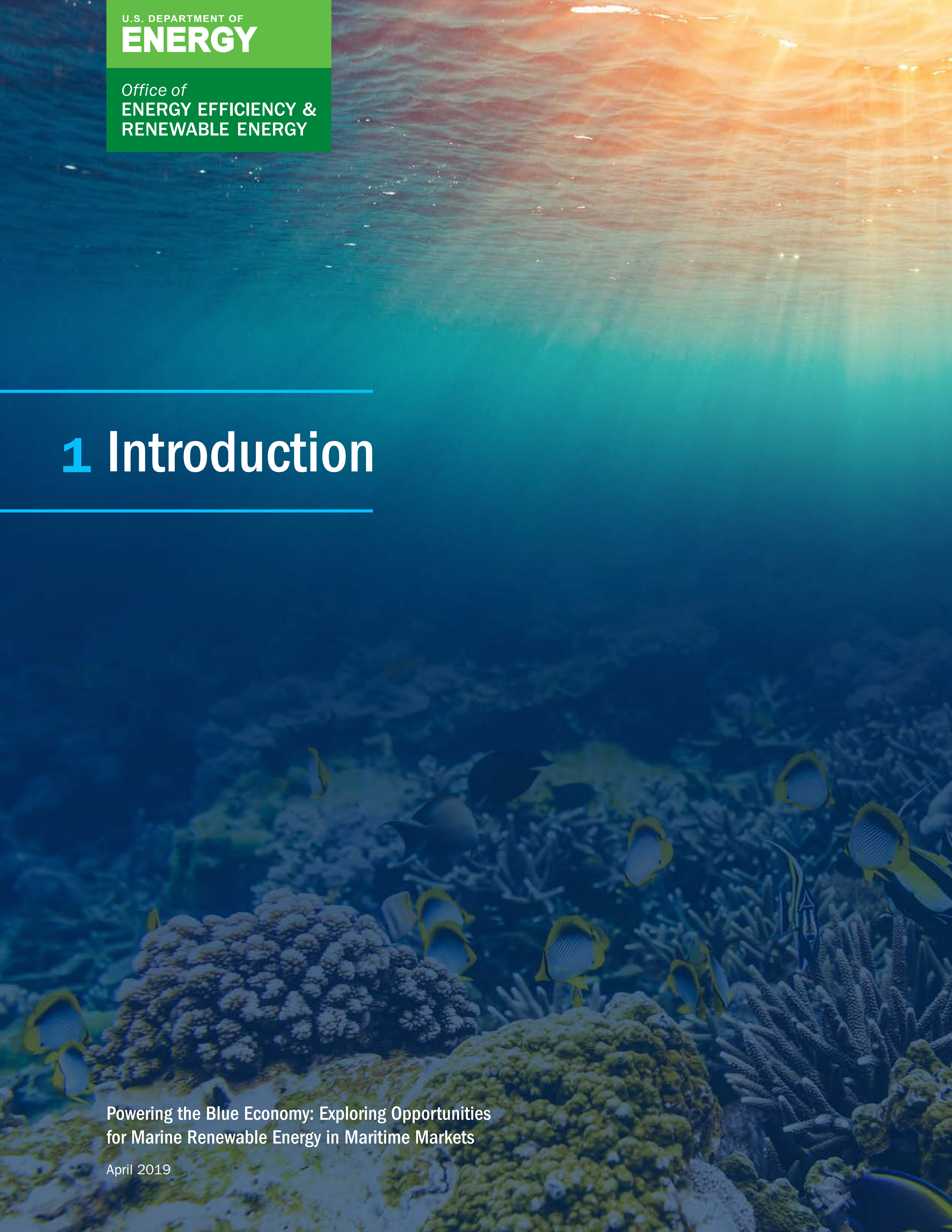

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

1 Introduction

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

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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.

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