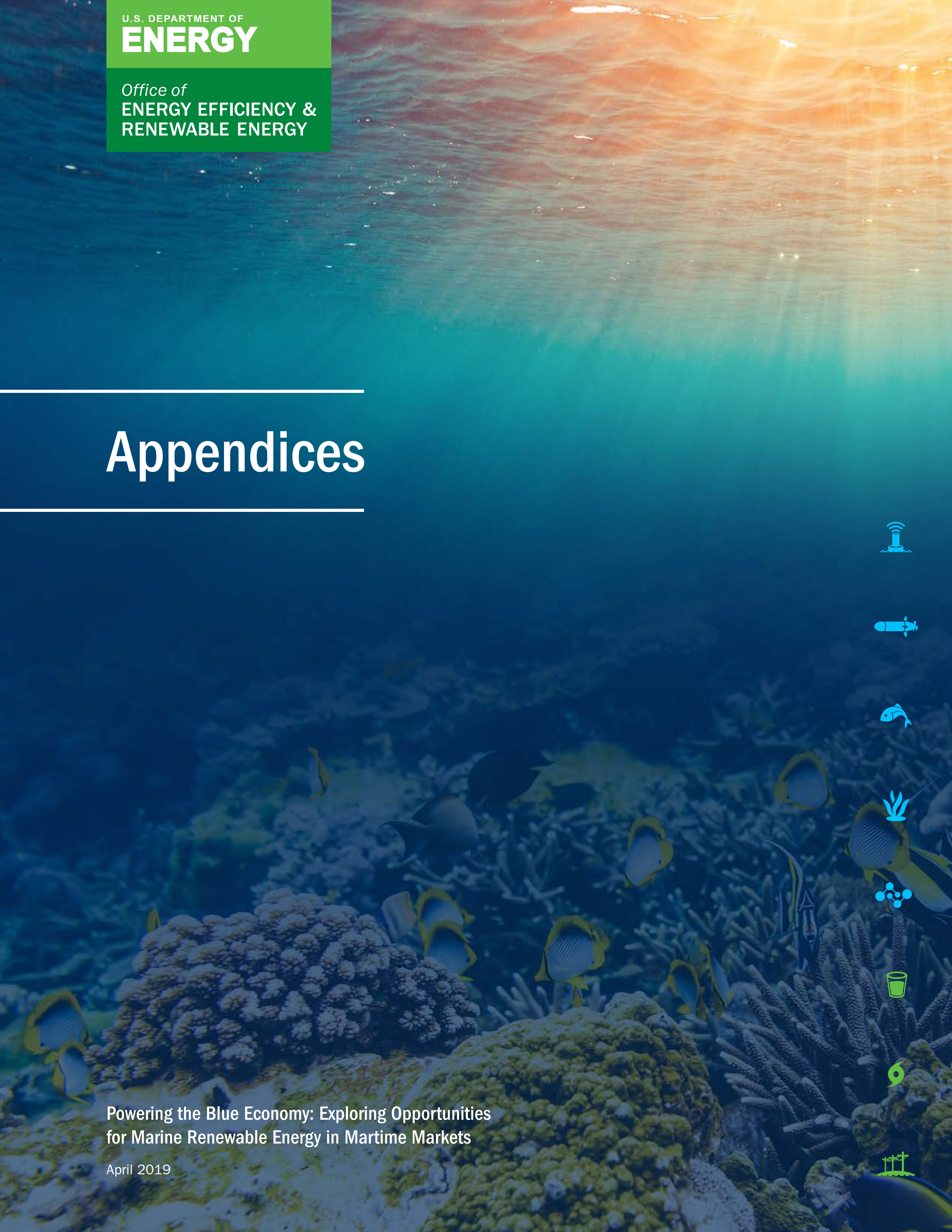

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Appendices

Powering the Blue Economy: Exploring Opportunities for Marine Renewable Energy in Martime 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.

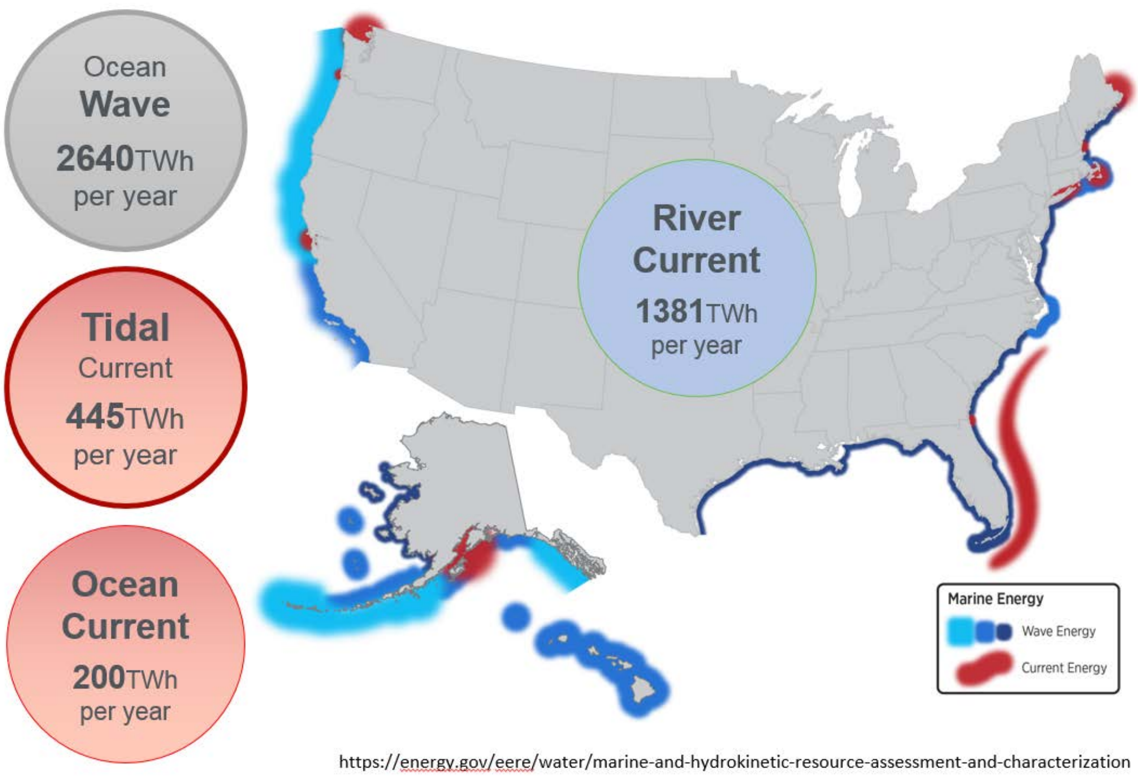

Figure A.1. The United States has significant distributed marine energy resources. This map qualitatively indicates estimated total resource intensity for wave, tidal, and ocean currents. Wider/brighter colors represent more energetic. Different markets may benefit from different marine energy resource 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)