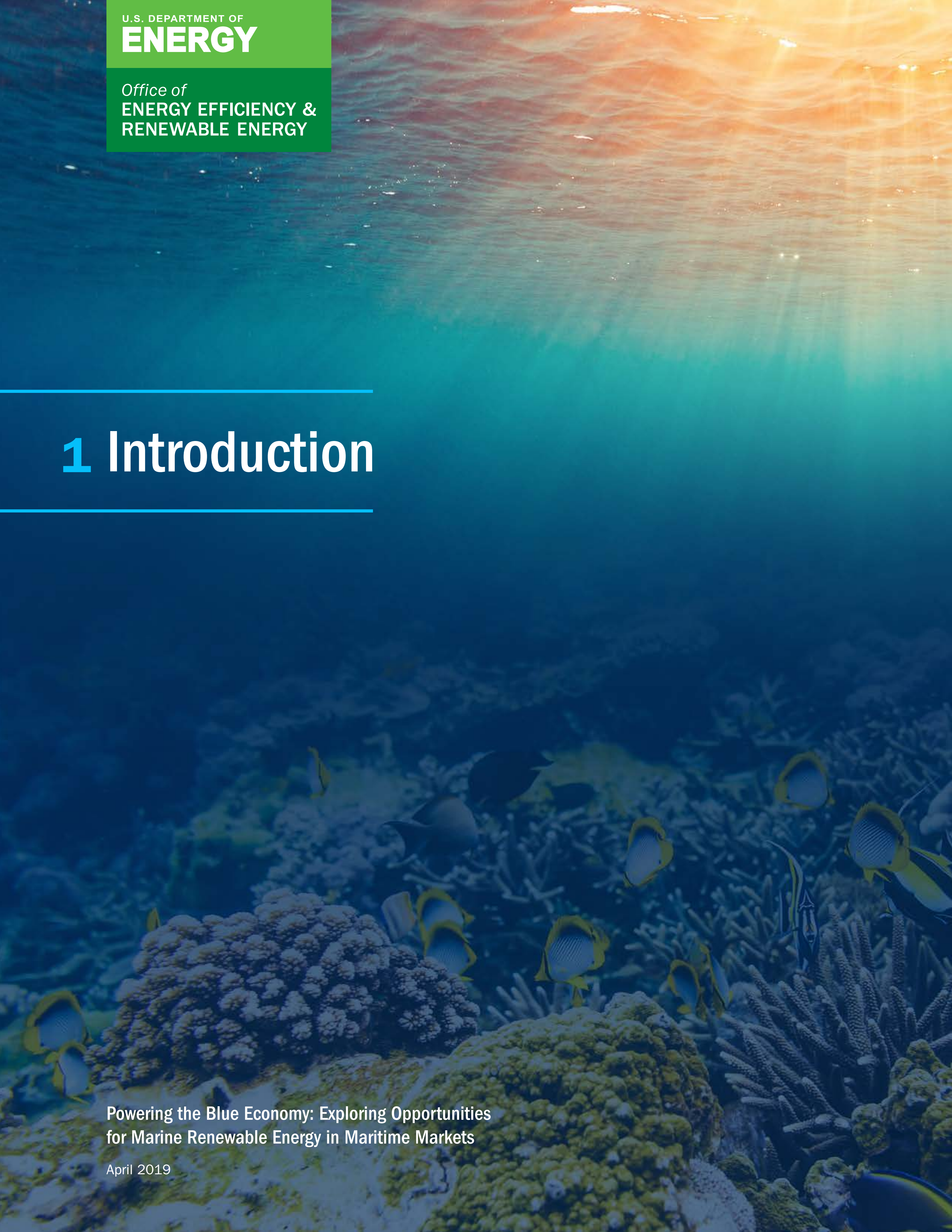
National Research Council. 2008. *National Research Council. 2008. Desalination: A National Perspective*. Washington, DC: The National Academies Press. https://doi.org/10.17226/12184.

PolitiFact. 2017. "How the U.S. Funds Disaster Recovery." Accessed April 2, 2018. http://www.politifact.com/truth-o-meter/article/2017/sep/14/how-us-funds-disaster-recovery/.

Research and Markets. 2017. *Global $2.65 Billion Unmanned Underwater Vehicles Market 2017-2021*. March 10. https://globenewswire.com/news-release/2017/03/10/934263/0/en/Global-2-65-Billion-Unmanned-Underwater-Vehicles-Market-2017-2021.html.

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY



1 Introduction

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

April 2019

1. Introduction

The U.S. power sector is rapidly evolving to include new and diverse forms of energy. Marine energy technologies, which convert the energy of ocean waves and tidal, river, and ocean currents into electricity and other forms of usable energy, hold promise as part of the national energy portfolio. Marine energy resources are geographically diverse, with high levels of wave energy in the Pacific Ocean; tidal energy resources located across the Northeast, Pacific Northwest, and Alaskan coasts; ocean current energy along the southern Atlantic coastline; and river current energy distributed throughout the country. The energy contained within these resources is sizable, predictable, reliable, and can be effectively developed in an environmentally responsible manner.

The U.S. Department of Energy's Water Power Technologies Office (WPTO) supports foundational science and early-stage research to rapidly improve performance and reduce costs of marine energy generation technologies. Since its formation in 2008, WPTO has primarily focused its activities to support technologies entering the grid-scale power market. In 2017, the office began a fact-finding mission to investigate potential markets for marine energy technologies beyond the grid. These markets can be broadly organized into two themes:

1. Providing power at sea to support offshore industries, science, and security activities
2. Meeting the energy and water needs of coastal and rural island stakeholders in support of resilient coastal communities.

Through the fact-finding process, WPTO is seeking to explore applications for which marine energy provides advantages and solves energy limitations. The spill-over effects from pursuing these near-term opportunities will advance marine energy technology readiness for cost-competitive utility-scale markets, and may also lead to unforeseen markets and opportunities.

Fact-finding activities have included workshops, analyses at national laboratories, and a Request for Information. This report summarizes and organizes the information collected from these various sources, identifies themes, and offers potential next steps. It represents a starting point—an initial understanding of opportunities to inform further detailed analyses and a long-term program strategy. Emerging from this process, WPTO has a deeper understanding of the set of opportunities for energy innovation in what can be broadly described as the "blue economy."

This report is informing WPTO engagement with coastal and ocean energy end users (e.g., stakeholders, industries, and agencies) to understand how marine energy could be uniquely suited to meet energy innovation needs to power growth in the blue economy. By seeking to understand the value proposition for marine energy in markets beyond the grid, this work complements and supports the existing marine energy strategy.

Marine Energy and the Blue Economy

The ocean has always provided a foundation for economic activity at local, regional, national, and global scales—as a source of food, energy, and recreation and as the superhighway for global trade. Our understanding of the ocean is improving, and with that our relationship with it is changing. We now have expanded knowledge of the value and vulnerabilities of the ocean, as well as an emerging set of technologies that are ever more capable of tapping into that value in a sustainable manner. Improved knowledge also brings greater clarity to the relationships between interconnected physical, chemical, biological, economic, and social systems that underlie ocean health. Emerging awareness of opportunities and constraints play out against the backdrop of expanding coastal populations and a growing demand for ocean-derived food, water, materials, energy, and knowledge. And still, much of the ocean is unexplored. Although some resources, particularly those close to shore, have been heavily exploited, others are either underutilized or undiscovered.

The oceans have an impact on the overall health of the planet and its sustainable development. Oceans and seas cover over two-thirds of the Earth's surface and about 40% of the world's population lives near coastlines. The ocean contributes to the global economy, with some estimates valuing the "gross marine product," which could be as high as $2.5 trillion based on direct outputs (e.g., fishing, aquaculture), services enabled (e.g., tourism, education), trade and transportation (e.g., coastal and oceanic shipping), and adjacent benefits (e.g., carbon sequestration, biotechnology) (Hoegh-Guldberg 2015).

The term "blue economy" is gaining traction among government, industry, and nonprofit sectors as an organizing principle that captures the interplay between economic, social, and ecological sustainability of the ocean. Interest in the blue economy spans multiple U.S. agencies, institutions, and businesses and is part of a global network of initiatives (The Economist Intelligence Unit 2015). This interest is fueling investment in next-generation maritime or "blue" technologies—autonomous vehicles to further ocean exploration, offshore aquaculture, battery and fuel cell technology for marine transportation, desalination and water treatment to serve coastal and island communities, and increasingly, offshore renewable energy, and alternative fuels, such as biofuels derived from marine algae and hydrogen from seawater. Given the tremendous value of the ocean, our ability to contribute to the blue economy in a sustainable manner has important implications with a wide range of potential societal and environmental benefits.

In the United States, industry clusters have begun to form around blue technologies in recognition of the common engineering, regulatory, and market challenges associated with working in the ocean. These regional clusters support knowledge sharing and cross-pollination, promote access to capital, and build foundations for partnerships. Activities and lessons learned by the marine energy sector could be leveraged by emerging blue technologies, and vice versa. Many blue technologies are still in the early or precommercial stage, with research and development (R&D) needs that cut across the jurisdiction of multiple public sector agencies. Because of this, blue economy technology advancement presents opportunities for coordination and collaboration at multiple levels—within and among government agencies; research institutions and the private sector; and companies and entrepreneurs developing integrated systems designed to function in the ocean environment.

Marine energy is included in most descriptions of the blue economy as an emerging blue technology sector. The WPTO marine energy vision reflects these sets of values: a U.S. marine energy industry that expands and diversifies the nation's energy portfolio by responsibly delivering predictable, affordable power from ocean and river resources. The blue economy provides WPTO with a chance to work with new government partners and across multiple technology sectors that are working to solve common engineering, regulatory, and innovation challenges. Through the process of researching and writing this report, we have gained a contextual understanding of our work and how our mission and goals might align and support a shared vision for the blue economy.

Marine energy could provide value as an enabling function to advance the goals of the blue economy. Achieving the WPTO vision of predictable and affordable power from oceans and rivers will require people, port facilities, and testing and R&D assets that leverage the knowledge and workforce associated with coastal industries. Removing power constraints and addressing the needs of coastal and ocean energy end users could accelerate growth in the blue economy and encourage sustained economic development. Ocean industries, such as aquaculture, are moving further offshore to take advantage of the scale of the ocean, yet moving further offshore requires access to consistent, reliable power untethered to land-based power grids. Oceanographic research and national security missions increasingly rely on autonomous sensors and unmanned vehicles that function with limited human intervention. Pushing these systems further offshore and staying on station longer requires new approaches to onboard energy generation, reliable remote recharging, and storage. Finally, marine energy could meet the energy and water needs of island and coastal communities, which often rely on expensive shipments of fuel and water to meet basic needs. Electricity and water are vulnerable to disruption during periods of bad weather or following natural disasters. Modular energy-water systems that take advantage of abundant local marine energy resources could provide greater energy and water security.

Report Objective

The objective of this report is to document the material gathered during a year-long effort intended to better understand a set of emerging opportunities and end uses associated with the blue economy that might be enabled or supported by co-development and integration with marine energy technologies. Each potential market is considered separately to provide a catalogue of information and references relevant to that particular market, such that each chapter can be considered a stand-alone product. The Summary and Conclusion chapter provides an initial look at themes and connections among markets and provides a high-level assessment of how technology integration and R&D targeting near-term markets could result in technology development that enables emerging or future markets. The Summary and Conclusion chapter further considers how energy innovation within the blue economy could provide early commercial opportunities and expand the value proposition of marine energy across multiple industries to eventually reach cost parity with other clean technologies in the utility-scale market. The report synthesizes information and trends across the various markets to effectively inform future explorations of these markets. This assessment is not a quantitative roadmap to guide strategic investments or initiatives. Future analyses and reports will build off this foundational research to provide more quantifiable and specific details on each market opportunity.

Report History

In fiscal years 2017 through early 2019, the U.S. Department of Energy WPTO Marine and Hydrokinetic Program conducted a project committed to fact finding and due diligence, identifying and studying the range of potential applications and markets for marine energy technologies. This effort began with the Marine Energy Technologies Forum: Distributed and Alternate Applications, an event during which attendees from various sectors discussed new potential applications for marine renewable energy and how emerging marine renewable energy technologies can help meet the energy needs of a range of coastal and marine industries.

Following the forum, WPTO sought further input from stakeholders through a Request for Information. As part of this process, WPTO released a draft report, *Potential Maritime Markets for Marine and Hydrokinetic Technologies*. The report detailed the current economic and technical landscapes for 12 topics: ocean observations, unmanned underwater vehicles/autonomous underwater vehicles recharge, data centers, high-cost utility grids, isolated community grids, canal power, aquaculture, algae, desalination of seawater, seawater mining, shoreline protection, and coastal resiliency and disaster recovery. Respondents spanning the public and private sectors submitted over 400 comments, all of which were reviewed and explored by the authors.

As WPTO's understanding of marine energy's potential to power the blue economy evolved and the final version of this report, *Powering the Blue Economy–Exploring Opportunities for Marine Renewable Energy in Maritime Markets*, came to be, the constructed waterways and utility-scale power chapters were omitted and information from the shoreline protection chapter was integrated into the coastal resiliency and disaster recovery chapter. Though all promising opportunities for marine energy and WPTO resources, the material contained in those chapters did not speak to the potential for marine energy in the blue economy, but rather described a resource type. The draft report contains these chapters and can be found online at https://eere-exchange.energy.gov/Default.aspx?Search=maritime%20markets&SearchType=.

Report Organization

In this final version of the report, eight nongrid markets for marine energy are split into two themes: Power at Sea and Resilient Coastal Communities. Power at Sea refers to off-grid and offshore applications wherein cabling and access to terrestrial-based energy are expensive and difficult to deliver. Within Power at Sea, there are chapters on ocean observation and navigation, underwater vehicle charging, marine aquaculture, marine algae, and seawater mining. Under the theme of Resilient Coastal Communities, marine energy applications are typically nearshore and support protection of coastal ecosystems and welfare of communities. Chapters in this theme are presented on desalination, coastal resiliency and disaster recovery, and community-scale isolated power systems. An additional chapter provides information on other applications that were not considered in detail but which may still hold opportunities for marine energy, including marine transportation, personal charging, ocean pollution cleanup, and underwater communications.

Each market chapter, which is listed within each theme by potential in the near term, contains a common set of analyses:

- Opportunity summary
- Application description and power requirements
- Market description, power options, and geographic relevance
- Marine energy potential value proposition
- Path forward, including R&D needs and potential partners.

Overall, the discussion in each market chapter provides an overview of potential new applications for marine energy, with the Summary and Conclusion chapter summarizing how emerging technologies and future research can help meet the energy needs of a wide range of coastal and marine industries moving forward.

Key Findings

Power At Sea

- Located farther from shore, ensuring that cabling and access to terrestrial-based energy is expensive and difficult to deliver. Typically, these locations have limited low-cost power options.
- Many of these activities and associated energy needs could be located in deep water (>100 meter depth).
- Generally, there is a desire to reduce reliance on fuel and batteries, as well as the risks and costs associated with chartering vessels and crews to deploy and retrieve equipment.
- Power is mission critical for many applications and failure to supply could lead to a complete loss of system; redundant power systems are common. To conserve power, instrument sampling rates and duty cycles are commonly set to lower-than-desired levels to extend battery life as long as possible, reducing temporal resolution of data.
- Incumbent power sources or technologies include solar photovoltaics, wind, diesel generators, and single-use or rechargeable batteries.

Ocean Observation and Navigation

- The oceans are being actively investigated, yet almost 80% have not been mapped or explored. Active development of new instruments, platforms, and tools is underway to support further exploration.
- The use of ocean instrumentation is often limited by battery capacity, data storage, and transmission to shore. Weather buoys, profiling instruments, tsunami warning devices, and other systems are limited in the amount of data they can collect and transmit, and the time they can remain at sea unattended.
- Marine energy could meet power needs for surface sensors, especially if integrated with solar power and battery storage. Subsurface instrument needs could be met by marine energy coupled with energy storage systems, such as batteries.
- Marine energy provides unique advantages for at-sea power generation including colocation with ocean observation sensors, navigation markers, and subsea inspection vehicles; continuous power generation coupled with energy storage; stealth characteristics for defense applications; and designs that are tailored to the marine environment.

- The world market for navigational and survey instruments more than doubled between 2001 and 2011, from $7.5 billion to $16 billion (Maritime Technology News 2012). Many of these instruments are used for ocean observation and navigation purposes, indicating a growing need for power at sea to supply these systems.

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

- Autonomous underwater vehicles (AUVs) and unmanned underwater vehicles (UUVs) perform underwater tasks without a tether or line to a surface ship, carrying instruments and sensors to monitor or inspect underwater environments.
- Although AUVs are a cheaper alternative to traditional vessels, power capacity of the vehicle's battery remains a limiting factor and keeps their missions limited in range and duration, often as little as 24 hours.
- Docking and recharge stations can extend the mission duration of underwater vehicles by recharging their batteries at sea, as well as providing a secure platform to dock vehicles between missions. Underwater docking stations are under development and not yet available commercially as they lack a practical power generation source.
- Powering underwater docking stations and recharging AUVs with marine energy could provide a reliable, locally generated power source, smoothed for intermittency by battery backup. Underwater recharging of AUVs would reduce the need to recall vehicles to the surface as frequently; save time and resources; improve human safety on ships at sea; increase mission duration, range, and stealth; and reduce carbon emissions.

Marine Aquaculture

- 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. The global aquaculture market is projected to be more than $55 billion by 2020 (Food and Agriculture Organization 2016).
- Aquaculture operations can occur in coastal or nearshore zones, and deepwater or offshore areas. Coastal aquaculture is the most predominant form of aquaculture, where pens or fish cages are deployed along the coastline or shellfish and seaweeds are grown on the shallow seabed.
- Offshore aquaculture operations typically use floating or submersible net pens or cages that are tethered to the seafloor and attached to buoys. There is a trend worldwide to move aquaculture operations further offshore, although the United States has no substantial offshore operations. Offshore 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 power for the crew living quarters (if the structures are manned); and recharging of transport vessels.
- Many types of aquaculture facilities could be partially or wholly powered by marine energy. Most wave energy converters (WECs) prefer highly energetic sea states for energy production, which may not be suitable for aquaculture operations. However, some WEC designs are better suited to operate in less energetic conditions. WECs may provide shelter in their lee for aquaculture operations.
- The low surface expression of most WECs will increase survival at sea, provide low visual impacts, and be more easily integrated with aquaculture facilities.

Marine Algae

- Macroalgae (seaweed) and some microalgae can be grown at commercial scale at sea to provide biomass for biofuel production; specialized chemicals for food processing, cosmetics, and pharmaceuticals; soil additives and fertilizers; animal fodder; and other end products.
- Algae grown at sea has a competitive advantage over terrestrial-based crops grown for biofuels because it does not require land, irrigation systems, added nutrients, or fertilizers. Macroalgae grown in farms for human and animal consumption are common around the world, but farms dedicated to crop production for biofuels are in the experimental stage. With the world's largest Exclusive Economic Zone, much of which has potential for growing algae, the United States has the potential to become a leader in sea-grown biofuels.
- The power requirements for large-scale macroalgae growing and harvesting operations at sea are not well understood but will likely resemble those for aquaculture operations including power for safety, navigation lights, and maintenance equipment; pumps for nutrients and ballast control; refrigeration and ice production; drying operations; marine sensors; recharging of autonomous underwater vehicles, and recharging transport vessels.
- Marine energy systems have the potential to be integrated into and co-developed with algal growing and harvesting systems. By replacing fossil fuels with marine energy, the biofuels industry could reduce harm to air and water quality; reduce supply chain and transport risks; and potentially reduce operational costs. The low surface expression of most WECs will increase survival at sea, provide low visual impacts, and be more easily integrated with algal facilities.

Seawater Mining: Minerals and Gasses

- Seawater contains large amounts of minerals, dissolved gases, and specific organic molecules that are more evenly distributed, albeit at lower concentrations, than in terrestrial locations. Lithium and uranium extraction are two of the more valuable materials under investigation.
- Passive adsorption and, to a lesser extent, electrochemical processes, are two different methods to extract elements and minerals directly from seawater. Several gases (e.g., carbon dioxide, hydrogen, and oxygen) can be electrolytically produced directly from seawater. Most systems are in early stages of development, but a strong market demand exists for many of the end products.
- Power required for each method varies. Potential uses for power will be to assist in deploying and retrieving long adsorbent films, extracting elements via electrochemical mechanisms or electrolysis, pumping seawater, and powering safety and monitoring equipment, as well as potentially powering the machinery or technology needed to remove elements from adsorbent material.
- Marine energy could open up unexploited opportunities in seawater mining, which could further expand mineral and gas markets. It is believed that linking an marine energy converter to a seawater mineral extraction technology could substantially enhance or enable the extraction process as a result of colocation benefits and greater power generation potential than other renewable technologies.
- By linking a seawater extraction technology to a local power source, a significant reduction in the overall costs to extract materials from seawater could be achieved.

Resilient Coastal Communities

- Applications are nearshore or onshore and contribute to the resiliency of coastal communities in the face of extreme events, such as tsunamis, hurricanes, flooding, or droughts.
- Visual impacts are an important consideration in project location.

- Customers are typically more price sensitive because of a greater number of incumbent technologies capable of supplying power at competitive costs.

- Relatively easy access for installation and operations than the power-at-sea applications, with more frequent maintenance intervals likely.

Desalination

- Desalination is an energy-intensive process because of the energy required to separate salts and other dissolved solids from water. In operation, the actual pressure required is approximately two times the osmotic pressure; for seawater, this translates to about 800–1,000 pounds per square inch. The energy required to run pumps that can achieve these high pressures account for approximately 25% to 40% of the overall cost of water (Lantz, Olis, and Warren 2011).

- Wave- or tidal-powered desalination could be used to directly pressurize seawater without generating electricity for a reverse-osmosis system, eliminating one of the largest cost drivers for the production of desalinated water.

- There are two primary market segments for desalination: water utilities and isolated or small-scale distributed systems. Large-scale desalination systems require tens of megawatts to run and provide tens of millions of gallons of desalinated water per day. Small-scale systems vary in size from tens to hundreds of kilowatts and provide hundreds to thousands of gallons of water per day.

- Marine energy resources are inherently located near potential desalination water supplies and high population concentrations along the coast, therefore areas that have unreliable grid connections or water infrastructure may receive dual benefits from marine energy systems. In the long term, marine energy could provide low-cost, emission-free, drought-resistant drinking water to larger municipalities.

- The National Renewable Energy Laboratory's (NREL's) simulation results suggest a direct pressurization application could be more cost competitive when producing water than a wave-energy system producing electricity given current cost estimates (Yu and Jenne 2017). This finding clearly signals a near-term market opportunity for wave energy, thereby requiring smaller cost reductions than grid-power applications.

Coastal Resiliency and Disaster Recovery

- Coastal areas support a large part of the human population but are under stress from sea level rise and increases in storm frequency and intensity. These areas are also prone to extreme events, such as tsunamis, tropical storms, and flooding. Deterioration of coastal areas can threaten the safety of the populations, including disruptions to communities, such as limiting access to freshwater and electricity for extended periods of time. These threats can result in displacement of human populations and public health risks.

- Coastal communities are addressing threats to coastal areas by focusing on hazard mitigation, preparedness for extreme events, response and recovery operations, and by improving the resiliency of critical infrastructure and emergency assets.

- Coastal resilience can be improved by fortifying natural shorelines like beaches and marshes, and by putting in place assets, such as distributed power generation sources, to support local microgrids.

- Marine energy devices could be integrated into coastal infrastructure, such as piers, jetties, groins, and breakwaters, providing the dual benefit of shoreline protection and power generation.

- Marine energy could also contribute to coastal microgrids, increasing generating source diversity and reducing reliance on hard-to-find diesel fuel during emergencies. Marine energy could be used to support other emergency needs, such as water treatment and supply (e.g., emergency desalination).

Isolated Power Systems: Community Microgrids

- Many remote communities are currently powered by diesel generation, and some with solar. Although diesel fuel is energy dense and provides on-demand power, it presents operational and logistical challenges. For example, many remote communities in Alaska depend on a few bulk fuel deliveries each year that are susceptible to supply chain disruptions and fuel price volatility.

- The cost range of diesel-generated power for most of the remote Alaska communities varies from $0.50 to over $1 per kilowatt-hour. For larger and less remote locations, costs are less, in the $0.19–$0.37 per kilowatt-hour range (Alaska Energy Authority 2016).

- Remote communities typically have microgrid power systems from 200 kilowatts to 5 megawatts, with high reliability being a key objective. First adopters are environmentally conscious resorts, small villages, and military bases.

- Marine energy technologies, operating individually or in conjunction with other generating sources, could help mitigate reliance on diesel fuel. For communities near rivers, reliable power can be produced from river current generators in sufficient capacity to offset a small community's entire load during the summer.

Other Applications

- This chapter identifies opportunities for future exploration that were not studied in previous chapters of this report. Additional applications for marine energy cover various topics, including electrified and hydrogen-fueled marine transportation, off-grid charging for industrial and consumer applications, ocean pollution cleanup and marine conservation, and subsea communications. These different applications cover a range of technology readiness levels from those that are in the conceptual-only stage to others with demonstrated pilot projects and paths to commercialization.

- Global pressures to reduce greenhouse gas emissions and improve local air quality are causing vessel operators and ports to modify engine systems. Modifications include using cleaner-burning fuels (e.g., liquid natural gas), diesel-electric hybrids, converting to fully electric operation, or incorporating hydrogen fuel cells. Demand for these technologies, as well as the fuel and energy to power and charge them, will increase. Marine energy's obvious colocation benefits may make them well suited as an energy provider.

- Portable electronic devices have created a global market for charging technologies, especially in areas without access to the electrical grid. The two primary off-grid charging solutions are portable battery packs and small transportable solar photovoltaic panels. Opportunities exist for marine energy to develop small charging systems using river or ocean resources.

- There are potential markets for marine renewable energy technologies within the marine conservation space, including ocean pollution cleanup, oil spill cleanup, and coral reef restoration. Applications for marine energy within these markets are limited at the moment and presently more concentrated nearshore.

- Data centers, in aggregate, are becoming one of the largest consumers of electricity in the world. As site development areas for data centers diminishes on land, some companies will look to deploy server farms offshore. Microsoft has even begun investigating subsea data centers enclosed in watertight containers. The ocean provides free cooling, which is historically one of the greatest costs in operating a data center, as well as the potential to be powered by locally sourced power from marine energy.

References

Alaska Energy Authority. 2016. “Renewable Energy Atlas of Alaska – A Guide to Alaska’s Clean, Local, and Inexhaustible Energy Resources.” Accessed April 20, 2018. http://alaskarenewableenergy.org/index.php/focusareas/renewable-energy-atlas/.

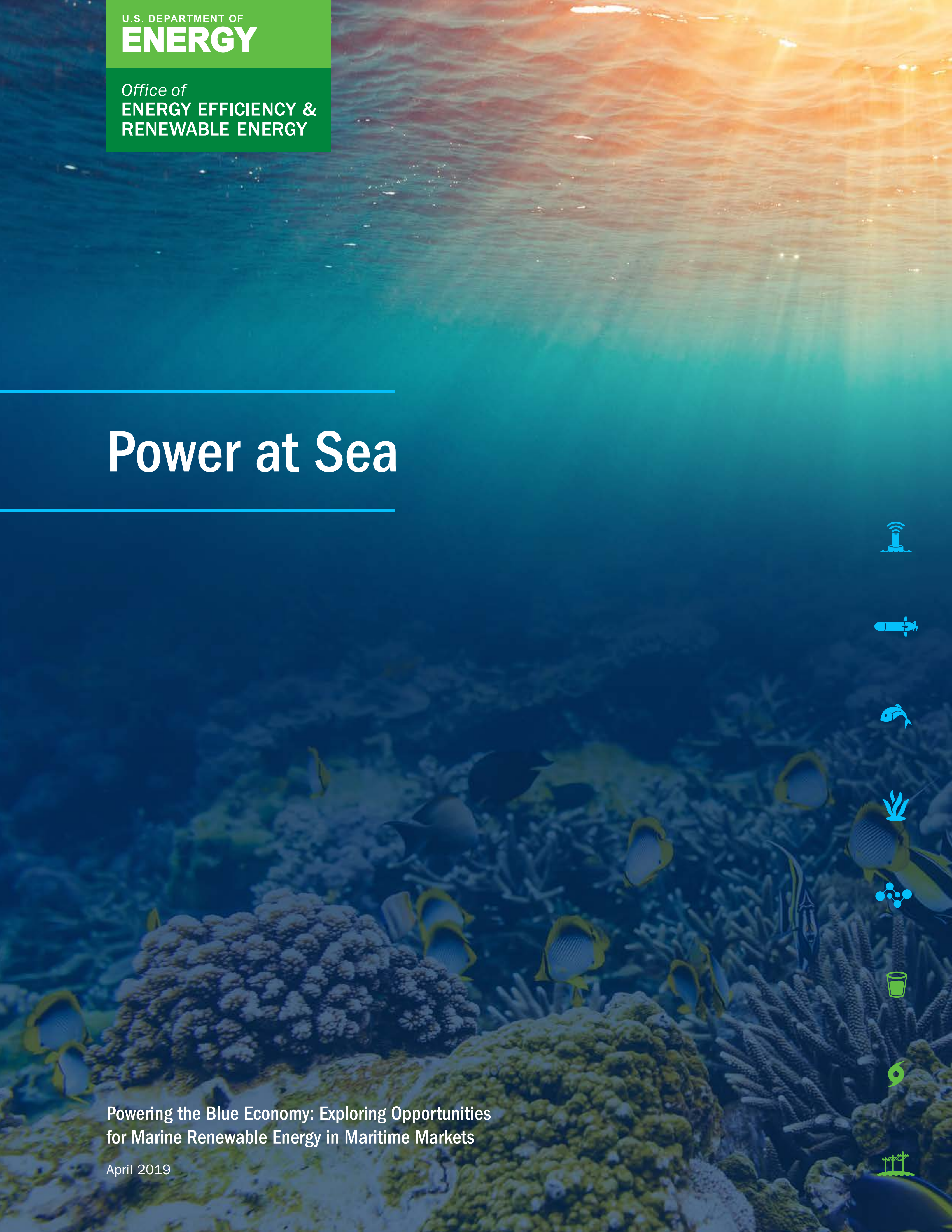
Hoegh-Guldberg, H. 2015. *Reviving the Ocean Economy, The case for action – 2015*. World Wide Fund for Nature. https://c402277.ssl.cf1.rackcdn.com/publications/790/files/original/Reviving_Ocean_Economy_REPORT_low_res.pdf?1429717323.

Lantz, Eric, Dan Olis, and Adam Warren. 2011. *U.S. Virgin Islands Energy Road Map: Analysis* (Technical Report). NREL/TP-7A20-52360. Golden, CO (US): National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy11osti/52360.pdf.

Maritime Technology News. 2012. *Market and Technology Trends in Underwater Sensors & Instrumentation*. https://www.researchgate.net/publication/292981347_Market_and_Technology_Trends_in_Sensors_and_Instrumentation.

The Economist Intelligence Unit. 2015. *The blue economy; Growth, opportunity, and a sustainable ocean economy*. https://www.woi.economist.com/content/uploads/2018/04/m1_EIU_The-Blue-Economy_2015.pdf.

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



U.S. DEPARTMENT OF
ENERGY
Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Power at Sea

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

April 2019

Power at Sea

Numerous applications and markets for marine energy show similarities and lend themselves to grouping. Many applications and markets displayed characteristics of being off grid and offshore, a group that has been labeled "Power at Sea" in this report. Commonalities among these applications include:

- By being located farther from shore, cabling and access to terrestrial-based energy is expensive and difficult to deliver. Typically, these locations have limited low-cost power options.
- Many of these activities and associated energy needs could be located in deep water (>100 meter depth).
- Stakeholders within the application demonstrate a strong desire to reduce fuel (e.g., diesel and new batteries) costs, supply chain costs, and risks, including ship and personnel time and cost to deploy and retrieve equipment.
- Power is mission critical and failure would be costly, so redundant systems are likely. To conserve energy, missions and operations are usually power limited—instruments, sampling rates, and duty cycles are limited to extend battery life long enough to ensure the system will survive at sea.
- Existing power sources available include solar photovoltaics, wind, diesel generators, single-use or rechargeable batteries (with ship and personnel time and cost to deploy and retrieve).

Within this theme, chapters are presented on ocean observation and navigation, underwater vehicle charging, offshore marine aquaculture, marine algae, and seawater mining. Chapters are presented in the order of perceived relevance to marine energy as a viable near-term market.

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

2 Ocean Observation and Navigation

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

April 2019

2. Ocean Observation and Navigation

Key Findings

- The oceans are being actively investigated, yet almost 80% have not been mapped or explored. Active development of new instruments, platforms, and tools is underway to support further exploration.
- The use of ocean instrumentation is often limited by battery capacity, data storage, and transmission to shore. Weather buoys, profiling instruments, tsunami warning devices, and other systems are limited in the amount of data they can collect and transmit, and the time they can remain at sea unattended.
- Marine energy could meet power needs for surface sensors, especially if integrated with solar power and battery storage. Subsurface instrument needs could be met by marine energy coupled with energy storage systems, such as batteries.
- Marine energy provides unique advantages for at-sea power generation including colocation with ocean observation sensors, navigation markers, and subsea inspection vehicles; continuous power generation when coupled with energy storage; stealth characteristics for defense applications; and designs that are tailored to the marine environment.
- The world market for navigational and survey instruments more than doubled between 2001 and 2011, from $7.5 billion to $16 billion (Maritime Technology News 2012). Many of these instruments are used for ocean observation and navigation purposes, indicating a growing need for power at sea to supply these systems.

Opportunity Summary

The use of maritime sensors and navigation aids is widespread and growing rapidly worldwide as new technologies enable multiple networked tools to economically monitor the ocean and often provide greater coverage than traditional shipboard methods (Venkatesan et al. 2018). Common marine buoys include surface ocean observation buoys with sensors that 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 as wireless data telemetry technologies become more commonplace (Venkatesan et al. 2018).

Battery life limits the useful duration of most observation and navigation equipment, making locally extracted ocean energy a feasible option for recharging these devices (Ayers and Richter 2016). As an alternative solution to solar and wind, marine energy devices could provide longer-term and more continuous 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. Ocean observation systems have been limited by material fatigue, biofouling, and instrument calibration drift (Brian Polagye, personal communication, August 2018). These challenges will continue even if marine energy devices provided power on a more continuous basis; however, the maintenance and automated systems used to mitigate these challenges would also benefit from power availability.

Although difficult to size, the international ocean observation market size is estimated to be greater than $16 billion (Maritime Technology News 2012) and growing. Overall, the per-unit-sensor power consumption is decreasing because of technological advances, and the total number of sensors on platforms is increasing, resulting in a net power increase. High-power devices (including active acoustics [e.g., scanning sonar]; video cameras; underwater lights; mobile, motorized sensor platforms) continue to need an external power supply (Delory and Pearlman 2018). Recent trends indicate that production of navigational and survey instruments has increased substantially in recent years (Maritime Technology News 2012), 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 power will be needed, and marine energy could be used to supplement the power for these instruments, or even enable new, higher-power applications.

Application

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 2.1). Oceanographic and meteorological sensors monitor the environment in near real time, improving our ability to understand and predict events, such as hurricanes, waves, sea level changes, and tsunamis. Navigation aids assist commercial and recreational ship traffic, marking areas of danger and zones for safe passage. This improves maritime safety by reducing the risks of collisions, allisions, or groundings.

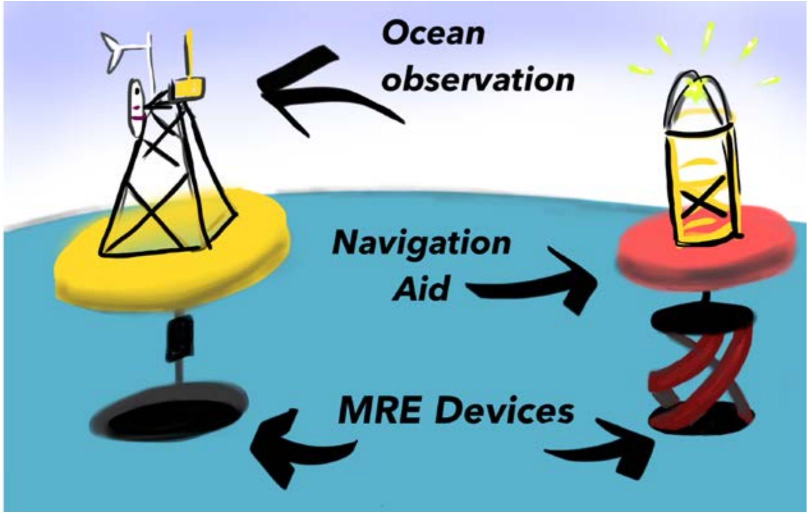


Figure 2.1. Marine renewable energy (MRE) application overview for ocean observation. *Image courtesy of Molly Grear, Pacific Northwest National Laboratory*

Power Requirements

The range of power requirements for ocean observation buoys and navigation aids, per installation, is estimated to be 10–600 kilowatts (Brasseur 2009), whereas many buoys operated by the National Oceanic and Atmospheric Administration (NOAA) require power that ranges from 40 to 200 watts. There are no accurate power estimates for overall ocean observation systems (Dana Manalang, personal communication, December 2017), as the systems are changing rapidly, although we know power requirements for specific individual instruments. 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).

Many important patterns of biological, chemical, and physical processes in the ocean happen at long timescales, from seasons to years or more, and can only be identified through long time series ocean observations (e.g., Edwards et al. 2010; Riser et al. 2016). For decades, long time series ocean observations were costly and required repeated visits to sites of interest, as well as periodic maintenance. To collect continuous time series, battery-powered instruments were left behind. Therefore, ocean instrumentation development was often limited by battery capacity and data storage.

In recent years, cabled ocean observing systems have been developed that deliver ample continuous power and communications, when coupled with energy storage, to remote ocean sites, enabling the development of new types of sophisticated and higher power in-situ devices that were not previously possible. Some examples include:

- High-definition camera systems[5]
- Mass spectrometers[6]
- Environmental sampling processors[7]
- Robotic systems.[8]

With the possibility of marine renewable energy devices delivering power at sea, there are similar opportunities for noncabled ocean observations. A variety of systems and subsystems could use marine energy, including electricity, as outlined in Figure 2.2. Although Figure 2.2 presents potential uses of marine energy to power various systems, not all potential uses will be practical to be powered by marine energy, as the presence and operation of a marine energy device could alter the intended measurements/observations (e.g., presence of marine energy device could alter behavior, community, composition, and so on).

---

[5] http://oceanobservatories.org/instrument-class/camhd/
[6] https://girguislab.oeb.harvard.edu/isms
[7] https://www.mbari.org/technology/emerging-current-tools/instruments/environmental-sample-processor-esp/
[8] https://www.oceannetworks.ca/groups/wally-benthic-crawler

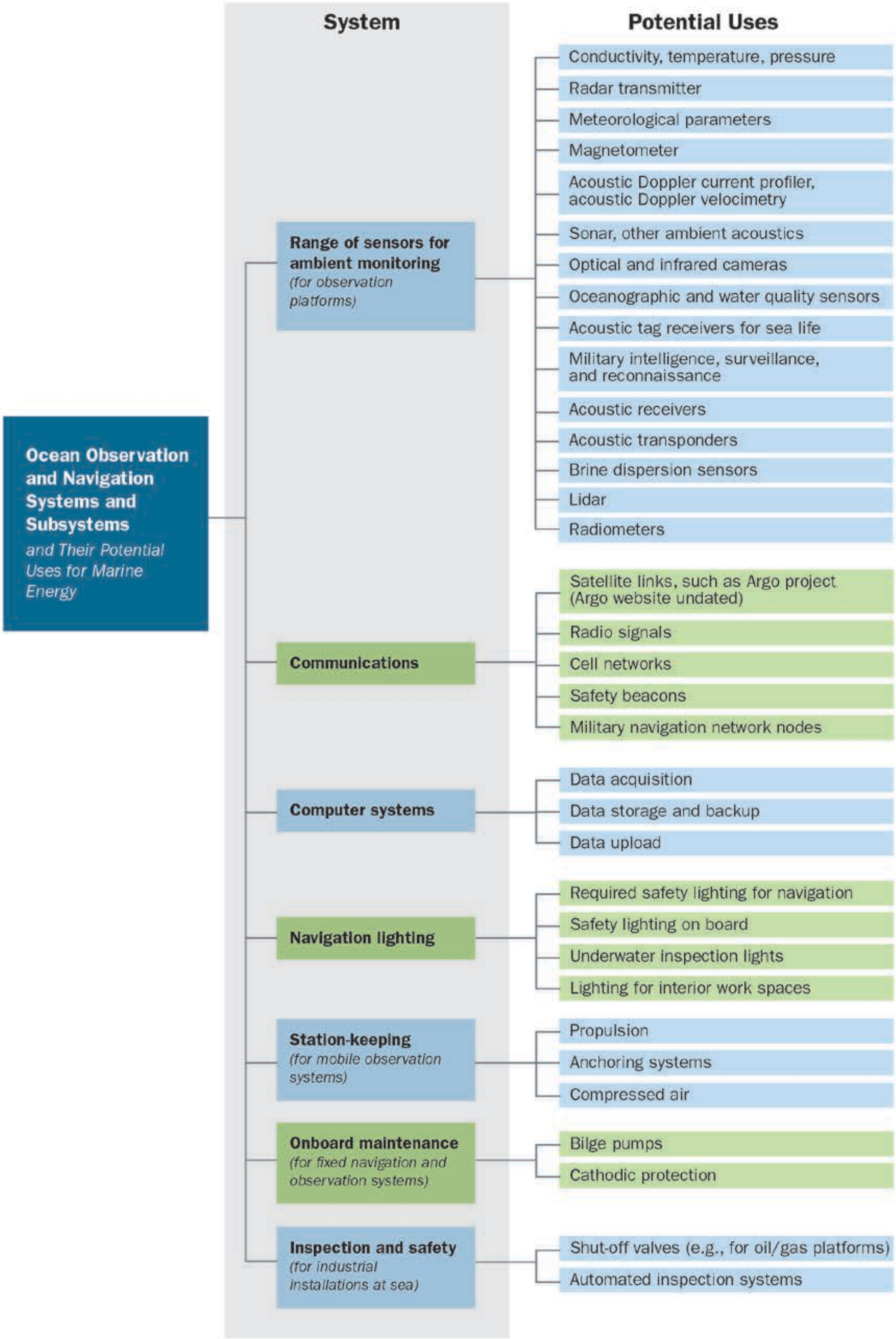


Figure 2.2. Ocean observation and navigation systems and subsystems and their potential uses for marine energy

Navigation Aids

Navigation aids generally include buoys, floats, air horns, and lights on the surface of navigable waterways (Figure 2.3). Power is needed for a variety of uses, such as lights, air horns, radar reflectors, air and water sensors, and data transmission (U.S. Coast Guard 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.

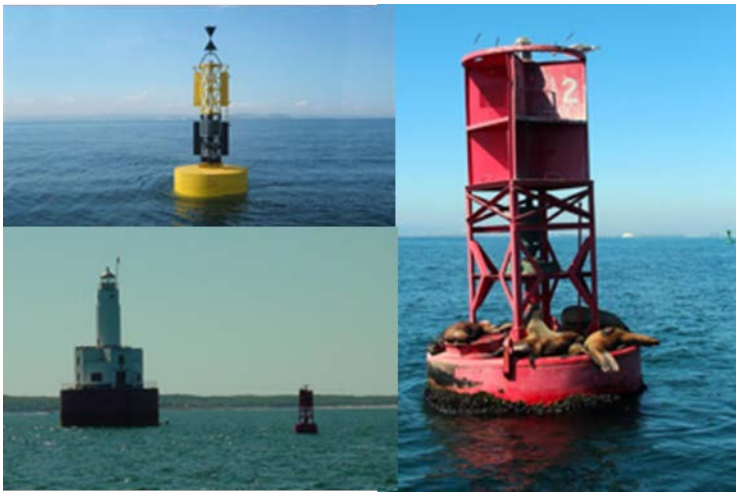


Figure 2.3. Navigation markers. *Photos courtesy of Polliechrome (bottom left) and Creative Commons (upper left, right)*

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. Integrated Ocean Observing System (IOOS) and the related regional system of Ocean Observing Systems (IOOS 2017; Figure 2.4), 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 Networks Canada 2019), the Taos array along the equator, tsunami warning systems off U.S. coastlines (NOAA 2017b, 2017c), and the array of profiling Argo floats (Argo undated).

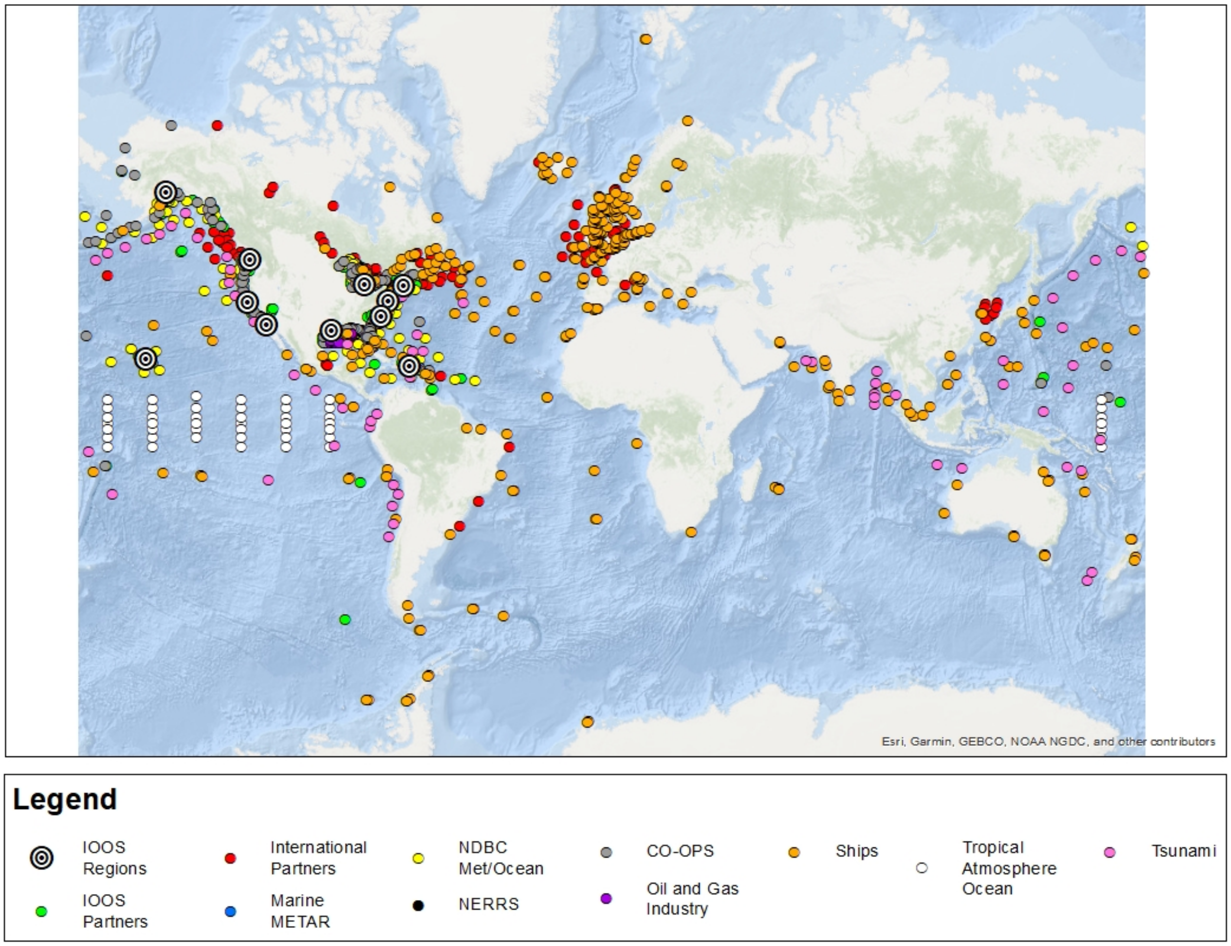


Figure 2.4. IOOS region and NOAA buoy/observation location map. *Image courtesy of Alicia Gorton, Pacific Northwest National Laboratory*

NOAA’s Chesapeake Bay Interpretive Buoy System is a network of buoys within Chesapeake Bay that collect meteorological, oceanographic, and water quality data (NOAA 2018). These “smart” buoys relay information wirelessly and interpret points within the bay. The latest data are available online, by calling toll-free, or via applications developed for smartphones. 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).

The oil and gas industry makes extensive use of marine sensors, ocean observation systems, and relevant data and information provided by these sensors/systems. Oil and gas operations make use of marine and ocean observation sensors to conduct environmental monitoring throughout the lifetime of an oil field, from preinstallation surveys/baseline studies to construction and installation, drilling and production, and decommissioning (Kongsberg 2013). Additionally, oil and gas operations make use of established ocean observation systems and networks for further environmental monitoring, forecasting, and to ensure safe operations. For example, one of the five general focus areas of the Gulf of Mexico Coastal Ocean Observing System focuses on safe and efficient marine operations, which include oil and gas operations (Gulf of Mexico Coastal Ocean Observing System 2016). Additionally, military and security uses of ocean observations include systems for port security, surveillance, and tracking, such as submarine tracking systems like the decommissioned sound surveillance system array (NOAA 2017a) and the Deep Reliable Acoustic Path Exploitation System under development (The Diplomat 2016).

Markets

Description of Markets

The world's sales 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 sales ($10.1 billion) in 2011 were for surveying, hydrographic, oceanographic, hydrological, meteorological, or geophysical instruments and appliances, whereas 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 can 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 marine energy 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, resulting in a net increase in energy needs (National Academies of Sciences, Engineering, and Medicine 2017). In addition, increased activity in the Arctic Ocean and remote locations has increased the demand for sensors that can withstand extreme conditions (Maritime Technology News 2012).

The domestic and international ocean observation and subsea inspection markets are growing, driven largely by increasing needs for early-warning systems for tsunami generation, weather patterns, climate variables, and other scientific questions (National Academies of Sciences, Engineering, and Medicine 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 research and development (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 marine energy systems. 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, active radar reflectors, satellite transceivers, 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 marine energy 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, Office of Naval Research, or the U.S. Department of Homeland Security. Government investments in ocean observation are critical for weather forecasting, marine resource management, maritime navigation, and climate change analyses (National Academies of Sciences, Engineering, and Medicine 2017). Furthermore, federal defense and security organizations invest in ocean observation for national security and ocean surveillance purposes. For example, the U.S. Department of Homeland Security has invested in the Autonomous PowerBuoy, coupling long-duration maritime vessel detection with wave power generation (Homeland Security News Wire 2012). Private foundations are also important funding partners for equipment and data collection capabilities. 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 platforms, require power for a range of operations including inspection of underwater systems, and the emergency shutdown of valves and other equipment. The need to meet increasingly stringent clean air and water regulations is moving petroleum producers to use alternate sources of power, which could include site-based marine energy. Similarly, unmanned offshore facilities require power that could be compatible with marine energy generation.

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, marine energy—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 marine energy devices could 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 and for applications where placement of PV panels is limited by available surface area. PV panels placed close to the sea surface may need more frequent maintenance and cleaning because of 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. Offshore wind turbines also require a stable platform for operation, which cannot be provided by offshore buoys. Diesel generators are impractical in remote locations in the middle of the ocean for many reasons, chief among them the need for refueling and maintenance. Backup storage may be required to match renewable generation with power needs for stand-alone or hybrid systems.

Geographic Relevance

NOAA's National Data Buoy Center (NDBC) operates and maintains more than 1,300 buoys (Figure 2.5) 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). The U.S. Department of Energy (2013) estimated 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. With the significant number of buoys and U.S. container ports located along the East and West Coasts, marine energy 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.

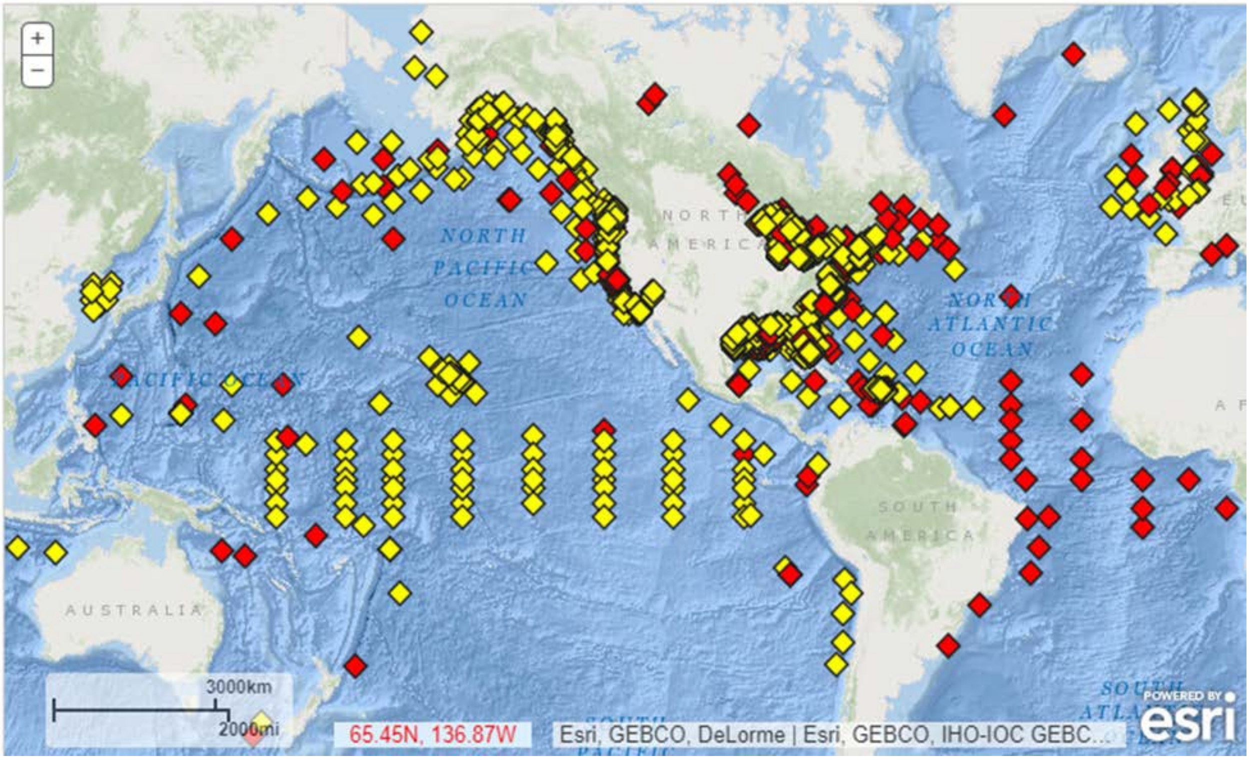


Figure 2.5. Locations of NOAA buoys. *Map courtesy of NOAA*

Marine Energy 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, marine energy could reduce costly site visits for maintenance and increase system availability. Operational marine energy systems could require less routine maintenance than other renewable systems. For example, individual offshore wind turbines require about five site visits per year, carried out by boat or helicopter (making the visits sea state and weather-dependent) (Röckmann et al. 2017). Additionally, solar installations require cleaning of PV plates to remove salt residue (Atkinson 2016).

Operational marine energy systems could require less routine maintenance than other renewable systems, such as wind turbines (with extensive infrastructure above water that will require lubrication and other maintenance) and solar installations (cleaning of PV plates to remove salt residue) (Rockmann et al. 2017; Atkinson 2016). Presently, marine energy is more expensive than many alternative renewable and traditional power sources; however, with future cost reductions and the availability of marine energy at sea in locations where other sources are less viable, marine energy 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 marine energy and battery energy storage systems. Marine energy provides unique advantages, including colocation with sensors, markers, and subsea inspection vehicles; continuous power generation when coupled with storage; better stealth characteristics; and designs tailored to the marine environment.

Opportunities for powering ocean observation sensors and navigation aids with marine energy occur throughout the coastal area and open ocean, where sufficient wave or current (tidal or ocean current) resources are present. The U.S. Department of Defense—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 2.6 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 830 total sensors (Ocean Observatories Initiative 2018).

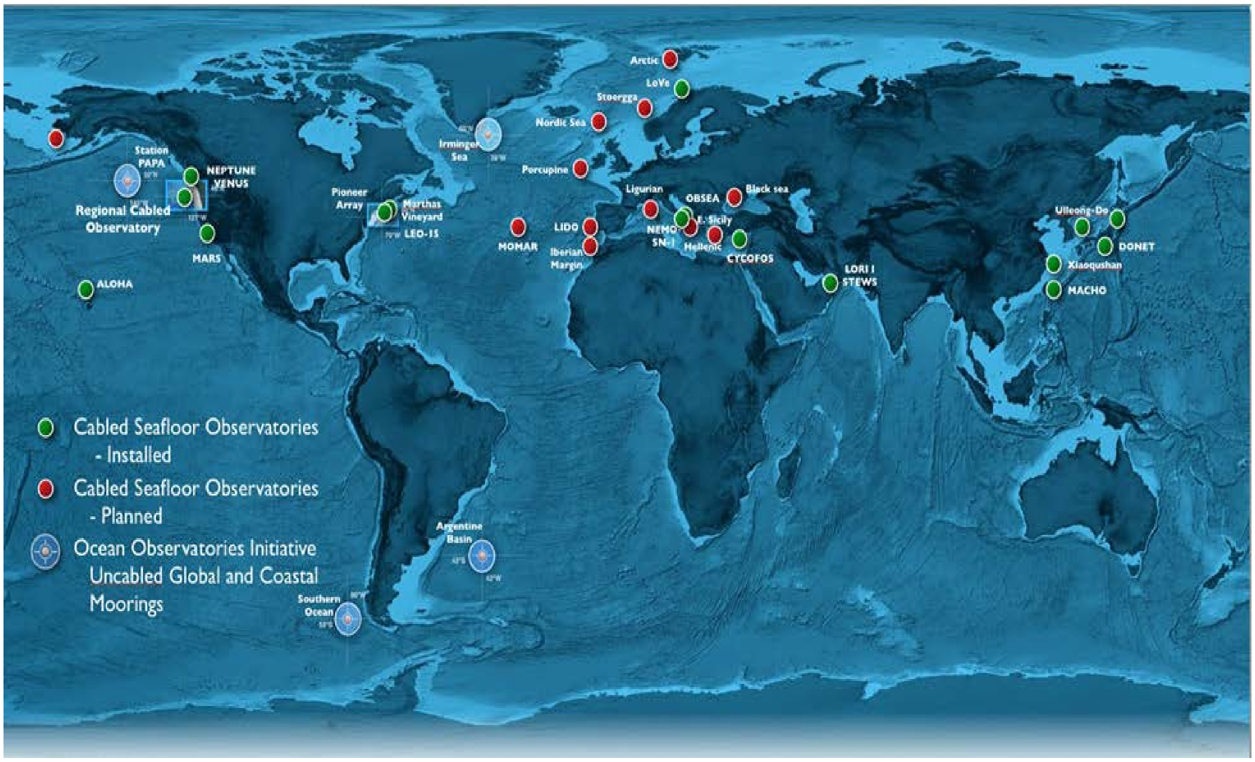


Figure 2.6. Installed and proposed seafloor observatories. *Image courtesy of Deborah Kelly and John Delaney*

Path Forward

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

Additionally, the U.S. military funds the continued development of ocean observation sensors, navigation aids, communications systems, and necessary power systems (diesel and/or PV plus battery), with large potential for marine energy to supplant). The military favors systems that are compact (low volume), lightweight, portable, surface expression/signature limiting, and reliable. 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 marine energy systems likely will.

Ongoing government investments are expected for purchasing and upgrading navigation aids, as well as developing, deploying, maintaining, and expanding/upgrading ocean observation systems (National Academies of Sciences, Engineering, and Medicine 2017). 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 marine energy 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; therefore, demonstrating a project without government support will require that industry partners be engaged early. These opportunities present significant potential for innovative marine energy devices to move forward with this market for marine energy 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 marine energy 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 marine energy 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 marine energy technologies for ocean observation and navigation aids and applications in underwater recharge, biofuels, and aquaculture, including the need to develop compatible marine energy devices and linkages that will operate independently over long periods of time.

To be successful and ensure marine energy 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, marine energy devices will need to demonstrate high efficiencies in environments with low resource energy (e.g., a wave energy converter must have high efficiency when transforming wave energy into electrical power in low sea states), will need to demonstrate long-term reliability and low maintenance requirements, and must not affect the environment that is being measured.

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 marine energy industry include NOAA Coastal Survey's NDBC, NOAA Pacific Marine Environmental Laboratory, IOOS, and the regional ocean observing systems, the U.S. Coast Guard, and the U.S. Department of Defense (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 marine energy developers.

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, 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.

References

Argo. Undated. “Current Status of Argo.” http://www.argo.ucsd.edu/About_Argo.html.

Atkinson, Gregory M. 2016. “Analysis of marine solar power trials on Blue Star Delos.” *Journal of Marine Engineering & Technology*. 15:3, 115-123, DOI: 10.1080/20464177.2016.1246907

Ayers, Jennifer M., and Kenneth Richter. 2016. “The potential of small-scale turbines and microbial fuel cells to support persistent oceanographic sensors.” *Oceans*. September 19–23. Monterey, CA. http://ieeexplore.ieee.org/document/7761015/authors.

Brasseur, L., M. Tamburri, and A. Pluedemann. 2009. “Sensor needs and readiness levels for ocean observing: an example from the ocean observatories initiative (OOI).” NSF Ocean Observatory Workshop.

Delory, E. and J. Pearlman, eds. “Challenges and Innovations in Ocean In Situ Sensors: Measuring Inner Ocean Processes and Health in the Digital Age.” Elsevier, 2018.

Edwards, M., Beaugrand, G., Hays, G.C., Koslow, J.A. and Richardson, A.J., 2010. “Multi-decadal oceanic ecological datasets and their application in marine policy and management.” *Trends in Ecology & Evolution*. 25(10), pp.602-610.

Gulf of Mexico Coastal Ocean Observing System. 2016. “Marine Operations.” Gulf of Mexico Coastal Ocean Observing System: Marine Operations. Accessed on October 31, 2018. http://gcoos.tamu.edu/?page_id=5080.

Homeland Security News Wire. 2012. “DHS funds more tests of autonomous power buoy for ocean surveillance.” Accessed on October 31, 2018. http://www.homelandsecuritynewswire.com/dr20120906-dhs-funds-more-tests-of-autonomous-power-buoy-for-ocean-surveillance.

iContainers. 2017. “Top 10 U.S. Container Ports.” https://www.icontainers.com/us/2017/05/16/top-10-us-ports/.

Integrated Ocean Observation Network. 2019. https://ioos.noaa.gov/.

Interactive Oceans. 2017. *The NEPTUNE Concept: A Regional Cabled Ocean Observatory in the Northeast Pacific Ocean*. https://interactiveoceans.washington.edu/story/The_NEPTUNE_Concept_A_Regional_Cabled_Ocean_Observatory_in_the_Northeast_Pacific_Ocean.

Kongsberg. 2013. Subsea Solutions for Environmental Monitoring: Monitoring platforms, Sensors & Applications. Accessed on October 31, 2018. https://www.km.kongsberg.com/ks/web/nokbg0397.nsf/AllWeb/2E7DBA635790AEABC1257BD70024A697/$file/environmental-monitoring-brochure.pdf?OpenElement.

Maritime Technology News. 2012. *Market and Technology Trends in Underwater Sensors & Instrumentation*. https://www.researchgate.net/publication/292981347_Market_and_Technology_Trends_in_Sensors_and_Instrumentation.

National Academies of Sciences, Engineering, and Medicine. 2017. *U.S. Ocean Observation Critical to Understanding Climate Change, but Lacks Long-term National Planning*. Accessed on October 31, 2018. http://www8.nationalacademies.org/onpinews/newsitem.aspx?RecordID=24919.

National Oceanic and Atmospheric Administration (NOAA). 2017a. “SOSUS (SOundSUrveillance System): General Information.” https://www.pmel.noaa.gov/acoustics/sosus_gen.html.

NOAA. 2017b. "The Tropical Atmosphere Ocean (TAO) Array: Gathering Data to Predict *El Niño*." https://celebrating200years.noaa.gov/datasets/tropical/welcome.html.

NOAA. 2017c. "Tsunami Messages for the Pacific Ocean (Past 30 days)." http://ptwc.weather.gov/?region=1.

NOAA. 2018. Chesapeake Bay Interpretative Buoy System. Accessed on October 30, 2018. https://buoybay.noaa.gov/.

Naval Today. 2018. "Ocean Power Technologies gets contract to design sensor buoys for US Navy." https://navaltoday.com/2016/09/15/ocean-power-technologies-gets-contract-to-design-sensor-buoys-for-us-navy/.

Ocean Observatories Initiative. 2018. "OOI By the Numbers." http://oceanobservatories.org/about/ooi-by-the-numbers/.

Ocean Networks Canada. 2019. http://www.oceannetworks.ca/Observatories.

Riser, S. C., Freeland, H. J., Roemmich, D., Wijffels, S., Troisi, A., Belbéoch, M., Gilbert, D., Xu, J., Pouliquen, S., Thresher, A. and Le Traon, P. Y. 2016. "Fifteen years of ocean observations with the global Argo array." *Nature Climate Change*. 6(2), p.145.

Röckmann C., Lagerveld S., and Stavenuiter J. 2017. "Operation and Maintenance Costs of Offshore Wind Farms and Potential Multi-use Platforms in the Dutch North Sea." In: Buck B., Langan R. (eds) Aquaculture Perspective of Multi-Use Sites in the Open Ocean. Springer, Cham, pp. 97-113.

The Diplomat. 2016. "US Navy Upgrading Undersea Sub-Detecting Sensor Network." https://thediplomat.com/2016/11/us-navy-upgrading-undersea-sub-detecting-sensor-network/.

United Nations Educational, Scientific, and Cultural Organization (UNESCO). 2009. European Earth Observation, future opportunities for business. http://www2.le.ac.uk/projects/g-step/info/documents/ValereMoutarlierEU.pdf.

UNESCO. 2017. "Observing the Global Oceans: The Global Ocean Observing System (GOOS)." http://www.unesco.org/new/en/natural-sciences/ioc-oceans/sections-and-programmes/ocean-observations-services/global-ocean-observing-system/.

U.S. Coast Guard (USCG). 2017a. *U.S. Aids to Navigation System: What You Need to Know About the Markers on the Water*. http://www.uscgboating.org/ATON/index.html.

USCG. 2017b. "U.S. Coast Guard Navigation Center." https://www.navcen.uscg.gov/.

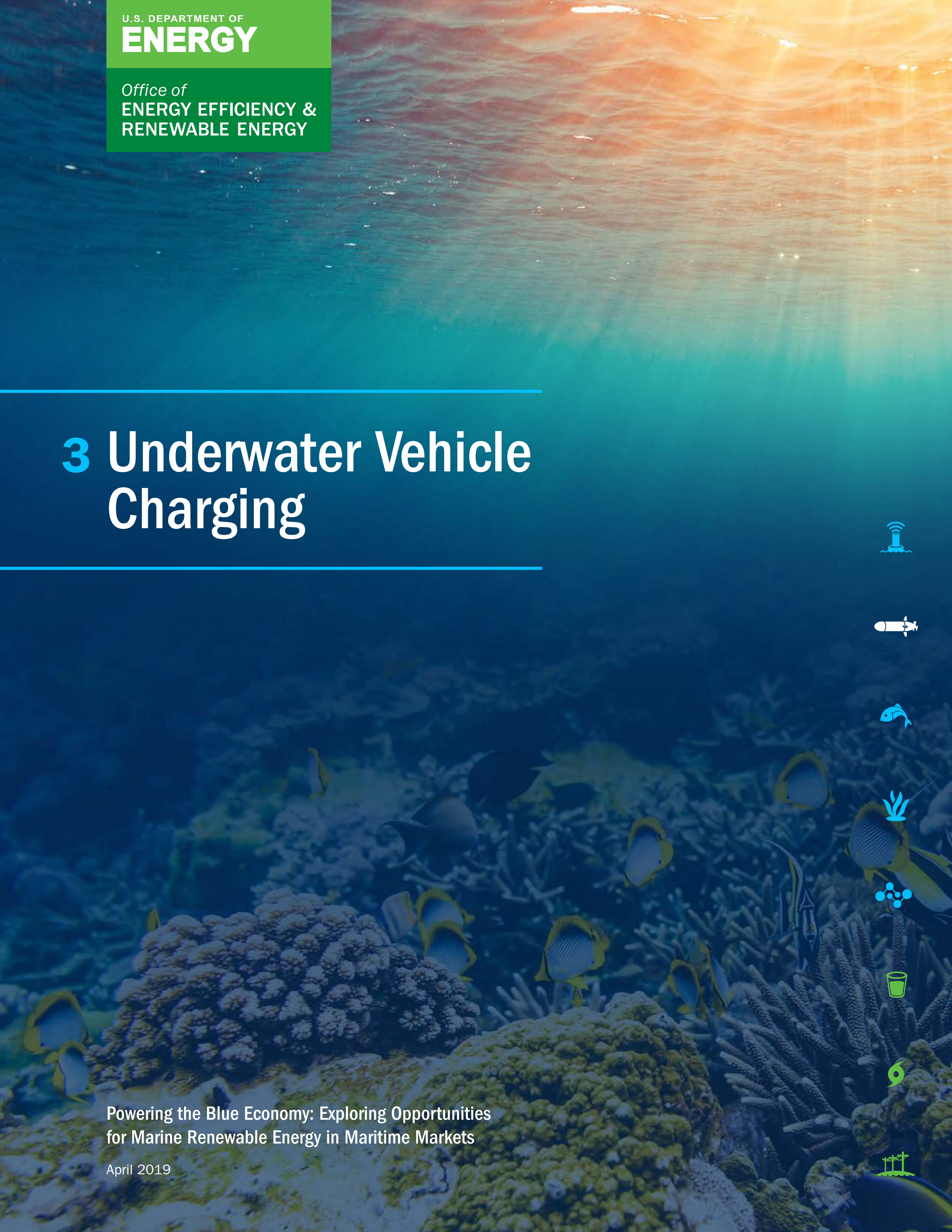
U.S. Department of Energy (DOE). 2013. Marine and Hydrokinetic Technologies Database. Office of Energy Efficiency and Renewable Energy. https://openei.org/wiki/Marine_and_Hydrokinetic_Technology_Database

U.S. Lighthouse Society. 2018. How to Become a Private Aid to Navigation. http://uslhs.org/resources/preservation-management/how-become-private-aid-navigation.

Venkatesan R., A. Tandon, D. Sengupta, K. N. Navaneeth. 2018. *Recent Trends in Ocean Observations*. In: Venkatesan R., A. Tandon, E. D'Asaro, M. Atmanand. (eds) Observing the Oceans in Real Time. Springer Oceanography. Springer, Cham.

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY



3 Underwater Vehicle Charging

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

April 2019

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

Key Findings

- Autonomous underwater vehicles (AUVs) and unmanned underwater vehicles (UUVs) are vehicles that perform underwater tasks without a tether or line to a surface ship, carrying instruments and sensors to monitor or inspect underwater environments.
- Although AUVs are a cheaper alternative to traditional vessels, power capacity of the vehicle's battery remains a limiting factor and keeps their missions limited in range and duration, often as little as 24 hours.
- Docking and recharge stations can extend the mission duration of underwater vehicles by recharging their batteries at sea, as well as providing a secure platform to dock vehicles between missions. Underwater docking stations are under development and not yet available commercially as they lack a practical power generation source.
- Powering underwater docking stations and recharging AUVs with marine energy could provide a locally generated reliable power source, smoothed for intermittency by battery backup. Underwater recharging of AUVs would reduce the need to recall vehicles to the surface as frequently; save time and resources; improve human safety on ships at sea; increase mission duration, range, and stealth; and reduce carbon emissions.

Opportunity Summary

AUVs and UUVs are used for observation, surveillance, persistent monitoring, ocean observation, and inspections of subsea infrastructure. These vehicles can also be equipped with ocean sensors to provide ocean observations and measurements. Currently, these vehicles are limited in their range and duration by the capacity of their batteries. Depending on the vehicle sensor payload, they may also have limited data storage space. These operation constraints mean that unmanned underwater vehicles require frequent recovery for recharge and data offload, which generally requires the assistance of a support vessel and crew.

Underwater charging and data offloading for AUVs and UUVs could reduce the reliance on expensive surface vessels and extend mission duration. Marine-energy-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 global AUV/UUV market is presently valued at $2.6 billion and is expected to double by 2022 (Research and Markets 2017), with customers in the defense, oil and gas, and research industries.

Application

Description of Application

AUVs or UUVs (hereafter called "AUVs") 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, monitoring of the seabed and underwater structures, and scientific studies. 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 of vessels and structures.

AUVs perform maritime tasks that once took a fleet of ships months to complete, as they can collect data faster and stay at sea longer than traditional vessels (Unmanned Systems Technology 2018). However, power remains a limiting factor, as 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 AUVs use onboard stored electric energy for propulsion, powering sensors, and acquiring data. The energy storage system capacity varies with system type, but typically no more than 40% of the interior of AUVs is devoted to the energy storage system. Deployment and recovery efforts for recharging AUVs are time sensitive and often limited by weather conditions, which pose a serious hazard to both the crew and the vehicle (Ewachiw 2014). Marine energy could provide an off-vehicle autonomous power source (i.e., at-sea recharging) for AUV recharging 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 3.1). At-sea recharging could also shorten the distance requirement for the energy storage system, thereby enabling more, smaller, and cheaper AUVs.

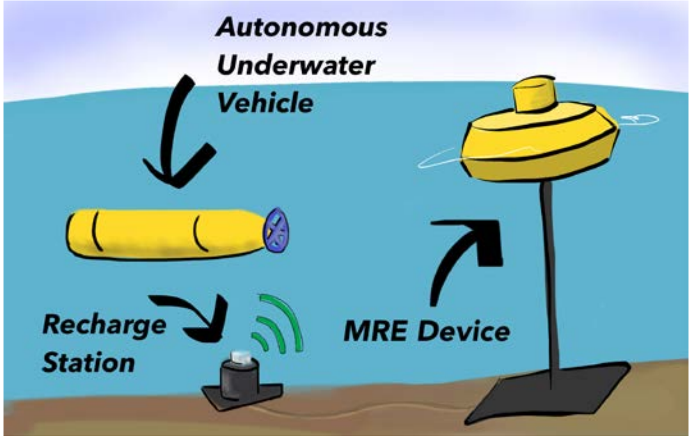


Figure 3.1. Marine energy application overview for underwater recharge of vehicles. *Image courtesy of Molly Grear, Pacific Northwest National Laboratory*

The opportunity to recharge AUVs underwater and to offload payload or data, as well as provide data storage on the recharge station, depends 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 3.2) that use wireless induction charging or plugged-in connections (Shepard News 2015; Townsend and Shenoi 2013). Opportunities for vehicle recharge include, but are not limited to (B. Polagye, personal communication, 2017):

- Locations that do not already have sources of power/communications. Temporary installations may be useful to meet environmental monitoring requirements in areas where industry exploitation may have an impact on the seabed or water quality.
- Long-duration survey operations in which mobile marine energy systems move with AUVs as they conduct mapping or search operations. Such a system would be more cost effective than deploying AUVs with manned vessels and have the potential to cover more area in a shorter period of time than if the vehicle is recovered, recharged, and redeployed every time the batteries are exhausted.
- Permanent installments for a particular purpose (e.g., aquaculture fisheries) that need maintenance, inspection, or monitoring over a long duration from AUVs and do not have access to grid power for vehicle recharge.

Autonomous Underwater Vehicles/Unmanned Underwater Vehicles

AUVs are self-guided, 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 can operate in intertidal waters, and some can dive up to 6,000 meters (m) deep (National Oceanic and Atmospheric Administration [NOAA] 2017a). Unmanned surface vehicles may be used to launch and recover AUVs and synchronize mission operations (Figure 3.3). Fully autonomous operations have onboard electrical sources to power propellers or thrusters to move the vehicle through the water. Power is also used to operate sensors on the instrument. Most AUVs use specialized batteries, yet some use fuel cells or rechargeable storage with solar power. AUV batteries require recharging, but some sensors can run for months at a time before a recharge is needed (NOAA 2017a). 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 3.2. Underwater Remus docking station. *Photo courtesy of Woods Hole Oceanographic Institution (WHOI)*

The duration of most AUV missions is typically 24 hours and is related to power consumption of onboard sonar and sensor systems. However, AUV missions have been extended in recent years; power management of systems has helped to extend these ranges. For example, the Monterey Bay Aquarium Research Institute (MBARI) operates a long-range AUV called Tethys that can cover ranges of 1,000 kilometers or more, and can have a mission duration of weeks at a time without returning to the surface (MBARI 2018; A. Hamilton, personal communication, 2017).

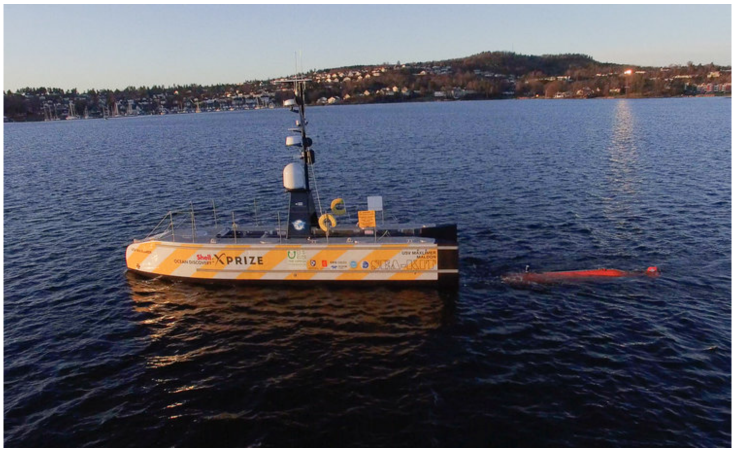


Figure 3.3. USV SEA-KIT, designed by Hushcraft LTd to act as a surface support vessel for the AUV, including the capacity to launch and recover the AUV and to provide subsea communications and positioning.

Source: ©Lew Abramson/lewabramson.com

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

- **Small AUVs**. AUVs between 3 and 10 inches (in.) in diameter. They can be man-portable and capable of deployment from a variety of platforms or even larger AUVs. Submarine deployment is possible. Endurance is typically from 10 to 25 hours, though emerging battery technology will increase this.
- **Medium AUVs**. AUVs between 10 and 21 in. in diameter. Medium AUVs can also be shore-, submarine-, or ship-launched and recovered with handling equipment. Payload volume can be 6 to 12 times larger than the small AUV class. Their endurance is typically double that of the small AUV, but can be even greater for the larger, medium-class AUVs.
- **Large AUVs**. AUVs between 21 and 84 in. in diameter. These AUVs will require appropriate handling equipment to support stowage, launch, and recovery on any seaborne hoist platform. Large AUVs can also be shore- or ship-launched with special handling equipment.
- **Extra-large AUVs**. AUVs with diameters larger than 84 in. Shore- or ship-launched with sufficient handling facilities, such as cranes and well decks. These AUVs likely have a hybrid energy system (diesel and battery) with an endurance measured in weeks.

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 3.4). However, new commercial gliders are available that can travel 10,000 kilometers (up to a 6,000 m depth), extending their endurance to more than a year of deployment time (J. Sobin, personal communication). The U.S. Navy makes extensive use of gliders as well (Naval Oceanographic Office 2017). While traveling, gliders relay their data to shore via satellite telemetry (Woods Hole Oceanographic Institution 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 marine energy devices operating at sea (NOAA 2017c).

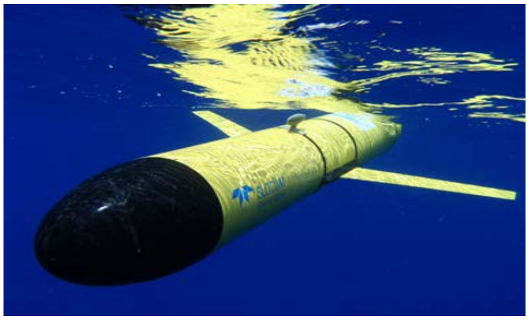


Figure 3.4. Teledyne Webb Research's Slocum glider. *Image courtesy of WHOI*

Remotely Operated Vehicles

Remotely operated vehicles (ROVs) (Figure 3.5) are connected to surface ships by cables or tethers 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 2017b). 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. 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. These untethered (or hybrid) ROVs have potential for utilizing underwater recharge, although they are unlikely to become a substantial market.

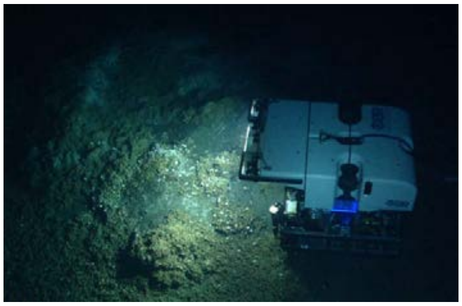


Figure 3.5. NOAA's Deep Discoverer remotely operated vehicle explores during a 2013 expedition to investigate the U.S. Atlantic canyons. *Photo courtesy of NOAA*

Docking Stations

Docking stations for AUVs 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 for some onboard data storage, as well as provide a gateway for communications to shore (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 3.6 includes 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. While the co-location of sensors and other technologies could potentially be a development barrier, this could also be an opportunity to co-develop more integrated and efficient devices and systems.

Underwater docking stations have not yet made the transition from demonstration to commercial operations (Dhanak and Xiros 2016), as designs are still undergoing research and development. 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. Additional examples of docking stations are shown in Figure 3.7 and Figure 3.8.

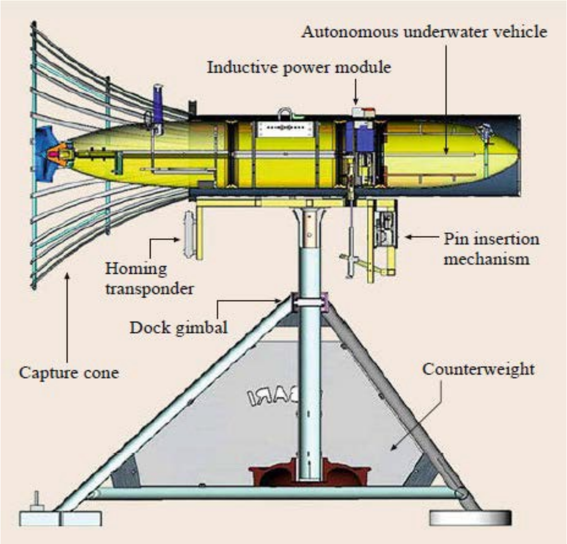


Figure 3.6. Model of a docking station with an AUV captured within the dock. *Image courtesy of Dhanak and Xiros (2016), SolidWorks drawing by Jon Erikson, MBARI*

Figure 3.7. Recovering a docking system for an autonomous underwater vehicle after a test deployment in Monterey Bay. *Photo by Brett Hobson ©2006 MBARI*

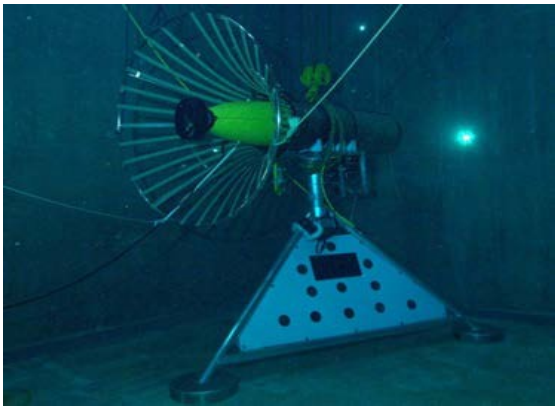


Figure 3.8. A docking system for an autonomous underwater vehicle being tank tested by the Monterey Bay Aquarium Research Institute. *Photo by Brett Hobson ©2006 MBARI*

Power Requirements

It is expected that all 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 per recharge station. Gish and Hughes (2017) cite that 200–500 watts of power is required for normal charging, yet faster charging is possible with increased power, which may be more desirable for some applications. A typical AUV recharge takes approximately4–8 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 marine energy, coupled with battery backup, would allow for recharging on demand. Energy storage may be required, as the supply/availability of energy may not always match the immediate demand for power.

A variety of systems and subsystems could use marine energy, including electricity, as shown in Figure 3.9.

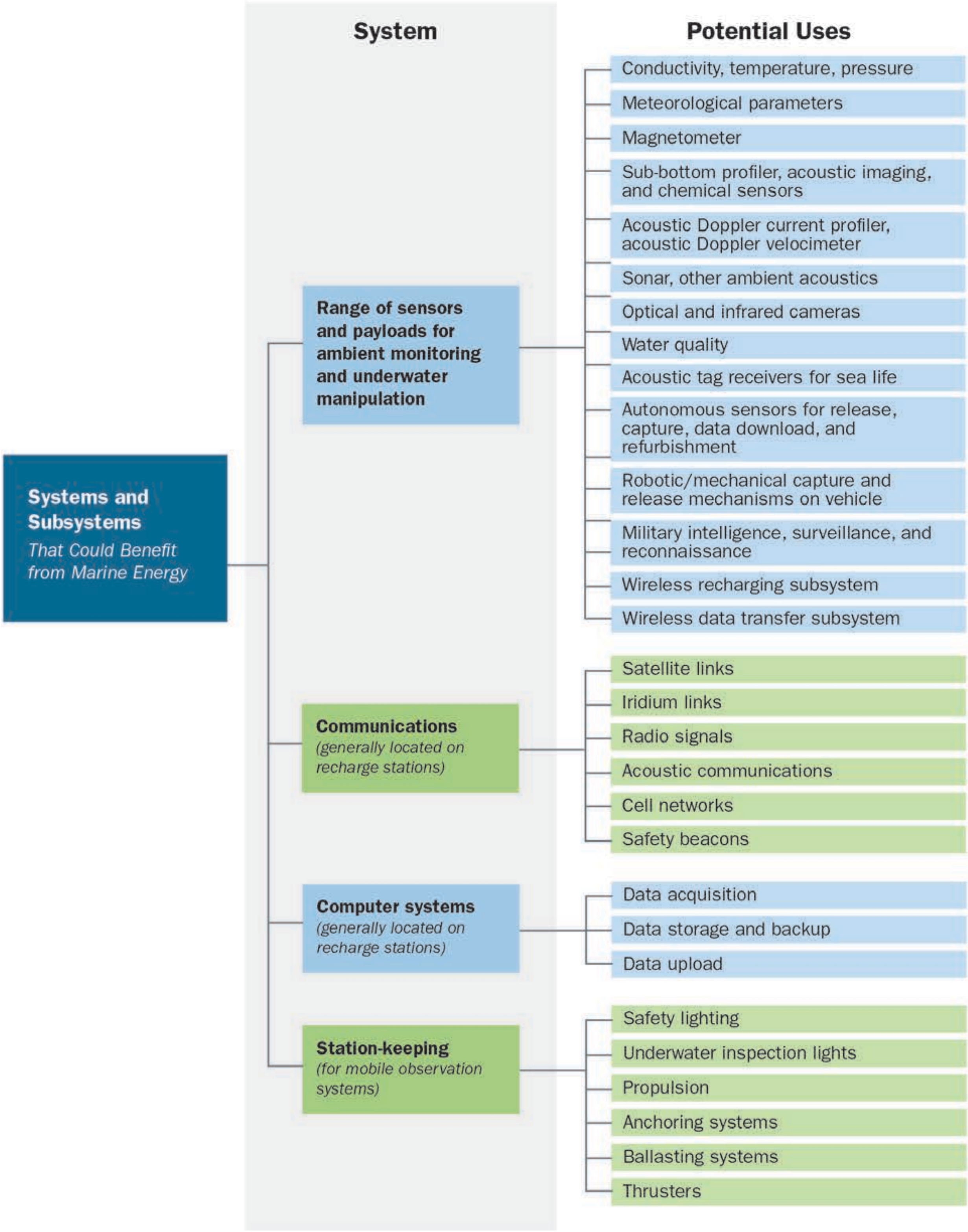


Figure 3.9. Vehicle systems and subsystems that could benefit from marine energy power

In addition, there will be uses for compressed air for active ballasting of recharge systems, which could be generated using mechanical energy from marine energy devices.

Markets

Description of Markets

Globally, the AUV market is estimated at $2.6 billion and it is expected to double by 2022 (Research and Markets 2017). The market for recharging AUVs 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, as the market growth is tied to the AUV market. Small stand-alone underwater recharge stations using undersea currents can produce power of approximately 1,500 watts for local AUV recharging (Ryan Frommelt, personal communication, October 2018).

The AUV market has been growing over the past several years as a result of the increasing demand for commercial, military, and scientific research applications. New investments in the market have been driven largely by the defense industry (Research and Markets 2017). 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 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 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 AUVs and charging capabilities, in addition to increased depth, endurance, vehicle maneuverability, and real- or near-real-time communications.

The key end users of the AUV market are the commercial sector (e.g., surveying and seabed mapping, offshore drilling, and pipeline inspections), followed by the defense and homeland security sectors (Markets and Markets 2017) and arctic exploration, as well as scientific uses.

As discussed in Shukla and Karki (2016), the oil and gas industry is making automation a priority because of 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 are heavily used for marine research applications by academia (e.g., WHOI), the federal government (e.g., NOAA), and the military.

The U.S. Department of Defense has identified nine mission categories for AUVs, including intelligence, surveillance, and reconnaissance; mine countermeasures; antisubmarine warfare; inspection/identification; oceanography; communications/navigation network node; payload delivery; information operations; and time-critical strike (Button et al. 2009). In 2016, the U.S. Department of Defense announced that they would be investing $600 million in AUVs over the next 5 years (Pomerleau 2016). Additionally, the United States Department of Homeland Security Science and Technology Directorate is interested in AUV research and has been supporting funding the development of an AUV 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 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.

Power Options

There are few viable options for powering an underwater vehicle recharge station other than marine energy (see Figure 3.10). Hydrogen-oxygen fuel cells are emerging as a viable underwater vehicle recharge station power source, but require a consistent and reliable supply of hydrogen for fuel. 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 charging will likely take place underwater, requiring extensive cabling from any surface power source and reducing stealth as a result of the surface expression. Solar and wind applications must be mounted at the surface. Placing solar photovoltaic 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.

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 monitoring. Ocean currents, especially fast-flowing western boundary currents, can approach speeds of 3–4 knots in some areas and could be harnessed for underwater vehicle recharging. However, operating these vehicles in fast-flowing ocean currents may increase operational complexity. Although operating vehicles in fast-moving currents may be problematic, the temporal and spatial (horizontal and depth) variations in their intensity and direction may be used for opportunistic propulsion and may present opportunities for vehicle recharging (B. Polagye, personal communication, 2017). 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.

Marine Energy Potential Value Proposition

AUVs 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 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 marine energy would provide a reliable, locally generated 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 marine energy.

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

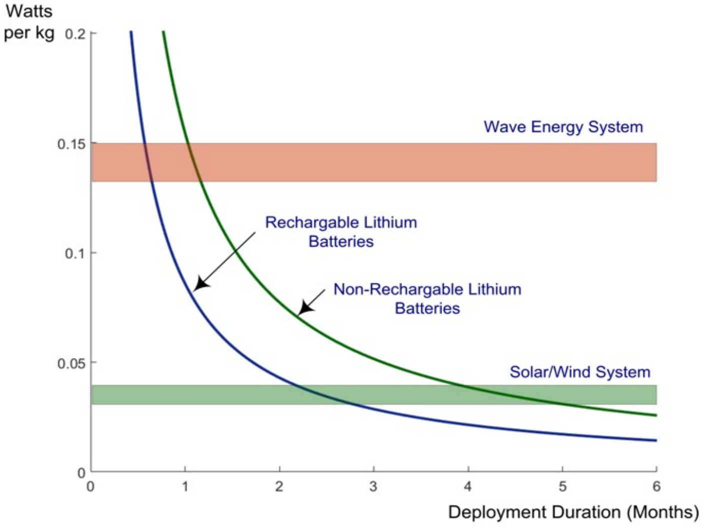


Figure 3.10. Energy requirements for deployment duration. *Image courtesy of Hamilton (2017)*

Opportunities for underwater recharging occur throughout the coastal area and open oceans where there is a need to survey or monitor using AUVs for extended periods of time (i.e., more than 1 month) (Figure 3.11 and Figure 3.12) and where sufficient wave or tidal resources are available. AUV operators typically prefer environments with minimal ocean currents when possible as it is easier for the vehicle to navigate and make headway.

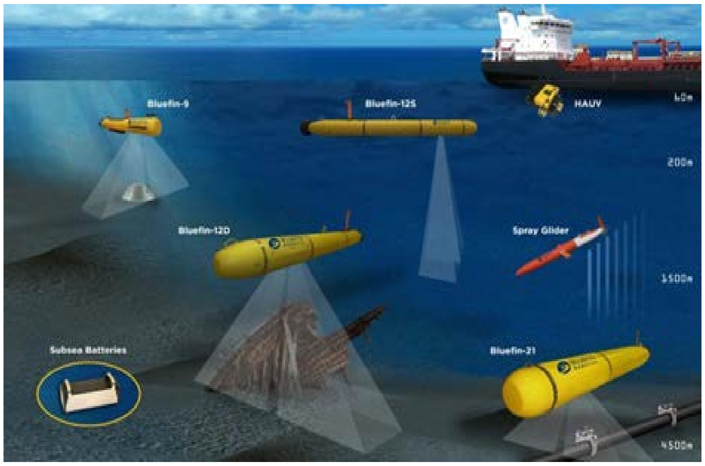


Figure 3.11. Opportunities for underwater recharging in all oceans, at all depths, for a variety of AUVs.
Image courtesy of Bluefin Robotics

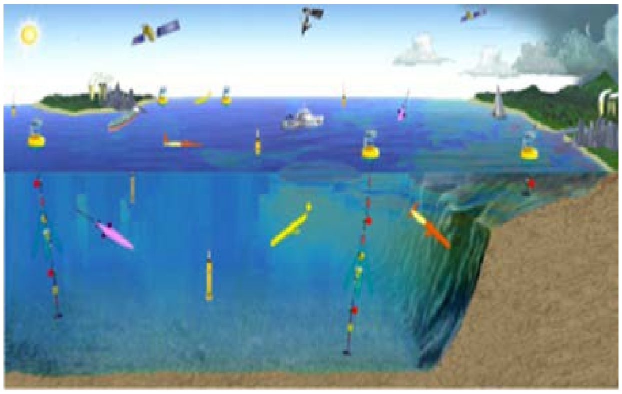


Figure 3.12. Underwater gliders and profiling arrays, representing a variety of AUVs, deployed in different areas of the ocean from shallow waters near land to the deep sea. *Image courtesy of ACSA, SeaExplorer, Creative Commons*

AUVs deployed for extended mission durations (e.g., more than 1 month) and/or those that consume a significant amount of power as a result of onboard instruments (e.g., sonar, sensors) may benefit from underwater recharging opportunities that can be powered using wave energy systems (A. Hamilton, personal communication, 2017); Hamilton (2017) estimates that wave energy systems provide a persistent form of energy that will be useful over AUV instrument deployment cycles. The power provided from wave energy systems is more persistent than that provided by battery power alone and is higher than the solar/wind system, as shown in Figure 3.10, for a recharge station built into an observation buoy. However, battery storage may be appropriate for shorter AUV deployment durations when recharging is unnecessary.

An emerging potential market within the U.S. Department of Defense sector (U.S. Navy and U.S. Air Force) supporting the swarm approach over traditional operations at sea is 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.

Path Forward

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

Research and development in this area should concentrate on the mechanical and electrical coupling of marine energy devices to the recharge stations and the integration with data transfer capabilities. Specific adaptations to existing marine energy designs (wave energy converters in particular) should be developed to eliminate surface expression and optimize for underwater power generation. Efficient low-speed (under one knot) underwater turbines need to demonstrate high reliability and efficiency. Marine energy devices have little deployment experience in deep water; thus, systems need to be reliably demonstrated in these locations 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 recharging 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 will increase adoption and drive down costs. Hamilton (2017) also highlights the need for numerical models for station-keeping system dynamics.

Oceanographic research institutions must continue research and development related to technology and vehicle development, instrumentation development, vehicle and platform reliability, and wave/current energy capture. The University of North Carolina's Coastal Studies Institute has been studying the Gulf Stream to harvest its energy using a submerged turbine. The turbine would be attached to an AUV with the ability to move the turbine to the location of the best resource (Coastal Review Online 2017). Potential market synergies exist between the application of marine energy for underwater vehicle recharging and marine energy's application for ocean observation, navigation markers, growing algae at sea, and aquaculture.

Other synergies exist between marine energy 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 AUVs and sensors (L3 2017). Additionally, Teledyne Energy Systems is presently developing the Sea Floor Power Node for deep-water AUV recharging applications using fuel cell power with refillable reactants (Utz et al. 2018). Teledyne is interested in extending this product to include a regenerative capability to reduce the reactant storage volume (M. Miller, personal communication, 2017). Integrating these and similar energy power and storage solutions with marine energy could improve mission operations and durations and allow for the incorporation of more power-demanding instruments.

Potential Partners

For the development of underwater vehicle recharging, potential U.S. mission-driven partners for the marine energy industry include government, academia, and industry. Within the U.S. government, potential partners include the U.S. Department of Defense (U.S. Navy, Defense Advanced Research Projects Agency), Department of Homeland Security, and government-funded ocean observatories, such as the U.S. Integrated Ocean Observing System and regional Ocean Observing Systems.

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, Woods Hole Oceanographic Institution, the University of Washington, University of North Carolina, North Carolina State University, and other research institutes, such as MBARI. Oceanographic institutions in other nations are similarly involved with the Global Ocean Observing System and are likely to have interests in underwater recharging 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 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 Wibotic and AeroJet Rocketdyne.

References

Button, Robert W., John Kamp, Thomas B. Burtin, and James Dryden. 2009. *A Survey of Missions for Unmanned Undersea Vehicles*. RAND National Defense Research Institute. https://www.rand.org/content/dam/rand/pubs/monographs/2009/RAND_MG808.pdf.

Coastal Review Online. 2017. "Project Looks to Tap Gulf's Stream's Energy." Accessed August 30, 2018. https://www.coastalreview.org/2017/05/project-looks-tap-gulf-streams-energy/.

Dhanak, Manhar R., and Xiros, Nikolas I. (Eds.). 2016. *Springer Handbook of Ocean Engineering*. Springer. http://www.springer.com/us/book/9783319166483.

Ewachiw, Mark A., Jr. 2014. "Design of an Autonomous Underwater Vehicle (AUV) Charging System for Underway, Underwater Recharging." *MS Thesis*. Massachusetts Institute of Technology. Cambridge, MA. pp 86. https://calhoun.nps.edu/handle/10945/43069.

Gish, L.A. and Hughes, H. 2017. Presentation: Underwater Recharging for Small Commercial AUVs. DOE Marine Energy Technologies Forum. December 6, 2017.

Gutierrez, Luis B., Carlos A. Zuluaga, Juan A. Ramirez, Rafael E. Vasquez, Diego A. Florez, Elkin A. Taborda, and Raul A. Valencia. 2010. "Development of an Underwater Remotely Operated Vehicle (ROV) for Surveillance and Inspection of Port Facilities." *ASME 2010 International Mechanical Engineering Congress and Exposition*, pp. 631–640. American Society of Mechanical Engineers. http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=1617008.

Hamilton, Andy. 2017. "Wave-Energy Conversion for Oceanographic Applications." Presentation at DOE Marine Energy Technologies Forum. December 5–7, 2017.

Huner, J.V. 1985. *Crustacean and Mollusk Aquaculture in the United States*. Springer, New York. 476 pp.

Liquid Robotics. 2018. Energy Harvesting Ocean Robot. https://www.liquid-robotics.com/platform/how-it-works/

L3. 2017. "Open Water Power." http://openwaterpower.com/.

Markets and Markets. 2017. *Unmanned Underwater Vehicles (UUV) Market worth 5.20 Billion USD by 2022*. https://www.marketsandmarkets.com/PressReleases/unmanned-underwater-vehicles.asp.

Monterey Bay Aquarium Research Institute (MBARI). 2017. *Autonomous Underwater Vehicle Docking*. https://www.mbari.org/autonomous-underwater-vehicle-docking/.

MBARI. 2018. "Long-range autonomous underwater vehicle *Tethys*." Accessed August 30, 2018. https://www.mbari.org/at-sea/vehicles/autonomous-underwater-vehicles/long-range-auv-tethys/.

MODUS. 2018. MODUS Seabed Intervention. http://modus-ltd.com/.

National Oceanic and Atmospheric Administration (NOAA). 2017a. "The Tropical Atmosphere Ocean (TAO) Array: Gathering Data to Predict El Niño." https://celebrating200years.noaa.gov/datasets/tropical/welcome.html.

NOAA. 2017b. "Tsunami Messages for the Pacific Ocean (Past 30 days)." http://ptwc.weather.gov/?region=1.

NOAA. 2017c. "What is an Ocean Glider?" https://oceanservice.noaa.gov/facts/ocean-gliders.html.

Naval Oceanographic Office. 2017. Spring WG/CSAB Update. https://www.ofcm.gov/groups/CSAB/Meetings/2017/2017-03/05-NAVO%20Overview%20Brief%20to%20CSAB%20LAR%20input%20Mar17%20v2.pdf.

Pomerleau, Mark. 2016. "DOD plans to invest $600M in unmanned underwater vehicles." *Defense Systems.* https://defensesystems.com/articles/2016/02/04/dod-navy-uuv-investments.aspx.

Research and Markets. 2017. *Global $2.65 Billion Unmanned Underwater Vehicles Market 2017-2021*. https://globenewswire.com/news-release/2017/03/10/934263/0/en/Global-2-65-Billion-Unmanned-Underwater-Vehicles-Market-2017-2021.html.

Shepard News. 2015. "US works on underwater UUV recharging." https://www.shephardmedia.com/news/uv-online/us-works-underwater-uuv-recharging/.

Shukla, Amit, and Hamad Karki. 2016. "Application of robotics in offshore oil and gas industry—A review Part II." *Robotics and Autonomous Systems*. Vol. 75, Part B, 508–524. https://doi.org/10.1016/j.robot.2015.09.013.

The Fish Site. 2016. *Underwater ROVs Making a Splash in Aquaculture*. https://thefishsite.com/articles/underwater-rovs-making-a-splash-in-aquaculture.

Townsend, Nicholas, and Ajit Shenoi. 2013. "Recharging autonomous underwater vehicles from ambient wave induced motions." *Oceans*. San Diego, CA. September 23–27, 2013.

Unmanned Systems Technology. 2018. Combined USV and AUV System Maps Ocean Floor. Accessed 8/30/2018. http://www.unmannedsystemstechnology.com/2018/01/combined-usv-auv-system-maps-ocean-floor/.

Utz, R., R. Wynne, M. Miller, R. Sievers, T. Valdez. 2018. "Lightweight System Design and Demonstration of a High Reliability, Air Independent, PEMFC Power System for an Untethered Subsea Power Node." Proceedings of the 2008 Power Sources Conference. pp. 203-206.

Woods Hole Oceanographic Institution. 2017. Coastal and Global Scale Nodes: Coastal Sliders. http://www.whoi.edu/ooi_cgsn/coastal-gliders.

Personal Communications

Andrew Hamilton, Monterey Bay Aquarium Research Institute

Brian Polagye, University of Washington, Pacific Marine Energy Center

Jake Sobin, Kongsberg

Mike Miller, Teledyne Energy Systems, Inc.

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

4 Offshore Marine Aquaculture

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

April 2019

4. Offshore Marine Aquaculture

Key Findings

- 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. The global aquaculture market is projected to be more than $55 billion by 2020 according to the Food and Agriculture Organization (FAO).

- 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 or shellfish and seaweeds are grown on the shallow seabed. Offshore aquaculture operations typically use floating or submersible net pens or cages that are tethered to the seafloor and attached to buoys. There is a trend worldwide to move aquaculture operations further offshore, although the United States has no substantial offshore installations.

- Offshore 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 power for the crew living quarters (if the structures are manned); and recharging of transport vessels.

- Many types of aquaculture facilities could be partially or wholly powered by marine energy. Most wave energy converters (WECs) prefer highly energetic sea states for energy production, which may not be suitable for aquaculture operations. However, some WEC designs are better suited to operate in less energetic conditions. WECs may provide shelter in their lee for aquaculture operations.

- The low surface expression of most WECs will increase survival at sea, provide low visual impacts, and be more readily integrated with aquaculture facilities.

Opportunity Summary

Aquaculture is the rearing of aquatic animals or the cultivation of aquatic plants for food. When used to produce fish, mussels, oysters, or similar organisms, it 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 17th top producer. Global aquaculture market growth is anticipated to accelerate through 2022 as a result of improvements in aquaculture systems, sustainable practices, and diversification of species (SeafoodSource 2018). Aquaculture operations have historically been limited to onshore or coastal sites, but in recent years groups are increasingly looking to offshore sites. These offshore sites will present unique challenges in terms of energy provisioning.

Aquaculture requires energy to power monitoring equipment, circulation pumps, feeding systems, and navigation lighting, as well as refrigerate the harvested product. These power needs are estimated to range between 4 and 715 megawatt-hours 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 marine energy, the industry could 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) extending 200 nautical miles, a significant portion of which could be used for aquaculture development. The advantages of colocating the energy source with aquaculture operations could potentially favor a marine energy power supply for this growing industry.

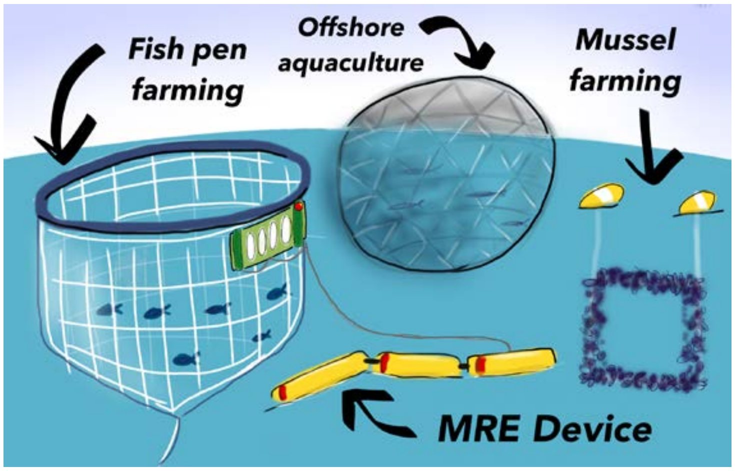


Figure 4.1. Marine renewable energy application overview for offshore marine aquaculture. *Image courtesy of Molly Grear, Pacific Northwest National Laboratory*

Application

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 4.1). 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 (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 (National Oceanic and Atmospheric Administration [NOAA] 2015), 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. Offshore aquaculture is not well-developed in many parts of the world including the United States. Although many governments around the world (including the United States) support the development of offshore aquaculture, there are many economic and regulatory barriers that will have to be overcome to fully develop the sector (Knapp and Rubino 2016; Johnson et al. 2017).

Globally, approximately 3 billion people rely on seafood as a primary source of animal protein (NOAA 2015), yet most capture fisheries[9] 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 4.2), resulting in a compound annual growth rate[10] of approximately 1.07%.

---

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

[10] 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).

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).

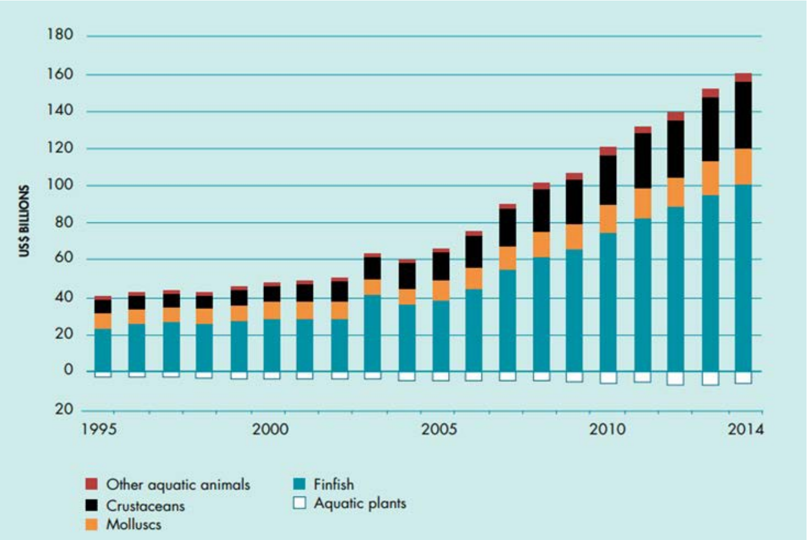


Figure 4.2. World aquaculture production volume and value of aquatic animals and plants (1995–2014).
Image from Food and Agriculture Organization of the United Nations (2016), reproduced with permission

Coastal Versus Offshore Aquaculture Operations

Aquaculture operations can occur in coastal or nearshore zones and deepwater 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 marine energy resources; moreover, offshore pens are becoming increasingly larger, requiring more power for lighting, bridge equipment, and feeding systems, for example (undercurrentnews 2018).

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 4.3 and Figure 4.4).

Figure 4.3. Open-ocean fish farming. *Photo courtesy of NOAA Fisheries*

Figure 4.4. Net pens for finfish rearing. *Photo courtesy of Creative Commons*

Figure 4.5. Shellfish farming. *Photo courtesy of Aquarium of the Pacific*

Shellfish Aquaculture

Most bivalve shellfish aquaculture in the United States is bottom-laid and does not require power except for maintenance or harvest vessels; some marginal growing waters could be made more productive with the addition of vertical advection of water from depth using low power pumps. 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 4.5). 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.

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 are 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.

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 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 researchers find that the power consumption for the Pacific oyster farm is similar to an average family home. For this operation, the purification system uses the most power (33.6 kilowatt-hours (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 can be used as a reference and general estimate. Aquatera (2014) also discusses the Greenius project, which 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. More detail can be found in Fiander et al. (2014).

Fish farms typically go through a 2- to 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 marine energy resources (Aquatera 2014). The seasonal peaks of energy needs for fish farms may not correspond with the seasonal availability of marine energy resources. Siting of coupled systems must take into account the seasonal energy availability, and may be somewhat mitigated by coupling marine energy resources with energy storage systems.

Markets

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 4.6). World aquaculture production of fish accounted for 44.1% of total production in 2014, up from 31.1% in 2004 (Figure 4.6). 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 4.7). 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.

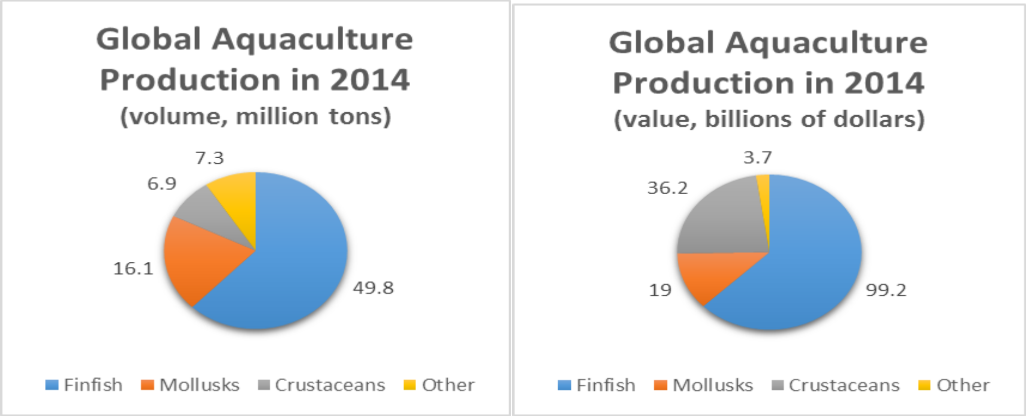


Figure 4.6. Global aquaculture production in 2014 in million tons (left) and billions of dollars (right). *Data from FAO (2016)*

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 (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 as a result of 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.

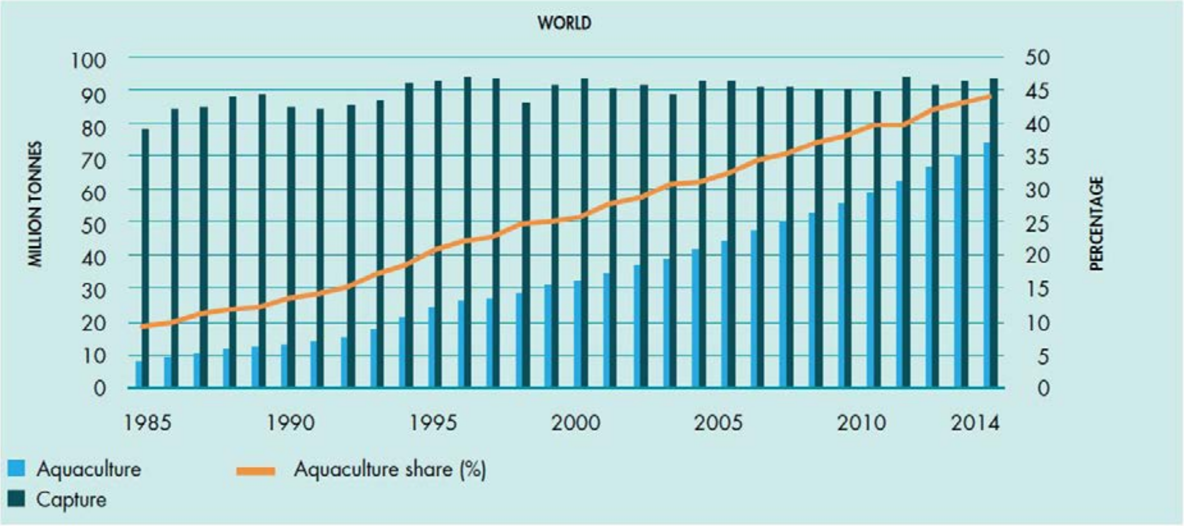


Figure 4.7. Global share of aquaculture in total production of aquatic animals. *Image from Food and Agriculture Organization of the United Nations (2016), reproduced with permission*

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 2015), half of which is from aquaculture (NOAA 2017). 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 Marine Energy Markets

The main drivers for aquaculture production are the increased global supply of fish for human consumption as a result of population growth, with estimates pointing toward further 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 2015). The U.S. Department of Agriculture (USDA) and Food and Drug Administration has urged North Americans to increase their seafood consumption from the current level of one meal a week (USDA 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 highertropic-level species (e.g., sea bass, salmonids, catfish, and shrimp), there will be a shift toward more intensive high-technology farming. This shift will drive increased energy needs for producers.

As a result of 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 good reason to seriously consider co-development with marine energy resources where possible.

Customers

Shore-based aquaculture operations may be a potential user of marine energy as a power 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 marine energy 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 Francaise de Développement, European Commission, and Deutsche Gesellschaft für Internationale Zusammenarbeit 2017). Their acceptance of higher-risk opportunities may encourage them to embrace the use of marine energy sources for their operations (Table 4.1).

Table 4.1. Simple Classification of Aquaculture Types (Adapted from Agence Française de Développement, European Commission, and Deutsche Gesellschaft für Internationale Zusammenarbeit [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	

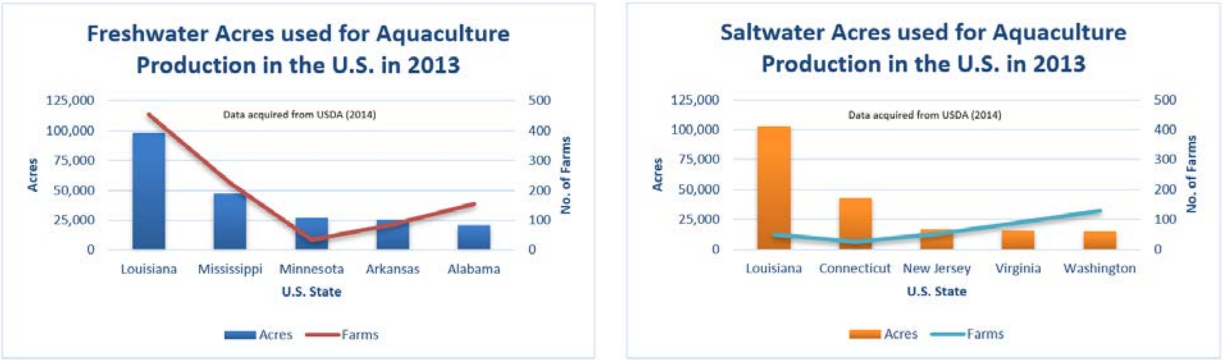
There are several U.S.-based aquaculture operations that may be interested in supplementing their power needs with marine energy. Catalina Sea Ranch is the first offshore aquaculture facility in the United States, with a 100-acre aquaculture facility on the periphery of the San Pedro Shelf. In 2017, Catalina Sea Ranch was awarded funding through the Advanced Research Projects Agency-Energy 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 Open Blue, Earth Ocean Farms, and Blue Ocean Mariculture.

Power Options

Aquaculture operations that require power have traditionally relied 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 solar photovoltaic panels to generate approximately 15,000 watts to oxygenate fish tanks and charge and maintain battery systems (NRG 2018). In the United States, photovoltaic panels are being used to power a conventional floating upwelling system that is used to force-feed nutrient-rich water to infant shellfish (Energy Smarts 2013).

Geographic Relevance

In 2013, the USDA estimated that the United States operated 2,256 freshwater and 876 saltwater aquaculture farms, totaling 249,274 and 213,455 acres, respectively (USDA 2014). Of the freshwater farms, Louisiana topped the list, with 454 farms totaling 97,904 acres (Figure 4.8a). Of the saltwater farms, Louisiana also topped the list, with 103,159 acres across 48 farms (Figure 4.8b); however, Florida operated the most farms (169 farms only totaling 1,078 acres). Moreover, this vast amount of area shows substantial overlap with excellent marine energy resources. Typically, offshore net pens and other aquaculture enclosures are sited in the calmest waters that provide adequate flow to supply nutrients and clean water while removing waste. These calmer waters may not coincide with the best wave or current resources; however, there are likely to be many locations where adequate wave resources can generate the amount of energy needed by aquaculture operations, particularly offshore, where heavy-duty cages and enclosures can withstand greater wave activity. 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 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, colocated with aquaculture installations, also has similar advantages to solar power for replacing diesel.



(a) (b)

Figure 4.8. Acres used for aquaculture production for (a) freshwater and (b) seawater. *Data acquired from USDA (2014)*

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 2015). The U.S. Department of Energy (DOE) (2016) estimated that the potential wave power in U.S. waters is 2,640 terawatt-hours (TWh) per year (almost 300 gigawatts), with the largest wave power resources located in Alaska and along the West Coast. Although the magnitude of potential tidal power is smaller than wave power (approximately 3 gigawatts), it is concentrated and often in close proximity to major coastal load centers (DOE 2016).

Marine Energy 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 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 renewable marine energy could help reduce negative impacts to air and water quality.

It should be noted that highly energetic waters with high waves and winds may threaten the safety and survivability of offshore marine aquaculture operations and ability for species growth. Wave or current power most useful for aquaculture operations will be in lower resource areas and could provide power for aquaculture needs coupled with storage to smooth power delivery. There are, however, additional marine energy applications for supporting aquaculture in remote communities that are limited because of lack of energy infrastructure and/or high existing costs.

A strong driver for transitioning aquaculture from fossil-fuel sources to renewables will likely be due to concerns over local air and water quality from emissions, rather than the cost of energy. Price point will be a factor, but is believed to be 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 marine energy include the low profile of wave or tidal energy converters for survivability at sea; the fact that marine energy 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). Marine energy could be a preferred power source for low-profile aquaculture pens in high latitudes relative to solar, because space to accommodate photovoltaic 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 meter (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 colocated 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 colocation of aquaculture and wave energy devices (Aquatera 2014). Colocating 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 valuable because of increased survival at sea, low visual impacts, and easier integration with aquaculture facilities, particularly compared with offshore wind. When competing 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.

Path Forward

The success of supplying marine energy 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 marine energy outputs to aquaculture operations. Close coordination with aquaculture researchers and operators will be needed for the marine energy industry to understand the needs of and opportunities for testing marine energy devices in conjunction with aquaculture pens or other facilities. In-water tests of net pens and marine energy devices will help to hone compatibilities between the systems and may help foster public acceptance of the new hybrid installations.

Potential Partners

Potential mission-driven partners for the marine energy industry include those from the government as well as 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 marine energy and aquaculture companies have expressed interest in exploring linkages, whereas others are already engaged. Marine energy industry players already active in linking marine energy 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, South Korea, and the Philippines. U.S. companies with offshore aquaculture interests include Kampachi Farms, Catalina Sea Ranch, Manna Fish Farms, and Innovasea.

By developing and adapting marine energy devices to provide power for aquaculture operations, the marine energy industry could move the route to commercial-scale development along further, 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 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 marine energy 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 recharging underwater vehicles and autonomous ocean observation sites.

References

Agence Française de Développement, European Commission, and Deutsche Gesellschaft für Internationale Zusammenarbeit. 2017. *Opportunities and challenges for aquaculture in developing countries*. Joint Report. https://europa.eu/capacity4dev/file/65255/download?token=ZDky6Mfb.

Aquatera. 2014. "Renewable power generation on aquaculture sites." *Scottish Aquaculture Research Forum*. http://www.sarf.org.uk/cms-assets/documents/152961-230407.sarf093.pdf.

Cision. 2013. "Global Soil Treatment Market, By Types (Organic Amendments, Pest & Weed Control, pH Adjusters) & Geography—Trends & Forecasts to 2017." *Research and Markets.*https://www.prnewswire.com/news-releases/global-soil-treatment-market-by-types-organic-amendments-pest--weed-control-ph-adjusters--geography---trends--forecasts-to-2017-229157371.html.

DOE (U.S. Department of Energy). 2013. Marine & Hydrokinetic Technologies. Department of Energy, Energy Efficiency and Renewable Energy.

DOE. 2016. Water Power Program. Water Power for a Clean Energy Future. https://www.energy.gov/sites/prod/files/2016/03/f30/Water-Power-Accomplishments-03302016.PDF

Engineering for Change. 2017. "A solar thermal aerator prototype could improve aquaculture in developing countries." https://www.engineeringforchange.org/news/solar-thermal-aerator-prototype-improve-aquaculture-developing-countries/.

EzGro Garden. 2016. Miami Science Barge. https://ezgro.garden/commercial-systems/miami-science-barge/.

Earth Institute. 2011. *The Science Barge Demonstrates Sustainable Urban Farming*. State of the Planet, Earth Institute, Columbia University. http://blogs.ei.columbia.edu/2011/05/14/the-science-barge-demonstrates-sustainable-urban-farming/.

Energy Smarts. 2013. "Massachusetts Oysters Go Solar." http://blog.mass.gov/energy/green-business/massachusetts-oysters-go-solar/.

Fiander, Leon, Mike Graham, Harry Murray, and Renee Boileau. 2014. "Land Based Multi-trophic Aquaculture Research at the Wave Energy Research Center." *Oceans*. St. John's, Newfoundland. DOI: 10.1109/OCEANS.2014.7003181. http://ieeexplore.ieee.org/document/7003181/.

Food and Agriculture Organization of the United Nations (FAO). 2016. *The State of World Fisheries and Aquaculture 2016: Contributing to Food Security and Nutrition for All*. Rome. http://www.fao.org/3/a-i5555e.pdf.

GlobalNewswire. 2016. "Global Soil Treatment Market Poised to Surge from USD 24.00 Billion in 2015 to USD 39.50 Billion by 2021." *MarketResearchStore.com*. https://globenewswire.com/news-release/2016/04/18/829687/0/en/Global-Soil-Treatment-Market-Poised-to-Surge-from-USD-24-00-Billion-in-2015-to-USD-39-50-Billion-by-2021-MarketResearchStore-Com.html.

Huner, J. V. 1985. Crustacean and Mollusk Aquaculture in the United States. Springer, New York.

Johnson, K, G. Dalton, and I. Masters. 2017. Building Industries at Sea: 'Blue Growth' and the New Maritime Economy. River Publishers. Gistrup, Denmark.

Knapp, G. and M. C. Rubino. 2016. "The Political Economics of Marine Aquaculture in the United States." *Reviews in Fisheries Science and Aquaculture* 24(3): 213-229.

Luening, Erich. 2017. "Trend toward more health-conscious eating bodes well for seafood market." *Aquaculture North America*. https://www.aquaculturenorthamerica.com/research/trend-toward-more-health-conscious-eating-bodes-well-for-sea-1321.

Markets and Markets. 2018. *Soil Treatment Market worth 36.29 Billion USD by 2020.* https://www.marketsandmarkets.com/PressReleases/soil-treatment.asp.

Mozaffarian, Dariush, and Eric B. Rimm. 2006. "Fish intake, contaminants, and human health: evaluating risks and benefits." *Journal of American Medical Association,* 296 (15): 1885-1899. https://www.ncbi.nlm.nih.gov/pubmed/17047219.

National Oceanic and Atmospheric Association (NOAA). 2011. The United States is an Ocean Nation. http://www.gc.noaa.gov/documents/2011/012711_gcil_maritime_eez_map.pdf.

NOAA. 2015. *Marine Aquaculture Strategic Plan: FY 2016-2020*. U.S. Department of Commerce. https://www.afdf.org/wp-content/uploads/8h-NOAA-Marine-Aquaculture-Strategic-Plan-FY-2016-2020.pdf.

NOAA. 2017. *What is an Ocean Glider*? https://oceanservice.noaa.gov/facts/ocean-gliders.html.

NRG. 2018. *Lashto Fish Farm in Haiti: NRG delivers solar-powered fish hatchery in the Caribbean*. http://www.nrg.com/renewables/projects/community/lashto-fish-farm-in-haiti/.

SeafoodSource. 2018. Technavio report: Global aquaculture market's growth accelerating through 2022. Accessed on 1/17/2019. https://www.seafoodsource.com/features/technavio-report-global-aquaculture-markets-growth-accelerating-through-2022.

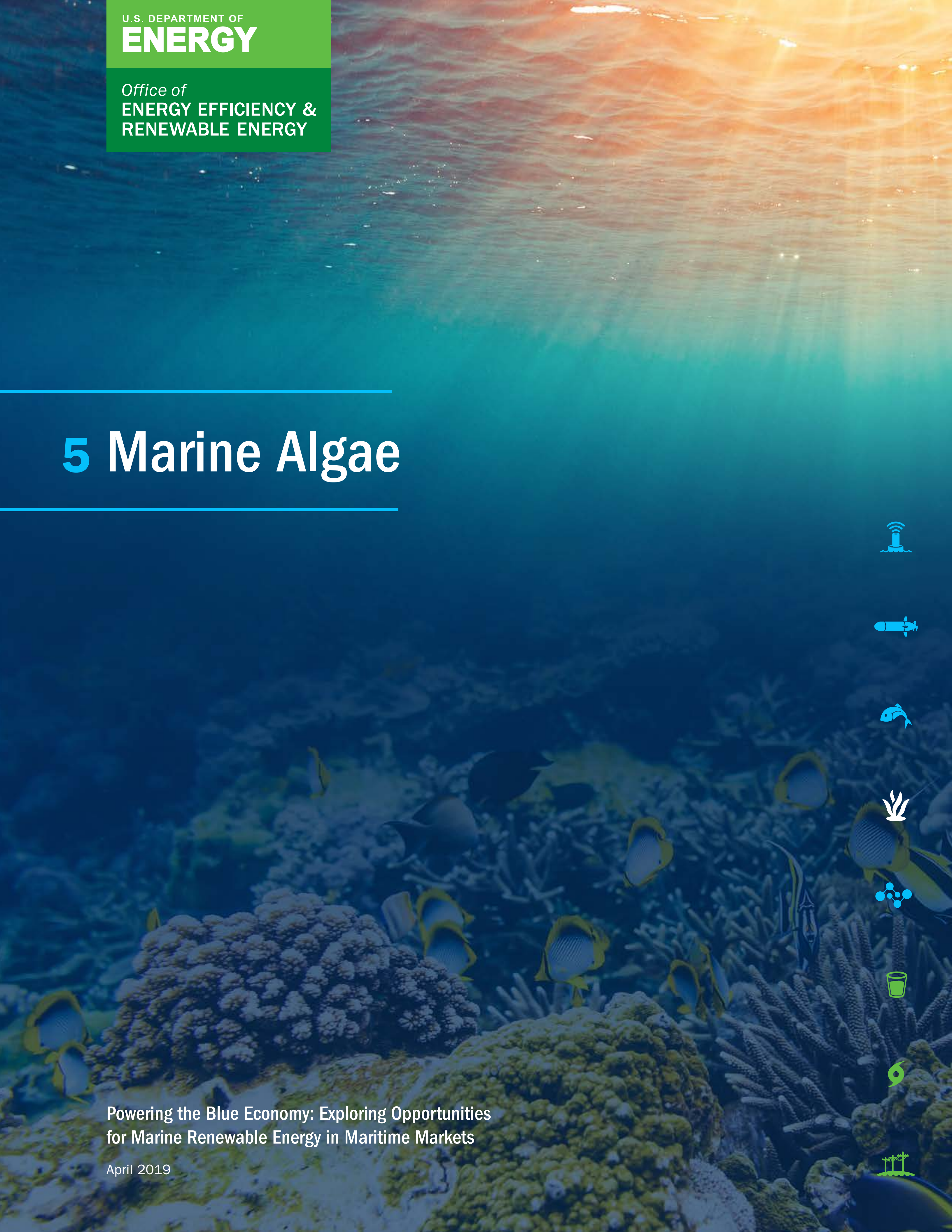
Toner, Damien, and Mo Mathies. 2002. "The Potential for Renewable Energy Usage in Aquaculture." *Aquaculture Initiative*. http://www.aquacultureinitiative.eu/Renewable%20Energy%20Report.pdf.

USDA. 2014. 2012 Census of Agriculture. Accessed on 1/17/2019. https://www.nass.usda.gov/Publications/AgCensus/2012/Online_Resources/Aquaculture/Aqua.pdf.

U.S. Department of Agriculture and Federal Drug Administration. 2010. *Dietary Guidelines for Americans 2010.* U.S. Department of Agriculture and U.S. Department of Health and Human Services. https://health.gov/dietaryguidelines/dga2010/DietaryGuidelines2010.pdf.

undercurrentnews. 2018. Expert Q&A: How to design offshore aquaculture pens. Accessed on 1/17/19.

Ye, Yimin, and Nicolas L. Gutierrez. 2017. "Ending fishery overexploitation by expanding from local successes to globalized solutions." *Nature Ecology and Evolution*. doi:10.1038/s41559-017-0179. https://www.nature.com/articles/s41559-017-0179?WT.feed_name=subjects_economics.



U.S. DEPARTMENT OF
ENERGY
Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

5 Marine Algae

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

April 2019

5. Marine Algae

Key Findings

- Macroalgae (seaweed) and some microalgae can be grown at commercial scale at sea to provide biomass for biofuel production; specialized chemicals for food processing, cosmetics, and pharmaceuticals; soil additives and fertilizers; animal fodder; and other end products.

- Algae grown at sea has a competitive advantage over terrestrial-based crops grown for biofuels because it does not require land, irrigation systems, added nutrients, or fertilizers. Macroalgae grown in farms for human and animal consumption are common around the world, but farms dedicated to crop production for biofuels are in the experimental stage. With the world's largest Exclusive Economic Zone, much of which has potential for growing algae, the United States has the potential to become a leader in sea-grown biofuels.

- The power requirements for large-scale macroalgae growing and harvesting operations at sea are not well understood but will likely resemble those for aquaculture operations including power for safety, navigation lights, and maintenance equipment; pumps for nutrients and ballast control; refrigeration and ice production; drying operations; marine sensors; recharging of autonomous underwater vehicles, and recharging transport vessels.

- Marine energy systems have the potential to be integrated into and codeveloped with algal growing and harvesting systems. By replacing fossil fuels with marine energy renewable energy, the biofuels industry could reduce harm to air and water quality; reduce supply chain and transport risks; and potentially reduce operational costs. The low surface expression of most WECs will increase survival at sea, provide low visual impacts, and be more easily integrated with algal facilities.

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 co-products. Micro and macroalgae have high levels of structural polysaccharides and low concentrations of lignins that can be made into feedstocks for the 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 higher than terrestrial biomass, but improvements in yields, scale, and operations could see algae become cost competitive with terrestrial crops (National Renewable Energy Laboratory 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 (Food and Agriculture Organization [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 via energy generated from marine energy devices by designing marine energy systems into growing and harvesting systems to provide off-grid power needs. Marine energy provides a unique advantage over other forms of energy generation by being less geographically limited at high latitudes where some macroalgae species thrive and could also provide shelter to more exposed sites by attenuating wave action while simultaneously generating power.

Application

Description of Application

Microalgae and Cyanobacteria

Marine algae includes microalgae and cyanobacteria. Microalgae comprise 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. Large-scale 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), where designs may consist of open raceway ponds as well as photobioreactors, and hybrids of these two system designs. 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 (U.S. Department of Energy [DOE] 2016).

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 research and development and have not yet established the need for a power alternative to the electrical grid or waste energy from other industrial processes (Figure 5.1).

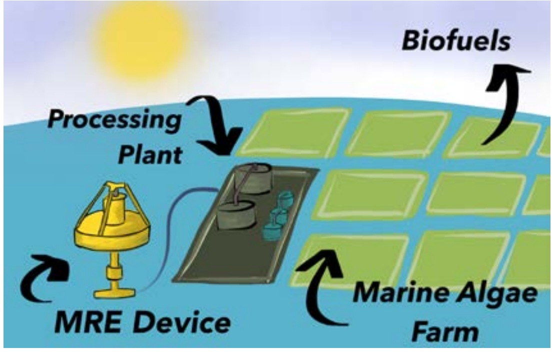


Figure 5.1. Marine renewable energy application overview for a macroalgae farm.
Image courtesy of Molly Grear, Pacific Northwest National Laboratory

Macroalgae

Macroalgae, more commonly known as seaweeds, are typically cultivated offshore or near coastal facilities (DOE 2016). 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 the seaweed 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 2016). Highly cultivated macroalgae (seaweed) crops for human consumption include *nori* (*Porphyra spp.*), *wakame* (*Undaria pinnatifida*), and *kombu* (*Laminaria japonica*) (FAO 2009).

DOE's Advanced Research Projects Agency-Energy (ARPA-E) Marine Research Inspiring Novel Energy Resources (MARINER) program provided funding starting 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 autonomous underwater vehicles for determining water quality, light, and nutrient availability, and measuring growth; and selective breeding and genomics technologies), ARPA-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 (Okinawa Institute of Science and Technology 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 research and development 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 5.2).

Biofuels

Biofuels from microalgae are in the development and demonstration stage; the lipid makeup and structure of macroalgae suggests that the same pathways will allow seaweeds to be used for biofuels in a similar manner. 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; ethanol; 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 photovoltaics, and biomass-generated electricity (Ghadiryanfar et al. 2017). Algal biomass is compatible with an integrated biorefinery that produces a variety of fuels and valuable coproducts (DOE 2016). Ethanol, biodiesel, biogas, renewable gasoline, diesel, and jet fuels are all possible products from algal biomass (DOE 2016). 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 5.2. 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 2016). 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 2016). Microalgae have also been used to produce antioxidants for the health food market, the most prominent being β-carotene from Dunaliella salina (DOE 2016). Algae have also been used to make bioflocculants and biodegradable polymers (DOE 2016).

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 2016).

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 well understood. However, the requirements for power will likely resemble those for aquaculture operations, including energy to power safety, navigation, and maintenance equipment; pumps for nutrients and structure controls; refrigeration and ice production; drying operations; marine sensors; recharging of autonomous underwater vehicles; hotel loads for living quarters (if the structures are manned), and transport vessels (Roesijadi et al. 2008). Some macroalgae farms are said to be using light-emitting diode lighting to boost production, which also requires a power source. 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.

Markets

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, the Philippines, Republic of Korea, Japan, and the Democratic People's Republic of Korea as the dominant producers (FAO 2016; Ghadiryanfar et al. 2017). 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 (Figure 5.3; FAO 2016). In 2004, the combined microalgae and macroalgae global market was estimated at $10–$12 billion (Oilgae 2017). Six macroalgae species and one microalgae species contributed most of the global aquatic plant production in 2014 (Table 5.1; FAO 2016).

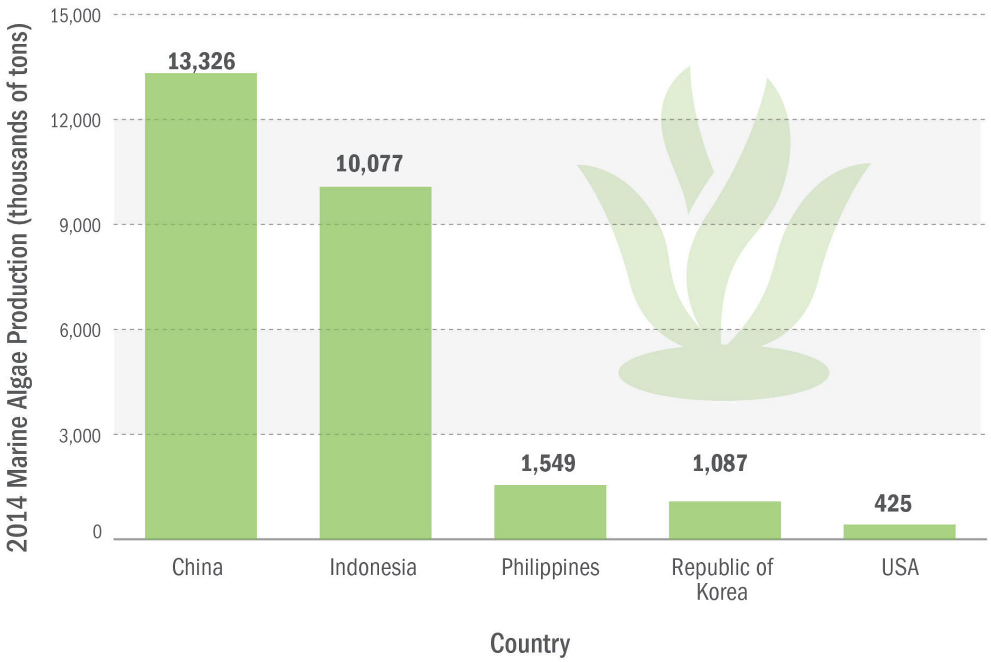


Figure 5.3. Global macroalgae production by nation

Table 5.1. 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 terrestrial and marine biofuels is approximately 1,324 million tons of oil equivalent[11] annually (International Energy Agency 2017); marine algal biofuels make up only a small portion of this as most grow operations are at the development stage. 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 2016). 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%, reaching $441.4 million by 2020 (DOE 2016). The global carotenoid market value (in general) was $1.5 billion in 2014 (DOE 2016). DOE (2016) estimates that the market size for specialty products, such as bioactive compounds, polysaccharides, and stable isotopes for research, is likely to be very small because of their specialized applications (DOE 2016).

Human Food and Animal Fodder

The global value of seaweed per annum for human food is estimated to be $5 billion (DOE 2016), and the global seaweed market as a whole is projected to reach a value of $17.59 billion by 2021 (Algae World 2016). The global value for animal feed is estimated to be $5 million (DOE 2016).

Additional Drivers for Algal Markets

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 2016); however, these blooms are unpredictable, and care would need to be taken not to upset the ecological balance in the harvest waters.

Future Growth

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-use products as shown in Table 5.2 (Nayar and Bott 2014). In each market, significant growth is expected (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 2016). 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

---

[11] 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.

(DOE 2016). 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 5.2. Global Production of Macroalgal Products 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	
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).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 marine energy 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.

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 marine energy could have a first-mover advantage. Offshore wind and solar energy could potentially be competitors of marine energy 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 2016). These renewable sources could supplant or supplement electrical grid or other industrial sources of energy for drying microalgae (DOE 2016); however, depending on the location of the site, tidal energy could also be a potential alternative to provide additional energy for the drying process.

Geographic Relevance

Areas of the South Atlantic and Gulf of Mexico, as well as the West Coast, Alaska, 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 2016).

Additionally, areas of the southwestern United States have been identified as the most suitable for closed systems for growing microalgae, such as photobioreactors (Figure 5.4; Quinn et al. 2011; DOE 2016).

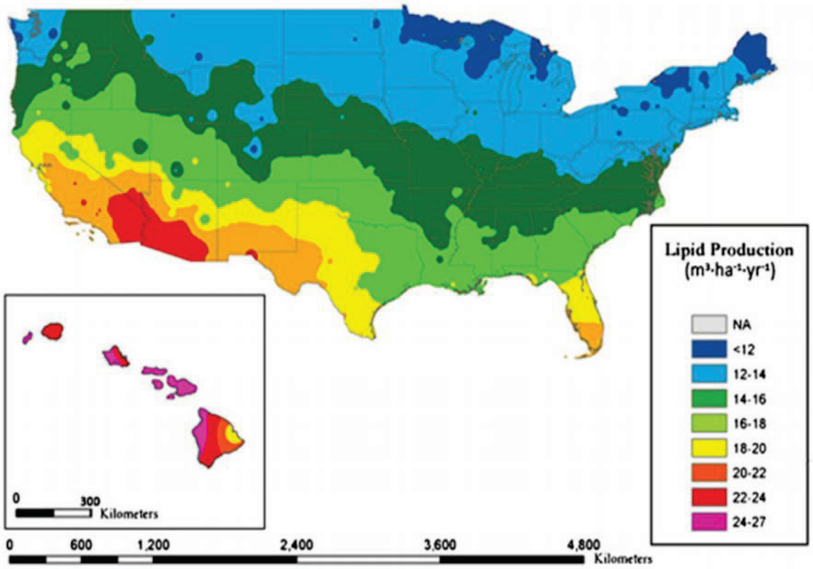


Figure 5.4. Modeled microalgae lipid productivity potential in the United States. *Image courtesy of Quinn et al. (2011)*

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

Marine Energy Potential Value Proposition

Marine energy systems could be integrated into growing and harvesting systems to provide off-grid power needs. By replacing fossil fuels with renewable marine energy, the biofuels industry could reduce harm to air and water quality, reduce supply chain and transport risks, and potentially reduce operational costs. Marine energy 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.

Marine energy has a potential advantage over solar and offshore wind when biofuel installations require low-profile infrastructure to avoid shading the algae from sunlight or improve its storm survivability characteristics, or reduce visual impacts when close to shore. With proposals for free-floating biofuel operations, the marine energy 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 abundant 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 sufficient 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. There are also potential low-power salinity/thermal gradient-based energy sources that might be useful for powering energy needs of algal growing operations at sea.

With the world’s largest Exclusive Economic Zone (National Oceanic and Atmospheric Administration 2015), much of which is viable for growing microalgae and macroalgae, the United States has the potential to become a leader in growth at sea for biofuels. Many of these waters overlap with significant marine energy resources that could develop systems in conjunction with the growing and harvesting operations.

Path Forward

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 co-products may spur expansion of macroalgae growth at sea, allowing for early marine energy markets.

Although algal biofuels offer 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 2016). 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 2016).

Ideally, the macroalgae for biofuels and the marine energy 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. The marine energy industry and researchers must closely track the design and development of offshore macroalgae grow and harvest operations underway with ARPA-E MARINER funding to determine power needs and understand the requirements for integrating marine energy 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 marine energy devices can be adapted for less-energetic areas (e.g., slower currents, reduced sea states) may become important, allowing for additional provision of marine energy to a broader base of macroalgae growing locations. As the first macroalgae operations are deployed, it would be useful for marine energy developers to design and deploy small-scale devices to test the feasibility and interface for providing power. The development of marine energy as a power source for offshore aquaculture operations could provide important direction for integration with the biofuels grow operations.

Potential Partners

Potential mission-driven partners for the marine energy industry include government agencies like DOE ARPA- E MARINER, National Oceanic and Atmospheric Administration Fisheries, U.S. Coast Guard, and the U.S. Department of Defense—specifically the Defense Advanced Research Projects Agency, the U.S. Air Force, U.S. Navy, and U.S. Army.

Private companies and consortia include the 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, Wärtsilä, 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 2016). These organizations may also serve as potential partners for an algae farm or marine energy developer pursuing the market.

By developing and adapting marine energy devices to provide power for macroalgae growth for biofuels operations, the marine energy industry could move further along the route to commercial-scale development while gaining much-needed revenue. Although marine energy 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 marine energy devices to those used for macroalgae growth operations will also be useful for encouraging the growth of aquaculture farms and devices for powering navigation markers as well as recharging underwater vehicles and autonomous ocean observation sites.

References

Advanced Research Projects Agency-Energy (ARPA-E). 2018. ARPA-E MARINER Program. https://arpa-e.energy.gov/?q=arpa-e-programs/mariner.

Algae World. 2016. “Commercial Seaweed Market Forecast.” May 8, 2016. http://news.algaeworld.org/2016/05/commercial-seaweed-market-forecast/.

Biofuels International. 2016. “Market study: Global biofuels market to grow to $246bn by 2024.” https://biofuels-news.com/display_news/10395/market_study_global_biofuels_market_to_grow_to_246bn_by_2024/.

Buschmann, Alejandro H., Carolina Camus, Javier Infante, Amir Neori, Álvaro Israel, María C. Hernández-González, Sandra V. Pereda, Juan Luis Gomez-Pinchetti, Alexander Golberg, Niva Tadmor-Shalev, and Alan T. Critchley. 2017. “Seaweed production: overview of the global state of exploitation, farming and emerging research activity.” *European Journal of Phycology*, 52:4, 391–406. http://dx.doi.org/10.1080/09670262.2017.1365175.

Chen, Huihui, Dong Zhou, Gang Luo, Shicheng Zhang, and Jianmin Chen. 2015. “Macroalgae for biofuels production: Progress and perspectives.” *Renewable and Sustainable Energy Reviews*. 47: 427–437. https://doi.org/10.1016/j.rser.2015.03.086.

Dębowski, Marcin, Marcin Zieliński, Anna Grala, and Magda Dudek. 2013. “Algae biomass as an alternative substrate in biogas production technologies—Review.” *Renewable and Sustainable Energy Reviews*. 27: 596–604. https://www.sciencedirect.com/science/article/pii/S1364032113004747.

Food and Agriculture Organization (FAO) of the United Nations. 2009. *Use of algae and aquatic macrophytes as feed in small-scale aquaculture: A review*. Rome. 135 pp. http://www.fao.org/docrep/012/i1141e/i1141e.pdf.

FAO. 2016. *The State of World Fisheries and Aquaculture 2016: Contributing to Food Security and Nutrition for All*. Rome. 200 pp. http://www.fao.org/3/a-i5555e.pdf.

Ghadiryanfar Hoffman, Justin, Ronald C. Pate, Thomas Drennen, and Jason C. Quinn. 2017. “Techno-economic assessment of open microalgae production systems.” *Algal Research*, 23: 51–57. https://www.sciencedirect.com/science/article/pii/S2211926416303046.

International Energy Agency (IEA). 2017. *Key world energy statistics.* https://www.iea.org/publications/freepublications/publication/key-world-energy-statistics.html.

Kinley, Robert D., Rocky de Nys Rocky, Matthew J. Vucko, Lorenna Machado, and Nigel W. Tomkins. 2016. “The red macroalgae *Asparagopsis taxiformis* is a potent natural antimethanogenic that reduces methane production during *in vitro* fermentation with rumen fluid.” *Animal Production Science* 56, 282-289. https://www.researchgate.net/publication/293800275_The_red_macroalgae_Asparagopsis_taxiformis_is_a_potent_natural_antimethanogenic_that_reduces_methane_production_during_in_vitro_fermentation_with_rumen_fluid.

National Oceanic and Atmospheric Association. 2015. *Marine Aquaculture Strategic Plan: FY 2016-2020*. U.S. Department of Commerce. 34 pp. https://www.afdf.org/wp-content/uploads/8h-NOAA-Marine-Aquaculture-Strategic-Plan-FY-2016-2020.pdf.

National Renewable Energy Laboratory. 2017. *2015 Bioenergy Market Report.* https://www.nrel.gov/docs/fy17osti/66995.pdf.

Nayar, Sasi, and Kriston Bott. 2014. "Current Status of Global Cultivated Seaweed Production and Markets." *World Aquaculture* (June): 32-37. https://www.researchgate.net/profile/Sasi_Nayar/publication/265518689_Current_status_of_global_cultivated_seaweed_production_and_markets/links/5656595608ae1ef92979fef9/Current-status-of-global-cultivated-seaweed-production-and-markets.pdf.

Oilgae. 2017. *Algae—Important Products and Applications*. http://www.oilgae.com/non_fuel_products/non_fuel_products_from_algae.html.

Okinawa Institute of Science and Technology. 2016. *Okinawa Mozuku—The Treasure Under the Sea*. August 9, 2016. https://www.oist.jp/news-center/press-releases/okinawa-mozuku-%E2%80%93-treasure-under-sea.

Quinn, J. C., K. Catton, N. Wagner, and T. H. Bradley. 2011. Current Large-Scale US Biofuel Potential from Microalgae Cultivated in Photobioreactors. Bioenerg. Res. DOI 10.1007/s12155-011-9165-z.

Roesijadi, Guri, Andrea Copping, Michael Huesemann, John Forster, and John Benemann. 2008. *Techno-Economic Feasibility Analysis of Offshore Seaweed Farming for Bioenergy and Biobased Products*. PNWD-3931. Richland, WA (US): Pacific Northwest National Laboratory. http://marineagronomy.org/sites/default/files/Roesijadi%20et%20al.%202008%20Techno-economic%20feasibility%20of%20offshore%20seaweed%20farming.pdf.

Seakura. 2018. *Seakura Super Seaweed*. http://www.seakura.net/.

Seaweed Energy Solutions. 2018. *Creating value from seaweed*. http://seaweedenergysolutions.com/en.

Technavio. 2017. Global Algae Oil Market 2017-2021. https://www.technavio.com/report/global-algae-oil-market. SKU: IRTNTR15081. Pp 60.

The Fish Site. 2013. "The Use of Algae in Fish Feeds as Alternatives to Fishmeal." https://thefishsite.com/articles/the-use-of-algae-in-fish-feeds-as-alternatives-to-fishmeal.

Titlyanov, Antoninovich Eduard, and Viktorovna Tamara Titlyanova. 2010. "Seaweed Cultivation: Methods and Problems." *Russian Journal of Marine Biology* 36, no. 4: 227–242. https://www.researchgate.net/publication/225469651_Seaweed_cultivation_Methods_and_problems.

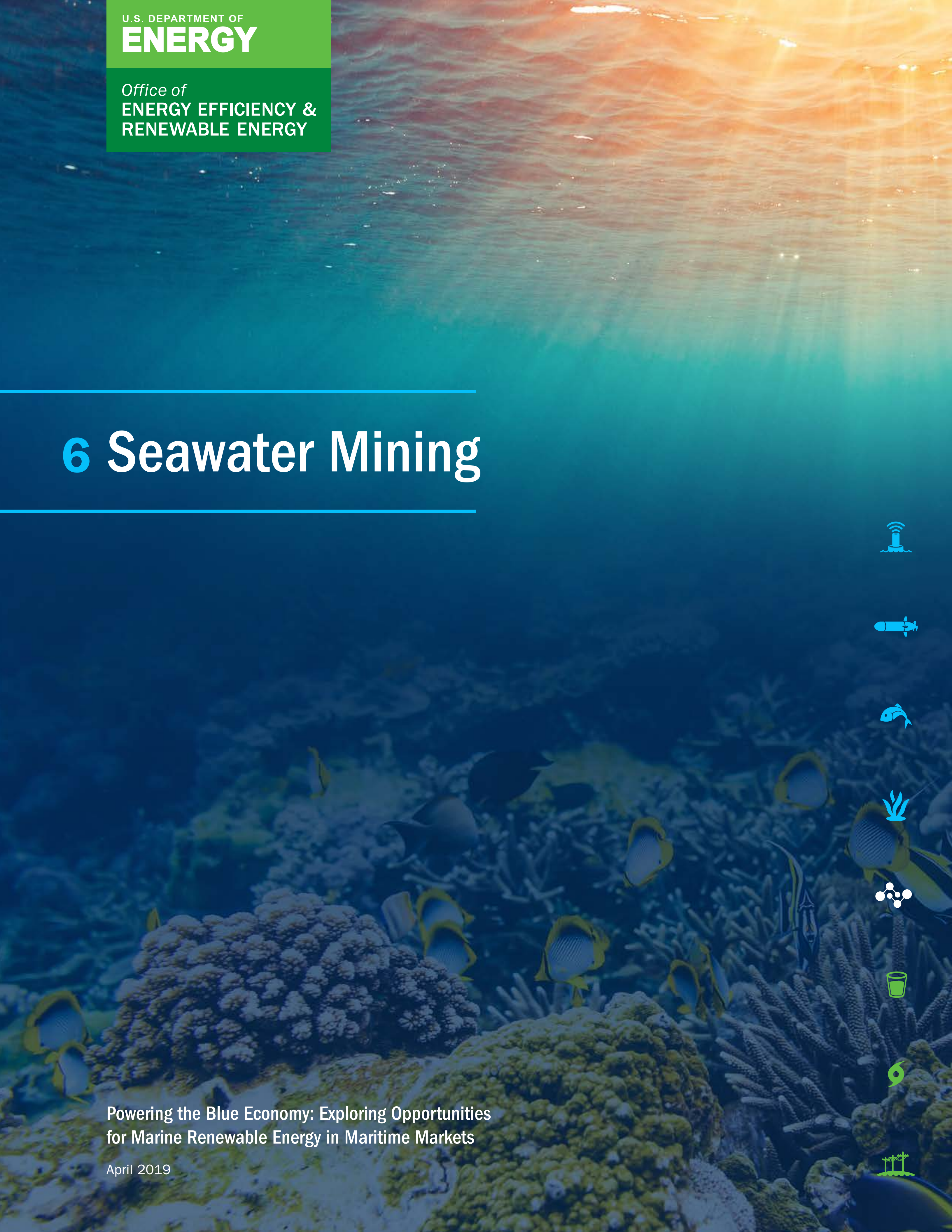
Transparency Market Research. 2018. *Marine Algae Extracts/Products Market—Global Industry Analysis, Size, Share, Growth, Trends and Forecast 2017–2025*. https://www.transparencymarketresearch.com/marine-algae-extracts-products-market.html.

Troell, Max, Peter Tyedmers, Nils Kautsky, and Patrik Rönnbäck. 2004. "Aquaculture and Energy Use." *Encyclopedia of Energy* 1: 97–108. https://www.researchgate.net/publication/279436218_Aquaculture_and_Energy_Use.

U.S. Department of Energy. 2016. *National Algal Biofuels Technology Review*. Office of Energy Efficiency and Renewable Energy, Bioenergy Technologies Office. https://www.energy.gov/sites/prod/files/2016/06/f33/national_algal_biofuels_technology_review.pdf.

World Energy Council. 2017. https://www.worldenergy.org/data/resources/country/united-states-of-america/gas/.

Zeewaar. 2018. Vitamin Sea. https://www.zeewaar.nl/uk/.



U.S. DEPARTMENT OF
ENERGY
Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

6 Seawater Mining

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

April 2019

6. Mining Seawater Minerals and Gasses

Key Findings

- Seawater contains large amounts of minerals, dissolved gases, and specific organic molecules that are more evenly distributed, albeit at lower concentrations, than in terrestrial locations. Lithium and uranium extraction are two of the more valuable materials under investigation.
- Passive adsorption, and to a lesser extent electrochemical processes, are two different methods to extract elements and minerals directly from seawater. Several gases (e.g., carbon dioxide, hydrogen, and oxygen) can be electrolytically produced directly from seawater. Most systems are in early stages of development, but a strong market demand exists for many of the end products.
- Power required for each method varies. Potential uses for power will be to assist in deploying and retrieving long adsorbent films, extracting elements via electrochemical mechanisms or electrolysis, pumping seawater, powering safety and monitoring equipment, as well as potentially powering the machinery or technology needed to remove elements from adsorbent material.
- Marine energy could open up unexploited opportunities in seawater mining, which could further expand mineral and gas markets. It is believed that linking a marine energy converter to a seawater mineral extraction technology could substantially enhance or enable the extraction process because of colocation benefits and greater power generation potential than other renewable technologies.
- By linking a seawater extraction technology to a local power source, a significant reduction in the overall costs to extract materials from seawater could be achieved.

Opportunity Summary

Seawater contains large amounts of minerals, dissolved gases, and specific organic molecules. 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. Minerals can be recovered from seawater using adsorption methods that do not require filtering vast amounts of seawater, while recovering other elements and compounds can require more energy-intensive processes.

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 REEs, 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. Critical materials are needed for many modern-day technologies, such as wind turbines, solar panels, and electric vehicles.

An energy source is needed to extract minerals or dissolved gases, preferably one that is locally generated, reasonably consistent, and that does not add to the complexity or maintenance needs of the extraction operation. Marine energy 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 6.1).

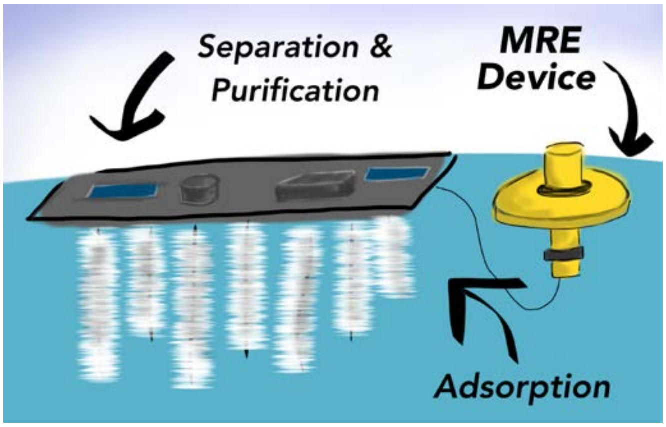


Figure 6.1. Marine energy application overview for mining seawater. *Image courtesy of Molly Grear, Pacific Northwest National Laboratory*

Application

Description of Application

The United States is import-reliant (imports are greater than 50% of annual consumption) for 31 of the 35 minerals designated as critical by the U.S. Department of the Interior (2018). The United States does not have any domestic production and relies completely on imports to supply its demand for 14 critical minerals (Diallo et al. 2015; U.S. Geological Survey 2018). Currently, China and Canada are the top two suppliers of critical minerals to the United States. In response to this concern, the U.S. government has published a list of critical minerals for the nation (Executive Order 13817). This reliance on foreign supply constitutes an industrial and national security concern (Congressional Research Services 2017). Development of a domestic source of critically needed materials from seawater would directly address the resource need and mitigate industrial and national security supply concerns.

The total mass of many of the critically needed elements is far 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 concentration of some elements (e.g., zinc, cadmium, copper, nickel, cobalt, and some REEs) below 500 meters (m), which is caused by an uptake of biologically required elements during primary production processes in surface waters 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.

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 from a freshwater or seawater source using renewable marine energy (European Marine Energy Center [EMEC] 2017a) and can be used as an energy storage medium. Producing gases (e.g., hydrogen, carbon dioxide, and oxygen) directly from a seawater source using marine renewable energy to power an electrochemical production process may be possible in the future as well. The need to move away from high carbon fuels for commercial shipping is imminent with the announcement of the International Maritime Organization's requirements that all international shipping reduce sulphur emissions from fuel oil (International Maritime Organization 2018). Recent work for the U.S. Maritime Administration is examining the use of hydrogen fuel cells for ferries and other maritime uses (Pratt and Klebanoff 2018).

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 research and development stage, but look promising for colocation 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 that are deployed and retrieved by a work vessel (Figure 6.2).

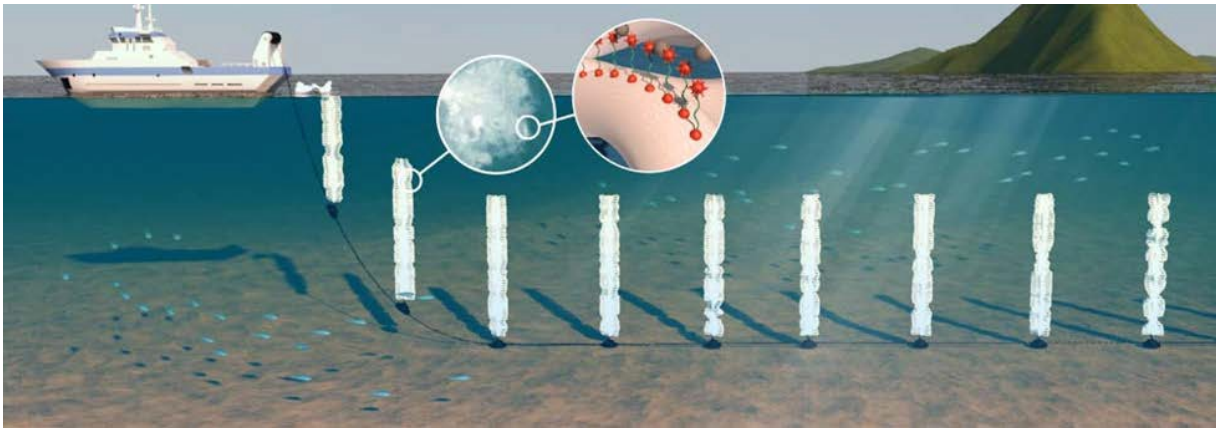


Figure 6.2. Conceptual deployment of amidoxime-based polymer adsorbent in coastal seawater for the passive extraction of uranium and other elements from seawater. *Source: Byers et al. (2018b)*

The cost of performing the extraction process can be 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. These applications focus primarily on 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, including cobalt (Haji and Slocum 2018).

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 marine energy power, including electricity (Table 6.1).

Intermittency of power is acceptable for the extraction of minerals and gases from seawater for periods of time of a few days. For both electrochemical and passive recovery processes, the collection simply ceases during a power loss, and the collection technology is not impaired, allowing operations to slow down or cease. Storage backup can help to maintain adequate power for essential parts of at-sea systems like navigation lights and safety gear.

Table 6.1. 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[12] adsorbent materials used to extract uranium from seawater through an electrochemical process (Figure 6.3). Compared to simple passive adsorption processes, applying an electrical field to the adsorption material 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.

---

[12] The amidoxime functional group, $-C(NH_2)=N-OH$, has a high affinity for sequestering uranium from a solution.

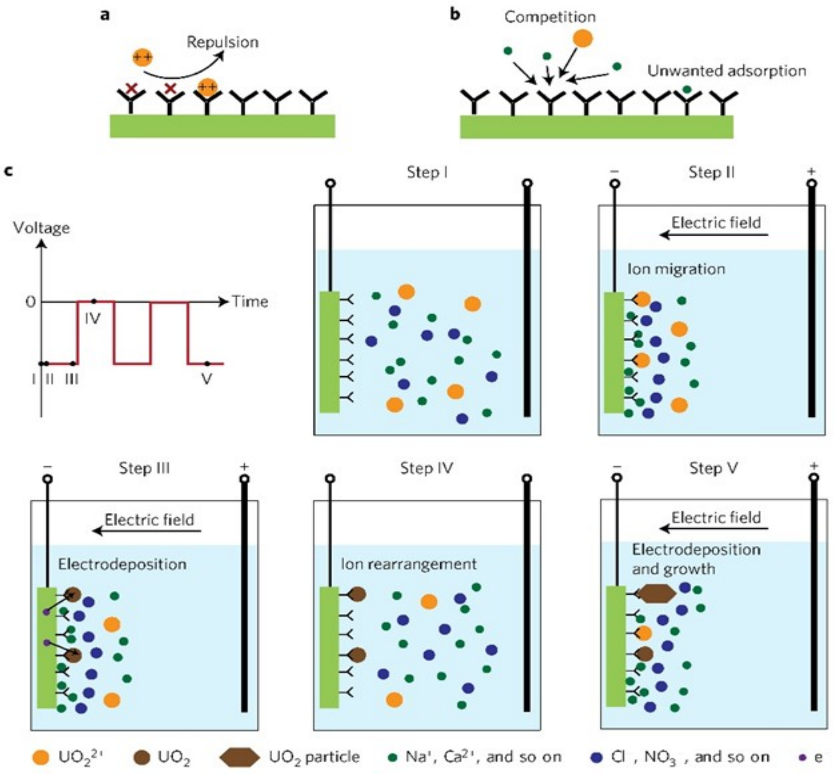


Figure 6.3. Schematics of physicochemical and half-wave rectified alternating-current electrochemical extraction.

Source: Liu et al. (2017)

A Mechanically Driven Seawater Extraction System

A potentially significant reduction in the cost to extract elements from seawater can be achieved by using power generated at sea from a marine energy 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 6.4 is 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-megawatt) nuclear plant.

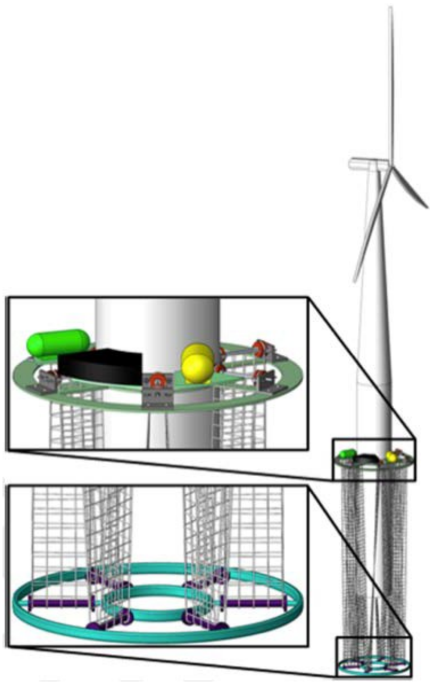


Figure 6.4. A conceptual model of a continuous seawater adsorbent extraction and elution system for the extraction of uranium from seawater integrated into an offshore wind platform providing the power to drive the system. *Image from Picard et al. (2014)*

The costs 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 6.4 and 6.5) predicted that by linking the seawater extraction system to a local power source, a significant reduction in the overall costs to extract uranium from seawater could be achieved (Byers et al. 2016, 2018a).

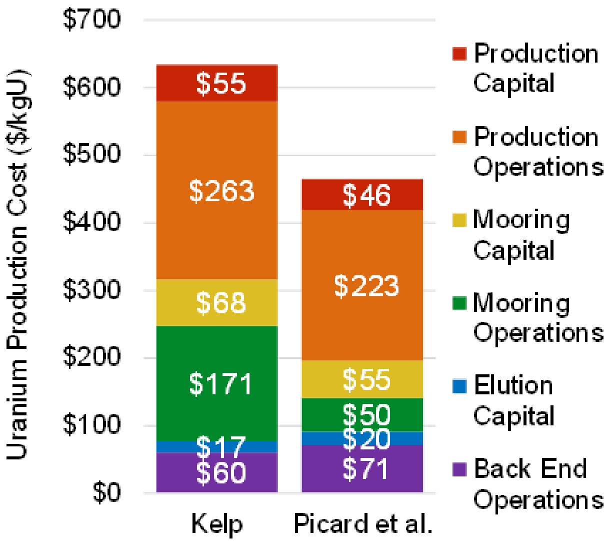


Figure 6.5. Comparison of the costs to extract uranium from seawater using a passive adsorption technology (Kelp) and a continuous adsorbent belt system attached to an offshore wind platform providing infrastructure support and power (Picard et al. 2014). *Image courtesy of Margaret Byers, University of Texas at Austin*

Haji et al. (2017a, 2017b) 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 6.6). A 1/10 scale model of this concept is depicted in Figure 6.6.

Figure 6.6. Adsorbent material encapsulating a protective sphere (left), and symbiotic machine for ocean uranium extraction (right). *Source: Haji et al. (2017a)*

Figure 6.7 compares the production cost to extract uranium from seawater by passive adsorption (kelp) and the SMORE system described by Haji et al. (2017a, 2017b). Incorporating a SMORE system using on-site power results in a 31% reduction in the production costs to extract uranium from seawater.

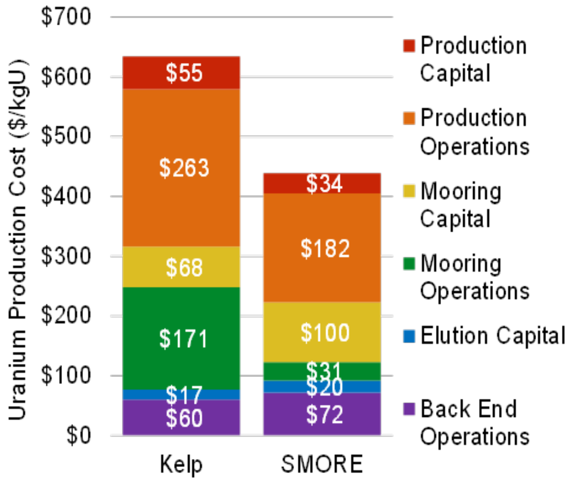


Figure 6.7. Comparison of the production costs to extract uranium from seawater by passive adsorption (Kelp) and the SMORE system. *From Haji et al. (2017a)*

Another concept for operating an on-site seawater extraction system is depicted in Figure 6.8 (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 through tanks containing solutions to strip off the uranium. Marine-energy-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 he 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.

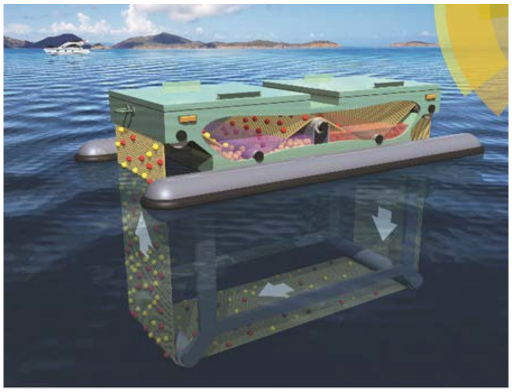


Figure 6.8. Conceptual process for the continuous collection of uranium from seawater using high-performance thin-film adsorbents coated onto a flexible woven belt structure. *Source: Chouyyok et al. (2016)*

Direct Electrochemical Extraction

A promising, but yet unproven, technology for the extraction of elements directly from seawater is electrochemical extraction (Figure 6.9). 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.

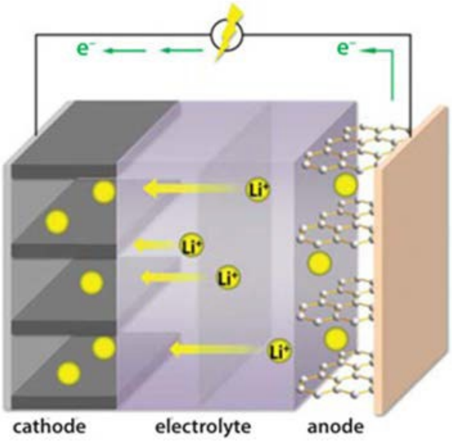


Figure 6.9. An electrochemical cell for the direct extraction of lithium ions from seawater. The cell is based on lithium-ion battery technology that has a high selectivity for lithium ions. *Source: Used with permission from Kam and Doeff (2012)*

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.

Production of Gases

Several gases (e.g., carbon dioxide, hydrogen, and oxygen) can be electrolytically produced directly from seawater. A current application of this technology is for production of carbon dioxide and hydrogen as precursors to synthetic fuel production. This same technology could likely be applied to the production of hydrogen as a means of energy storage as well.

Energy Storage Through Hydrogen Production

The European Marine Energy Center is producing hydrogen gas as a means to store unused renewable energy produced from tidal and wind energy (EMEC 2017b). The hydrogen gas is being produced in the outer Orkney islands, off the northeast coast of Scotland, by 500- to 1,000-kilowatt (kW) solid oxide fuel cells—or electrolyzer, for short—that runs in regenerative mode to achieve electrolysis of fresh water and produce both hydrogen and oxygen (Figure 6.10). The hydrogen is transported to the main Orkney island for use in the intraisland ferry system and land transport. The hydrogen is compressed and transported to a fuel cell where it is converted back to electricity for local use. The electrolyzers used by EMEC to generate hydrogen and oxygen 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 stand-alone units to multiunit systems that are greater than 10,000 kW. The typical energy needs of electrolyzer units are around 5 kilowatt-hours per m^3 of hydrogen. 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.

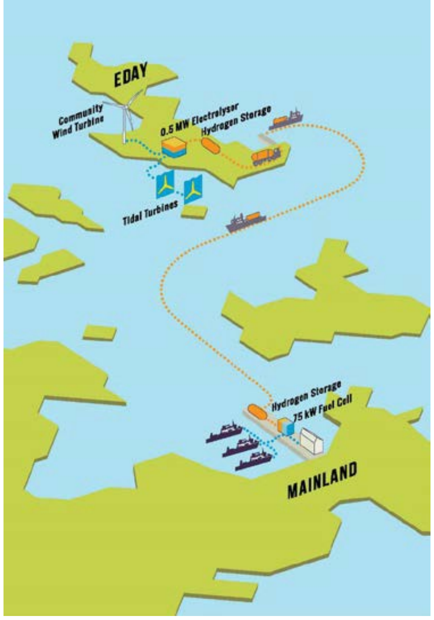


Figure 6.10. Schematic of production, transport, and storage of hydrogen gas from renewable generation for use in fuel cells at EMEC in Orkney, United Kingdom. *Source: Surf 'n' Turf, European Marine Energy Center*

Synthetic Fuel Production

The U.S. Naval Research Laboratory has developed technology for extraction of carbon dioxide gas and hydrogen gas 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 carbon dioxide and hydrogen 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 its exposure to market volatility and its dependency on at-sea resupply. Key operational parameters for the production of synthetic jet fuel are given in Figure 6.11.

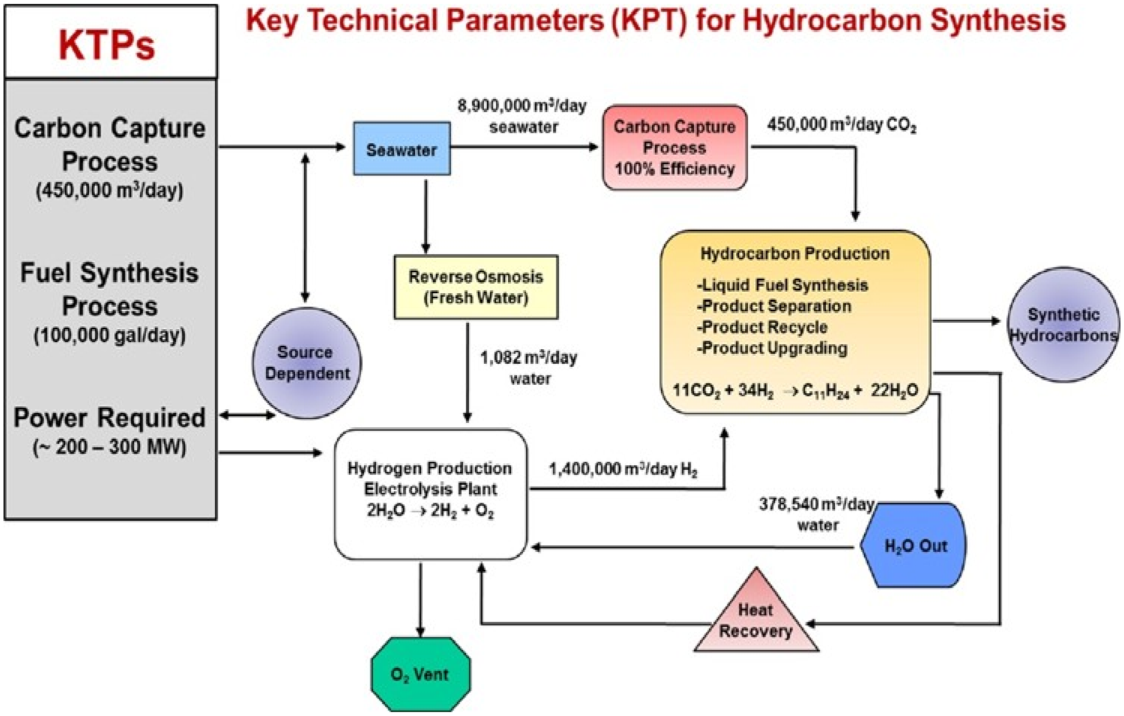


Figure 6.11. Operational parameters for the synthesis of 100,000 gallons of jet fuel per day.
Reproduced from Willauer et al. (2012), with permission of AIP Publishing

This technology has the potential to mitigate the effects of carbon-dioxide emissions from burning fossil fuels because the carbon source for the production of the fuel and other energy-rich molecules is seawater. Moreover, by not burning fossil-derived fuel, harmful emissions of sulfur and nitrogen compounds are also mitigated. The process becomes completely carbon-dioxide neutral if the power required to drive the process (200–300 megawatts) also comes from a renewable energy source.

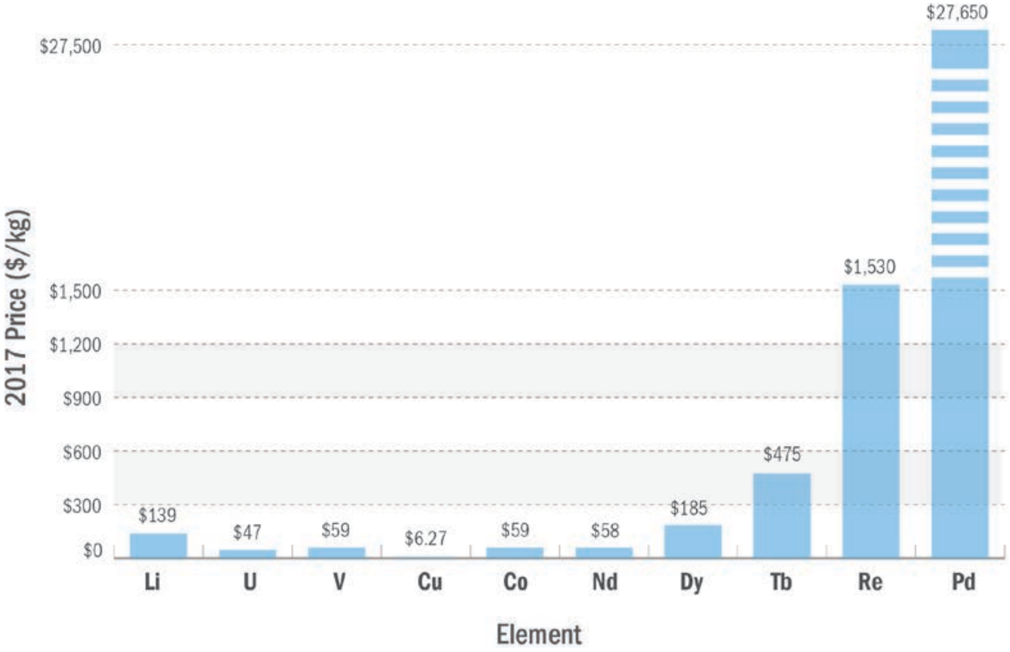
Markets

Description of Markets

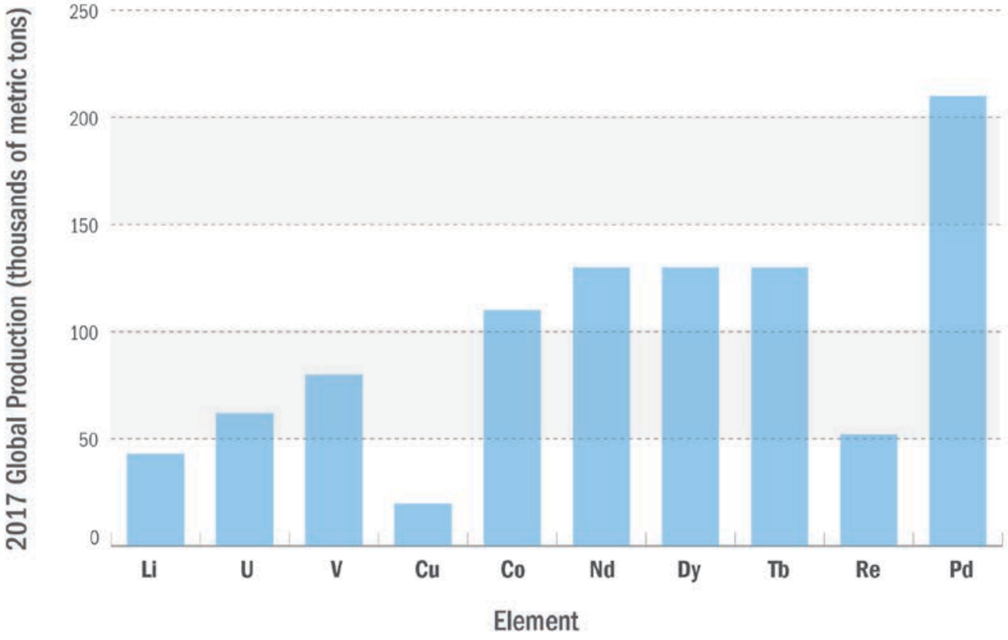
Critical minerals are often defined as those mineral resources that are essential to the nation's economy or for national defense purposes, and for which there is potential for supply disruptions. The target elements are those needed for development and deployment of clean energy technology (U.S. Department of Energy [DOE] 2011), advanced military applications (U.S. Department of Defense 2015), and essential civilian and industrial uses. Of particular importance are those elements in which the United States does not have significant domestic resources, or that possess a 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 (Massachusetts Institute of Technology 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 because of reduced build-out of nuclear power plants but is expected to recover over the next decade as a result of increased power needs in the United States and internationally. Global demand for uranium is currently 67,000 tons per year, or about $8.7 billion (World Nuclear News 2017).

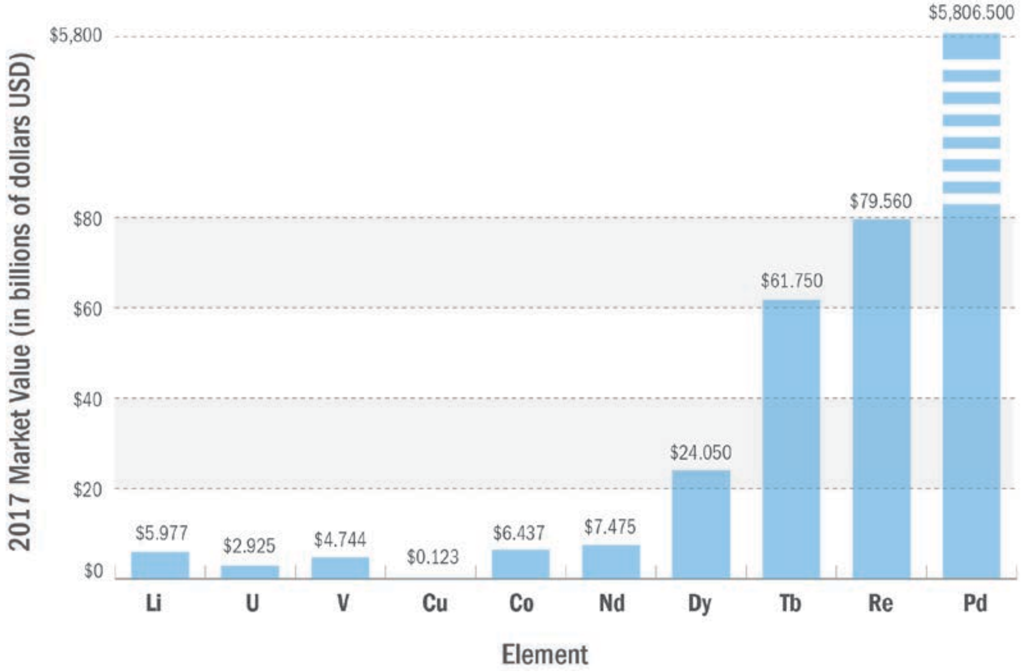
As an example, if initially 10% of the present worldwide market for minerals could be extracted from seawater, the markets would be substantial (see Figure 6.12a, b, and c), ranging from $123 million for copper to as much as $5.8 trillion for the precious metal palladium (Figure 6.12c).



(a)



(b)



(c)

Figure 6.12. Estimates of global markets for 10 key elements that could be extracted from seawater. Figure 6.12a shows the 2017 market price for 10 elements; Figure 6.12b provides the 2017 global production of the 10 elements; and Figure 6.12c shows the potential market value of the 10 key elements, based on 2017 market prices (Figure 6.12a), and assuming that 10% of the global production of an element (Figure 6.12b) could be extracted 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. Therefore, producing hydrogen from a seawater source 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 marine energy 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 marine-energy-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 MP Mine Operations LLC, 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; The Marine Executive 2017). Marine energy could supply the power to drive an electrolyzer, to produce hydrogen, oxygen, carbon dioxide, and other potential gases. With the current technology, a freshwater source for electrolysis will be needed, but future technologies may be able to use seawater directly. Domestic and international chemical companies and transport organizations are likely partners for gases, such as hydrogen and ammonia, to power fuel cells or synthesize fuels at land-based operations.

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. For defense purposes, the United States can only use uranium that has been enriched by U.S.-origin companies. In addition, there is a stockpile of uranium from decommissioned plants operated by 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, ferries, and short-haul truck routes (Table 6.2) (The Verge 2018).

Table 6.2. Pilot Projects Underway Using Hydrogen as a Transportation Fuel (The Verge 2018)

Project Name	Project Type	Project Partners
RiverCell – Elektra	Towboat	Technical University of 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
United Parcel Service	Short-haul trucks and vans	United Parcel Service, General Motors, City of Sacramento

Power Options

As an on-site power generation source, marine energy 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. Marine energy could 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 marine 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. Marine energy could produce power at the seawater extraction site without the need to refuel or risk spills from diesel. Marine energy 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 photovoltaic panels and corrosion of wind components, and to reduce visual impacts. Seawater mining operations are likely to be in open water. The marine energy industry is in a unique position to design devices that can accommodate these operations.

Geographic Relevance

There are many opportunities for mining REEs, uranium, lithium, other minerals, and producing gases throughout coastal areas and the open ocean, where sufficient tidal and current resources are present. U.S. wave resources are abundant off the coasts of Hawaii, Alaska, the West Coast, and the Northeast. Moreover, these areas will also have the necessary surface currents to meet the minimum requirements for passive adsorption systems.

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 because of 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 as a result of continental runoff and proximity to margin sediments.

It is unlikely that any seawater extraction technology will occur in the deep ocean (> 1,000 m deep), because of the difficulties of developing technologies that work under extremely high pressure, as well as the added logistic and engineering challenges of operating an extraction system so far from the surface power source and surface support and retrieval system necessary to transport the extracted materials to the surface. 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 marine energy resources (largely wave resources) include the warmer waters off Hawaii, the Caribbean, and the Pacific islands.

Marine Energy Potential Value Proposition

Marine energy could open up unexploited opportunities in seawater mining, which could further expand mineral and gas markets. Both technologies (seawater mining and marine energy development) are at early technology readiness levels; synergies may exist if the technologies were set to mature simultaneously. 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 a marine energy 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, marine energy could enable extraction of dissolved gases from seawater directly through catalytic conversion or through an electrolyzer by providing the power needed to continuously supply a charge across the electrodes. Auxiliary power needs could be satisfied by marine energy, 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 marine energy 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 marine energy 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 a marine energy device under development for the extraction of uranium from seawater. Alternatively, marine energy 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 marine energy 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 6.13 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 (Calcium = 416,000 parts per billion [ppb]; magnesium = 1,295,000 ppb; uranium = 3.3 ppb). Note that the adsorbent retains significant amounts of several other elements, including vanadium, copper, nickel, zinc, cobalt, and chromium. The adsorbent also retains REEs 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.

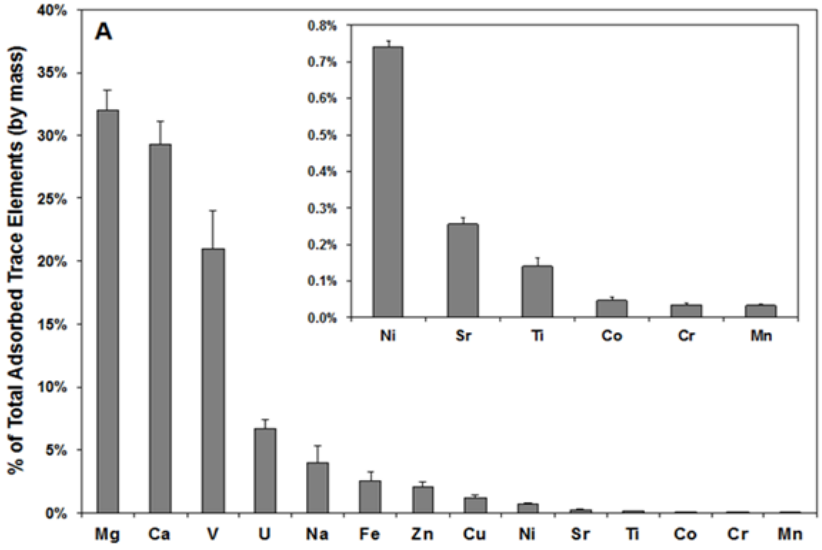


Figure 6.13. Relative abundance of elements absorbed by the Oak Ridge National Laboratory amidoxime-based polymeric uranium adsorbent AF1 after 56 days of seawater exposure. *Figure from Kuo et al. (2016)*

Production of Gases from Seawater

Through electrolysis or catalysis, seawater can serve as a resource for the production of hydrogen, oxygen, and potentially other gases. This process has no location limitations, with the exception that with current electrolyzer technology a freshwater source is required. This means that to use seawater directly, it must first be purified of salts using a technology like reverse osmosis. As technologies advance, production of gases directly from seawater is possible.

Path Forward

Extraction of minerals and gases from seawater will require extensive research and development to create viable industries. Marine energy power generation could be an important catalyst to move these technologies from the pilot stage to full scale.

However, the coupling of marine energy and seawater extraction technologies would 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 the 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 a 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 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 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 marine energy 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.

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 interest to research this topic (within both DOE and U.S. Department of Defense) as a potential domestic source of critically needed materials.

Within 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 2013; 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 2017). The Advanced Manufacturing Office at DOE will also benefit from development of seawater extraction technology to obtain the critical materials needed to develop clean energy technologies, such as structural metal alloys, magnets, light-emitting devices, lasers, catalysts, pigments, batteries, and other high-tech applications (King et al. 2016), as well as support for their desalination initiatives. There are likely partnering opportunities with the U.S. Department of Defense 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).

References

Bardi, Ugo. 2010. “Extracting Minerals from Seawater: An Energy Analysis.” *Sustainability*, April 9, 2, 980–992. doi:10.3390/su2040980. http://www.mdpi.com/2071-1050/2/4/980.

Bradley, Matthew J., Ramagopal Ananth, Heather D. Willauer, Jeffrey W. Baldwin, Dennis R. Hardy, Felice DiMascio, and Frederick W. Williams. 2017. “The role of catalyst environment on CO_2 hydrogenation in a fixed-bed reactor.” *Journal of CO_2 Utilization*, 17: 1–9. http://dx.doi.org/10.1016/j.jcou.2016.10.014.

Byers, M., M. Haji, E. Schneider, and A. Slocum. 2016. “A Higher Fidelity Cost Analysis of Wind and Uranium from Seawater Acquisition symBiotic Infrastructure.” Transactions of the American Nuclear Society, Vol. 115, Las Vegas, NV, November 6–10, 2016.

Byers, M., M. Haji, A. Slocum, and E. Schneider. 2018a. “Cost optimization of a symbiotic system to harvest uranium from seawater via an offshore wind turbine.” *Ocean Engineering*. 169:227-241.

Byers, M., S. Landsberger, E. Schneider. 2018b. “The use of silver nanoparticles for the recovery of uranium from seawater by means of biofouling mitigation.” *Sustainable Energy & Fuels*, 10: 2133-2368.

Chouyyok, Wilaiwan, Jonathan W. Pittman, Marvin G. Warner, Kara M. Nell, Donald C. Clubb, Gary A. Gill, and R. Shane Addleman. 2016. “Surface functionalized nanostructured ceramic sorbents for the effective collection and recovery of uranium from seawater.” *Dalton Transactions*, 45: 11312-11325. DOI: 10.1039/c6dt01318j. http://pubs.rsc.org/en/content/articlelanding/2016/dt/c6dt01318j/unauth#!divAbstract.

Chung, Kang Sup, Jae Chun Lee, Eun Jin Kim, Kyung Chul Lee, Yang Soo Kim, and Kenta Ooi. 2004. “Recovery of Lithium from Seawater Using Nano-Manganese Oxide Adsorbents Prepared by Gel Process.” *Materials Science Forum*, Vols. 449–452, pp. 277–280. https://www.scientific.net/MSF.449-452.277.

Chung, Wook-Jin, Rey Eliseo C. Torrejos, Myoung Jun Park, Eleazer L. Vivas, Lawrence A. Limjuco, Chosel P. Lawagon, Khino J. Parohinog, Seong-Poong Lee, Ho Kyong Shon, Hern Kim, and Grace M. Nisola. 2017. “Continuous lithium mining from aqueous resources by an adsorbent filter with a 3D polymeric nanofiber network infused with ion sieves.” *Chemical Engineering Journal*, February. 309: 49–62. http://dx.doi.org/10.1016/j.cej.2016.09.133.

Congressional Research Services. 2017. Rare Earth Elements in National Defense: Background, Oversight Issues, and Options for Congress. https://fas.org/sgp/crs/natsec/R41744.pdf.

Diallo, Mamadou S., Madhusudhana Rao Kotte, and Manki Cho. 2015. “Mining Critical Metals and Elements from Seawater: Opportunities and Challenges.” *Environmental Science & Technology*, April 20, 49 (16), pp 9390–9399. DOI: 10.1021/acs.est.5b00463. https://pubs.acs.org/doi/abs/10.1021/acs.est.5b00463.

DOE (U.S. Department of Energy). 2010. *Nuclear Energy Research and Development Roadmap: Report to Congress*. Washington, DC. http://energy.gov/ne/downloads/nuclear-energy-research-and-development-roadmap.

DOE. 2013. Marine and Hydrokinetic Technologies Database. Office of Energy Efficiency and Renewable Energy. https://openei.org/wiki/Marine_and_Hydrokinetic_Technology_Database.

DOE. 2017. Geothermals Technology Program extraction of critical minerals. https://www.energy.gov/eere/articles/eere-announces-4-million-critical-materials-recovery-geothermal-fluids.

Dorner, Robert W., Dennis R. Hardy, Frederick W. Williams, Heather D. Willauer. 2011. “C_2-C_{5+} olefin production from CO_2 hydrogenation using ceria modified Fe/Mn/K catalysts.” *Catalysis Communications,* 15: 88–92. https://doi.org/10.1016/j.catcom.2011.08.017.

European Marine Energy Centre (EMEC). 2017a. *World's first tidal-powered hydrogen generated at EMEC.* http://www.emec.org.uk/press-release-worlds-first-tidal-powered-hydrogen-generated-at-emec/.

EMEC. 2017b. *An innovative community project in Orkney that uses surplus electricity generated from renewable energy to split water, making hydrogen gas as a fuel.* http://www.surfnturf.org.uk/page/renewables and http://www.surfnturf.org.uk/page/hydrogen.

Gao, Qianhong, Jiangtao Hu, Rong Li, Zhe Xing , Lu Xu, Mouhua Wang, Xiaojing Guo, and Guozhong Wu. 2016. "Radiation synthesis of a new amidoximated UHMWPE fibrous adsorbent with high adsorption selectivity for uranium over vanadium in simulated seawater." *Radiation Physics and Chemistry*, 122: 1–8. http://dx.doi.org/10.1016/j.radphyschem.2015.12.023.

Gill, Gary A., Li-Jung Kuo, Chris J. Janke, Jiyeon Park, Robert T. Jeters, George T. Bonheyo, Horng-Bin Pan, Chien Wai, Tarang Khangaonkar, Laura Bianucci, et al. 2016. "The Uranium from Seawater Program at PNNL: Overview of Marine Testing, Adsorbent Characterization, Adsorbent Durability, Adsorbent Toxicity, and Deployment Studies." *Industrial & Engineering Chemistry Research*, 55: 4264-4277. DOI: 10.1021/acs.iecr.5b03649. http://cafethorium.whoi.edu/website/publications/Gill%20et%20al%20U%20from%20seawater%20E&EC%202016.pdf.

Guo, Xiaojing, Liangliang Huang, Cheng Li, Jiangtao Hu, Guozhong Wu, and Ping Huai. 2015. "Sequestering uranium from $UO_2(CO_3)_3^{4-}$ in seawater with amine ligands: density functional theory calculations." *Physical Chemistry Chemical Physics*, 17: 14662-14673. DOI: 10.1039/c5cp00931f. http://pubs.rsc.org/en/content/articlelanding/2015/cp/c5cp00931f#!divAbstract.

Guo, Xiaojing, Xiao-Gen Xiong, Cheng Li, Hengfeng Gong, Ping Huai, Jiangtao Hu, Chan Jin, Liangliang Huang, and Guozhong Wu. 2016. "DFT investigations of uranium complexation with amidoxime-, carboxyl- and mixed amidoxime/carboxyl-based host architectures for sequestering uranium from seawater." *Inorganica Chimica Acta*, 441: 117–125. http://dx.doi.org/10.1016/j.ica.2015.11.013.

Haji, Maha N. and Alexander H. Slocum. 2016. "Design of a Symbiotic Device to Harvest Uranium from Seawater through the use of Shell Enclosures." *Proceedings of the 2016 American Nuclear Society Winter Meeting and Nuclear Technology Expo*. https://www.researchgate.net/publication/316341320_Design_of_a_Symbiotic_Device_to_Harvest_Uranium_from_Seawater_through_the_use_of_Shell_Enclosures.

Haji, Maha N., Jessica Drysdale, Ken Buesseler, and Alexander H. Slocum. 2017a. "Ocean Testing of a Symbiotic Device to Harvest Uranium from Seawater through the Use of Shell Enclosures." Proceedings of the 27th International Ocean and Polar Engineering Conference. June 25–30. https://www.onepetro.org/conference-paper/ISOPE-I-17-356.

Haji, Maha N., Margaret Flicker Byers, Erich A. Schneider, and Alexander H. Slocum. 2017b. "Cost Analysis of Wind and Uranium from Seawater Acquisition symBiotic Infrastructure Using Shell Enclosures." Transactions of the American Nuclear Society, Vol. 116, San Francisco, California, June 11–15, 2017. http://ansannual.org/wp-content/data/polopoly_fs/1.3584860.1494347393!/fileserver/file/768424/filename/032.pdf.

Haji, Maha N., and Alexander H. Slocum. 2018. An Offshore Solution to Cobalt Shortages. *Submitted to Renewable & Sustainable Energy Reviews.*

Hall, Susan, and Margaret Coleman. 2013. "Critical Analysis of World Uranium Resources." *USGS Scientific Investigations Report 2012–5239*, 56 pp. https://pubs.usgs.gov/sir/2012/5239/.

Hara, Kazuhiro, Seiya Fujiwara, Tetsumasa Fujii, Satoru Yoshioka, Yoshiki Hidaka, and Hirotaka Okabe. 2016. “Attempts to capturing ppb-level elements from sea water with hydrogels.” *Progress in Nuclear Energy*, 92: 228-233. https://www.sciencedirect.com/science/article/pii/S0149197015001341.

International Maritime Organization. 2018. “IMO sets 2020 date for ships to comply with low sulphur fuel oil requirement.” http://www.imo.org/en/MediaCentre/PressBriefings/Pages/MEPC-70-2020sulphur.aspx.

Kavakli, Pınar Akkas, Noriaki Seko, Masao Tamada, and Olgun Güven. 2005. “Adsorption Efficiency of a New Adsorbent Towards Uranium and Vanadium Ions at Low Concentrations.” *Separation Science and Technology*, 39: 1631-1643. https://www.tandfonline.com/doi/abs/10.1081/SS-120030785.

Kavakli, Pınar Akkas, Noriaki Seko, Masao Tamada, and Olgun Güven. 2007. “Radiation-Induced Graft Polymerization of Glycidyl Methacrylate Onto PE/PP Nonwoven Fabric and Its Modification Toward Enhanced Amidoximation.” *Journal of Applied Polymer Science*, Vol. 105, 1551–1558. https://onlinelibrary.wiley.com/doi/full/10.1002/app.25023.

Kim, Jungseung, Costas Tsouris, Richard T. Mayes, Yatsandra Oyola, Tomonori Saito, Christopher J. Janke, Sheng Dai, Erich Schneider, and Darshan Sachde. 2013. “Recovery of Uranium from Seawater: A Review of Current Status and Future Research Needs.” *Separation Science and Technology*, 48: 367–387, 2013. DOI: 10.1080/01496395.2012.712599. https://www.tandfonline.com/doi/abs/10.1080/01496395.2012.712599.

King, A., R. Eggert, and K, G Schneider. 2016. Chapter 283 - The Rare Earths as Critical Materials. In Handbook on the Physics and Chemistry of Rare Earths. 50: 19-46.

Kung, Stephen. 2016. “Fuel Resources Program: Seawater Uranium Recovery.” *Material Recovery and Waste Form Development—2016 Accomplishments*. pp. 132–145. Idaho National Laboratory. https://inldigitallibrary.inl.gov/sites/sti/sti/7267868.pdf#page=135.

Kuo, Li-Jung, Christopher J. Janke, Jordana R. Wood, Jonathan E. Strivens, Sadananda Das, Yatsandra Oyola, Richard T. Mayes, and Gary A. Gill. 2016. “Characterization and Testing of Amidoxime-Based Adsorbent Materials to Extract Uranium from Natural Seawater.” *Industrial and Engineering Chemistry Research*, 55, 4285−4293. DOI: 10.1021/acs.iecr.5b03267. https://onlinelibrary.wiley.com/doi/abs/10.1002/slct.201701895.

Kuo, Li-Jung, Gary A. Gill, Costas Tsouris, Linfeng Rao, Horng-Bin Pan, Chien M. Wai, Christopher M. Janke, Jonathan E. Strivens, Jordana R. Wood, Nicholas Schlafer, and Evan K. D’Alessandro. 2018. “Temperature Dependence of Uranium and Vanadium Adsorption on Amidoxime-Based Adsorbents in Natural Seawater.” *Chemistry Select.* 3: 843-848. DOI: 10.1002/slct.201701895. https://onlinelibrary.wiley.com/doi/abs/10.1002/slct.201701895.

LCW Supercritical Technologies. 2017. *Highly efficient, robust, and low-cost polymer adsorbent for removing metal species*. https://www.lcwsupertech.com/.

Liu, Chong, Po-Chun Hsu, Jin Xie, Jie Zhao, TongWu, Haotian Wang, Wei Liu, Jinsong Zhang, Steven Chu, and Yi Cui. 2017. “A half-wave rectified alternating current electrochemical method for uranium extraction from seawater.” *Nature Energy*, 2: 1-8, article number 17007. doi:10.1038/nenergy.2017.7. https://www.nature.com/articles/nenergy20177.

Massachusetts Institute of Technology. 2017. *The Future of Strategic Natural Resources: Rare Earth Elements Supply and Demand.* http://web.mit.edu/12.000/www/m2016/finalwebsite/problems/ree.html.

Mordor Intelligence. 2018. *Rare Earth Elements Market—Segmented by Element, End-User Industry, and Region—Growth, Trends, and Forecast (2018–2023)*. https://www.mordorintelligence.com/industry-reports/global-rare-earth-elements-ree-market-industry.

Nishihama, Syouhei, Kenta Onishi, and Kazuharu Yoshizuka. 2011. "Selective Recovery Process of Lithium from Seawater Using Integrated Ion Exchange Methods." *Solvent Extraction and Ion Exchange*, 29:3, 421-431, DOI: 10.1080/07366299.2011.573435. https://www.tandfonline.com/doi/abs/10.1080/07366299.2011.573435.

Park, Myoung Jun, Grace M. Nisola, Eleazer L. Vivas, Lawrence A. Limjuco, Chosel P. Lawagon, Jeong Gil Seo, Hern Kim, Ho Kyong Shon, and Wook-Jin Chung. 2016. Mixed matrix nanofiber as a flow-through membrane adsorber for continuous Li^+ recovery from seawater. *Journal of Membrane Science*, 510: 141–154.

Parker, Bernard F., Zhicheng Zhang, Linfeng Rao, and John Arnold. 2018. "An overview and recent progress in the chemistry of uranium extraction from seawater." *Dalton Transactions*, 47: 639-644. DOI: 10.1039/c7dt04058j. https://www.researchgate.net/publication/321960920_An_overview_and_recent_progress_in_the_chemistry_of_uranium_extraction_from_seawater.

Picard, Mathieu, Camille Baelden, You Wu, Le Chang, and Alexander Slocum. 2014. "Extraction of Uranium from Seawater: Design and Testing of a Symbiotic System." *Nuclear Technology*, 188: 200-217. http://dx.doi.org/10.13182/NT13-144.

Pratt, Joseph, and Leonard Klebanoff. 2018. *Optimization of Zero Emission Hydrogen Fuel Cell Ferry Design, With Comparisons to the SF-BREEZE*. Report to MARAD. 190 pp. Sandia National Laboratories, Livermore, California. https://www.marad.dot.gov/wp-content/uploads/pdf/SFBreeze-Optimization-Study.pdf.

Red Book. 2017. Uranium 2016: Resources, Production and Demand. A Joint Report by the Nuclear Energy Agency and the International Atomic Energy Agency. Report available at: https://www.oecd-nea.org/ndd/pubs/2016/7301-uranium-2016.pdf.

Shankleman, Jessica, Tom Biesheuvel, Joe Ryan, and Dave Merrill. 2017. "We're Going to Need More Lithium." *Bloomberg Businessweek*, September 7. https://www.bloomberg.com/graphics/2017-lithium-battery-future/.

Sodaye, Hemant, S. Nisanb, C. Poletiko, Sivaraman Prabhakar, and P.K. Tewari. 2009. "Extraction of uranium from the concentrated brine rejected by integrated nuclear desalination plants." *Desalination*, 235: 9–32. https://doi.org/10.1016/j.desal.2008.02.005.

Tamada, Masao. 2010. "Current Status of Technology for Collection of Uranium from Seawater." *International Seminar on Nuclear War and Planetary Emergencies—42nd Session*: 243-252. https://doi.org/10.1142/9789814327503_0026.

The Marine Executive. 2017. World's First Hydrogen-Powered Cruise Ship Scheduled. October 3. https://www.maritime-executive.com/article/worlds-first-hydrogen-powered-cruise-ship-scheduled#gs.JqpkQeg.

Tsouris, Costas. 2017. "Uranium extraction: Fuel from Seawater." *Nature Energy*, 17022 (2017). DOI: 10.1038/nenergy.2017.22. https://www.nature.com/articles/nenergy201722?WT.feed_name=subjects_electrochemistry&error=cookies_not_supported.

The Verge. 2018. "Toyota's hydrogen fuel cell trucks are now moving goods around the port of LA." https://www.theverge.com/2017/10/12/16461412/toyota-hydrogen-fuel-cell-truck-port-la.

Tullis, Paul. 2018. "How Hydrogen Could Help Clean Up the Global Shipping Industry." *Oceans Deeply*, January 10. https://www.newsdeeply.com/oceans/articles/2018/01/10/how-hydrogen-could-help-clean-up-the-global-shipping-industry.

U.S. Department of Defense. 2015. *Strategic and Critical Materials 2015 Report on Stockpile Requirements*. https://www.hsdl.org/?view&did=764766.

U.S. Department of the Interior. 2017. Executive Order 13817. Final List of Critical Materials 2018. 82 FR 60835.

U.S. Department of the Interior. 2018. Final List of Critical Minerals 2018. https://www.federalregister.gov/documents/2018/05/18/2018-10667/final-list-of-critical-minerals-2018.

U.S. Geological Survey. 2018. Mineral commodity summaries 2018: U.S. Geological Survey. https://doi.org/10.3133/70194932.

U.S. Naval Research Laboratory. 2016. NRL Seawater Carbon Capture Process Receives U.S. Patent. https://www.nrl.navy.mil/media/news-releases/2016/NRL-Seawater-Carbon-Capture-Process-Receives-US-Patent.

U.S. Naval Research Laboratory. 2017. NRL Receives US Patent for Carbon Capture Device: A Key Step in Synthetic Fuel Production from Seawater. https://www.nrl.navy.mil/news/releases/nrl-receives-us-patent-carbon-capture-device-key-step-synthetic-fuel-production-seawater.

U.S. Naval Research Laboratory. 2018. Energy Transformation & Storage Alternatives Program. https://www.nrl.navy.mil/mstd/branches/6300.2/alternative-fuels.U Switch for Business. 2018. Average business gas and electricity consumption. Accessed on March 2, 2018. https://www.uswitchforbusiness.com/business-energy/average-business-electricity-gas-consumption.

van Biert, Lindert, Milinko Godjevac, K. Visser, and Aravind Purushothaman Vellayani. 2016. "A review of fuel cell systems for maritime applications." *Journal of Power Sources*, 327: 345–364. http://dx.doi.org/10.1016/j.jpowsour.2016.07.007.

Willauer, Heather D., Dennis R. Hardy, Kenneth R. Schultz, and Frederick W. Williams. 2012. "The feasibility and current estimated capital costs of producing jet fuel at sea using carbon dioxide and hydrogen." *Journal of Renewable and Sustainable Energy*, 4, 033111. https://dx.doi.org/10.1063/1.4719723.

Willauer, Heather D., Felice DiMascio, Dennis R. Hardy, and Frederick W. Williams. 2017. "Development of an Electrolytic Cation Exchange Module for the Simultaneous Extraction of Carbon Dioxide and Hydrogen Gas from Natural Seawater." *Energy Fuels* 31: 1723−1730. https://pubs.acs.org/doi/10.1021/acs.energyfuels.6b02586.

World Nuclear News. 2017. "Uranium producers prepare for market recovery." May 2. http://www.world-nuclear-news.org/UF-Uranium-producers-prepare-for-market-recovery-02051701ST.html.

World Nuclear Organization. 2018a. Uranium Enrichment. http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/uranium-enrichment.aspx.

World Nuclear Organization. 2018b. US Nuclear Fuel Cycle. http://www.world-nuclear.org/information-library/country-profiles/countries-t-z/usa-nuclear-fuel-cycle.aspx.

Zhang, Huijun, Lixia Zhang, Xiaoli Han, Liangju Kuang, and Daoben Hua. 2018. "Guanidine and Amidoxime Cofunctionalized Polypropylene Nonwoven Fabric for Potential Uranium Seawater Extraction with Antifouling Property." *Industrial & Engineering Chemistry Research* 57, 1662−1670. DOI: 10.1021/acs.iecr.7b04687. https://pubs.acs.org/doi/abs/10.1021/acs.iecr.7b04687.

U.S. DEPARTMENT OF
ENERGY
Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Resilient Coastal Communities

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

April 2019

Resilient Coastal Communities

Numerous applications and markets for marine energy show similarities and lend themselves to grouping. Many applications and markets displayed characteristics of being ideally suited to coastal development directly or indirectly supporting communities. These applications are grouped under "Resilient Coastal Communities" in this report. Commonalities among these applications include:

- Applications are nearshore or onshore and contribute to the resiliency of coastal communities in the face of extreme events, such as tsunamis, hurricanes, flooding, or droughts.
- Visual impacts are an important consideration in project location.
- Customers are typically more price sensitive because of a greater number of incumbent technologies capable of supplying power at competitive costs.
- Relatively easy access for installation and operations than the power-at-sea applications with more frequent maintenance intervals likely.

Within this theme, chapters are presented on seawater desalination, coastal resiliency and disaster recovery, and community-scale isolated power systems. Chapters are presented in the order of perceived relevance to marine energy as a viable near-term market.

U.S. DEPARTMENT OF
ENERGY
Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

7 Desalination

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

April 2019

7. Desalination

Key Findings

- Desalination is an energy-intensive process because of the energy required to separate salts and other dissolved solids from water. In operation, the actual pressure required is approximately two times the osmotic pressure; for seawater, this translates to about 800–1,000 pounds per square inch. The energy required to run pumps that can achieve these high pressures account for approximately 25% to 40% of the overall cost of water (Lantz, Olis, and Warren 2011).

- Wave- or tidal-powered desalination could be used to directly pressurize seawater without generating electricity for a reverse-osmosis system, eliminating one of the largest cost drivers for the production of desalinated water.

- There are two primary market segments for desalination: water utilities and isolated or small-scale distributed systems. Large-scale desalination systems require tens of megawatts to run and provide tens of million gallons of desalinated water per day. Small-scale systems vary in size from tens to hundreds of kilowatts and provide hundreds to thousands of gallons of water per day.

- Marine energy resources are inherently located near potential desalination water supplies and high population concentrations along the coast, therefore areas that have unreliable grid connections or water infrastructure may receive dual benefits from marine energy systems. In the long term, marine energy could provide low-cost, emission-free, drought-resistant drinking water to larger municipalities.

- The National Renewable Energy Laboratory's (NREL's) simulation results suggest a direct pressurization application could be more cost competitive when producing water than a wave-energy system producing electricity given current cost estimates (Yu and Jenne 2017). This finding clearly signals a near-term market opportunity for wave energy, requiring smaller cost reductions than grid-power applications.

Opportunity Summary

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

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

NREL has researched and modeled wave-powered concepts that directly pressurize reverse-osmosis seawater desalination systems, bypassing the need for significant energy generation. In fact, NREL's simulation results suggest a direct pressurization application could be more cost competitive when producing water than a wave-energy system producing electricity given current cost estimates (Yu and Jenne 2017). This finding signals a near-term market opportunity for wave energy requiring smaller cost reductions before the technology is commercially competitive with grid-power applications.

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

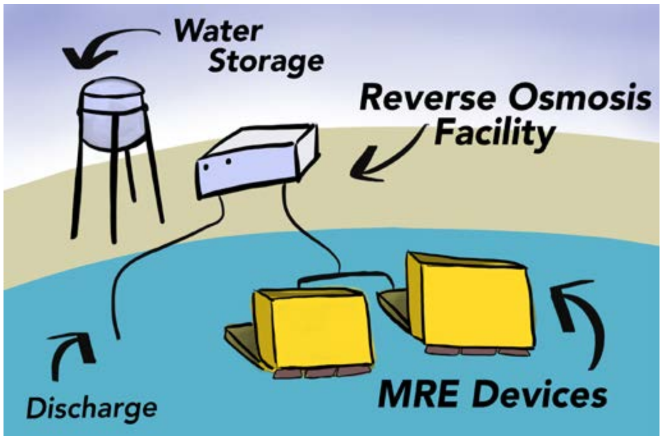


Figure 7.1. Marine renewable energy (MRE) application overview for desalination. *Image courtesy of Molly Grear, Pacific Northwest National Laboratory*

Application

Description of Application

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

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

The most likely near-term marine energy technologies for desalination are nearshore wave and tidal technologies, particularly because of the proximity to shore, enabling easier access to standard desalination equipment. Nearshore technologies allow for more equipment to be located on land, require simpler installation techniques, and have lower maintenance costs. However, environmental and permitting challenges associated with brine discharge and inlet designs (e.g., velocity restrictions) may incentivize deepwater technologies as wave energy converter (WEC) technologies mature. Of course, the additional cost associated with getting clean water to shore, either through pumping or secondary transport, will have to be weighed against permitting cost reductions.

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

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

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

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

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

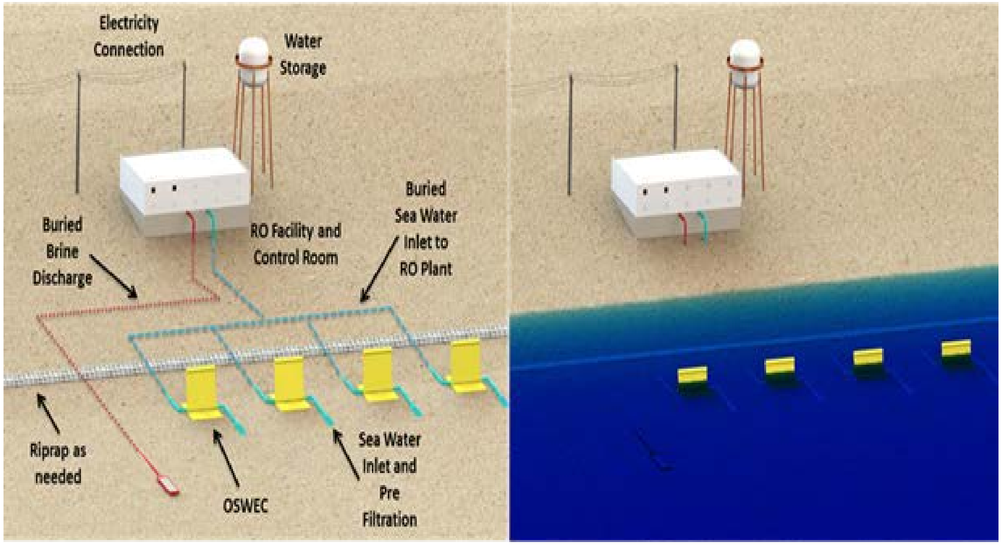


Figure 7.2. Rendering of a wave-powered desalination plant ("RO" is reverse osmosis). *Source: NREL*

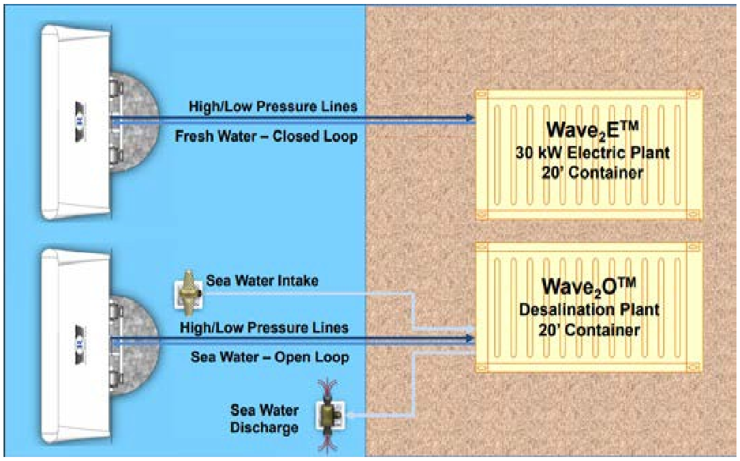


Figure 7.3. Configuration of Resolute Marine's Wave2O desalination system. *Image courtesy of Resolute Marine*

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

Figure 7.4. SAROS wave-powered desalination demonstration unit

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

Power Requirements

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

Table 7.2. Energy Use for Traditional Reverse-Osmosis Process

Energy Process	Existing Fuel	Use Pattern	Criticality	Average Site Energy Usage	Reference
Traditional seawater reverse osmosis	Grid/diesel	24 hour	Critical—performance	2.5–4.0 kilowatt-hours/ cubic meter (m3)	Voutchkov (2013)
WEC-powered seawater reverse osmosis	-	24 hour	Critical—performance	2.8 kilowatt-hours/m3 equivalent power	Yu and Jenne (2017)
Distribution	Grid/diesel	24 hour	Critical—performance	Varies with distance and elevation	

Markets

Description of Markets

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

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

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

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

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

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

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

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

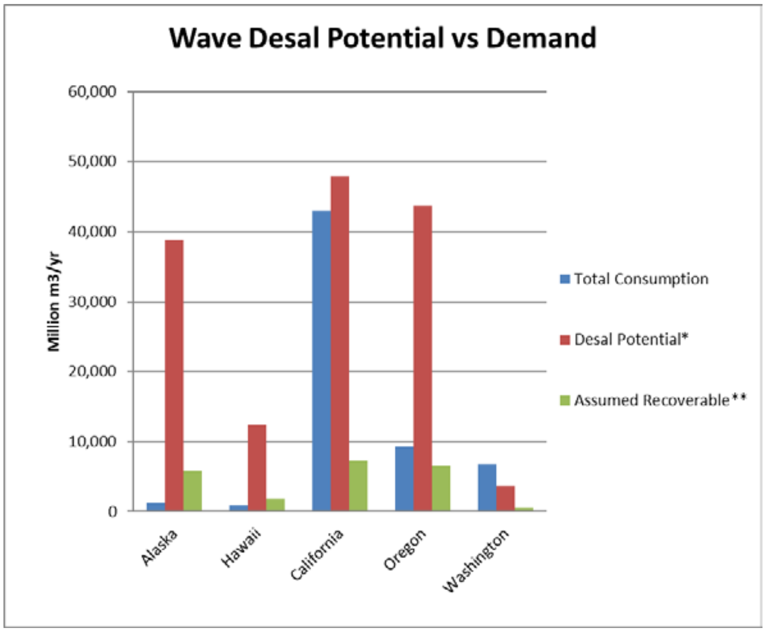


Figure 7.5. The total clean water consumption by state compared to what can be produced using local wave energy

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

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

Power Options

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

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

Geographic Relevance

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

Marine Energy Potential Value Proposition

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

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

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

Path Forward

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

The high energy requirements for desalination, whether at the large or distributed scale, require very similar, if not identical, marine energy technology advancements as we expect with utility-scale marine energy. Large-scale water utilities will require water production that is equivalent to multimegawatt marine energy arrays. However, similar to the comparison of isolated power markets and utility-scale power markets, the early marine energy desalination opportunities will likely be able to take advantage of much smaller-scale marine energy devices. This will provide marine energy developers with the ability to develop marine energy technologies with lower financial risk and reduced installation and maintenance per unit. Although, additional analysis is still needed to quantify the size of these smaller markets.

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

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

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

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

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

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

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

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

Potential Partners

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

References

Carlsbad Desalination Project. 2017. “FAQs.” Accessed February 2018. http://www.carlsbaddesal.com/faqs.html.

Cooley, Heather, and Newsha Ajami. 2012. *Key Issues for Desalination in California: Costs and Financing*. Oakland, CA: Pacific Institute. http://pacinst.org/publication/costs-and-financing-of-seawater-desalination-in-california/.

DeOreo, W., P. Mayer, L. Martien, M. Hayden, A. Funk, M. Kramer-Duffield, R. Davis, J. Henderson, B. Raucher, P. Gleick, M. Heberger. 2011. *California Single-Family Water Use Efficiency Study* (Technical Report). Aquacraft, Inc. Water Engineering and Management, Boulder, CO (US). http://water.cityofdavis.org/Media/PublicWorks/Documents/PDF/PW/Water/Documents/California-Single-Family-Home-Water-Use-Efficiency-Study-20110420.pdf.

Ghadiryanfar Hoffman, Justin, Ronald C. Pate, Thomas Drennen, and Jason C. Quinn. 2017. “Techno-economic assessment of open microalgae production systems.” *Algal Research*, 23: 51–57. https://www.sciencedirect.com/science/article/pii/S2211926416303046.

Kam, K. and M. Doeff. 2012. “Electrode Materials for Lithium Ion Batteries.” Materials Matters, Aldrich Materials Science. 7(4), 56. https://www.sigmaaldrich.com/content/dam/sigma-aldrich/docs/Aldrich/Brochure/1/material-matters-v7n4.pdf.

Kilcher, Levi, and Robert Thresher. 2016. *Marine Hydrokinetic Energy Site Identification and Ranking 3909 Methodology Part I: Wave Energy* (Technical Report). NREL/TP-5000-66038. Golden, CO (US): National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy17osti/66038.pdf.

Lantz, Eric, Dan Olis, and Adam Warren. 2011. *U.S. Virgin Islands Energy Road Map: Analysis* (Technical Report). NREL/TP-7A20-52360. Golden, CO (US): National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy11osti/52360.pdf.

Lantz, Eric, Maureen Hand, and Ryan Wiser. 2012. *The Past and Future Cost of Wind Energy: Preprint*. NREL/CP-6A20-54526. Golden, CO (US): National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy12osti/54526.pdf.

National Oceanic and Atmospheric Administration. 2017. “What percentage of the American population lives near the coast?” Accessed April 2, 2018. https://oceanservice.noaa.gov/facts/population.html.

National Research Council. 2008. *Desalination: A National Perspective.* Washington, DC: The National Academies Press. https://doi.org/10.17226/12184.

Resolute Marine Energy. 2017. *Resolute Marine Launches Feasibility Studies in Cape Verd*e. Accessed February 2018. http://www.resolutemarine.com/news/resolute-marine-launches-feasibility-studies-in-cape-verde.

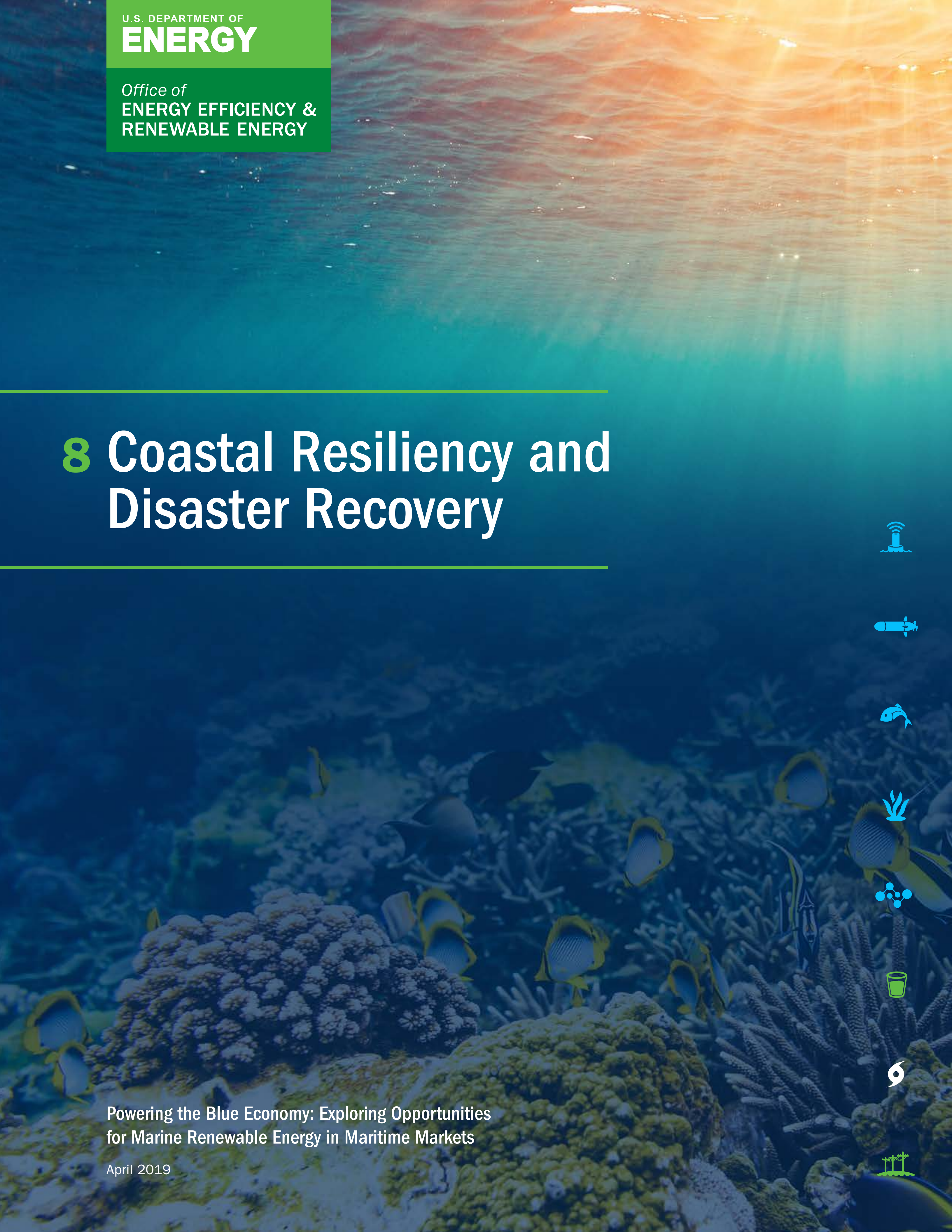
Southern California Coastal Water Research Project. 2012. *Management of Brine Discharge to Coastal Waters Recommendations of a Science Advisory Panel*. Technical Report 694, Costa Mesa, CA. https://www.waterboards.ca.gov/water_issues/programs/ocean/desalination/docs/dpr051812.pdf.

Voutchkov, Nikolay. 2013. *Desalination Engineering Planning and Design*. McGraw-Hill.

Warner, Ethan, Kristi Moriarty, John Lewis, Anelia Milbrandt, Amy Scwab. 2017. *2015 Bioenergy Market Report.* Prepared by the National Renewable Energy Laboratory for the U.S. Department of Energy. https://www.nrel.gov/docs/fy17osti/66995.pdf.

Water Reuse Association. 2012. *Seawater Desalination Costs*. https://watereuse.org/wp-content/uploads/2015/10/WateReuse_Desal_Cost_White_Paper.pdf.

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



U.S. DEPARTMENT OF
ENERGY
Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

8 Coastal Resiliency and Disaster Recovery

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

April 2019

8. Coastal Resiliency and Disaster Recovery

Key Findings

- Coastal areas support a large part of the human population but are under stress from sea level rise and increases in storm frequency and intensity. These areas are also prone to extreme events, such as tsunamis, tropical storms, and flooding. Deterioration of coastal areas can threaten the safety of the populations, including disruptions to communities, such as limiting access to freshwater and electricity for extended periods of time. These threats can result in displacement of human populations and public health risks.

- Coastal communities are addressing threats to coastal areas by focusing on hazard mitigation, preparedness for extreme events, response and recovery operations, and by improving the resiliency of critical infrastructure and emergency assets.

- Coastal resilience can be improved by fortifying natural shorelines like beaches and marshes, and by putting in place assets like distributed power generation sources to support local microgrids.

- Marine energy devices could be integrated into coastal infrastructure, such as piers, jetties, groins, and breakwaters, providing the dual benefit of shoreline protection and power generation.

- Marine energy could also contribute to coastal microgrids, increasing generating source diversity and reducing reliance on hard-to-find diesel fuel during emergencies. Marine energy could be used to support other emergency needs, such as water treatment and supply (e.g., emergency desalination).

Opportunity Summary

Roughly one-third of human populations live within 100 kilometers of a coastline and continued migration toward coastal areas is expected to increase this proportion to one-half by 2030 (Small and Nicholls 2003; MEA 2005). The close proximity of populations to the coast, along with the potential impacts of climate change and sea level rise on storm intensity and frequency, will require communities to plan for events that will place more residents, homes, and businesses in the path of increasingly dangerous and costly storms (Texas A&M undated). Coastal communities must integrate resiliency and disaster recovery planning into decision-making processes, facilitating the understanding of where and how communities are vulnerable to loss from coastal hazards, and adapting planning and development practices to mitigate these vulnerabilities (Texas A&M undated). There are opportunities for marine energy to support coastal resiliency and disaster recovery planning and prevention.

Increases in the frequency of extreme weather events and 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 (National Oceanic and Atmospheric Administration [NOAA] 2017b, 2018; U.S. Global Change Research Program 2014). Shoreline protection structures, such as breakwaters, could also house marine energy devices, providing power to marinas and small ports. 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, including 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, the Federal Emergency Management Agency (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 comprising 103 generator sizes, ranging from 1.5 kilowatts (kW) to 1.825 megawatts (MW) (Danjczek 2014), requiring that shipments of diesel be continually delivered into disaster zones. Marine energy 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 marine energy. 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 Fiscal Year (FY) 2017 and an additional $6.7 billion for major declarations (PolitiFact 2017).

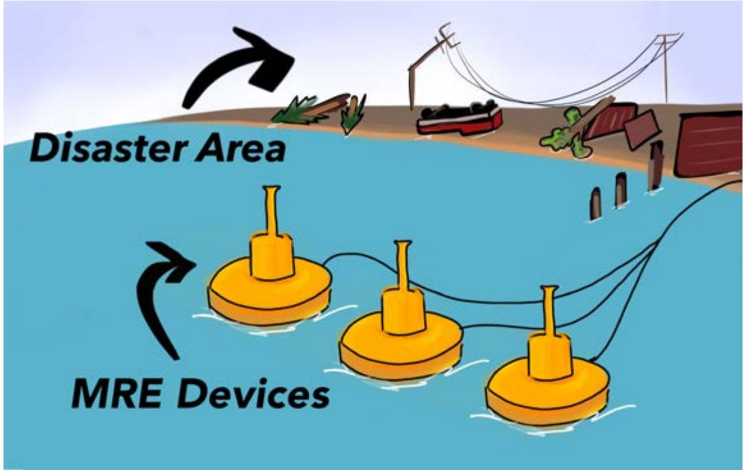


Figure 8.1. Marine energy application overview for emergency response. *Image courtesy of Molly Grear, Pacific Northwest National Laboratory*

Application

Description of Application – Shoreline Protection

Coastal resiliency consists of actions planned and executed to defend against storms, sea level rise, tectonic events and resulting tsunamis, and other hazards, some of which are sudden and unexpected (such as storms and tsunamis), while others are slower and more predictable.

Before a disaster strikes, it is possible to prepare coastal communities to be more resilient to coastal disasters using marine energy, both by augmenting natural defenses, like beaches, and integrating power generation into existing or future shoreline protection infrastructure.

Shoreline protection and defense of coastal environments is a growing necessity in the face of sea level rise and more intense storms. The development of breakwaters, berms, groins, storm surge barriers, and other similar coastal structures will increase globally, presenting the opportunity for the integration of marine energy devices, as well as retrofitting into existing structures (Figure 8.2). The power generated could be delivered to marinas, ports, local communities, or aid in sand replenishment of beaches.

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.

Beach Nourishment

Beach nourishment (or replenishment) is the U.S. Army Corps of Engineer's (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, including beaches that are directly affected by sea level rise. Typically, nourishment activities take place as part of a scheduled project or in response to a coastal storm.

The selection of equipment for nourishment projects is a function of the location and character of the sediment borrow area.[13] 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 (Great Lakes Dredge and Dock 2018).

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 wave energy converters (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 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.

As discussed in Mustapa et al. (2017), oscillating water column devices consist of two elements: the reinforced concrete structure that acts as an oscillating chamber and a group of turbine generators. The first integrated oscillating-water-column breakwater was constructed at Sakata Port, Japan. In 2008, the first multiturbine facility consisting of 16 chambers integrated with vertical breakwaters was successfully constructed at the port of Mutriku, Spain (Figure 8.2). In 2012, construction began on the biggest oscillating-water-column-breakwater integration project, the Resonant Wave Energy Converter 3, in the harbor of Civitavecchia, Italy (Figure 8.3). Currently, only eight of 17 caissons are constructed.

---

[13] 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.

Figure 8.2. Mutriku, Spain, oscillating-water-column-breakwater integration. *Source: obs/Voith GmbH*

The Port of Civitavecchia and the new dock

The new dock

The new dock and the REWEC3 Caissons

The REWEC3 Caissons

Source: Port Authority of Civitavecchia

Figure 8.3. The Resonant Wave Energy Converter 3 Device in Civitavecchia Port, Italy. *Photos from Maestrale (2017)*

Storm Surge Barriers

Storm surge barriers (flood barriers) are another form of coastal protection designed to prevent storms from causing flooding in 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 8.4), the largest storm surge barrier in the world (5.6 miles long). Oosterscheldekering, known as the Eastern Scheldt, has also been equipped with five tidal turbines, with a total capacity of 1.2 MW, enough generation to power 1,000 Dutch households (M Power 2018).

Figure 8.4. Oosterscheldekering storm surge barrier in the Netherlands. *Photo from Amazing Planet (2014)*

Figure 8.5. Five tidal turbines integrated with the Oosterscheldekering storm surge barrier in the Netherlands. *Photo from HydroWorld.com (2015)*

Power generated from marine energy devices could be used to supplement other energy sources during emergency response and disaster relief activities, offsetting the heavy reliance on diesel generators (Table 8.1). 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 marine energy 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.

Description of Application – Disaster Recovery

In 2016, the U.S Department of Homeland Security (DHS) published the *National Response Framework* (DHS 2016), which provides a guide on 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 8.1 provides a summary of each response core capability and the critical tasks to achieve its objective.

Table 8.1. Requirements for Marine Energy Power To Meet Core Capabilities After a Coastal Disaster, as in the National Preparedness Goal. *Source: DHS (2016)*

Task	Power Needs
Planning	No power required; tasks carried out in advance of disasters
Public information and warning	Electricity needed for communications systems, radio systems, and cell towers to equip personnel to provide ongoing information to the community
Operational coordination	Electricity needed for emergency management centers, including lighting, heating/cooling, and communications
Infrastructure systems	Electricity needed to augment fuel for hybrid and electric vehicles, communications, debris removal equipment, communications, and debris disposal
Critical transportation	Augment fuels for vehicles and other means of evacuation, including boats, delivery of vital supplies, heating/cooling, lighting for evacuees, processing drinking water, and communications
Environmental response/ health and safety	Supply electricity and clean water for medical assistance, lighting, heating/ cooling, and communications
Fatality management services	Provide refrigeration for morgues, transportation for medical personnel and bodies, and communications
Fire management and suppression	Provide power for water pressure and pumping, lighting, and communications for fire crews
Mass care services	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	Augment fuel for search and rescue vehicles, lighting, and communications
On-scene security, protection, and law enforcement	Provide power for emergency equipment, including lighting, communications, and medical care
Operational communications	Provide power for communications among rescue personnel, field crews, emergency centers, and local and regional authorities; provide power for tools to rebuild communications infrastructure
Logistics and supply chain management	Augment fuel for vehicles to deliver supplies, transport the injured or ill, and provide power for communications equipment and lighting
Public health, healthcare, and emergency medical services	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 power for communications and lighting

Electrical Grid Blackstart

As described in Feltes and Grande-Moran (2008), electrical grids are designed to be resilient and maintain operations and consistent voltages over time. However, system power outages occasionally occur because of human error or natural occurrences, such as lightning strikes, hurricanes, or electromagnetic pulses. When a portion of the grid goes down, it is restored with assistance from a neighboring area of the grid. In circumstances in which there is an isolated portion of the grid, or 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 the Federal Energy Regulatory Commission (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, the commission, 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 Federal Energy Regulatory Commission (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 (U.S. Department of Energy 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).

To increase grid resiliency and prepare for potential black-start operations in the event of a blackout, several 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 or operate as distinct islands for which no connection point between the utility grid and microgrid exists, and 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. Wind turbines are the most utilized renewable energy generation technology in microgrids around the world. There is a reasonable distribution of microgrid sizes, ranging from microgrids that generate less than 20 kilowatts to those that produce more than 60 MW (IEC 2014).

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). Marine energy technologies could become a significant player in microgrids associated with recovery of generation in coastal areas.

Power Requirements

Beach Nourishment

As discussed earlier, energy generated from integrating marine energy 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), marine energy devices may need to be easily mobilized so that power can be used in either location. Table 8.2 presents 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 8.2. Estimated Power Requirements for Beach Nourishment Vessels

Beach nourishment Vessels	Estimated Power Consumption
Trailing suction hopper dredge[14] Cutter section dredge[15]	Propulsion power: 3,000 horsepower (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)
Booster pump[16]	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)
Hydraulic unloader[6]	Main pump power: 3,600 hp–14,400 hp (2,686 kW–10,742 kW)
Trailing suction hopper dredge[17]	Total installed power: 6,800 hp (5,073 kW)

Disaster Recovery

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; for shoreline communities, this power could be supplied by marine energy devices off the coast. For communities along sizable rivers, riverine devices could supply power in the same manner. Power needs include 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, and shelters.

Markets

Description of Markets – Shoreline Protection

With 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 coastal infrastructure, with specific priorities to serve mandated functions. The USACE FY19 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.

USACE projects follow legislation, which follows public demand, after devastating coastal storms (USACE 2003). 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 constructed 71 specifically authorized shore protection projects at over $1.2 billion. 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.

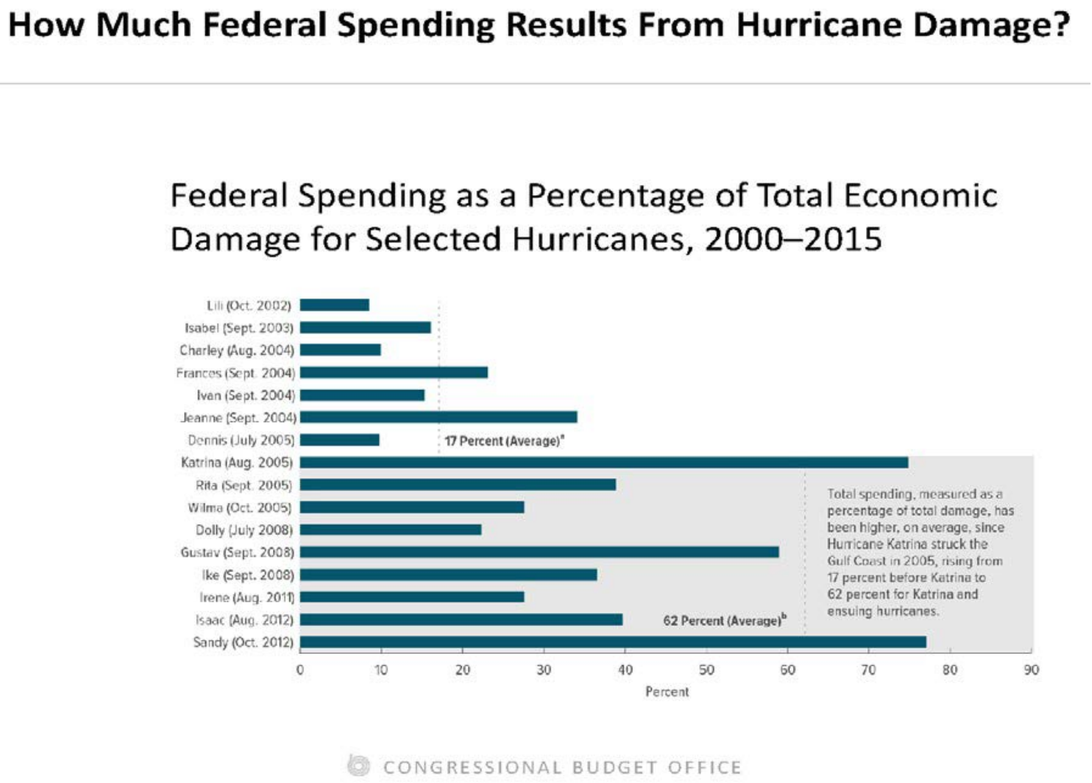
As a steward of the U.S. Outer Continental Shelf energy and mineral resources, the Bureau of Ocean Energy Management (BOEM) oversees access to offshore areas where sand and other materials are mined for beach nourishment projects. As of July 2015, BOEM has executed 48 leases and agreements for coastal restoration projects and conveyed more than 109 million cubic yards 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).

As discussed in Manasseh et al. (2017), there are several factors that favor the use of marine 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 stabilization; and (2) low-lying coastal communities that are at the greatest risk of inundation from sea level rise (NOAA 2017b).

Description of Markets – Disaster Recovery

FEMA's Disaster Relief Fund plays the largest role in U.S. disaster recovery efforts, in cooperation with other federal and state agencies. 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 ($615 million in FY17), and major declarations ($6.7 billion in FY17). 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.

Figure 8.6 summarizes the amount of federal funds spent on hurricane disaster relief in the United States in relation to the total economic damage (generated before economic data from Hurricane Harvey and Hurricane 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).



Total spending, measured as a percentage of total damage, has been higher, on average, since Hurricane Katrina struck the Gulf Coast in 2005, rising from 17 percent before Katrina to 62 percent for Katrina and ensuing hurricanes.

Figure 8.6. Federal government hurricane recovery dollars. *Image from Struyck (2017)*

Increases in extreme weather events and sea level rise (NOAA 2017b, 2018; Melillo et al. 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, and 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 2017a). 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 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, such as terrorist attacks on the electrical grid or other essential services, local relief efforts may become the front line for recovery. Marine energy technologies could provide valuable supplemental power to businesses, residences, and government facilities to improve recovery time and grid resiliency.

Power Options

Diesel generators, solar energy, and battery energy storage systems are the main sources of competition to marine energy 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. Marine energy must prove reliability that is equal to or greater than other renewable technologies in order to be competitive.

Geographic Relevance

The application of marine energy devices for disaster recovery is potentially relevant for all ocean, river, and Great-Lake-adjacent emergency response activities in the United States and globally. Along the U.S. West Coast, large magnitude earthquakes from the Cascadia Subduction Zone that are likely to create large tsunamis that may threaten the coasts of British Columbia, Washington, Oregon, and Northern California (Pacific Northwest Seismic Network 2018). These areas along U.S. coastlines have strong marine energy resources that could contribute to power needs for emergency recovery, including power needed for air traffic control, communications, emergency lighting, emergency response operations and activities, refrigeration, residences and businesses, and sewage and sanitation systems.

Marine Energy Potential Value Proposition

Shoreline Protection

Marine energy devices 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. Nearshore marine energy devices may also de-energize and reduce the destructive forces of storm-driven waves, thereby mitigating damage to coastal infrastructure. In response to threats of sea level rise and increasing frequency and intensity of coastal storms, many new coastal structures will be constructed or improved, providing an opportunity for marine energy integration. Power from integrated marine energy devices could be used to power local communities, marinas and ports (e.g., navigation lights, recharging 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 a single commercial prototype of wave and marine current energy conversion technology ranged between $11 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 an existing breakwater structure as an integrated platform
- Improves WEC device reliability, allowing energy extraction to occur during heavy wave conditions; this is different than 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.

Disaster Recovery

Marine energy 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. Marine energy could also contribute to coastal microgrids or a more diversified macrogrid to increase resiliency. During emergency recovery and grid restart efforts, easily transported and deployed devices are advantageous. For example, Marine Power Systems is developing and testing a wave energy device called WaveSub that can be deployed by barge (Marine Power Systems 2018).

Depending on the constraints of the location and needs of a community or grid, marine energy devices could be hardened or prestaged for quick deployment after a disaster. Hardened marine devices would need to be designed to withstand severe precipitation, wind, extreme wave heights, and currents. Prestaged marine energy devices might need to be designed to be rapidly deployed to supply power to critical infrastructure.

Rising sea levels and extreme weather events have challenged communities to become more resilient and rely more heavily on locally available, alternative energy sources. Marine energy 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, marine energy 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 marine energy 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 on the island, the lack of black-start grid capability continues to plague the island's utility and people.

Coastal communities could be a direct customer of marine energy during emergency response periods. Federal agencies such as FEMA, USACE, and DHS could also use the energy harvested by marine energy devices to supplement emergency power during response efforts. Additionally, civilian and volunteer organizations, such as the American Red Cross, could use marine energy to aid their response efforts. Isolated coastal grids often depend 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 could see marine energy as a viable means to carry out a black start of isolated coastal grids, allowing for investment in ready standby wave devices in strategic locations nearshore. For example, Oregon passed legislation that increased the state's renewables portfolio standard to 50% renewables by 2040, which includes wave, tidal, and ocean thermal energy (Oregon Department of Energy 2018), with explicit reliance on marine energy and other renewables to assist in coastal recovery and grid black start (Oregon Department of Energy 2011).

Path Forward

Path Forward – Shoreline Protection

Integrating marine energy devices with shore protection structures will require early engagement with public and private agencies to identify opportunities to colocate devices with coastal infrastructure, during the design phase of new construction or the redesign of existing structures for improvements and upgrades.

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, including marine energy, as part of their Energy Management Action Plan.

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).

Shore protection alternatives in the form of beach nourishment, living shorelines, and/or hard structures are being instituted by communities to provide resiliency to coastlines and the electrical grid.

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 carbon dioxide emissions (Siemens 2017). Regulations in Europe stipulate that the European Union's carbon dioxide 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 marine energy devices integrated into coastal protection structures in the vicinity of a port or harbor.

Although 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 Renewable Electric Energy From Sea concept developed by de Almeida (2017) consists of a nearshore fixed submerged caisson placed on the seafloor at low depth. The design and porosity of the structure allows water to flow inside the structure, thereby driving a low head hydropower turbine. 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 model captured about one- to two-fifths of the power that it would capture if it were installed in a small-scale river dam. The model demonstrated evidence that the Renewable Electric Energy From Sea structure was successful at breaking/dissipating waves. Another novel concept is being developed by Zyba, a British wave energy startup, 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 the 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 marine energy 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.

Path Forward - Disaster Recovery

Emergency managers and officials at the federal, state, and local levels should be made aware of the potential for marine energy 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 marine energy devices can be conditioned and made available on a reliable basis, in conjunction with storage solutions, to pave the way for adding marine energy to the emergency management toolkit. As a first step, areas with known sufficient marine energy resources for generation should be mapped to local disaster needs and strategies, along with a potentially high-impact demonstration project to support a disaster management scenario.

Following Oregon's lead, coastal states could examine the potential for explicitly adding marine energy to the list of renewables and other energy sources used for emergency response and grid restart. As an example, Verdant Power completed an extensive analysis of the weather and water dynamics of Superstorm Sandy in Long Island Sound and at its East River RITE site where a tidal turbine had previously been deployed and tested. Findings indicate a benign impact of an extreme storm on a commercial array of tidal turbines at the test location (Corren et al. 2014). Additionally, coordination will be needed among local communities, FEMA, and state emergency managers to ensure that marine energy is available as a disaster recovery energy option.

Planning and testing the placement of standby-ready marine energy 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 marine energy devices will be efficiently distributed to the grid or other relevant consumers in the event supplemental power is needed.

If marine energy devices were deployed along coastlines, when the power is not being used for emergency response and disaster relief efforts, it can be distributed to the local grid, used for coastal/nearshore aquaculture operations, desalination operations, or stored for future emergency response uses.

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

Potential Partners

Various coastal management and engineering organizations could be relevant partners. This includes federal agencies such as NOAA, BOEM, USACE, and 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. Other potential partners include civilian and volunteer organizations, such as the American Red Cross.

Regional and state-level utilities might invest in marine energy to ensure that small isolated coastal grids have black-start ability. Microgrids are inherently suitable for maintaining power supply during or after a disaster (IEC 2014) and integrating marine energy as a power source would improve grid resiliency. Marine energy devices could be used in bigeneration microgrids alongside diesel.

References

Balkan Green Energy News. 2016. SINN Power testing wave energy conversion in Heraklion. https://balkangreenenergynews.com/sinn-power-testing-wave-energy-conversion-in-heraklion/.

BBC. 2017. "Tesla solar power arrives in Puerto Rico." Accessed April 2, 2018. http://www.bbc.com/news/technology-41747065.

Bureau of Ocean Energy Management. 2016. *Stewardship of U.S. Outer Continental Shelf Energy and Mineral Resources: Strategic Framework*. https://www.boem.gov/Strategic-Framework/.Colthorpe, Andy. 2017. "California battery's black start capability hailed as 'major accomplishment in the energy industry.'" *Energy Storage News*. https://www.energy-storage.news/news/california-batterys-black-start-capability-hailed-as-major-accomplishment-i.

Corren, D., J. Colby, and M.A. Adonizio. 2014. Superstorm Sandy and the Verdant Power RITE Project. Proceedings of the 2nd Marine Energy Technology Symposium. April 15-18, 2014, Seattle, Washington.

Danjczek, Peter. 2014. "Mass-Power Outage in Disasters: Addressing Inefficiencies in FEMA's Generator Mission." Johns Hopkins University.

de Almeida, JPPG Lopes. 2017. REEFS: An artificial reef for wave energy harnessing and shore protection - A new concept towards multipurpose sustainable solutions. *Renewable Energy*, Vol. 114, 817-829. https://doi.org/10.1016/j.renene.2017.07.076.Dean, Robert G., and Dalyrmple, Robert A. 2002. "Coastal Processes with Engineering Applications." *Cambridge University Press*.

Federal Energy Regulatory Commission. 2016. Report on the FERC-NERC-Regional Entity Joint Review of Restoration and Recovery Plans. https://www.ferc.gov/legal/staff-reports/2016/01-29-16-FERC-NERC-Report.pdf.

Feltes, James W., and Carlos Grande-Moran. 2008. Black Start Studies for System Restoration. IEEE 2008. Pp. 8.

Great Lakes Dredge and Dock. 2018. Shore Protection & Beach Restoration. Accessed February 23, 2018. https://www.gldd.com/wp-content/uploads/2016/01/GLDD_Shore-Protection-and-Beach-Restoration_Letter.pdf.

Harris, Michael. 2017. SINN Power gets grant to continue wave energy device research. HydroWorld.com. http://www.hydroworld.com/articles/2017/08/sinn-power-gets-grant-to-continue-wave-energy-device-research.html.

HydroWorld.com. 2015. "World's largest 5-turbine tidal array installed in the Oosterschelde barrier, The Netherlands." September 30, 2015. Accessed on November 9, 2018. https://www.hydroworld.com/articles/2015/09/world-s-largest-5-turbine-tidal-array-installed-in-the-oosterschelde-barrier-the-netherlands.html.

International Electrotechnical Commission (IEC). 2014. Microgrids for disaster preparedness and recovery with electricity continuity plans and systems. http://www.iec.ch/whitepaper//pdf/iecWP-microgrids-LR-en.pdf.

Lempriere, Molly. 2017. "CCell: the energy to save coral." *Power Technology*. https://www.power-technology.com/features/ccell-energy-save-coral/.Lin, Daniel. 2017. "How a Pacific Island Changed from Diesel to 100% Solar Power." *National Geographic*. https://news.nationalgeographic.com/2017/02/tau-american-samoa-solar-power-microgrid-tesla-solarcity/.

Lopes, J. A. Peças, C. L. Moreira, and F. O. Resende. 2005. Microgrids Black Start and Islanded Operation. N Proceedings of the 15th PSCC, Liege, 22-26. Pp. 7.

M Power. 2018. Tidal Power Plant in Dutch Delta Works. Accessed February 28, 2018. https://www.mpower-energy.com/projects/eastern-scheldt/.

Maestrale. 2017. Newsletter n.2: April/2017. Accessed on November 9, 2018. https://maestrale.interreg-med.eu/fileadmin/user_upload/Sites/Blue_Growth/Projects/MAESTRALE/Library/Deliverables1streport/MAE_D.2.2.1_Newsletter_2_EN_2017-04.pdf

Marine Power Systems. 2018. "WaveSub: The Future of Energy." Accessed August 10. http://marinepowersystems.co.uk/.

Maritime Journal. 2011. First Commercial Wave Power Plan Opens. July 14, 2011. Accessed November 9, 2018. https://www.maritimejournal.com/news101/marine-renewable-energy/first-commercial-wave-power-plant-opens

McKay, J. 2014. "5 Trends for Emergency Management and Public Safety for 2014 and Beyond." *Emergency Management*. http://www.govtech.com/em/disaster/5-Trends-Emergency-Management-2014.html.

Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-Being*. Island Press

Melillo, Jerry M., Terese (T.C.) Richmond, and Gary W. Yohe, Eds., 2014: Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, 841 pp. doi:10.7930/J0Z31WJ2

Minkel, J. R. 2008. "The 2003 Northeast Blackout-Five Years Later." *Scientific American*. https://www.scientificamerican.com/article/2003-blackout-five-years-later/.

Mustapa, M.A., O.B. Yaakob, Y.M. Ahmed, C. Rheem, K.K. Koh, and F.A. Adnan. 2017. Wave energy device and breakwater integration: A review. *Renewable and Sustainable Energy Reviews* 77, 43-58. https://doi.org/10.1016/j.rser.2017.03.110NOAA. 2017a. "What percentage of the American population lives near the coast?" Accessed April 2, 2018. https://oceanservice.noaa.gov/facts/population.html.

NOAA. 2017b. Climate Change: Global Sea Level. https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level.

NOAA. 2018. Extreme Events. https://www.ncdc.noaa.gov/climate-information/extreme-events

Oregon Department of Energy. 2011. Distributed Energy Resilience Study. Prepared by R.W. Beck for Oregon Department of Energy. Pp.148.

Oregon Department of Energy. 2018. "Renewable Portfolio Standard." Accessed on March 7, 2018. http://www.oregon.gov/energy/energy-oregon/Pages/Renewable-Portfolio-Standard.aspx.

Oregon National Guard. 2013. Initiate Conceptual Design for Camp Rilea Ocean Renewable Energy Program. Prepared for Oregon National Guard under OWET agreement OIC1113.MDS2A2.10.

Pacific Northwest Seismic Network. 2018. "Tsunami Overview." Accessed October 8, 2018. https://pnsn.org/outreach/earthquakehazards/tsunami.

PolitiFact. 2017. "How the U.S. Funds Disaster Recovery." Accessed April 2, 2018. http://www.politifact.com/truth-o-meter/article/2017/sep/14/how-us-funds-disaster-recovery/.

Port of Los Angeles. 2014. Port of Los Angeles Energy Management Action Plan. https://www.portoflosangeles.org/DOC/DRAFT%20POLA%20E-MAP_July%202014.pdf.

Siemens. 2017. Totally Integrated Power-Innovative power distribution for ports & harbors-Concept for profitable and safe electric power distribution. http://w3.siemens.com/powerdistribution/global/EN/consultant-support/download-center/tabcardpages/Documents/Planning-Manuals/Innovative-Power-Distribution-for-Ports-and-Harbors.pdf.

Small, C and Nicholls, R. 2003. "A global analysis of human settlement in coastal zones." *Journal of Coastal Research.* 19 584-599

Struyck, Ryan. 2017. "What past federal hurricane aid tells us about money for Harvey recovery." CNN. https://www.cnn.com/2017/08/31/politics/hurricane-harvey-recovery-money/index.html.

Texas A&M. Undated. "Coastal Resilience." Accessed on January 14, 2019. https://coastalresilience.tamu.edu/.

U.S. Army Corps of Engineers (USACE). 2003. The Corps of Engineers and Shore Protection. National Shoreline Management Study. IWR Report 03-NSMS-1.

USACE. 2018a. Beach Nourishment: Restoring our coast and reducing flood damage risk. Accessed February 23, 2018. http://www.nad.usace.army.mil/Portals/40/docs/Sandy%20Related%20Docs/BEACH%20NOURISHMENT.pdf.

USACE. 2018b. "President's Fiscal 2019 Budget for U.S. Army Corps of Engineers Civil Works Program released." Accessed April 3, 2018. http://www.usace.army.mil/Media/News-Releases/News-Release-Article-View/Article/1438488/presidents-fiscal-2019-budget-for-us-army-corps-of-engineers-civil-works-progra/.

USACE. 2018c. Risk Management Strategies. Accessed on March 13, 2018. http://www.nad.usace.army.mil/CompStudy/Risk-Management-Strategies/.

USACE. 2018d. FACT SHEET - Sea Bright to Manasquan, NJ Beach. U.S. Army Corps of Engineers (USACE). 1984. Shore Protection Manual. Vicksburg, Mississippi, USA.

U.S. Department of Energy. 2015. *United States Electricity Industry Primer*. DOE/OE-0017. https://www.energy.gov/sites/prod/files/2015/12/f28/united-states-electricity-industry-primer.pdf.

U.S. Department of Homeland Security. 2016. *National Response Framework*. Third Edition. Pp. 58. Washington D.C.

U.S. Global Change Research Program. 2014. "National Climate Assessment." https://nca2014.globalchange.gov/.

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

9 Community-Scale Isolated Power Systems

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

April 2019

9. Isolated Power Systems: Community Microgrids

Key Findings

- Many remote communities are currently powered by diesel generation, and some with wind. Although diesel fuel is energy dense and provides on-demand power, it presents operational and logistical challenges. For example, many remote communities in Alaska depend on a few bulk fuel deliveries each year that are susceptible to supply chain disruptions and fuel price volatility.

- The cost range of diesel-generated power for most of the remote Alaska communities varies from $0.50 to over $1 per kilowatt-hour (kWh). For larger and less remote locations, costs are less, in the $0.19–$0.37 per kWh range (Alaska Energy Authority 2016b).

- Remote communities typically have microgrid power systems from 200 kW to 5 megawatts (MW), with high reliability being a key objective. First adopters are environmentally conscious resorts, small villages, and military bases.

- Marine energy technologies, operating individually or in conjunction with other generating sources, could help mitigate reliance on diesel fuel. For communities nearby rivers, reliable power can be produced from river current generators in sufficient capacity to offset a small community's entire load during the summer.

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, according to studies completed by the National Renewable Energy Laboratory. Nearly all are currently dependent on diesel generators for some or all of their power. The energy cost is higher than the national average, sometimes more than $1/kWh, and it varies with the price of oil. The reason the cost is high is largely because of supply chain logistics. Transporting diesel is difficult, expensive, and, in many cases, requires extensive storage capacity.

Remote and isolated communities are not the only groups that suffer from high fuel costs. The U.S. Department of Defense (DOD) operates dozens of bases in similar regions and they are facing significant pressure 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 2018). 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 2016). For the DOD, transporting diesel fuel to forward-operating bases and remote operating adds additional risk to military personnel that must deliver the fuel. Isolated resorts are another category of microgrid consumer, such as fishing resorts in Alaska. 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 marine energy resources: wave energy or tidal current for coastal and island communities and river current for inland locations (Alaska Energy Authority 2016a; Kilcher and Thresher 2016; Kilcher et al. 2016; Figure 9.1). 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 an impetus for marine energy deployment as costs decrease over time.

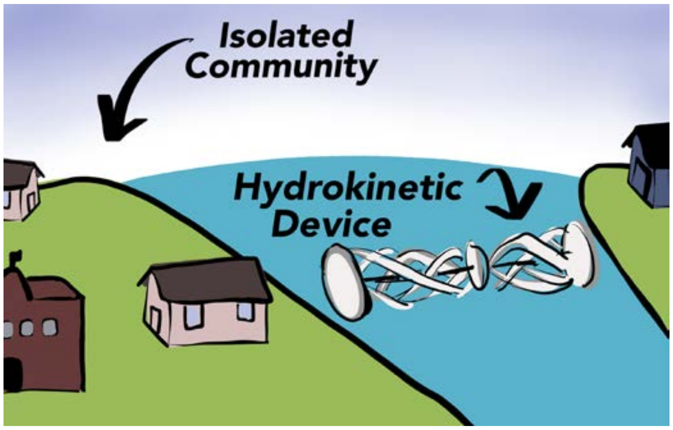


Figure 9.1. Hydrokinetic energy application overview for isolated communities. *Image courtesy of Molly Grear, Pacific Northwest National Laboratory*

If marine energy technology costs become significantly lower than diesel costs, and competitive with solar photovoltaics (PV) and wind, the technologies could improve the financial viability of remote communities by reducing dependency on the state subsidy that is at risk. Cost and availability of PV and wind varies depending on the resource (annual and seasonal), and the logistics for installation and maintenance. If further cost reduction allows costs to fall below the subsidized rate, the cost of living would be further reduced and allow more money to circulate in the local economy. With lower and stable energy prices, the risk barrier for developing new business enterprises is reduced.

Application

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 9.2, many remote communities are currently powered by diesel generation, some with a wind turbine. 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. Although barge delivery of fuel to remote locations is expensive, air freight is far more expensive (Alaska Energy Authority 2016a). 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 9.2. Wind generators with oil storage tanks in foreground. *Image by Ian Baring-Gould, National Renewable Energy Laboratory 16097*

Marine energy 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. Igiugig, 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 because of 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 because of 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 Bering 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 wave energy converter (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 (National Renewable Energy Laboratory undated). 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. Although the wave height varies, 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 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 because of the lack of an ice barrier during winter storms; therefore, the latitude limits for WEC devices in the Bering Seas appear 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 marine energy technologies. Bases always have backup generation on-site for necessary resilience, so the focus will be integrating marine energy generation with existing power sources and/or backup generation to establish effective microgrid capability. The requirements for marine energy technologies will be the same for all generation capabilities (i.e., to ensure that reliable, quality power is available continuously to accomplish DOD missions).

Power Requirements

Remote communities typically have microgrid power systems from 200 kW to 5 MW, with high reliability being 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.

Markets

Description of Markets

By definition, 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 chapter, 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 marine energy 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 coast of Maine, four inhabited islands in the Northern Mariana Islands, and some islands in American Samoa (Kilcher and Thresher 2016). Other major island territories, such as Guam, have larger utilities and are not covered in this report.

There is a growing number of remote and ecotourist resorts. Some are included in the power systems of isolated communities 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 marine energy technologies will still apply. DOD has nine bases in Alaska; about half are coastal and could benefit from marine energy 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). Therefore, a competitive marine energy system could have a large global market space to develop.

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. Although 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 (Alaska Energy Authority 2016a). 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 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 (Alaska Energy Authority 2016b). In Wales, Alaska, two 60-kW wind generators can provide up to 150% penetration. In other words, the wind generators can 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. Because of logistics constraints and grid size, installed wind generators 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 marine energy technologies if they can reduce project cost and demonstrate reliability.

For midlatitude and tropical 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 because of 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 marine energy technologies are available at competitive prices. However, marine energy 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 marine energy technologies offer; cost will be an important but secondary factor.

Geographic Relevance

U.S. markets include coastal and interior Alaska, islands off the coast of Maine, smaller Hawaiian Islands, and smaller territorial islands. Remote resorts are present, from Bering Sea 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 temporary dams.

In high-latitude locations like Alaska, electrical power consumption is greatest in the winter and lowest in the summer. Although 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, a result of 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. This means that river current generation will usually need to be complemented with other generation technologies in the Alaska market. 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.

Marine Energy Potential Value Proposition

Marine energy technologies offer price certainty, relief from transport logistics, and reduced pollution risk. Marine energy devices do not have a fuel cost and are therefore not subject to the energy cost variations that diesel generators have as a result of oil market volatility. Although currently more expensive than other renewable energy technologies, marine energy 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). Marine energy as a part of a mix of generation resources creates a more reliable system because a single point of failure or change in resource has less impact on the system.

The availability and reliability of marine energy varies by resource: river current has an integration advantage because of the near-continuous power generation, and tidal current is predictable and available for most of every day. The short periods of no tidal current generation couple well with energy storage technology. 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 marine energy technologies in complex hybrid systems.

Like all renewable energy, if marine energy 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 generator provides 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 marine energy 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. The lower and slower variation of marine energy technologies could increase the level of penetration before additional storage or demand response is required.

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 2013). Inexpensive storage could eliminate the penetration limits imposed by diesel generators and allow for greater flexibility when using all variable-generation sources including marine energy up to and including 100% penetration.

Beyond this penetration level, storage or demand response is required (Defense Advanced Research Projects Agency undated). 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 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.

Path Forward

The advantage of this market for developing marine energy technologies is that the cost of generated electricity is high; therefore, the cost and performance requirements of marine energy technology must meet are less difficult than the general utility market. Although it will be more expensive to install and maintain marine energy 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. Although 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 (Figure 9.3). 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.

Figure 9.3. Ice breakup on the Yukon River in Alaska. *With permission from yukonriverbreakup.com*

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 because of 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 financial, 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 marine energy devices need better integration management controls for microgrids so developers can incorporate marine energy 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 marine energy device type and configuration, it may or may not have inertia (resistance to rapid changes in frequency) like the diesel generators have because of their spinning mass being electrically directly coupled to the grid. Technology for synthetic inertia in generation connected through inverters has been developed and commercially deployed with large wind power plants in Quebec, Canada.

Potential Partners

This market can serve as a development step for marine energy technologies in that it provides a 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. There are financial hurdles unique to these small applications, such as the cost of developing feasibility studies being high per dollar of project and finding financing sources for small projects that are using new technology. The U.S. Department of Energy has an Office of Indian Energy Policy that periodically releases funding opportunities to help tribal governments and communities develop local energy resources.

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, then 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,[14] and the Strategic Environmental Research and Development Program,[15] which targets prototype test projects and early market entrance projects; and the Energy Resilience and Conservation Investment Program,[16] which targets commercially viable energy technologies that enhance base energy, security, and resilience.

---

[14] https://serdp-estcp.org/About-SERDP-and-ESTCP/About-ESTCP

[15] https://serdp-estcp.org/About-SERDP-and-ESTCP/About-SERDP

[16] http://www.hnc.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-View/Article/490653/energy-division-energy-conservation-investment-program-ecip-validation/

References

Alaska Energy Authority. 2016a. Power Cost Equalization Program: Statistical Data by Community (obtained spreadsheet of the data). The State of Alaska, Department of Commerce, Community, and Economic Development, Alaska Fuel Price Report: Current Community Conditions. https://www.commerce.alaska.gov/web/Portals/4/pub/Fuel_Price_Report_July_2016.pdf.

Alaska Energy Authority. 2016b. "Renewable Energy Atlas of Alaska – A Guide to Alaska's Clean, Local, and Inexhaustible Energy Resources." Accessed April 20, 2018. http://alaskarenewableenergy.org/index.php/focusareas/renewable-energy-atlas/.

Defense Advanced Research Projects Agency. Undated. "Creating Breakthrough Technologies and Capabilities." https://www.darpa.mil/.

Defense Science Board. 2016. Task Force on Energy Systems for Forward/Remote Operating Bases – Final Report. http://www.dtic.mil/dtic/tr/fulltext/u2/1022571.pdf.

Demer, Lisa. 2016. "Bush Alaska locked into high gas prices for fuel delivered last summer and fall." *Anchorage Daily News*, May 31, 2016.

Energy Resilience & Conservation Investment Program Validation. 2018. Energy Division – Energy Resilience & Conservation Investment Program. Fact Sheet. http://www.hnc.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-View/Article/490653/energy-division-energy-conservation-investment-program-ecip-validation/.

GE Reports Staff. 2017. "Power and Light for 13,000 Indonesian Villages." Accessed April 1, 2018. https://www.ge.com/reports/power-light-13000-indonesian-villages/.

Kilcher, Levi, and Robert Thresher. 2016. *Marine Hydrokinetic Energy Site Identification and Ranking Methodology Part I: Wave Energy* (Technical Report). NREL/TP-5000-66038. Golden, CO (US): National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy17osti/66038.pdf.

Kilcher, Levi, Robert Thresher, and Heidi Tinnesand. 2016. *Marine Hydrokinetic Energy Site Identification and Ranking Methodology Part II: Tidal Energy* (Technical Report). NREL/TP-5000-66079. Golden, CO (US): National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy17osti/66079.pdf.

National Renewable Energy Laboratory. Undated. U.S. State Solar Resource Maps. https://www.nrel.gov/gis/solar.html.

Power and Water Corporation. 2013. *Solar/Diesel Mini-Grid Handbook*. http://acep.uaf.edu/media/87693/SolarDieselGridHandbook.pdf.

U.S. DEPARTMENT OF
ENERGY
Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

10 Other Applications

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

April 2019

10. Other Applications

This chapter identifies opportunities for future exploration that were not studied in-depth in other chapters of this report. Additional applications for marine energy cover various topics, including electrified and hydrogen-fueled marine transportation (e.g., boats and aircraft, as shown in Figure 10.1), off-grid charging for industrial and consumer applications, ocean pollution cleanup and marine conservation, subsea communications, and offshore data centers. These different applications cover a range of technology readiness levels, from those that are in the conceptual-only stage to others with demonstrated pilot projects and paths to commercialization.

Key Findings

- Global pressures to reduce greenhouse gas emissions and improve local air quality are causing vessel operators and ports to modify engine systems. Modifications include using cleaner-burning fuels (e.g., liquid natural gas), diesel-electric hybrids, converting to fully electric operation, or incorporating hydrogen fuel cells. Demand for these technologies, as well as the fuel and energy to power and charge them, respectively, will increase. Marine energy's obvious colocation benefits may make them well-suited as an energy provider.

- Portable electronic devices have created a global market for charging technologies, especially in areas without access to the electrical grid. The two primary off-grid charging solutions are portable battery packs and small transportable solar photovoltaic (PV) panels. Opportunities exist for marine energy to develop small charging systems using river or ocean resources.

- There are potential markets for marine renewable energy technologies within the marine conservation space; including ocean pollution cleanup, oil spill cleanup, and coral reef restoration. Applications for marine energy within these markets are limited at the moment and presently more concentrated nearshore.

- Data centers, in aggregate, are becoming one of the largest consumers of electricity in the world. As site development area for data centers diminishes on shore, some companies will look to deploy server farms offshore. Microsoft has even begun investigating subsea data centers enclosed in watertight containers. The ocean provides free cooling, historically one of the greatest costs in operating a data center, as well as the potential to receive locally sourced power from marine energy.

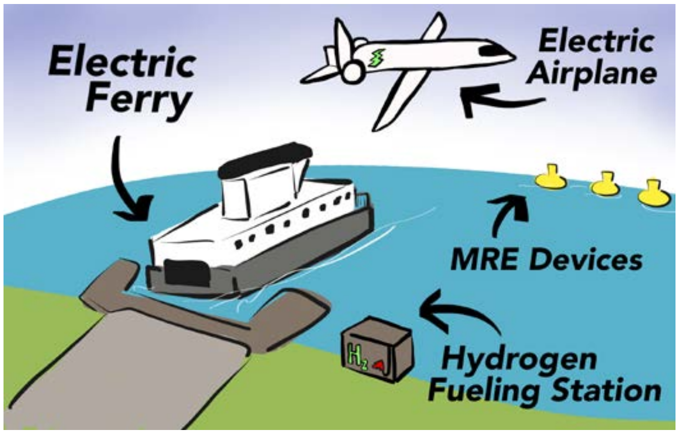


Figure 10.1. Marine renewable energy (MRE) applications for electric and hydrogen-fueled marine transportation. *Image courtesy of Molly Grear, Pacific Northwest National Laboratory*

Marine Transportation: Powering Boats and Aircraft

Potential Marine Energy Application and Market

There are several different opportunities for using marine energy. 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. On a much smaller scale, charging could also be used for moored recreational power boats, which use batteries to start their engines, and for remotely operated or semiautonomous work boats (e.g., ASV Global's unmanned marine systems). Concepts also exist for integrating wave energy technologies directly into boat hulls, thus circumventing the need for charging stations (The Maritime Executive 2017). 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 (e.g., moored, station kept, or floating unmoored) for water surface and airborne craft to use for recharging to "hop" and extend useful ranges. As discussed in Chapter 6, another opportunity for powering vessels from marine energy would be through the production of hydrogen from seawater and the subsequent fueling of vessels with hydrogen-powered propulsion systems.

Global pressures to reduce greenhouse gas emissions and increase local air quality are causing significant changes to the shipping sector. According to the International Maritime Organization, the United Nations body that regulates the shipping industry, shipping accounts for approximately 3.1% of annual global CO_2 emissions and 15% of annual global NO_x emissions (International Maritime Organization 2014). The organization has set requirements for cutting greenhouse gas emissions—including a 2020 global 0.5% sulfur cap affecting up to 70,000 ships, which has created significant pressure 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) by using diesel-electric hybrids, converting to fully electric vessels, or incorporating hydrogen fuel cells. One company, Wärtsilä, has developed a wireless charging system for easy transfer of power from the shore to a docked vessel. This inductive charging technology is particularly suitable for fully electric vessels using batteries that spend little time at the dock, such as ferries.

Figure 10.2. The first all-electric ferry operating in Noray, the MF Ampere (left) and the Port-Liner fully electric canal cargo vessel in development and capable of autonomous operation (right). *Sources: www.siemens.com/press and Port-Liner*

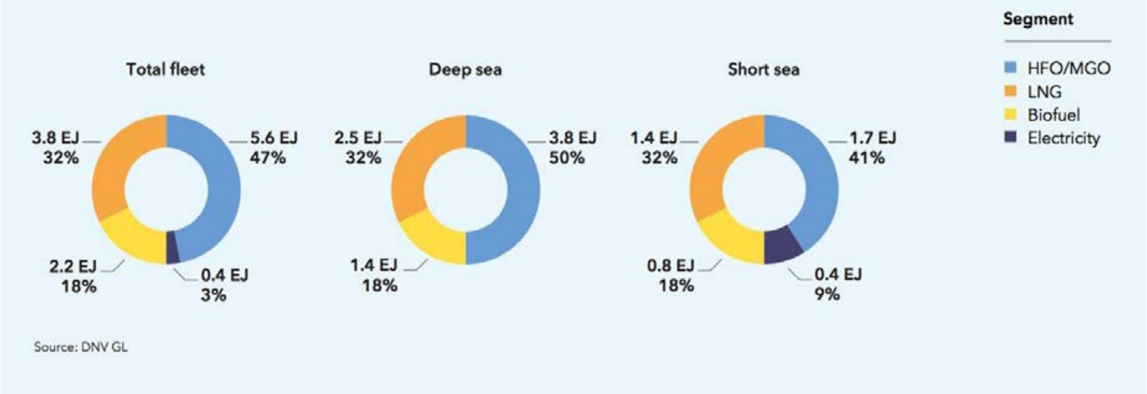
A ramp-up of research, development, and implementation of electrification and automation in global shipping fleets is occurring, but it lags behind terrestrial transportation and focuses on short-distance trips. Some companies are developing, and customers are using, fully electric vessels for passenger ferries and short-haul cargo transport in canals and rivers, along with recreational craft (DNV GL 2017a, 2017b; Guarnieri 2018). Electric ferries are presently in operation in Norway, and the first fully electric barges will soon be launched in the ports of Amsterdam, Antwerp, and Rotterdam (Figure 10.2), with more than 4 megawatt-hours of battery packs inside the largest ships. Recently, a 600-passenger electric hybrid ferry, the Enhydra, was put into service in San Francisco Bay, using lithium-ion battery packs, an electric traction motor, and a biodiesel-powered engine. In 2017, the Washington State Department of Commerce launched an initiative called Washington Maritime Blue, with a vision to convert the state ferry system to electric propulsion, including electrification of the state's three largest ferries as a priority demonstration project.

A Norwegian delegation was invited to Washington to share best practices on cluster formation and electrification in support of the state's Maritime Blue strategy (The Maritime Executive 2018). As part of the strategy, DNV GL conducted a global benchmarking of Washington against global maritime capitals of the world. Another concept has also been presented for integrating wave power systems directly into a ship's hull to convert wave energy into compressed air, which could be used as potential energy or on demand to generate electricity (The Maritime Executive 2017). Similarly, it is possible that wave-dampening systems used on recreational boats that are anchored or moored could be designed to capture this wave energy and use the energy to charge batteries and store power for electric propulsion.

The world's first fully electric and potentially autonomous container barges are expected to be operating soon in the Netherlands. Five barges able to carry twenty-four 20-foot containers weighing up to 425 tonnes for 15 hours will be in operation, with six larger 110-meter-long barges, carrying 270 containers capable of running for 35 hours in development (Holter and Hodges 2018). Also in 2018, 185 battery-powered ships will be operational or scheduled for delivery worldwide, most in Norway and France (DNV GL 2017b). A total of 7,300 inland ships in Europe are anticipated to eventually be electric (Holter and Hodges 2018).

A significant number of electric vessels are forecast to be operational by 2040 and 2050. The DNV GL (DNV GL 2017a) analysis supporting this forecast assumes that batteries will only be capable of powering small vessels for short-haul operations, presumably because of energy density and battery costs (Figure 10.3). Short-haul sea shipping will use 37% of the total energy, or 4.3 exajoules, and in this sector, electricity can constitute a significant share (9%) of energy use, comprising 0.4 exajoules (DNV GL 2017b) (Figure 10.3).

For cutting greenhouse gas emissions, hydrogen-powered vessels can provide another zero-emissions alternative, if the hydrogen is produced from renewable energy, such as from seawater electrolysis using marine energy. Hydrogen is considered by some shipping industry executives and energy experts to be the fuel of the future for cruise liners, ferries, and container ships (Tullis 2018). This presents an opportunity for marine energy to produce the hydrogen for fueling these vessels and make it locally available, such as at port refueling stations. For example, the European Marine Energy Center is producing hydrogen gas to store unused renewable energy produced from tidal and wind energy (European Marine Energy Centre 2017). The hydrogen is then transported to the main Orkney island for use in the intraisland ferry system and land transport.



Source: DNV GL

Figure 10.3. DNV GL forecasts a shipping energy mix by 2050 with 37% of total shipping energy use (4.3 exajoules) in short-sea shipping, and in this sector, electricity constitutes a significant share (9%) of energy use. Note: HFO = heavy fuel oil and MGO = marine gas oil. *Source: DNV GL (2017b)*

Several factors are likely to drive transition to hydrogen-fueled vessels, including increased environmental regulations around carbon emissions, the ability to generate hydrogen locally from electrolyzers, and the anticipated decreases in the costs of fuel cells. Several pilot projects are underway using hydrogen as a transportation fuel, including for towboats, passenger ships, ferries, and short-haul truck routes, as discussed in Chapter 6. Construction of the first hydrogen cell boat, dubbed Water-Go-Round, is expected to be completed by September 2019 and operate as a passenger ferry in San Francisco Bay. Although never turned into a working prototype, a fuel-cell vessel was previously considered for the San Francisco Bay Area through a feasibility study conducted by Sandia National Laboratories on a high-speed, 150-passenger design, called SF-BREEZE (Pratt and Klebanoff 2016). For longer distance travel, a recent Sandia National Laboratories report demonstrated the technical and economic feasibility of a hydrogen-powered research vessel (dubbed the ZERO-V), which would need to go at least 2,400 miles, or 15 days, before requiring a refuel, which is enough to get from San Diego to Hawaii (Klebanoff et al. 2018).

Aircraft

The use of autonomous and remotely operated electric-propelled aircraft is rapidly growing for commercial purposes, emergency management, military operations, and environmental monitoring. Fully electric passenger aircraft are in development, including autonomous vertical takeoff or landing crafts, such as Cora from Kitty Hawk, with stated speeds of more than 150 kilometers per hour and a range in excess of 100 kilometers (Kitty Hawk 2018). The National Aeronautics and Space Administration (NASA) has an active program, X-57, developing an electric aircraft with a speed of 172 miles per hour (mph), 140 kilowatts continuous, 300 kilowatts maximum, 69.1 kilowatt-hours (47 kilowatt-hours usable) (NASA 2017; Figure 10.4). Other examples include Lilium's first electric vertical takeoff and landing jet and Airbus' development of a flight demonstrator testing a 2-megawatt hybrid-electric propulsion system.

Numerous companies are also developing short transport air taxis, including Joby Aviation, which is designing an aircraft to hold five people with a range of more than 150 miles on one charge and that is "100 times quieter during takeoff and landing than a helicopter and near-silent during flyovers" (Vance and Stone 2018). Further, aerial drones are being used for a variety of coastal and offshore applications, including delivery of shipments to maritime industries (e.g., Wilhelmsen Ship Services), and are currently limited by range and duration.

Figure 10.4. NASA X-57 aircraft. *Source: NASA Langley/Advanced Concepts Lab, AMA, Inc.*

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. Extended utilization of both electric and autonomous craft could serve multiple applications, including scientific missions, weather monitoring, military and homeland security, and passenger travel. These charge stations could also be combined with underwater vehicle charge stations, and in locations where this dual purpose could be useful.

Path Forward

Opportunities could exist off grid, such as charging stations in remote terrestrial locations or locations without grid accessibility, or at sea (e.g., moored, station kept, or floating unmoored) for craft to use recharge and extend ranges. The requirements of these recharge stations should be compared with 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- and hydrogen-powered vessels will depend on evolving regulations, fuel costs, battery energy densities and costs, and fuel cell commercialization and costs. System life cycle cost and value analyses should be conducted for different shipping use cases to assess the utility, limitations, and key hurdles for electrified and hydrogen-powered water transport across areas without feasible grid connection. Marine energy's relative or collaborative potential contribution to charging station power and hydrogen refueling stations can then be assessed from this perspective.

Off-Grid Small Device Consumer and Industrial Charging

Potential Marine Energy 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 Market Insights 2017; Research Nester 2018). At present, the two primary off-grid charging solutions are portable battery packs and small transportable solar PV panels (Figure 10.5). The majority of off-grid charging of small personal electronic devices is accomplished with portable battery packs, typically in the 5,000–50,000 milliampere hour (mAh) range. Larger-scale battery packs are also available, serving applications such as buildings or townships, and an early pilot project between Tesla and Nova Innovation has demonstrated integration of tidal power and battery storage. 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/ampere hour, or about $40 for a battery that can charge three smartphones with one charge.

Figure 10.5. Pocket Power 15K Power Bank, Belkin, the connected things division of Foxconn Interconnect Technology, and solar PV charger (Goal Zero Nomad 14 $150, 14-W Peak). *Sources: Belkin and Goal Zero*

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- to 50-watt (W) range are more suitable. These PV-battery systems have seen increased adoption as prices have decreased within recent years (Wu et al. 2017; World Bank 2018). These smaller PV systems are now available commercially around $12/W or $80 for a 7-W peak panel that can charge one phone in a few hours with decent solar irradiance. Panels are also now more flexible and can be incorporated into clothing, packs, and other equipment (Wu et al. 2017).

In addition, small wind turbines are available for off-grid charging and are a competitor on the scale of watts to kilowatts. New portable consumer wind generators are 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. Microwind turbines are available in the 20- to 500-W range (U.S. Department of Energy 2018), with several commercially available and some portable. For example, in 2011, Arista Power introduced a line of human-portable, three-bladed microwind turbines designed to provide battery charging capability at remote and off-grid locations for military and other applications. These operate in wind speeds of 7–45 mph. Primus Wind Power also sells a series of off-grid, small-scale wind turbines for both marine- and land-based applications. These wind systems fill a small niche market that could be competitive with marine energy applications.

New hybrid technologies combine the ability to produce power from both wind and water. For example, the flexible WaterLily wind and water turbine system has recently 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 (Figure 10.6). The turbine is anchored with a supplied cord in the current, and a power cable is run to shore to charge devices directly or to the 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 a PV system at $12/W.

Figure 10.6. WaterLily—A water and wind turbine for charging personal electronics (www.waterlilyturbine.com). *Source: WaterLily*

Turbine systems for charging batteries on boats have been available commercially for some time (e.g., Watt and Sea Hydrogenerators, Eclectic Energy Sail-Gen, and Save Marine Hydrogenerator). For instance, the Watt and Sea Hydrogenerator 300-W 12-volt (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 10.7).

Figure 10.7. Watt and Sea Hydrogenerator 300-W 12-V Cruising 24”. *Source: Watt and Sea*

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

Path 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 and market traction). A cheap, easily deployed, marine renewable energy charger would likely be useful to hikers, recreational boaters, and off-grid coastal communities. It could also have potential application for survival craft, such as lifeboats and life rafts, that have limited available sources of energy.

Ocean Pollution Cleanup and Marine Conservation

Potential Marine Energy Application and Market

There are potential markets for the application of marine renewable energy technologies to marine conservation topics, including ocean pollution cleanup, oil spill cleanup, and coral reef restoration. Plastic debris and contaminants in the ocean are pervasive and physically harmful to wildlife and the environment. Marine plastic has even been found in seafood destined for human consumption (Rochman et al. 2013a, 2013b; Browne et al. 2008; Lithner, Larsson, and Dave 2011; Teuten et al. 2009). No one knows exactly how much plastic is 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 1 ton of plastic. By 2050, the ratio will be 1:1 (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. In addition to the collection of plastics, marine energy potentially adds a method to collect surface slicks of spilled petroleum and other contaminants, having the additional benefit of cleaning the environment and protecting wave power and desalination equipment from hydrocarbon fouling. An additional marine conservation application that could potentially utilize marine energy includes the restoration of coral reefs, such as using wave energy to support reef restoration via electrolysis of seawater to produce limestone.

Most debris that makes it to the ocean eventually winds 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” because of the prevalence of trash (Figure 10.8). There are five major gyres in the world’s oceans, and each contains plastic debris. When it comes to cleanup efforts, the best solutions are those that prevent trash from reaching the ocean. However, there is an immense amount of plastic already in the ocean, and it needs to be removed before it degrades into dangerous microplastics.

Figure 10.8. Illustration of Pacific Ocean garbage patches. *Image from National Oceanic and Atmospheric Administration*

Although there are many proposed technical solutions to address ocean plastic pollution, three popular examples include:

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 solutions are examples of coastal cleanup efforts; they attempt to remove trash and debris from the water before it reaches a major body of water. Some of these devices are within easy access of a grid connection, but for other applications, marine energy provides the best power option due to proximity to strong currents or waves. For example, the Trash Wheel converts river currents into mechanical energy to power its conveyor belt for trash collection.

The Ocean Cleanup 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 cleanup devices for each of the major gyres.

In addition to marine plastics, various other types of contaminants in the marine environment can impact marine life and human health, including oil spills. According to the National Oceanic and Atmospheric Administration’s (NOAA’s) Office of Response and Restoration, oil spills of varying size happen along U.S. coasts, the Great Lakes, and rivers almost every day, with involvement of federal agencies in more than 100 responses to spills or vessel groundings each year (NOAA 2018a). Given the frequency of spills, development of methods for efficient oil-water separation has been of global interest. The environmental and economic demands highlight the urgent need for functional materials that can achieve oil/water separation efficiently. In ocean settings, oil spills can spread over large distances and persist for weeks to months, with associated response cleanup methods requiring sustained power over the course of a spill. Although largely unexplored, ocean energy could potentially power the oil-water separators, skimmers, and other cleanup methods used to collect surface contaminations of spilled petroleum and other pollutants.

There are a variety of semiautonomous vehicles being used in ports and harbors to help with cleanup, though nothing at a significant scale yet. For example, the WasteShark is being used to collect plastic, algae, and weeds in marinas and is even capable of collecting oil from the surface of the water. It is an unmanned electric catamaran that primarily gets its power from solar panels and storage in onboard batteries. In addition, Chicago nonprofit Urban Rivers developed a prototype floating robot to help clean up trash from the Chicago River and is developing designs for next-generation models.

An additional marine conservation application that could utilize marine energy technologies includes the restoration of coral reefs, which are being threatened around the world. As temperatures rise, mass coral bleaching events and infectious disease outbreaks are occurring more frequently, and the rising acidity of the oceans threatens reefs by making it harder for corals to build their skeletons (NOAA 2018b). Novel ways are being explored to repair these reefs by using electricity to accelerate coral growth on steel frames. For example, Zyba developed the patented CCell technology, an ultralightweight wave energy converter to generate electricity and grow artificial coral reefs from minerals in the water through an electric process known as Biorock. These techniques are currently being used in various locations to stimulate coral growth, including the Great Barrier Reef and Bali (Smithsonian 2016; New Scientist 2018).

Path Forward

There is a global need in the world's oceans for the development of technologies to efficiently remove marine debris and contaminants from seawater, given their pervasive and destructive nature, and to otherwise aid in marine conservation efforts. Removing plastic debris from the ocean is costly and unregulated. Should cleanup efforts to remove ocean plastic from remote or at-sea locations gain traction and funding, the requirements of cleanup systems should be compared with the costs and value of appropriate marine-energy-, wind-, and/or PV-energized charging stations, or hybrid systems inclusive of multiple renewable energy technologies. With regard to oil spills, federal spill response efforts are triggered for spills of a certain size and use various techniques for minimizing the impacts of hydrocarbons on the marine environment and human health. There may be an opportunity to incorporate marine energy devices into powering oil-water separators, which could be explored in partnership with federal agencies (e.g., NOAA and the United States Coast Guard) and companies and universities actively supporting spill response efforts. In addition, marine energy has the potential to aid in the conservation and restoration of coral reefs, such as has been demonstrated using lightweight wave energy converters to grow artificial reefs off some coastal communities.

Offshore Communications

Potential Marine Energy Application and Market

An expansive network of underwater communications infrastructure plays a critical role in global data transmission. This network comprises submarine communications cables that are laid on the seabed between land-based stations and carry telecommunication signals across the oceans (Figure 10.9). As of early 2018, there were approximately 448 submarine cables in service around the world, equating to more than 1.2 million kilometers of submarine cables in service globally (TeleGeography 2018). A vast majority (99%) of all transoceanic data traffic goes through undersea cables, including internet usage, phone calls, and text messages, at a speed that is up to eightfold faster than satellite transmissions (Starosielski 2015). Modern submarine cables use fiber-optic technology with optical fiber repeaters that are powered by a constant direct current passed down the conductor, near the center of the cable, and power feed equipment is installed at the terminal stations. Marine renewable energy may present an opportunity for powering new cables, as well as the network of environmental sensors that have been proposed for integration into these cables (Lentz and Howe 2018).

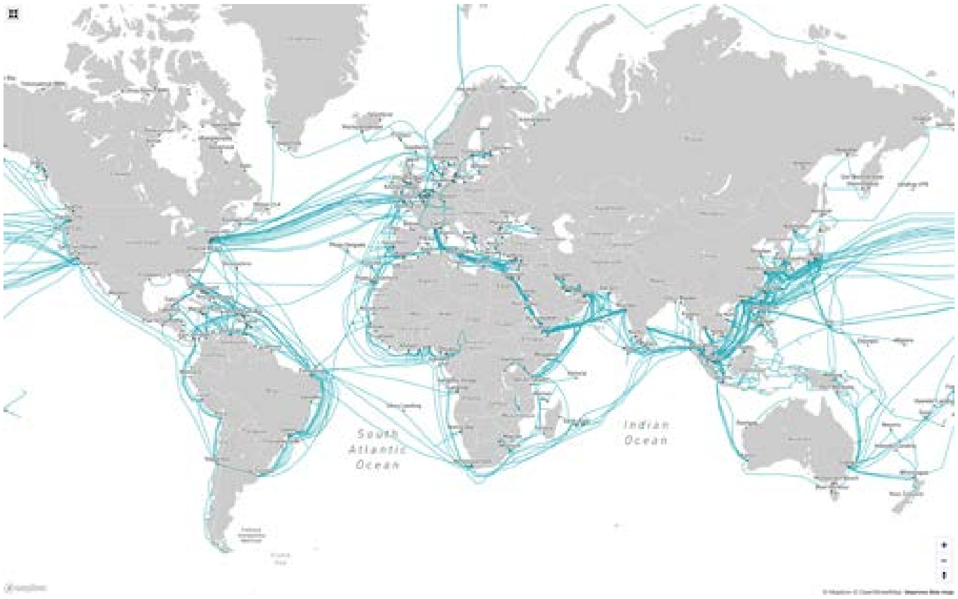


Figure 10.9. Map of global operational submarine cables. *Source: ©Network Atlas (www.networkatlas.com); Image courtesy of Kapany Networks, Inc.*

The International Telecommunication Union; Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization; and the World Meteorological Organization established a joint task force in late 2012 to investigate the use of submarine telecommunications cables for ocean and climate monitoring and disaster warning. Two of the technical challenges for integrating environmental sensors into submarine cables include power consumption limits and delivery of power to external sensors (Lentz and Howe 2018). The additional power required by integrating scientific sensors into cables could be provided by marine renewable energy at each of the nodes where sensors are installed, likely at the optical fiber repeaters.

Another potential underwater communications market for marine energy applications is represented in the underwater acoustics market. According to a recent market research report, the underwater acoustic communication market is expected to grow from $1.31 billion in 2017 to $2.86 billion by 2023 (MarketsandMarkets 2018). Several major factors are identified as driving the growth of this market, including the increase in the adoption of underwater acoustic modems in the oil and gas and naval defense sectors. As discussed in Chapter 3, autonomous underwater vehicles can also be equipped with underwater acoustic modems that are used for communications because they explore the ocean and gather data during monitoring missions. These autonomous underwater vehicles could potentially be recharged at stations powered by marine energy.

Path Forward

Underwater communication networks of both fiber-optic cables and acoustic modems play a critical role in various sectors, including global telecommunications, the energy industry, defense operations, and ocean observing. There are also proposals to couple environmental sensors into submarine cables for ocean and climate monitoring and early disaster warning—an application that would require additional power sources. As these communication networks continue to develop, and environmental monitoring networks are integrated, there may be an opportunity for marine renewable energy to power these systems. For example, marine energy could be integrated at the telecommunication cable repeaters, where it has also been proposed that integration of environmental sensors would occur. Opportunities for partnering include major telecommunications companies, the oil and gas sector, the U.S. Navy, and universities. They also consist of the International Telecommunication Union; Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization; and World Meteorological Organization Joint Task Force.

Offshore Data Centers

Potential Marine Energy Application and Market

The explosion of cloud computing and internet-based content—from movie streaming to cryptocurrency mining—has created significant growth and evolution in the build-out of server centers. These servers have a tremendous electricity demand; in the United States alone it represents 70 terawatt-hours per year, or almost 2% of total U.S. electricity consumption in 2014 (Shehabi et al. 2016). Customers in this market require uninterrupted power and often have 100% renewable energy targets, but they remain price sensitive, which limits the type of renewable energy utilized. Data centers need electricity for powering the computer servers and auxiliary systems, often referred to as "energy overhead." Historically, cooling has represented a large part of a data center's energy overhead, but in recent years this portion has been decreasing because of improved efficiencies in hardware and facility design (Cutler et al. 2017). Still, companies look for opportunities to reduce this cost. For example, companies such as Google, Microsoft, and Nautilus Data Technologies have been experimenting with using water, including seawater, for cooling instead of the more common air-cooling methods (e.g., Figure 10.10). Evolving small "edge caching" data centers, located near coastal population centers, increasingly need rapid paths to deployment and scalability, reduced costs, and access to reliable renewable power (NOAA 2017; Microsoft 2018).

Figure 10.10. Google data center opened in 2011 in Hamina, Finland (left) with closed-loop water cooling (right). *Source: ©2018 Google LLC, used with permission. Google and the Google logo are registered trademarks of Google LLC*

As costs and reliability of marine energy technologies continue to improve, they have the potential to provide local, renewable power to shore- and sea-based data centers, reduce cooling electrical loads, and share infrastructure and installation and operation and maintenance efforts. These technologies can also be part of a rapidly scalable edge node system at coastal population centers and in remote communities. Other data center types, including temporary data centers for emergency and military management, require extreme ease of deployment and reliability, along with proven integration with storage and backup generation sources. Further, marine energy devices have the potential to replace or extend diesel supplies and operational times for these temporary centers. Combined, this is a potential multibillion-dollar market and is only expected to grow as computing needs increase (Jones Lang LaSalle IP, Inc. 2017; RECAP 2017).

The data center sector is rapidly expanding and evolving, with major players, such as Amazon, Microsoft, 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; International Data Corporation 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" (RECAP 2018). Many of these data centers are located in areas with inexpensive, reliable electricity, and some have been located in northern latitudes to leverage 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 and increase 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 (i.e., extending close to the customer and possibly even on-site, for both commercial and residential) and will host cached content, known as "edge caching" (Figure 10.11). These small centers could have tens to hundreds of servers and typically have power loads in the tens to hundreds of kilowatts and potentially larger.

Off-grid temporary or "pop-up" data centers for events, emergency response, or military operations are now regularly utilized. These are typically mobile truck-based or container-based systems with only a few servers and 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 10.11. Edge data center from Edge Micro. *Photo from edgemicro.com*

Data centers between the temporary and hyperscale data center extremes also exist. This is a highly dynamic sector that is quickly evolving as a result of 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.

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 of high-quality power, are typically grid connected, and employ backup storage and power supplies. The Project Natick modular subsea data center recently deployed by Microsoft (and discussed more in the upcoming sections) is a 240-kilowatt data center module with 12 racks containing 864 standard Microsoft data center servers and 27.6 petabytes of disk (Microsoft 2018; Figure 10.12). This data center is as powerful as several thousand high-end consumer personal computers and has enough storage for about 5 million movies. Temporary data centers with few servers and low power requirements (hundreds of kilowatts) are currently either grid connected with some battery backup, and/or powered by diesel generators.

Figure 10.12. Microsoft Project Natick Phase 2–modular submersed server with renewable ocean energy and ocean cooling, Scotland. *Photo by Scott Eklund/Red Box Pictures*

Path Forward

Customers for marine energy power specific to data centers would be any of the large technology firms that build and operate data centers, such as Amazon, Microsoft, Google, Apple, 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 interest in pop-up data centers that could be powered by marine energy. The Federal Emergency Management Agency utilizes and sponsors activities in disaster preparedness and response and could be a potential partner for temporary data center development and deployment. Local renewable power enables replacing or supplementing diesel-supplied power. Simple and fast setup paired with very high reliability is essential for these markets. 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. Lastly, offshore oil and gas service providers are also potential partners worth investigating if pursuing offshore data center developments.

References

Browne, M. A., A. Dissanayake, T. S. Galloway, D. M. Lowe, and R. C. Thompson. 2008. "Ingested microscopic plastic translocates to the circulatory system of the mussel, Mytilus edulis (L)." *Environ. Sci. Technol.* 42, 5026–5031. https://www.ncbi.nlm.nih.gov/pubmed/18678044.

Cisco. 2016. Cisco Global Cloud Index: Forecast and Methodology, 2015–2020. http://www.cisco.com/c/dam/en/us/.

Cutler, Ben, Spencer Fowers, Jeffrey Kramer, and Eric Peterson. 2017. "Want an Energy-Efficient Data Center? Build It Underwater." *IEEE Spectrum*. https://spectrum.ieee.org/computing/hardware/want-an-energyefficient-data-center-build-it-underwater.

DNV GL. 2017a. "Low Carbon Shipping Towards 2050." Accessed April 8, 2018. https://www.dnvgl.com/publications/low-carbon-shipping-towards-2050-93579.

DNV GL. 2017b. "Energy Transition Outlook 2017: Maritime Forecast to 2050." Accessed April 8, 2018. https://eto.dnvgl.com/2017/maritime.

European Marine Energy Centre. 2017. "World's first tidal-powered hydrogen generated at EMEC." Accessed April 8, 2018. http://www.emec.org.uk/press-release-worlds-first-tidal-powered-hydrogen-generated-at-emec/.

Gartner. 2016. Top 10 Technology Trends Impacting Infrastructure & Operations. http://www.gartner.com/smarterwithgartner/.

Genesis Market Insights. 2017. Portable Solar Charger Market By Type (Amorphous solar charger, Mono-crystalline solar charger, Hybrid solar charger, Poly-crystalline solar charger) By Application (Backpack portable solar charger, Small portable solar charger, Fold out portable solar charger) - Global Outlook Analysis and Industry Forecast, 2018–2023. https://www.genesismarketinsights.com/viewreport/80/30/Portable-Solar-Charger-Market-.

GOV.UK. 2018. Future of the Sea: A Report from the Government Chief Scientific Adviser. Government Office for Science, United Kingdom. Accessed April 8, 2018. https://www.gov.uk/government/collections/future-of-the-sea.

Guarnieri, M. 2018. Electrifying Water Buses: A Case Study on Diesel-to-Electric Conversion in Venice. Institute of Electrical and Electronics Engineers. Industry Applications Magazine, Vol. 24, Issue 1, Page 42. January 2018.

Holter, M., and J. Hodges. 2018. "The Next Ferry You Board Might Run on Batteries." *Bloomberg*, March 12, 2018. https://www.bloomberg.com/news/features/2018-03-13/the-next-ship-you-board-might-run-on-batteries.

International Data Corporation. 2017. Worldwide Semiannual Public Cloud Services Spending Guide. https://www.idc.com/getdoc.jsp?containerId=prUS42321417.

International Maritime Organization. 2014. Reduction of GHG Emissions from Ships. Third IMO GHG Study - Final Report. Marine Environment Protection Committee 67th Sessions. Accessed November 30, 2018. http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/MEPC%2067-INF.3%20-%20Third%20IMO%20GHG%20Study%202014%20-%20Final%20Report%20(Secretariat).pdf.

Jones Lang LaSalle IP, Inc. 2017. Data Center Outlook: A Wave of Global Momentum. North America. http://www.us.jll.com/united-states/en-us/Research/.

Kitty Hawk. 2018. "Meet Cora." YouTube video, 2:45. Posted by Kitty Hawk, March 12, 2018. https://www.youtube.com/watch?v=LeFxjRMv5U8.

Klebanoff, Leonard E., Joseph W. Pratt, Robert T. Madsen, Sean A. M. Caughlan, Timothy S. Leach, et al. 2018. Feasibility of the Zero-V: A Zero-Emission, Hydrogen Fuel-Cell, Coastal Research Vessel. Sandia National Laboratory Report, SAND2018-4664. Accessed November 26, 2018. https://energy.sandia.gov/transportation-energy/hydrogen/market-transformation/maritime-fuel-cells/.

Lentz, S. and B. Howe. 2018. SMART Cable Systems: Integration of Sensors into Telecommunications Repeaters, IEEE/MTS Oceans Kobe. Accessed November 1, 2018. https://www.itu.int/en/ITU-T/climatechange/task-force-sc/Documents/Lentz-Howe-OceansKobe-SMART-cables-sensor-integration.pdf.

Lithner, D., A. Larsson, and G. Dave. 2011. "Environmental and health hazard ranking and assessment of plastic polymers based on chemical composition." *Sci. Total. Environ*. 409, 3309–3324. https://www.ncbi.nlm.nih.gov/pubmed/21663944.

The Maritime Executive. 2017. Wave Energy Concept Ready for Ship Propulsion. Accessed November 1, 2018. https://www.maritime-executive.com/article/wave-energy-concept-ready-for-ship-propulsion.

The Maritime Executive. 2018. Norway's Experience Helps Washington Ferries Go Electric. Accessed November 26, 2018. https://www.maritime-executive.com/article/norway-s-experience-helps-seattle-ferries-go-electric.

MarketsandMarkets. 2018. "Underwater Acoustic Communication Market by Interface Platform, Communication Range, Application (Environmental Monitoring, Pollution Monitoring, Climate Recording, Hydrography, Oceanography), End User, and Geography—Global Forecast to 2023." Accessed November 1, 2018. https://www.marketsandmarkets.com/PressReleases/underwater-acoustic-communication.asp.

Microsoft. 2018. "Project Natick." Accessed October 29, 2018. http://natick.research.microsoft.com/.

National Atmospheric and Space Administration. 2017. NASA Armstrong Fact Sheet: NASA X-57 Maxwell. https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-109.html.

National Oceanic and Atmospheric Administration (NOAA). 2017. *Tsunami Messages for the Pacific Ocean (Past 30 days)*. http://ptwc.weather.gov/?region=1.

NOAA. 2018a. Looking for information about oil spills? Accessed November 1, 2018. https://response.restoration.noaa.gov/about/media/looking-information-about-oil-spills.html.

NOAA. 2018b. How does climate change affect coral reefs? Accessed November 26, 2018. https://oceanservice.noaa.gov/facts/coralreef-climate.html.

New Scientist. 2018. Divers are attempting to regrow Great Barrier Reef with electricity. Accessed November 26, 2018. https://www.newscientist.com/article/2180369-divers-are-attempting-to-regrow-great-barrier-reef-with-electricity/.

Pratt, Joseph W. and Leonard E. Klebanoff. 2016. Feasibility of the SF-BREEZE: a Zero-Emission, Hydrogen Fuel Cell, High-Speed Passenger Ferry. Sandia National Laboratory Report, SAND2016-9719. Accessed November 26, 2018. https://energy.sandia.gov/transportation-energy/hydrogen/market-transformation/maritime-fuel-cells/sf-breeze/.

RECAP. 2017. "Global Data Center Market: Market Briefing." Irish Center for Cloud Computing. Accessed April 7, 2018. https://recap-project.eu/media/market-briefings/.

RECAP. 2018. What Makes a Data Center "Hyperscale?" Accessed November 1, 2018. https://recap-project.eu/news/hyperscale-data-center/.

Research Nester Pvt. Ltd. 2018. Global Portable Solar Charger Market Size, Demand, Opportunity & Growth Outlook 2023. https://www.researchnester.com/reports/portable-solar-charger-market-global-demand-analysis-opportunity-outlook-2023/247.

Rochman, C. M., E. Hoh, B. T. Hentschel, and S. Kaye. 2013a. "Long-Term Field Measurement of Sorption of Organic Contaminants to Five Types of Plastic Pellets: Implications for Plastic Marine Debris." *Environ. Sci. Technol.* 47 (3), 646–1654. http://dx.doi.org/10.1021/es303700s.

Rochman, C. M., M. A. Browne, B. S. Halpern, B. T. Hentschel, E. Hoh, H. K. Karapanagioti, L. M. Rios-Mendoza, H. Takada, S. Teh, and R. C. Thompson. 2013b. "Policy: Classify plastic waste as hazardous." *Nature* 14: 169-71. https://www.nature.com/articles/494169a.

Shehabi, Arman, Sarah Josephine Smith, Dale A. Sartor, Richard E. Brown, Magnus Herrlin, Jonathan G. Koomey, Eric R. Masanet, Nathaniel Horner, Inês Lima Azevedo, and William Lintner. 2016. *United States Data Center Energy Usage Report*. LBNL-1005775. Berkeley, California (US): Lawrence Berkeley National Laboratory.

Smithsonian. 2016. This Coral Restoration Technique Is 'Electrifying' a Balinese Village. Accessed November 26, 2018. https://www.smithsonianmag.com/science-nature/coral-restoration-technique-electrifying-balinese-village-180959206/.

Starosielski, N. 2015. *The Undersea Network*. Durham, NC: Duke University Press.

TeleGeography. 2018. Submarine cable 101 - Submarine Cable Frequently Asked Questions. Accessed November 1, 2018. https://www2.telegeography.com/submarine-cable-faqs-frequently-asked-questions.

Teuten, E. L., J. M. Saquing, D. R. U. Knappe, M. A. Barlaz, S. Jonsson, A. Björn, S. J. Rowland, R. C. Thompson, T. S. Galloway, R. Yamashita, et al. 2009. *Philos Trans R Soc Lond B Biol Sci.* 364: 2027–2045. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2873017/.

Tullis, P. 2018. "How Hydrogen Could Help Clean Up the Global Shipping Industry." *Oceans Deeply*, January 10. https://www.newsdeeply.com/oceans/articles/2018/01/10/how-hydrogen-could-help-clean-up-the-global-shipping-industry.

U.S. Department of Energy. 2018. WindExchange Small Wind Guidebook. Accessed November 1, 2018. https://windexchange.energy.gov/small-wind-guidebook.

Vance, A., and B. Stone. 2018. "Air-Taxi Startup Has a Working Prototype and a Fresh $100 Million." *Bloomberg*, February 1, 2018. https://www.bloomberg.com/news/articles/2018-02-01/air-taxi-startup-joby-has-a-working-prototype-and-a-fresh-100m.

World Bank. 2018. The 2018 Global Off-Grid Solar Market Trends Report. Accessed April 8, 2018. https://www.lightingglobal.org/2018-global-off-grid-solar-market-trends-report/.

Wu, C., T. W. Kim, T. Guo, and F. Li. 2017. "Wearable ultra-lightweight solar textiles based on transparent electronic fabrics." *Nano Energy* 32 (February): 367–373. https://doi.org/10.1016/j.nanoen.2016.12.040.

U.S. DEPARTMENT OF
ENERGY
Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

11 Summary and Conclusion

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

April 2019

11. Summary and Conclusion

This report outlines the information gathered in a fact-finding effort to identify potential applications and markets for marine energy technologies beyond utility-scale, grid-connected power generation markets. The year-long effort involved engaging with key stakeholders and information sources to explore evolving power needs and use opportunities at sea and along the U.S. coastlines. The fact-finding effort for this report specifically focused on identifying available information on high-level energy and project requirements, market dynamics, challenges to market entry, paths to market, and further analysis and technology research and development (R&D) needs.

The marine energy resources considered in this report included ocean waves, tidal, river, and ocean currents. The wide range of potential applications for these marine energy resources spans onshore, nearshore, and open-ocean, grid-connected, and autonomous energy systems. Depending on the application, marine energy generation could serve as a sole energy source or be integrated into a hybrid marine energy system, which might include wind, solar, diesel, and storage to meet differing annual load requirements. Marine energy technologies could be applied to a wide range of applications, with energy vectors including both electrical power (e.g., electrolysis, battery charging, and community microgrids) and mechanical power (e.g., reverse osmosis, compressed air, ice, and sediment transport).

Power at Sea and Resilient Coastal Communities

The various marine energy markets explored in this report were grouped into two different thematic areas (Figure 11.1). A portion of the applications identified in this report are focused on providing power at sea in off-grid and offshore locations to support a variety of ocean-based activities, which we refer to as Power at Sea markets. Power at Sea markets include ocean observation and navigation, marine aquaculture, seawater mining, underwater vehicle charging, and marine algae. The other markets are more coastal in nature and concerned with energy and water needs of remote, island, rural communities, and bases, on or close to land; we refer to these as Resilient Coastal Communities markets. Resilient Coastal Communities markets include desalination, isolated communities, and coastal resiliency and disaster recovery. Organizing around these groups can help support stakeholder network formation, interdisciplinary coordination, and interagency cooperation that is needed for identifying high-priority shared goals across the blue economy, as well as codevelopment of energy and maritime market technologies.

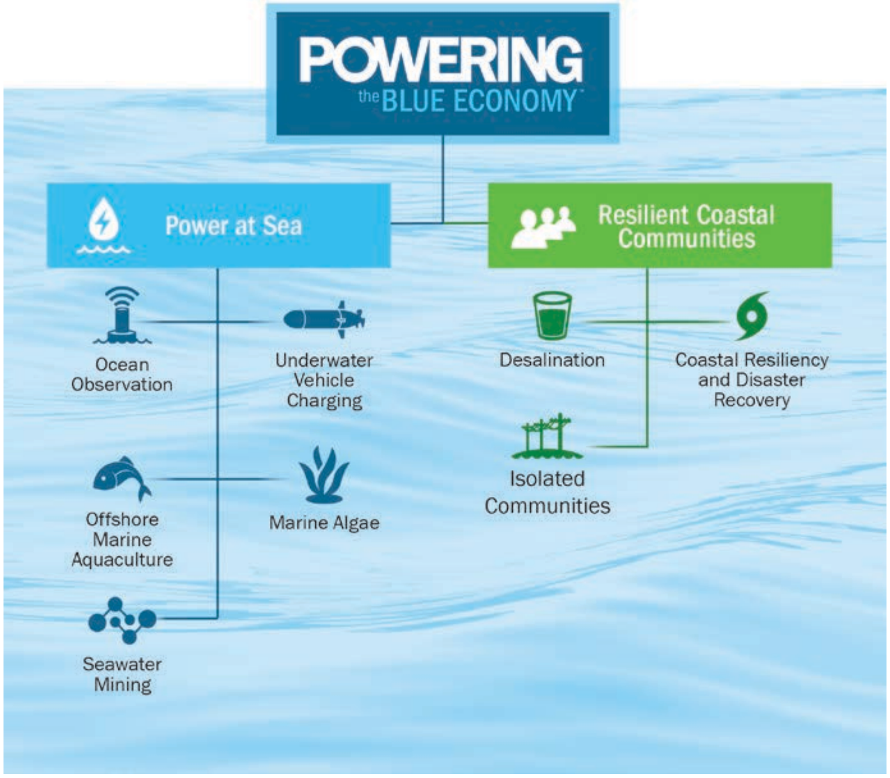


Figure 11.1. Marine power applications explored in this report

In terms of distance from shore, each marine energy market qualitatively spans different ranges of applicability from nearshore to the deep ocean, with implications for marine energy integration (Figure 11.2). The identified ranges are qualitative because the applicability of a market to different regions will continue to change as technologies and markets evolve. Distance from shore is an important consideration when discussing environmental conditions (e.g., water depth), access to shore-based resources (e.g., grid power access), and ease or mode of access to project sites (e.g., port and vessel availability).

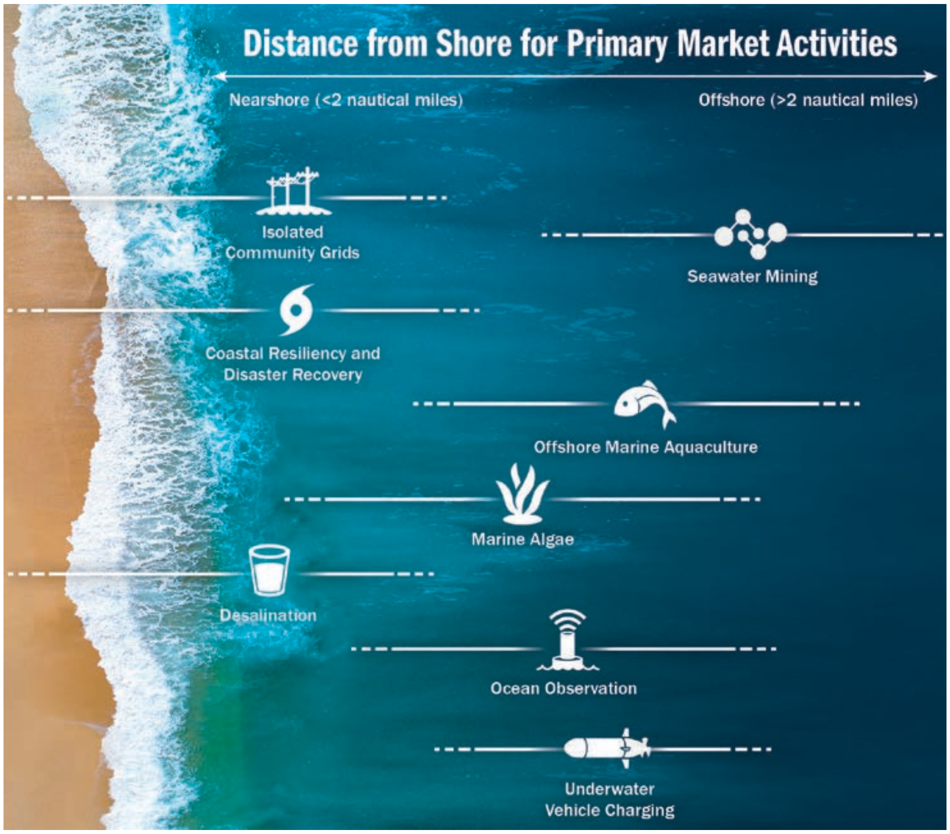


Figure 11.2 Qualitative map of the distance-from-shore application ranges for Power at Sea and Resilient Coastal Communities markets

Geographically, the Power at Sea markets are relevant across most U.S. offshore regions and from nearshore to deep water, given broad evolving activities in ocean exploration and potentially growing markets for offshore marine aquaculture, marine algae, and seawater mining. Significant ocean observing campaigns are ongoing in the Atlantic, Gulf of Mexico, and Pacific offshore regions and would be well served by new marine energy technologies that could extend the scope and life of these missions, thereby providing longer environmental time series and allowing data collection in areas not previously sampled. The markets for marine aquaculture, marine algae, and seawater mining are relatively nascent in the United States and could be supported by marine energy. Technology attributes, such as the ability to operate in variable- and low-energy environments, codesign to leverage developing project requirements, and flexibility to accommodate an evolving permitting process would be highly valued in these markets.

Major commonalities across Power at Sea markets include:

- Located out to distances far from shore, such that cabling and access to terrestrial-based energy is expensive and difficult to deliver. Typically, these locations have limited low-cost power options.
- Need to reduce fuel (e.g., diesel and new batteries), supply chain costs, and risks, including ship and personnel time, and cost to deploy and retrieve equipment.
- Power is mission critical for many applications and failure to supply power could lead to complete loss of the system, with redundant power systems being needed. To conserve power, instrument sampling rates and duty cycles are commonly set to lower-than-desired levels to extend battery life, with the impact of reducing temporal and/or spatial resolution of data.

- Existing power sources available include solar photovoltaics, wind, diesel generators, and single-use or rechargeable batteries.

The Resilient Coastal Communities markets are more broadly relevant geographically across the United States, including desalination and coastal resiliency and disaster recovery. Isolated power systems have relevant geographies spanning primarily Alaska, Hawaii, and U.S. island territories.

Major commonalities across Resilient Coastal Communities markets include:

- Applications are nearshore, with load near or onshore.
- Visual (viewshed) impacts are an important consideration.
- There may be some challenges to acceptance and permitting for some nearshore markets.
- It is easier to have redundant power sources in these markets.
- Energy for these applications is a significant percentage of overall project cost.

The set of industries targeting coastal/onshore versus offshore/deepwater technology development opportunities are generally different from one another in terms of regulations, stakeholders, engineering needs, data availability, equipment needs, workforce, and research communities. However, opportunities for marine energy within these broad market categories possess several commonalities that could inform similar technology advances, including effective stakeholder and interagency engagement; alignment with supporting industries and clusters; and necessary R&D, testing, and validation capabilities at national labs and university partners.

Organizing functionally around these themes could support network formation and interdisciplinary coordination needed for codevelopment of energy and maritime market technologies. Tapping into existing and emerging networks could provide new engagement opportunities for marine energy specialists, access to knowledge, and opportunities in crossover markets. The same is true for the Resilient Coastal Communities theme—there are existing networks and resources focused on sustainable coastal development, energy/water needs of island communities, and rural infrastructure modernization that could be approached so as to leverage opportunities and expertise across multiple markets.

Finally, organizing around these themes can reveal opportunities to invest in cross-cutting technologies and R&D that support all markets within a given theme. For example, progress is needed in operational reliability, resource assessment and forecasting, integration of marine energy production with storage (e.g., microgrids at sea), and novel deployment and maintenance strategies. This kind of cross-cutting research could create multiple innovation pathways across many markets. Similarities can be anticipated between near and offshore markets, including installation, operation, and management constraints and concerns; marine energy device archetypes that may have desirable traits based on location; marine energy device survivability concerns; the types and needs of customers; and energy storage challenges.

Power Needs Across Markets

All eight of these markets are to some degree growth-limited by energy. For some markets, marine energy could replace an existing energy supply chain that might be more expensive, such as ship travel to replace batteries in ocean observing systems. For other markets, marine energy could provide local energy abundance not currently attainable by other means to enable new innovation pathways and create opportunities that would not otherwise exist.

As identified in this study, the existing and evolving applications span wide power needs from watts to megawatts, and substantial distances from shore, along with variable energy requirements and tolerance to intermittent power over days, weeks, months, years, and between years. There is a better understanding of energy needs and limitations in near-term markets than for emerging and future markets, where significant uncertainty still exists. For example—analysis and Request for Information comments for this report indicate offshore aquaculture is a rapidly emerging industry driven by global factors, such as protein availability, but there is not a clear picture of the overall need for energy in this market. Energy needs for mineral mining and marine algae production are unclear—many of the present concepts for these applications largely take advantage of ocean temperature, upwelling, or ocean currents to circulate water across farming operations. There will likely be a need for additional electrical or mechanical power that might be provided by marine energy, but the degree to which marine energy could outcompete other sources, like solar or offshore wind, is less clear. This is not to say that these markets are not suitable for marine energy, only that additional analysis is needed to understand appropriate innovation pathways.

Marine Energy Value

Numerous unique attributes of marine energy that could be valuable enablers for blue economy markets were identified. These attributes can be broadly organized within the groupings of marine energy “resource-focused” attributes and marine energy “technology-focused” attributes, which are discussed in greater detail in the individual chapters and summarized here.

The United States is fortunate that it has diverse and abundant marine energy resources. Forecastable, energy-dense waves, tides, currents, and rivers can be found throughout the Exclusive Economic Zone and off the continental United States, Alaska, and Hawaii, and island territories. To date, most research into the marine energy resource potential has been focused on applicability to the grid electricity market. The focus has thus been on high-intensity resources close to shore that have the prospect of providing the lowest levelized cost of energy to a continental grid power market. This report focuses on cataloging and investigating the nongrid market opportunities for marine energy and puts a broader lens on the assessment of the resource. As new markets and interests emerge, different attributes of resources and relevant conversion technologies may become clearer. Emerging markets might also open opportunities in ocean thermal energy conversion, salinity gradients, or other marine energy resources.

There are various unique technology-focused attributes of marine energy that could be leveraged to provide a new source of energy to blue economy markets, including the ability to provide both electrical and mechanical power, potential for lack of surface expression, opportunities for codesign with other application infrastructure, common supply chains with other ocean industries, and the ability to provide resilient power during disruptive events. Direct use of mechanical energy requires no conversion to electricity, potentially increasing system efficiency and reducing use of critical materials (e.g., no rare-earth elements). Water itself serves as the raw material input across multiple applications (e.g., desalination, hydrogen production, mineral extraction) and can also provide ambient water cooling at low project cost (e.g., data centers). From a mechanical perspective, marine energy devices can also dampen platform motion and/or reduce waves, with benefit to several applications (e.g., shoreline protection, aquaculture). In addition, the unique high-energy density and subsurface characteristics of the marine energy resource could result in smaller form factors for generation technology and designs with no surface expression, with implications for ease of deployment, survivability, visual impact, and security.

Marine Energy Market Potential

This report provides available data and information, along with stakeholder input, across multiple potential marine energy markets. Publicly available market data and forecasts are incomplete for the total sector; the energy-related equipment/services/contracts portions; portions of each market for which marine energy is relevant; and relevant portions of each market that marine energy could hope to capture, especially for nascent or nonexistent markets. As outlined further in the upcoming Recommended Next Steps section, additional analysis of the evolving project requirements and scenarios for marine energy competitive positioning is needed.

Although this report does not make projections and estimations to fill in these gaps, based on available information it is clear that, collectively, the existing markets are presently in the billions of dollars market size range, with the present and future possible markets also estimated in the billions of dollars. Available market information that was identified in the report is outlined in each chapter and summarized in Appendix C.

The eight different markets featured in this report range from existing robust markets through prospective future markets, with significant activities in emerging markets, some of which marine energy could help enable. As outlined in Table 11.1, this understanding of market maturity and readiness helps to build a picture of what applications may have nearer-term possibilities and which applications might be riskier markets.

Given the evolving nature of the blue economy, the opportunity exists to innovate and develop new marine energy technologies that are tailored to meet the needs of specific markets. Thus, there are multiple choices for marine-energy-generating devices that might fit one application better than another. Marine energy is playing within an opportunity space that consists of other energy sources, including diesel, batteries, solar, and wind. Marine energy has to provide a benefit for the particular application that is more competitive than, or complementary with, the existing forms of available energy. Application-by-application case studies would help to determine the most suitable existing and future markets for marine energy integration, taking advantage of the unique strengths that marine energy technologies can provide.

Table 11.1 Perceived Blue Economy Market Readiness

	Near Term	Emerging	Future
Power at Sea			
Ocean Observation and Navigation	X		
Underwater Vehicle Charging	X		
Offshore Marine Aquaculture		X	
Marine Algae		X	
Mining Seawater Minerals and Gasses			X
Resilient Coastal Communities			
Desalination	X		
Coastal Resiliency and Disaster Recovery		X	
Community-Scale Isolated Power Systems	X		

Stakeholder Engagement

Stakeholders in these markets are as varied as the markets themselves. Any given market may include regulators, insurance providers, technology developers, private investors, and customers. For this report, emphasis was placed on end users and potential technology development partners, as both groups are believed to be of the most interest to marine energy technology developers.

In established blue economy markets, it is relatively clear that the major stakeholders and customers are larger companies or government organizations. For example, ocean observation clearly has critical stakeholders within the National Oceanic and Atmospheric Administration (specifically within the U.S. Integrated Ocean Observing System, Ocean Exploration, and the National Data Buoy Center), the National Science Foundation, and the U.S. Department of Defense. In contrast, desalination is largely driven by local and regional utilities.

For emerging markets, it is still not clear who the major players are in some cases, but startups and small businesses clearly play a role. For example, offshore aquaculture in the United States is underdeveloped and there are only a handful of businesses that have, or are seeking, permitting for projects in federal waters. The underwater vehicle recharging market is somewhat of an outlier. Although this is believed to be an emerging market, a surprising number of large organizations like defense contractors, oil and gas majors, and the U.S. Navy are involved. One would expect these groups to be more risk averse to emerging technologies such as these, but mission needs seem to overcome these concerns.

Future markets are more uncertain, and the same is true of their stakeholders. These markets are still largely constrained to conceptual plans or lab research projects in academia and there are few, if any, companies pursuing them at the moment. The major stakeholders for these groups tend to be government and university R&D laboratories.

Benefits to the Nation

This report focuses on significant market opportunities for the application of marine energy technologies, given existing power constraints and other limitations in current and growing markets. Many of these applications and missions are important from a national perspective.

U.S. national security could be enhanced through the development of the markets identified in this report. For example, this could include advanced ocean sensors with longer mission durations and minimal expression; or greater and more resilient emergency response functions in the face of a disaster or a prolonged drought; and the acquisition of critical minerals from the sea. America's trade gap could also be reduced should offshore aquaculture or marine algae industries expand their capacity and development in the U.S Exclusive Economic Zone. Another example is the integration of wave energy converters with traditional coastal infrastructure, such as breakwaters, groins, jetties, and seawalls, where the ancillary value provided by wave energy converters in the further development of the coastal defense and resilience of a particular locality is more significant than the primary value of providing localized electricity generation. Considering the diversity of potential benefits, the various opportunities explored in this report represent significant value beyond economic.

Powering the Blue Economy aligns with the *2017 National Security Strategy*, specifically with the following goals of the United States: "We will improve America's technological edge in energy, including nuclear technology, next-generation nuclear reactors, better batteries, and advanced computing, carbon-capture technologies, and opportunities at the energy-water nexus. The United States will pursue an economic strategy that rejuvenates the domestic economy, benefits the American worker, revitalizes the U.S. manufacturing state…". In addition, the report directly supports the President's Executive Order 13840 on Ocean Policy to Advance the Economic, Security, and Environmental Interests of the United States: "It shall be the policy of the United States to:…(d) facilitate the economic growth of coastal communities and promote ocean industries, which employ millions of Americans, advance ocean science and technology, feed the American people, transport American goods, expand recreational opportunities, and enhance America's energy security."

All blue economy sectors depend on energy, and in the unique applications outlined in this report, energy innovation can drive growth. Expanding demand for ocean-derived food, materials, energy, and knowledge is driving rapid growth in the emerging blue economy for both ocean-based and nearshore industries.

For example, ocean industries, such as aquaculture, are expanding and moving farther offshore to take advantage of the vast scale of the ocean. Moving farther offshore requires access to consistent, reliable power untethered to land-based power grids. Oceanographic research and national security missions increasingly rely on autonomous sensors and unmanned vehicles that function with limited human intervention.

Closer to shore—rural coastal and island communities often rely on expensive shipments of fuel and water to meet basic needs. Electricity and water are vulnerable to disruption during periods of bad weather or following natural disasters. Removing power constraints and addressing the needs of other coastal and ocean energy end users could accelerate growth in the blue economy and create new opportunities for sustained economic development. Marine renewable energy presents a novel and innovative suite of technologies that could help in removing some of these constraints.

Near-term opportunities could provide early commercial success for marine energy technologies, but also broadly help the nation expand economic development opportunities, revitalize coastal and port infrastructure, increase the diversity and resilience of our power systems, and position the United States to lead in the international development of technologies and projects that responsibly leverage the broad and diverse potential of ocean, wave, and tidal, river, and ocean current resources.

An important and broad advantage of marine energy development in various markets and applications is the value proposition of devices for the electric grid. Maritime markets present opportunities to learn more about the unique value that marine energy devices could contribute to future grid-scale applications. System attributes, such as production capacity, ancillary services, reliability services, and resiliency, are all broad benefits of marine energy deployment. Development of marine energy technologies integrated with various application of Power at Sea and Resilient Coastal Communities could lead to a better understanding of device attributes and their inclusion in future grid expansion and electricity planning. A number of specific advantages to highlight are the deferred or avoided costs of transmission investments to remote, coastal locations; reduced integrations costs; the ability to provide seasonal peaking power; the avoidance of crowded land-based generation siting; and more predictable generation. In addition, for coastal resiliency and disaster recovery applications, marine energy devices can be integrated to provide critical black-start capabilities or other services in the face of grid disruptions or coastal inundations affecting power systems. Finally, marine energy technologies are distributed and decentralized, thereby allowing for deployment in microgrid configurations or providing necessary diversity to local and remote power generation systems. The application and integration opportunities described in this report present unique opportunities to further develop marine energy market value and technological evolution.

Recommended Next Steps

This report outlines how marine energy could be utilized in various applications but does not identify areas where marine energy is most likely to gain market traction or where the largest probable markets are. Defining future analyses and next steps to better understand each market opportunity and the portfolio of opportunities is a critical objective of this report. Techno-economic analyses to further clarify these potential opportunities, along with enabling R&D objectives, are outlined in this section. To compete with and/or be complementary to other energy technologies in these different potential applications, marine energy technologies must exploit their unique attributes and differentiate from other energy sources. For example, for a given application, questions that might be asked include: is a limited surface expression a requirement? Are there significant power needs at potential project sites that cannot be met by cables (e.g., far offshore)? Does distributed resource diversity make the cost/benefit of marine energy attractive (e.g., to complement high-latitude solar irradiation and wind)? Is there a need to de-energize waves or currents to protect at-sea operations?

Marine energy alone, with storage, or in hybrid generation systems may have a value proposition that could contribute to increased mission scale in existing markets or the creation of new offshore markets. Integration of marine energy could enable the cost-effective leveraging of untapped or “stranded” energy and other assets in the ocean and potentially enable/unlock entirely new, as yet unknown, large future markets. The markets identified in this report could create near-term commercial opportunities for marine energy technologies and companies, attract a diverse set of development partners, educate stakeholders and the public, develop a supply chain, and reduce risks and costs. Experience and revenue gained from successes in nearer-term blue economy applications will enable further investment in R&D, an expanding value proposition, and meet the needs of additional markets, including more cost-competitive utility-scale power markets.

Key questions to answer to gain further insight into where, how, and when marine energy technologies may have the best potential for application and market viability include:

- What are the unique and distinguishable requirements of these individual diverse markets that need to be satisfied by the marine energy technologies that are currently available or could be developed in the future? What are the specific energy needs/load profiles for each evolving application?
- What are the unique and distinguishable attributes of marine energy technologies that make them more attractive, cost effective, and socially desirable than or complementary with other energy solutions for each blue economy application?
- Which markets have the highest probability of marine energy market success from technical and economic perspectives? Which markets have the largest achievable size for marine energy? Which applications have the fastest potential time to market? How can marine energy attributes be applied to currently unidentified uses and future markets?
- Which application has the most motivated stakeholders/customers/codevelopment partners and the best access to R&D and project development capital?
- What are the priority challenges to overcome to create options for competing in multiple markets, and what is the best way to overcome them?
- What is the sum of direct and indirect benefits and values for the nation, society, the environment, and the economy beyond direct revenue from energy production—enabled and unlocked by onshore, nearshore, and offshore marine energy?

Recommended Analyses

To address these questions, the following additional analyses are recommended:

- **Market analysis/marine renewable energy design requirements**. Assess detailed project needs and evolving needs over the next 5–10 years. Use project case studies as frameworks to determine energy required for each application, including annual/monthly/daily megawatt-hours, peak power, and average power. Consider site selection for projects, resource modeling, conceptual design, (hybrid) power system design and simulation, project cost and business model analysis, and failure mode, effects, and criticality analysis.
- **Cross-resource and technology hybrid power system assessment**. Explore resource levels, variability, predictability, and power generation alternatives to meet missions including hybrid systems with integrated storage. Determine best opportunities for marine energy to operate alone, with storage, and with storage, solar, wind, diesel, and other technologies.
- **Detailed market opportunity assessments**. Take a deeper look at Power at Sea and Resilient Coastal Community markets to fill in estimate and forecast gaps. Project total sector development and growth (including marine energy enabling potential), energy portion of sector economic activity, and addressable marine energy market opportunity and evolution. Present status and forecast scenarios of evolution of each marketplace, including size, requirements, dynamics, and marine energy technology features, benefits, and costs. Quantify total available market and forecast achievable market share/size. Conduct competitive positioning and business case analyses.
- **Marine energy innovation pathways**. Conduct further analysis to understand how key R&D efforts and learning within near-term markets could create innovation pathways that fulfill more of the needs of related emerging future applications and markets. Consider lower-risk paths to commercialization, such as using initial applications to provide options for potential additional markets (Sinfeld and Solis 2016).

Research and Development

Although more specific, detailed mission and design requirements are described in the application chapters, some common high-level R&D technology objectives identified for marine energy devices include the following:

- **Reliability**. Minimum level of proven availability needed. Marine energy devices will need to operate autonomously for prolonged periods, on the sea surface, at depth underwater, and offshore, with proven reliability and survivability.
- **Efficient installation, operation, and maintenance**. Specialized vessels and equipment drive up costs. Cost-effective, low-risk, and vessel-independent installation methods are needed. Ease of repair with relatively unskilled labor in remote locations is essential for many markets. Some applications will require very long maintenance intervals.
- **Mechanical systems integration**. For some applications, marine energy converters must be integrated into other offshore systems, such as docking stations or aquaculture pens. Co-optimization possibilities and opportunities exist to reduce costs as a result of shared infrastructure. Some applications may not need electricity but might require pressurized air or seawater instead. As an example, desalination requires new designs and research on how wave energy converters can effectively be integrated with pumps, reverse-osmosis systems, and membranes.
- **Electrical systems integration**. Many Power at Sea solutions will involve nano- or microgrids at sea—incorporating marine energy, and potentially solar photovoltaics, and offshore wind, with integrated storage (batteries or accumulators). Effective system designs and controls are needed to meet cyclical needs reliably.
- **Supervisory control and data acquisition system development**. Reliable, high-performance operation of autonomous control and communication systems is needed for remote hybrid power systems, dependable system operations, station keeping, and so on.
- **Designs for effectiveness in low-energy resources**. Many applications within the blue economy are in areas with a low marine energy resource. For very low resource intensities, the hydrodynamics and economics may differ from that of high-energy environments, therefore requiring new innovations in device design.
- **Designs and operation for environmental compatibility and stakeholder acceptance**. Marine energy systems and the systems they power must meet environmental regulations. R&D is needed to understand and provide solutions for potential environmental effects to reach acceptable environmental risk. Social acceptance is related to environmental risk, as well as to interactions with other ocean users. Research and engagement with stakeholders is needed to reduce conflicts with users and gain social acceptance.

Marine energy faces many inherent engineering challenges associated with converting high-intensity resources to usable energy, compounded by the harshness of offshore and deepwater environments. Maritime markets present smaller, scalable, and potentially low-cost iterative design environments that could accelerate the development curve for some technology innovations. Although not all of this experience will be directly applicable to the continued development of larger utility-scale systems, there should be significant relevant learning. The smaller-scale systems, faster R&D cycles, and efficient open-water deployments for blue economy applications will provide near-term experience with engineering and design for customer requirements, manufacturability, transportability, and operability. Some key transferable areas include model validation; hardening, such as system reliability and survivability; installation, operation, and maintenance, including lower-cost installation, operation, and maintenance, with minimal infrastructure and skill levels; reliable operation without human intervention over extended periods of time; performance, including control systems, hydrodynamics, and design principles; interconnection with microgrids and derisking of electrical equipment and components; open-water validation and operation experience; supply chain development; understanding potential environmental effects; and determining stakeholder acceptance of new technologies.

The Future

Marine energy technologies have numerous attributes that may offer a unique value proposition to different present, evolving, or future activities in the blue economy. Although work remains, there is potential to contribute to increased mission scale and growth in existing markets and to contribute to the creation of new economic, scientific, and defense activities. Explored through partnerships with emerging ocean industry and government partners, marine energy could be transformative for the blue economy, enabling significant new value from the ocean for the nation. Beyond the markets analyzed in this report, new and high-impact applications for marine energy likely exist on the horizon in the blue economy, thus continuing to widen the scope of potential applications and markets. Big and creative "blue sky" thinking is required to advance application of sustainable technologies and renewable energy to meet the grand challenges. Significant opportunities offered by the blue economy include the opportunity to contribute to an ocean-based economy that provides social and economic benefits for current and future generations, while restoring, protecting, and maintaining the diversity, productivity, and resiliency of marine ecosystems.

References

Sinfield, J. V. and F. Solis. 2016. "Finding a Lower-Risk Path to High-Impact Innovations." *MIT Sloan Management Review*.

The White House. 2017. *National Security Strategy*. https://www.whitehouse.gov/wp-content/uploads/2017/12/NSS-Final-12-18-2017-0905.pdf.

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Glossary

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

April 2019

Glossary

Alternating current: An electric current that reverses its direction at regularly recurring intervals.

Aquaculture: The cultivation of aquatic organisms (such as fish or shellfish), especially for food.

Array: An arrangement of similar devices. In ocean energy devices, this means a number of similar devices arranged into a single group to provide a combined energy output. Also known as a farm.

Autonomous underwater vehicle: An unmanned vehicle designed to operate underwater without guidance according to preprogrammed instructions.

Auxiliary power: Electric power that is provided by an alternate source and that serves as backup for the primary power source at the station main bus or prescribed sub-bus.

Availability: Percentage of time an energy device is operational and able to convert energy.

Axial flow: Having the fluid or gas flowing parallel to the axis.

Benefit-to-cost ratio: An indicator, used in cost-benefit analysis, to identify the relationship between the cost and benefits of a proposed project.

Biodiesel: A fuel that is similar to diesel fuel and is derived (usually) from vegetable or plant oil.

Bulk power market: Type of energy market that is restricted to wholesale suppliers and retailers (resellers) and a few select large-scale customers. Retailers who acquire energy on the wholesale market for resale elsewhere are typically responsible for providing any ancillary services needed by their eventual customers. These services can include peak supply and back-up service, which may also be acquired on the wholesale market.

Capacity factor: Same as load factor or full-load factor. The ratio of the mean generation to the peak generation on a renewable energy generator. Either expressed in percentage (referring to a reference time period) or in equivalent full load hours per year.

Capital expenditure: An amount paid out that creates a long-term benefit (as one lasting beyond the taxable year).

Combined-cycle hydropower: Increasing hydropower production by installing hydrokinetic turbines behind existing conventional hydropower stations. The hydrokinetic turbines will capture additional power from the energy remaining in water currents exiting the hydropower station.

Commercial viability: The state of a technology having proven both a high readiness and technology performance level such that an array-scale project is deemed investment worthy, being safe, reliable, and cost competitive.

Conductivity: The ratio of the electric current density to the electric field in a material.

Conversion efficiency: The conversion efficiency (η) of a device is the proportion of energy converted to a useful form (e.g., electricity) compared to the total energy available to the device.

Cross-flow turbines: A low-speed water turbine wherein the water passes through the turbine transversely, or across the turbine blades.

Desalination: Removal of salt and other minerals from seawater to make it suitable for human consumption and/or industrial use. Reverse osmosis is a commonly used desalination method in which saltwater is forced through a membrane that allows water molecules to pass but blocks other molecules, such as salt and various minerals.

Device: An individual unit capable of absorbing power and converting it to electricity (or other energy form for delivery in case of nonelectric applications); the device is just one subsystem alongside a number of others making up the system.

Direct current: An electric current flowing in one direction only and substantially constant in value.

Distributed energy: On-site generation or decentralized energy in which electrical generation and storage is performed by a variety of small, grid-connected devices referred to as distributed energy resources.

Edge caching: The use of caching servers to store content closer to end users.

Electrical load: An electrical part or portion of a circuit that consumes (active) electric power.

Electrolysis: Electrolysis is the process of using electricity to split water into hydrogen and oxygen. This reaction takes place in an electrolyzer.

Electromagnetic pulse: A pulse of high-intensity electromagnetic radiation generated especially by a nuclear blast high above the Earth's surface and held to disrupt electronic and electrical systems.

Energy density: The amount of energy (as in a beam of radiation) per unit volume.

Energy efficiency: The goal to reduce the amount of energy required to provide products and services.

Energy storage: The capture of energy produced at one time for use at a later time. A device that stores energy is generally called an accumulator or battery.

Exclusive Economic Zone: Extends no more than 200 nautical miles from the territorial sea baseline and is adjacent to the 12 nautical mile territorial sea of the United States, including any other territory or possession over which the United States exercises sovereignty. Within this zone, the United States has sovereign rights for the purpose of exploring, exploiting, conserving, and managing natural resources, whether living or nonliving, of the seabed and subsoil and the superjacent waters and with regard to other activities for the economic exploitation and exploration of the zone, such as the production of energy from the water, currents, and winds.

Floating point absorber: A floating structure that absorbs energy from all directions through its movements at/near the water surface.

Frequency control: A process to maintain stability in the power system. In power systems, when the load is more than the supplying power, the frequency in the system will drop.

Fuel cells: A device that continuously changes the chemical energy of a fuel (such as hydrogen) and an oxidant directly into electrical energy.

Grid resiliency: The ability of an electric grid to reduce the magnitude and/or duration of disruptive events. The effectiveness of an electric grid depends on its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event.

Hydraulic pressure: The pressure of hydraulic fluid that is exerted in all directions of a vessel, hose, or anything in which it is supposed to exert the force per unit area. This pressure is responsible for creating the flow in a hydraulic system as fluid flows from high to low pressure.

Hydropower: The production of electricity by water power.

Hyperscale data center: A computer architecture that expands and contracts based on the current needs of the business. Scalability is seamless and involves a robust system with flexible memory, networking, and storage capabilities.

Inductive power transfer: The transmission of electrical energy from a power source to an electrical device without the use of cord conductors.

Installed capacity: The installed capacity of a device is the total power that the device can produce when operating correctly and at full power output. Traditionally, this is the installed capacity of the electrical generator in a device. Installed capacity is usually measured in kilowatts or megawatts.

Intermittent energy source: Any source of energy that is not continuously available for conversion into electricity and outside direct control because the used primary energy cannot be stored.

International Energy Agency – Ocean Energy Systems: General ocean energy glossary. https://www.ocean-energy-systems.org/publications/oes-reports/guidelines/document/ocean-energy-glossary-2007-/.

International Electrotechnical Commission (IEC) TC114 Marine Energy Terminology Technical Specification: IEC TS 62600-1. Marine Energy – Wave, Tidal, and other Water Current Converters – Part 1: Terminology. http://www.iec.ch/dyn/www/f?p=103:7:0::::FSP_ORG_ID,FSP_LANG_ID:1316,25/.

Isolated power systems: An ungrounded electrical service for various applications that remain in operation in the event of a single line-to-ground fault situation.

Internet of things: The networking capability that allows information to be sent to and received from objects and devices (such as fixtures and kitchen appliances) using the internet.

Kilowatt-hour: Amount of energy transferred. One kilowatt for 1 hour. Equivalent to electric heater running for 1 hour.

Levelized cost of energy: The lifetime project costs divided by lifetime energy production, resulting in the total present value cost of operating a power plant. Levelized cost of energy characterizes the average price in $/kilowatt-hour that a power plant must receive to break even over its operational lifetime.

Life cycle: The implementation of a project over all of its stages: engineering (includes permitting), procurement, construction, installation, operations, maintenance, decommissioning, disposal. Usually used in the context of levelized cost of energy.

Load balancing: The use of various techniques by electrical power stations to store excess electrical power during low demand periods for release as demand rises.

Marine energy: Renewable energy that may be harnessed by exploiting an aspect of the physical, chemical, or thermodynamic characteristics of oceans and seas, including tidal movement, wave motion, thermal gradients, salinity gradients, and currents.

Megawatt-hour: Is equal to 1,000 kilowatts of electricity used continuously for 1 hour.

Operational expenditure: Money spent on the ongoing costs of running a business or organization, such as wages and rent on premises.

Oscillating water column: A type of wave energy converter that harnesses energy from the oscillation of the seawater inside a chamber or hollow caused by the action of waves.

Overtopping: The rising of water over the top of a barrier.

Performance: In most cases, as in the clause “performance and reliability,” performance generally refers to the energy capture and conversion efficiency, but in the case of technology performance level, performance refers to all attributes of the array and any necessary supporting infrastructure that impact the techno-economic viability of the technology.

Point absorber: A floating structure that absorbs energy from all directions through its movements at/near the water surface. It converts the motion of the buoyant top relative to the base into electrical power.

Power take-off: A system incorporated to a renewable energy device that allows energy to be converted from the physical motions of the device to a useful form, such as electricity.

Project: Captures all aspects of a demonstration or deployment, including (if applicable depending on scale and product produced from project) permitting, training/securing workforce, arranging power purchaser or nonelectric product buyer, and so on, that may not be captured by “system.” Projects can be pilot or commercial and can be at the device or array scale. A commercial project involves selling electricity to a grid (utility or micro), or a nonelectric product. A utility project is a specific commercial project delivering electricity as its product, at higher capacities serving a grid of significant size.

Readiness: The degree to which technology has progressed from an early stage of development (i.e., conceptualization) through to commercialization, wherein the technology and its application in an array and supporting infrastructure have been derisked to a degree the technology is certifiable/insurable at reasonable rates commensurate to other similar energy projects).

Reliability: Broad term intended to include all system aspects that affect the availability (percent of time the energy conversion system is not in operation and thus available to convert energy from the resource and deliver the product—electricity—to the end user). For instance, downtime of the system regardless of the degree of severity—from an unreliable component that breaks but can be fixed through to the failure of the system to survive—are all covered in the “reliability” term for the purpose of this strategy document.

Resiliency: The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions.

Reverse osmosis: The movement of freshwater through a semipermeable membrane when pressure is applied to a solution (such as seawater) on one side of it.

Run-of-river turbine: A device that harvests energy from flowing water to generate electricity in the absence of a large dam and reservoir.

Survivability: A measure of a device's ability to remain intact and operational in extreme environmental conditions.

System: Refers to the device, mooring, grid connection (or energy delivery in case of nonelectric applications) subsystems as well as effort and infrastructure for installation, operation, and maintenance, recovery over the lifecycle.

Technologies: Refers to any and all components, devices, systems, or arrays at any scale.

Technology performance level: Metric that rates a technology on a scale of 1 to 9 for having the necessary attributes to be techno-economically viable in a target market of high energy intensity, low cost of energy.

Technology readiness level: Metric that ranks a technology on a scale of 1 to 9, from the beginning of exploration and planning to the commercial application of the technology.

Terawatt-hour: Electrical energy consumption rate equivalent to a trillion watts consumed in 1 hour.

Tidal turbine: A device that converts the kinetic energy from the movement of water coming from a change in tide into electricity.

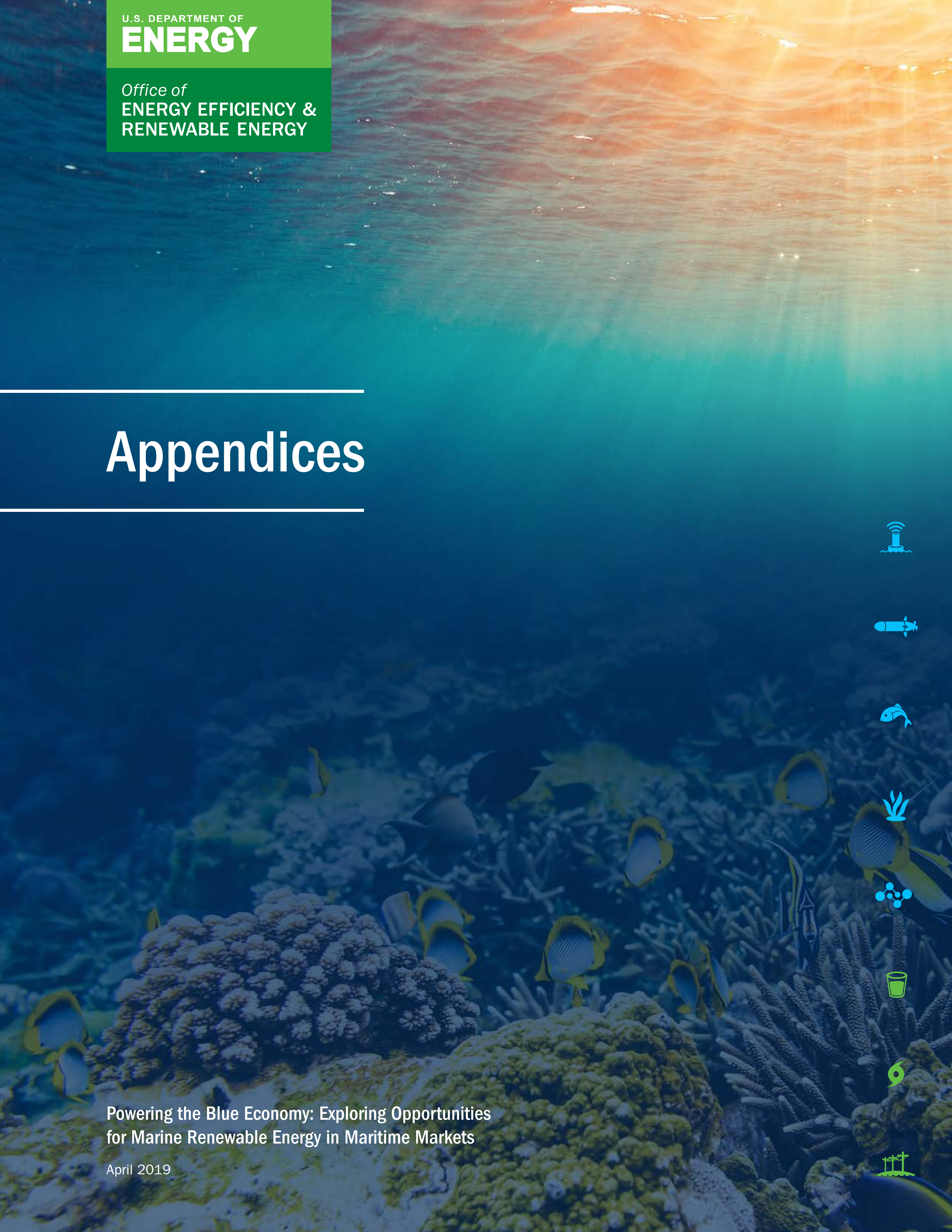
Utility-scale generation: An electricity generation facility that feeds power into the grid and supplies a utility with energy for their customers.

Variable generation: An energy resource, like renewable energy, that is nondispatchable because of its fluctuating nature.

Voltage: A quantitative expression of the potential difference in charge between two points in an electrical field.

Wave energy converter: A technology that can convert the energy of waves into useful energy, such as electricity.

Wave power generation: The capture of energy of wind waves to do useful work (e.g., electricity generation, water desalination, or pumping water).



U.S. DEPARTMENT OF
ENERGY
Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Appendices

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

April 2019

Appendix A. Marine Energy Overview

The ocean is constantly in motion and is nonuniform in temperature and salinity, indicating areas of potential energy. Marine energy technologies extract energy from waves, currents, and thermal and salinity gradients and convert it into useful mechanical or electrical energy. This appendix provides an overview of the key concepts in understanding marine renewable energy, including technology types, resource, cost estimates, and research and development (R&D). Research efforts are currently focused on proving functionality; evaluating technical and economic viability; and generating cost, performance, and reliability data for a variety of devices. A video created by the U.S. Department of Energy, "Marine and Hydrokinetic 101," explains how these technologies work and highlights some of the Water Power Program's efforts in R&D in this area (U.S. Department of Energy 2013). The following topics provide background information and sources for further understanding marine energy concepts.

Technology Types

Marine energy represents an emerging industry with hundreds of potentially viable technologies, depending on the resource and application. These technologies can be classified into the following categories: attenuators, point absorbers, oscillating wave surge converters, oscillating water columns, overtopping/terminator devices, submerged pressure differential devices, bulge wave technologies, and rotating masses. Emerging designs for new types of devices include the wave rotor and flexible structures.

Tidal, ocean, and river current turbines convert the kinetic energy of flowing water into electricity in the same manner that a wind turbine converts the kinetic energy of wind into electricity. The four typical tidal energy devices are: an axial-flow horizontal-axis turbine, a vertical-axis cross-flow turbine, a shrouded (venturi-augmented) axial-flow horizontal-axis turbine, and an articulated-arm oscillating hydrofoil generator. Cross-flow turbines can have the rotor spin axis oriented either horizontally or vertically. Tidal barrages are dam structures built across the mouth of an estuary with a high tidal range.

Further information can be found at the following websites:

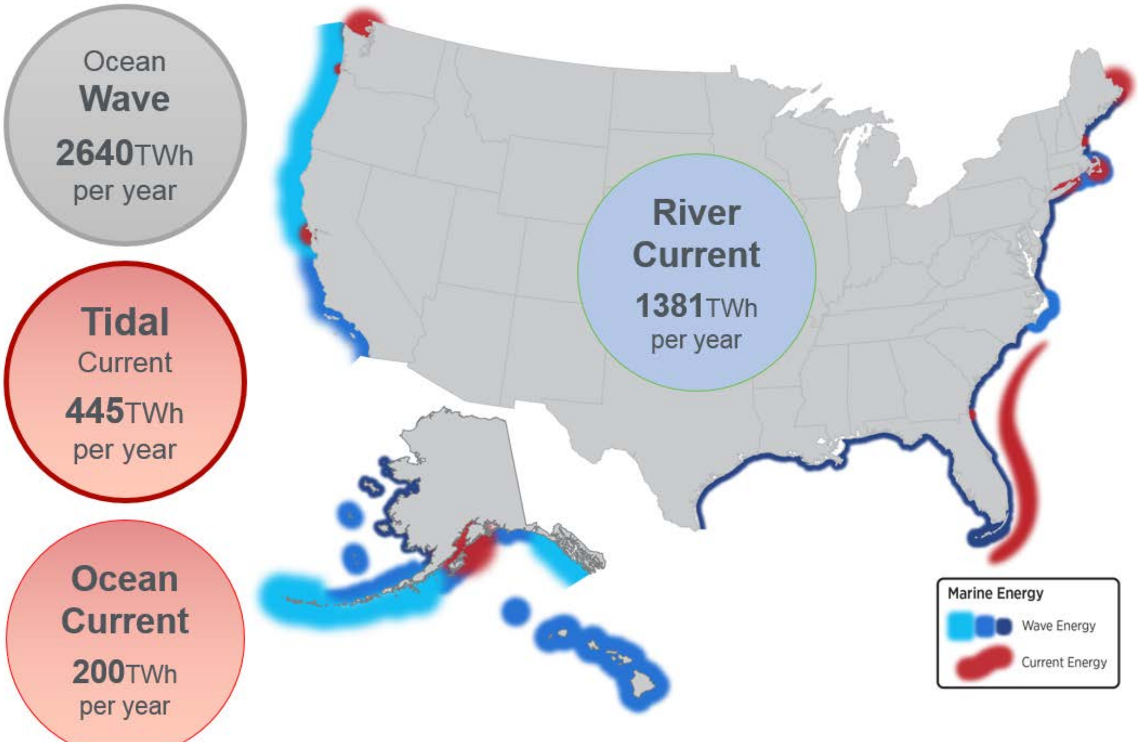
- https://www.energy.gov/eere/water/marine-and-hydrokinetic-technology-development-and-testing
- https://www.nrel.gov/analysis/re-futures.html
- https://www.ocean-energy-systems.org/about-oes/what-is-ocean-energy/
- https://openei.org/wiki/Marine_and_Hydrokinetic_Technology_Database
- http://www.emec.org.uk/marine-energy/wave-devices/
- http://www.emec.org.uk/marine-energy/tidal-devices/.

Resource

The United States has significant, distributed marine energy resources based on the resource assessments conducted by the U.S. Department of Energy Water Power Technologies Office for wave, tidal streams, ocean currents, river currents, and ocean thermal gradients. There are three levels of resource assessments: 1) theoretical resource potential–annual average amount of physical energy that is hypothetically available, 2) technical resource potential–portion of a theoretical resource that can be captured using a specific technology, and 3) practical resource potential–portion of the technical resource that is available when other constraints—such as economic, environmental, and regulatory considerations—are factored in. The Water Power Program is committed to identifying resource potential and continuing to refine these assessments as marine energy resources are further developed.

Energy can be extracted from three general types of flowing water: tidal currents, ocean currents, and river currents. Tidal range is very predictable, although it can be modified by local weather conditions. Good ocean current resources are generally found close to continents on the western boundary of ocean basins, such as the Gulf Stream in the Atlantic Ocean. Ocean currents are generally slower than tidal currents, but they are more consistent and less cyclical. River currents are geographically limited and will vary in intensity with the seasons and terrestrial precipitation. Although tidal energy is very location-specific, the worldwide theoretical power of tidal energy has been estimated at around 1,200 terawatt-hours (TWh)/year (yr) (Huckerby et al. 2016). Within the United States, the theoretical resource potential is estimated at 445 TWh/yr for tidal streams, 200 TWh/yr for ocean currents, and 1,381 TWh/yr for river currents.

Wave energy is forecastable and tends to vary in intensity with the seasons. The range of wave energy potential at various sites tends to fluctuate between 15 and 75 kilowatts/meter, which is the likely operational range of most wave energy converters. The worldwide theoretical potential of wave power has been calculated as 29,500 TWh/yr; just within the United States, the theoretical resource potential is 1,594–2,640 TWh/yr.



https://energy.gov/eere/water/marine-and-hydrokinetic-resource-assessment-and-characterization

Figure A.1. The United States has significant distributed marine energy resources. This map qualitatively indicates estimated total resource intensity for wave, tidal, and ocean currents. Wider/brighter colors represent more energetic. Different markets may benefit from different marine energy resource profiles.

Source: https://energy.gov/eere/water/marine-and-hydrokinetic-resource-assessment-and-characterization

Further information can be found at the following websites:

- https://energy.gov/eere/water/marine-and-hydrokinetic-resource-assessment-and-characterization
- https://maps.nrel.gov/mhk-atlas/
- https://webstore.iec.ch/publication/22593 (International Electrotechnical Commission [IEC] standard for wave resource assessment)
- https://webstore.iec.ch/publication/22099 (IEC standard for tidal resource assessment).

Levelized Cost of Energy

The levelized cost of energy (LCOE) is an integrated metric for assessing marine energy technologies, combining cost and performance estimates. LCOE is a measure of the revenue per megawatt-hour (MWh) of grid-tied electricity production needed for an electricity-generating venture to "break even" with respect to project capital and operating expenses and satisfies a minimum rate of return for investors over the project's lifetime.

Marine energy technology development and adoption will be accelerated both domestically and internationally through R&D programs targeted at utilization of baseline cost scenarios and use of standardized cost reporting methodologies and assumptions. Prototype marine energy technologies require significant cost reduction before they can compete with other forms of grid-compatible electricity generating technologies. Limited technology and project cost data exist for the different marine energy technology types, making it challenging to assess baseline costs and identify high-impact R&D opportunities.

The International Energy Agency Technology Collaboration Programme for Ocean Energy Systems undertook an investigation of LCOE for wave, tidal, and ocean thermal energy conversion technologies that drew upon industry's state-of-the-art knowledge around the costs to deploy and operate each technology in its current state and the cost reductions that are foreseen on the route to product commercialization (International Energy Agency 2015). For each technology, consideration was given to the costs and operational parameters of projects at three development phases: 1) the first precommercial array in wave and tidal, 2) the second precommercial array in wave and tidal, and 3) the commercial-scale target. Forecasted LCOE for the first commercial-scale project was in the range of $120–470/MWh for wave energy and $130–280 $/MWh for tidal energy. Costs over the long term are expected to decrease from the first commercial project level as experience is gained with deployment. Significant cost reductions in LCOE are anticipated from the current stage of deployment to the commercial target, including a cost reduction of 50%–75% for wave energy and 61% for tidal energy. For comparison, typical LCOE estimates for deployed energy systems and diesel systems are updated and provided annually by the Energy Information Administration (2018).

Further information can be found at the following websites:

- https://openei.org/community/document/mhk-lcoe-reporting-guidance-draft
- https://energy.sandia.gov/energy/renewable-energy/rmp
- https://www.ocean-energy-systems.org/oes-projects/task-7-cost-of-energy-assessment-for-wave-tidal-and-otec-at-an-international-level/#tab-results
- https://www.eia.gov/outlooks/aeo/.

National Laboratories

The Water Power Technologies Office funds several national laboratories to conduct early-stage research to accelerate innovative water power technologies. U.S. Department of Energy national laboratories have served as the leading institutions for scientific innovation in the United States for more than 70 years. Today, 17 national laboratories address large-scale, complex R&D challenges with a multidisciplinary approach that translates basic science into innovation. The national labs also work with industry, academia, and many other stakeholders to solve scientific challenges while providing test facilities, sophisticated instrumentation, and deep expertise. The laboratories with water power expertise include Argonne National Laboratory, Idaho National Laboratory, the National Renewable Energy Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, and Sandia National Laboratories.

Further information can be found at https://www.energy.gov/eere/water/national-labs-and-water-power.

National Marine Energy Centers

The three national marine renewable energy centers serve as umbrella organizations in the United States for wave, current, tidal, and in-river academic and scientific research. The centers include the Pacific Marine Energy Center (previously known as the Northwest National Marine Renewable Energy Center), Hawaii National Marine Renewable Energy Center, and Southeast National Marine Renewable Energy Center. The Pacific Marine Energy Center focuses on the responsible advancement of marine energy, including wave, tidal, riverine, and offshore wind resources. It is a consortium of universities that includes researchers from the University of Washington, Oregon State University, and University of Alaska Fairbanks. The Pacific Marine Energy Center is also the operator for several test sites, including a new grid-scale wave energy test site, PacWave, which is currently under development. The Hawaii National Marine Renewable Energy Center, operated by the University of Hawaii, emphasizes wave energy and ocean thermal energy conversion and boasts a collaborative wave energy test site with the U.S. Navy. The Southeast National Marine Renewable Energy Center, operated by Florida Atlantic University, focuses on ocean currents and ocean thermal energy conversion and specializes in environmental baseline observation systems.

Further information can be found at the following websites:

- https://www.pmec.us/
- http://hinmrec.hnei.hawaii.edu/
- http://snmrec.fau.edu/
- https://www.energy.gov/eere/water/marine-and-hydrokinetic-technology-development-and-testing.

Industry Standards

IEC TC-114 is a technical committee (TC) that develops and manages standards for the global marine energy industry. The United States is a participating member of TC-114 and its membership activities are directed by its national committee, the American National Standards Institute. The scope of TC-114 is to prepare international standards for marine energy conversion systems. The primary focus is on conversion of wave, tidal, and other water current energy into electrical energy, although other conversion methods, systems, and products are included, as well as monitoring methods. Tidal barrage and dam installations, as covered by TC-4, are excluded. The standards produced by TC-114 will address terminology; management plans for technology and project development; performance measurements of marine energy converters; resource assessments; design and safety, including reliability and survivability; deployment, commissioning, operation, maintenance, retrieval, and decommissioning; electrical interface, including array integration and/or grid integration; testing laboratory, manufacturing, and factory acceptance; and additional measurement methodologies and processes.

Further information can be found at the following websites:

- https://www.iec.ch/tc114
- https://www.tc114.us/.

Environmental Considerations

Further information can be found at the Tethys Knowledge Base for marine renewable energy at https://tethys.pnnl.gov/marine-renewable-energy.

U.S. Marine Energy Data Repositories

Further information, including the marine energy databases and systems one pager, can be found at the following websites:

- https://www.energy.gov/sites/prod/files/2015/01/f19/marine energy_DBsystems1pager.pdf
- https://www.energy.gov/eere/water/water-power-technologies-office-projects-map.

Hydrodynamic Testing Facilities Database

Further information, including the Hydrodynamic Testing Facilities Database, can be found at the following websites:

- https://openei.org/wiki/Hydrodynamic_Testing_Facilities_Database
- https://www.energy.gov/eere/water/pacwave.

Funding for Water Power R&D Projects

Further information can be found at https://www.energy.gov/eere/water/articles/how-are-water-power-research-and-development-projects-funded.

Water Power Technology Office News Updates

Further information can be found at https://www.energy.gov/eere/water/subscribe-water-power-technologies-office-news-updates.

References

Energy Information Administration. 2018. *Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2018*. https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.

Huckerby, J., H. Jeffrey, A. de Andres, L. Finlay. 2016. An International Vision for Ocean Energy. Version III. Published by the Ocean Energy Systems Technology Collaboration Programme. https://www.ocean-energy-systems.org.

International Energy Agency Technology Collaboration Program for Ocean Energy Systems. 2015. International Levelised Cost of Energy (LCOE) for Ocean Energy Technologies. https://www.ocean-energy-systems.org/publications/oes-documents/market-policy-/document/international-levelised-cost-of-energy-for-ocean-energy-technologies-2015-/.

U.S. Department of Energy. 2013. Energy 101: Marine and Hydrokinetic Energy. https://www.youtube.com/watch?v=ir4XngHcohM&feature=youtu.be.

Appendix B. U.S. Department of Energy Water Power Technologies Office

The U.S. Department of Energy (DOE) Water Power Technologies Office (WPTO) works to support foundational science and the early-stage research and development (R&D) needed to rapidly improve and reduce costs of marine energy generation technologies. These marine energy technologies convert the energy contained in ocean waves and tidal, river, and ocean currents into electricity or other useful forms of energy. The program must support R&D efforts that lead to significant reductions in the cost of marine energy that enable the industry to compete in U.S. energy generation markets. By 2035, the program has set the goal of reducing the cost of marine energy technologies by 80% compared to a 2015 baseline. This corresponds to reducing the cost of wave energy from a baseline of $0.87/kilowatt-hour (kWh) down to $0.17 /kWh and reducing the cost of tidal, river, and ocean current technologies from a baseline of $0.56/kWh down to $0.11/kWh. Four main challenges to marine energy industry development have been identified, which together illustrate why the development of commercial technologies is challenging, and highlight why high-risk, early-stage R&D is necessary to catalyze transformative solutions. These challenges include the following:

- The unique and complex engineering issues faced in designing devices that can efficiently convert dynamic marine energy resources into usable energy
- The related but distinct difficulties of reliably deploying and operating marine energy systems in harsh marine environments
- Additional barriers related to permitting processes and access to testing infrastructure that limit the ability of technology developers to rapidly move through multiple, iterative design and testing cycles
- Limited information is available on the technologies and potential markets, along with undeveloped supply chains.

DOE currently plays a unique and central role in supporting the development of new, cutting-edge technologies and the establishment of a strong and competitive industry in the United States. The marine energy program provides substantial financial support to researchers at a wide range of organizations (e.g., universities, private companies, national laboratories, and nonprofits) to focus on solutions to high-priority challenges that are difficult for the nascent marine energy industry to address on its own. A number of different vehicles are utilized, including competitive funding opportunity announcements, cooperative research and development agreements between national laboratories and commercial entities, activities led directly by national laboratory researchers via annual operating plan agreements, and yearly small-business innovative research calls. The program is constantly evaluating the appropriate roles and contributions of different types of entities. Private technology development companies lead the design, manufacturing, and testing of individual devices and specialized components, whereas DOE national laboratories focus on foundational R&D into areas like controls-system principles and new materials that inform and improve designs across a wide range of systems, along with providing the industry with support for testing and data collection that allow for meaningful evaluation of performance and cost of various marine energy device archetypes.

The marine energy program also continues to explore new mechanisms to carry out its work, such as prizes and competitions (e.g., the Water Security Grand Challenge), and the new small-business voucher program that enables small companies to access world-class national lab facilities and expertise. Priority areas for DOE are those in which targeted government support at early stages in R&D processes can generate knowledge that is broadly applicable to many different types of technology developers and researchers. Given the current maturity level of the industry and various technologies, it is extremely important to remain open to and supportive of a wide variety of ideas, innovations, and potential solutions to the most pressing universal challenges. It should also be acknowledged that DOE R&D investments alone will not be able to resolve all challenges, and that significant levels of effort from a diverse array of companies and organizations will also be required to quickly advance marine energy technologies and the goals of the industry. There are types of work that are very well-suited and appropriate for DOE to lead, others where it makes sense for DOE to support activities that are led by the industry, and some areas where DOE involvement is not needed or appropriate.

WPTO is exploring partnerships between the marine renewable energy industry, coastal stakeholders, and blue economy sectors to address two thematic challenges:

1. Providing power at sea to support offshore blue economy activities
2. Meeting the energy and water needs of rural island and coastal stakeholders in support of resilient coastal communities.

WPTO is developing a strategy to advance opportunities for R&D activities and cross-industry partnerships between the blue economy and marine renewable energy industry. The strategy lays the groundwork for an R&D, innovation, and engagement portfolio that complements the existing WPTO marine energy strategy. It will create pathways to accomplish the following goals:

- Contribute to national goals for growth in the blue economy and resilient coastal communities through innovative use of marine renewable energy
- Accelerate marine-energy grid readiness through near-term opportunities, supporting the WPTO marine and hydrokinetic strategy and mission
- Understand the marine energy value proposition beyond the grid, expanding to include emerging ocean markets uniquely suited to marine energy technology attributes.

For additional information on WPTO marine energy activities, visit:

- https://www.energy.gov/eere/water/water-power-technologies-office
- https://www.energy.gov/eere/water/marine-and-hydrokinetic-energy-research-development
- https://www.energy.gov/water-security-grand-challenge.

For information on 2017 accomplishments, visit:

- https://www.energy.gov/sites/prod/files/2018/04/f51/WPTO%202017%20Annual%20Accomplishments.pdf.

For information on marine energy, visit:

- https://www.energy.gov/eere/articles/how-are-ocean-waves-converted-electricity.
- https://www.energy.gov/articles/capturing-motion-ocean-wave-energy-explained.

For related videos, visit:

- https://youtu.be/ir4XngHcohM.
- https://www.pbs.org/video/newshour-goes-maine-tidal-energy-project-powers/.

  https://www.pbs.org/newshour/show/scientists-work-to-harness-power-from-hawaiis-waves.

Appendix C. Blue Economy Market Size and Growth Rates

This report in general, and this appendix specifically, summarizes the due diligence and fact finding of the Powering the Blue Economy project. The market facts and estimates in the report are the best information we could identify during the initial high-level cataloging of the market opportunities. These market facts and figures should not be viewed as a complete and thorough understanding of the opportunities for marine energy to power the blue economy but rather a starting point for future market research.

Table C.1. Powering the Blue Economy Market Sizes and Growth Rates That Have Been Captured in This Report

Explored Powering the Blue Economy Market	Market Segment	Market Size	Compound Annual Growth Rate or Other Growth Statement	Source
Ocean Observation and Navigation	Navigational and survey instruments	Nearly doubled between 2001 and 2011, from $7.5 to $16 billion Sixty-three percent of the exports ($10.1 billion) in 2011 were for surveying, hydrographic, oceanographic, hydrological, meteorological, or geophysical instruments and appliances, whereas navigational instruments totaled 37% ($5.8 billion)		Maritime Technology News (2012)
Underwater Vehicle Charging: Autonomous Underwater Vehicles, Unmanned Underwater Vehicles, and Remotely Operated Vehicles	Global autonomous underwater vehicle/ unmanned underwater vehicles market	Presently valued at $2.6 billion	Expected to double by 2022	Research and Markets (2017)
Offshore Marine Aquaculture	Global aquaculture market	Projected to be more than $55 billion by 2020		Food and Agriculture Organization (FAO) (2016)
	The world aquaculture production of fish and plants	In 2014, 73.8 million tons of fish were grown in global aquaculture operations with an estimated first-sale value of $160.2 billion: 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)	1.07%	FAO (2016)
	Farmed aquatic plants	Up to 27.3 million tons ($5.6 billion)		Food and Agriculture Organization (2016)
	Offshore farms global market	Projected to be more than $55 billion by 2020		Food and Agriculture Organization (2016)
	Global soil treatment market	Valued at $24 billion in 2015 and is expected to reach $39.5 billion by 2021	8% soil amendments as well as seafood	GlobalNewswire (2016)

Explored Powering the Blue Economy Market	Market Segment	Market Size	Compound Annual Growth Rate or Other Growth Statement	Source
Marine Algae	Antioxidant ß-carotene, produced from microalgae	$392 million in sales in 2010		U.S. Department of Energy (DOE) (2016)
	Global production of macroalgal products estimated in 2014	See Table 5.2		Nayar and Bott (2014)
	Biofuels international	Oil equivalent of 1,324 million tons In 2016, the global biofuel market was valued at $168.18 billion and is projected to reach $246.52 billion by 2024	4.92% biofuels	• International Energy Agency (2017) • World Energy Council (2017) • 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		DOE (2016)
	Natural food colors market in North America	$441.4 million by 2020	7.1%	DOE (2016)
	Global carotenoid market	$1.5 billion in 2014		DOE (2016)
	Aquatic plants (seaweed included)	27.3 million tons were harvested in 2014, totaling $5.6 billion		Food and Agriculture Organization (2016)
	Combined microalgae and macroalgae global market	$10–$12 billion		Oilgae (2017)
	Seaweed per annum for human food	$5 billion		U.S. Department of Energy ([DOE] 2016)
	Seaweed animal feed	$5 million		DOE (2016)
	Algae for specialty products, such as bioactive compounds, polysaccharides, and stable isotopes for research	Likely to be very small because of their specialized applications		DOE (2016)
	Global seaweed market	$17.59 billion by 2021		Algae World (2016)

Explored Powering the Blue Economy Market	Market Segment	Market Size	Compound Annual Growth Rate or Other Growth Statement	Source
Seawater Mining: Minerals and Gasses		See Table 6.12 (Estimates of Global Markets for 10 Key Minerals That Could be Mined from Seawater)		
	The current global market for rare-earth elements	$10 billion; The global market is estimated to be roughly $20 billion by 2030	6%	Mordor Intelligence (2018)
		See Figure 6.2		
	Uranium	67,000 tons per year, or about $8.7 billion		World Nuclear News (2017)
Desalination	Global seawater reverse-osmosis market	Capital and operational expenditures were approximately $2.6 billion and $3.8 billion, respectively, in 2015	Anticipated to reach over $4.5 billion and $5.2 billion, respectively, in 2020	Global Water Intelligence (2016)
	U.S. market for seawater reverse osmosis	Capital and operational expenditures were approximately $129 million and $124 million, respectively, in 2015	Anticipated to reach approximately $344 million and $195 million, respectively, by 2020	Global Water Intelligence (2016)
	Energy consumption for the existing seawater reverse-osmosis market in the United States	Accounts for about $45 million per year in electricity consumption using the 2015 market size and approximately $70 million using the 2020 projections	Anticipated 20% increase in capacity by 2020	Global Water Intelligence (2016)
Coastal Resiliency and Disaster Recovery	Federal Emergency Management Agency's Disaster Relief Fund	$615 million in Fiscal Year 2017 and an additional $6.7 billion for major declarations		PolitiFact (2017)
	Between 1950 and 2000, the U.S. Army Corps of Engineers has constructed 71 specifically authorized shore protection projects	$1.2 billion		U.S. Army Corps of Engineers (2013)

Explored Powering the Blue Economy Market	Market Segment	Market Size	Compound Annual Growth Rate or Other Growth Statement	Source
	U.S. beach nourishment	2,910 nourishment events spanning 447 projects, utilizing approximately 1.5 billion cubic yards of nourishment material along 790 miles of coast, totaling almost $6 billion		National Beach Nourishment Database (2018)
Community-Scale Isolated Power Systems	Isolated U.S. communities with a load less than 5 megawatts	70 megawatts, which is $350 million in marine energy technologies installed cost (assuming $5 per Watt installed)		Kilcher and Thresher (2016)
Other Applications	Underwater acoustic communication market	Increased from $1.31 billion in 2017 to $2.86 billion by 2023		Markets and Markets (2018)

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

For more information, visit water.energy.gov

DOE/GO-1020195157 · April 2019

Cover composite images from iStock 917614562, 614436826.

Hawaii photo from Michael Olsen