Quadrennial Technology Review 2015

Chapter 4: Advancing Clean Electric Power Technologies

Technology Assessments

U.S. DEPARTMENT OF ENERGY

Quadrennial Technology Review 2015

Marine and Hydrokinetic Power

Chapter 4: Technology Assessments

NOTE: *The 2015 U.S. Department of Energy (DOE) Quadrennial Technology Review (QTR) addresses opportunities for the Nation as a whole. As it is not specific to DOE (or any other federal agency), the QTR and this Technology Assessment do not propose nor discuss funding levels or specific funding mechanisms for national RDD&D activities. This MHK Technology Assessment does not address land-based river and stream resources in detail; it focuses on ocean-based resources.*

Introduction

Marine and hydrokinetic (MHK) technologies convert the energy of waves, tides, and river and ocean currents into electricity. With more than 50% of the U.S. population living within 50 miles of the nation's coasts,[1] MHK technologies hold significant potential to supply renewable electricity to consumers in coastal load centers, particularly in the near term in areas with high costs of electricity and longer term in high resource areas in close proximity to major coastal load centers. MHK resource assessments identify a total U.S. technical resource potential[2] of approximately 1250–1850 terawatt-hours (TWh) of generation per year from ocean wave,[3] ocean current,[4] ocean tidal,[5] and river current energy.[6] Of this, the U.S. continental technical resource potential is approximately 500–750 TWh/year. For context, roughly 90,000 homes can be powered by 1 TWh of electricity generation each year.[7] A cost-effective MHK industry could provide a substantial amount of electricity for the nation owing in large part to its unique advantages as a source of energy, including its vast resource potential, its close proximity to major coastal load centers, and its long-term predictability and near-term forecastability. There are also substantial benefits to maintaining a diversified portfolio of renewables contributing to the grid's energy mix. For example, it is an operational advantage that MHK's output varies from solar and wind resource contributions to the grid in ways that complement their resource loads and potentials.[8,9] MHK also has different geographical and land use requirements as compared with wind, solar, and geothermal, opening up more energy resource options for a diverse national energy portfolio.

Overall, MHK technologies are in an early stage of research and development (R&D), with a wide variety of designs and architectures, and there are no full-scale, multiple-device commercial deployments in the United States at this time. The nation has the opportunity to focus on the technologies with the most abundant resources that have potential for techno-economic viability and can be deployed in markets with high energy costs in the near-term, while supporting next-generation "game-changing" technologies that have the potential to be cost competitive with conventional resources in the longer term.

Specific opportunities for national research, development, demonstration, and deployment (RDD&D) on MHK include, but are not limited to, the following:

- Applied R&D to greatly improve today's technology through innovation in controls, power take-off, and structural components to increase energy capture efficiency and reliability
- Demonstration of technology performance and readiness through testing to establish techno-economic viability for early, near-term markets

- Development of wave energy converter (WEC) extreme conditions modeling processes to reduce uncertainty and risk in the WEC design process by providing developers with a better means of predicting survival loads (in addition, continued development of better modelling capabilities for WECs in all conditions)
- Revolutionary, or breakthrough, technology innovation to develop technologies that go well beyond the current state
- Facilitation of access to testing facilities that enable a systematic progression through technology readiness and performance towards commercialization, thereby reducing the cost and risk of technology demonstration for developers
- Development of a supply chain in close proximity to resource load centers (e.g., through establishment of ports and vessels infrastructure and an MHK workforce)
- Development of resource classification schemes for MHK resources analogous to the resource classifications used by the wind industry
- Development and validation of cost-effective environmental monitoring instrumentation and methodologies to avoid or mitigate impacts of MHK technologies
- Reduction in time and cost for obtaining permits and certification to facilitate project developer financial backing

Improving the performance and reducing the cost of MHK through technology advancements, demonstrating reliability and survivability at needed testing and verification infrastructure, and addressing uncertainties about potential environmental impacts in order to reduce permitting barriers are key factors in reaching commercialization. These activities would allow markets to adopt clean energy from MHK resources that will positively impact the nation's energy portfolio, reduce carbon emissions, and strengthen the nation's clean energy economy.

Market Application and Impact

MHK technologies have the potential to provide a significant low-carbon energy supply contribution for many regions of the United States. For example, extracting just five percent of the technical resource potential for the United States could result in MHK powering several million American homes with clean energy. Wave energy alone has the potential to supply up to 380–470 TWh/year for the continental United States, with large potentials primarily on the Pacific coast and lesser amounts on the Atlantic coast. While wave energy has the largest resource potential, other MHK sources also have significant potential in the following local regions:

- Ocean tidal energy in east and west coast locations with narrow passageways between a bay and the ocean
- Open-ocean current energy off the Atlantic Southeast coast
- River current energy in most states

In the near term, as MHK technologies mature, locations with significant MHK resource potential and high energy costs, such as at remote U.S. Department of Defense (DOD) installations and isolated or islanded communities, are ideal because they are cost-competitive markets for the technology and would help demonstrate commercial readiness. These early market applications would demonstrate pathways to realizing MHK cost reductions for larger-scale deployments in the future.

As an example, the DOD has a goal to use 25% renewable energy by 2025, which equates to an installed renewable capacity of 3 gigawatts (GW). Under DOD, the Department of the Navy's individual goal is 1 GW. The National Renewable Energy Laboratory and Navy evaluated the long-term potential for MHK deployments at Navy installations, and the screening results concluded promising potential for future wave and ocean current deployments near naval installations. The study indicated that 60 total locations met the technical criteria for wave potential within 10 miles of a DOD site; 40 total sites met the technical criteria for tidal potential within 1 mile, and 13 total sites met the technical criteria for ocean current within 10 miles of a DOD site.[10] For markets with high energy costs—including some DOD installations—avoidance of diesel fuel for electricity generation (with potential environmental and energy security issues) can be reduced by deployment of renewable energy, including MHK energy technologies.

Other near-term market applications may include locations with high energy costs and strong resource potential, which primarily are small communities with isolated power grids in Alaska, Hawaii, and other remote coastal communities.[11] Such areas have enough potential MHK resource to meet domestic load demands both for grid-connected domestic load centers and isolated village power generation in the near term and possibly to serve as a potential exporter of excess capacity in the long term, depending on future transmission development. While the high energy costs and energy resource potential at these locations make them attractive sites for today's MHK technologies, several challenges often limit deployment, including access to infrastructure, transportation costs, supply chain, permitting uncertainties, grid integration, and limited scalability, all impacting capital costs. Investing in R&D that leads to increases in annual energy production (AEP), reduced capital costs, and operation and maintenance (O&M) expenditures as well as a better understanding of the resource will drive costs under the local hurdle rates of approximately 12–15 cents per kilowatt-hour (kWh) by 2030. Facilitating deployment of MHK technologies in these early market opportunities over the near term would accelerate technology advancement through learning in the above challenge areas that can be applied to future MHK technologies.

In the mid- to long-term, MHK devices must compete in the commercial utility-scale market as cost-competitive alternatives to other forms of electricity generation in order to meet the potential that the resource has to offer. Reaching this mid- to long-term goal requires catalyzing revolutionary technology advancements today. Not only do these technologies hold opportunities for expanding the clean energy portfolios of multiple regions, but successful MHK industry development would support maritime jobs and market growth. It is important to note that significant cost reductions are required in order to realize these deployments and maritime market base. Opportunities and challenges for MHK RDD&D are discussed in more detail below. The nation can conduct techno-economic analyses with industry input to better understand MHK resources, required R&D pathways, and deployment potential.

State of the Industry

The first known patent to use energy from ocean waves dates back to 1799,[12] and the first study of large-scale tidal power plants was by the U.S. Federal Power Commission in 1924.[13] A renewed interest in MHK technologies was motivated by the 1973 oil embargo, but their development has been sporadic. Only prototypes and early production models have been deployed in demonstration projects. The current state of the industry can be compared to the early stages of the wind energy industry in the 1980s, in that many concepts have been proposed with a wide variety of methods for energy capture and conversion but with little technology convergence. There are limited data available to identify low cost of energy, high-performance solutions with high reliability; convergence on identified leading solutions would allow focused future investments.

Figures 4.N.1 and 4.N.2 illustrate several concepts for wave, tidal, ocean, and river current devices that have been considered and/or are currently under technology development. A more comprehensive list of MHK device configurations, current projects, and development companies is provided by the U.S. Department of Energy (DOE) Marine and Hydrokinetic Technology Database on the OpenEI Web site.[14]

Figure 4.N.1 Examples of Wave Energy Devices

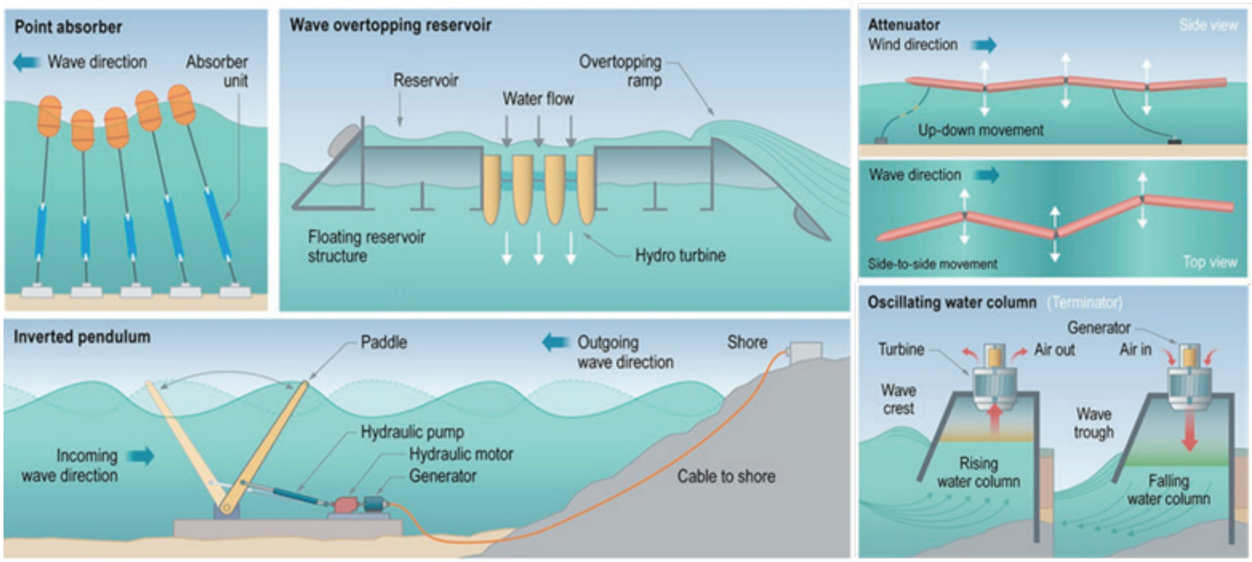
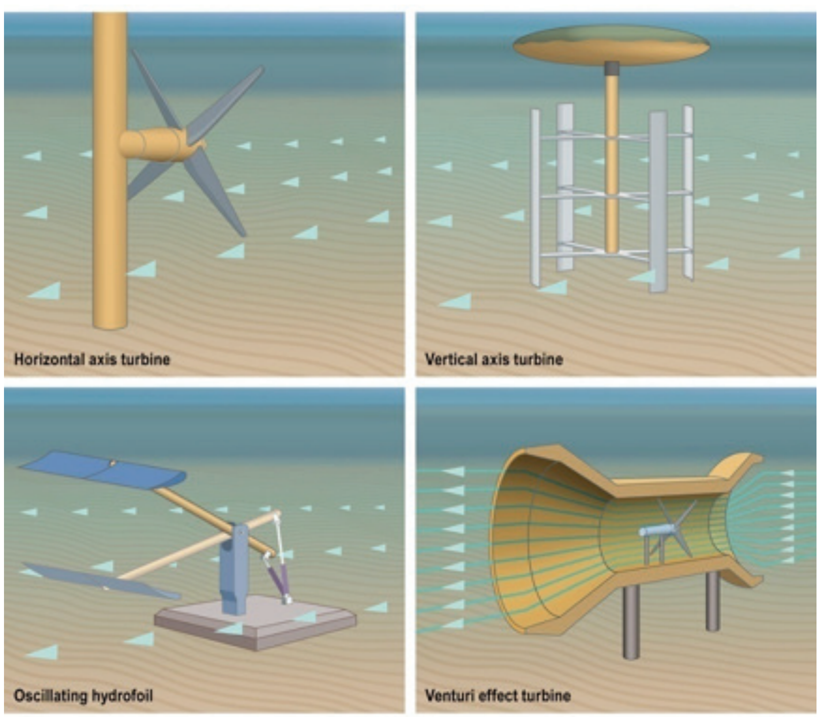


Figure 4.N.2 Examples of Tidal, Ocean, and River Flow Energy Conversion Devices



The most recent development cycle for MHK technologies was initiated in Europe over a decade ago, and it has been gaining momentum. Worldwide, over 100 companies are developing MHK technologies. However, the capacity of MHK devices installed around the world is quite small, only tens of megawatts, and these installations are generally engineering prototype test devices or small several-unit demonstration wave and tidal projects.[15] In the United States, there are over a dozen companies actively developing prototype wave, tidal, ocean, and river current devices. However, private sector entities, especially small start-up companies, are often constrained by technical and demonstration milestones necessary to obtain the next source of funding. Several of the U.S. prototypes have been tested in open water for short periods of time, but none have been deployed for multiyear array-scale demonstration testing. As of the end of 2014, four companies held licenses from the Federal Energy Regulatory Commission (FERC) for MHK technology deployment projects, with 11 other projects in the development pipeline (holding a preliminary permit or in pre-filing for a license).

At the current prototype stage of development, increasing energy capture, operational efficiency, structural performance, reliability, and survivability prior to large-scale deployment represent the most promising opportunities for advancing MHK technologies toward techno-economic viability. This is consistent with early wind turbine development experience in California in the 1980s and 1990s.

National RDD&D Opportunities

The administration's goal is to generate 80% of the nation's electricity from clean energy sources by 2035, reduce carbon emissions 26–28% below 2005 levels by 2025, and reduce carbon emissions 83% by 2050, leading the world in clean energy innovation and stimulating jobs and economic growth with a clean energy economy.

The nation can take action to enable and accelerate widespread U.S. deployment of clean, affordable, reliable, and domestic MHK power to promote national security, economic growth, and environmental quality by developing a balanced program of technology planning, research, development, testing, analysis, evaluation, and communication that would increase the viability and acceptance of MHK technologies.

The following sections discuss national opportunities for RDD&D technology advancement in MHK as informed by industry, academic, and other expert input.

Overview of Challenges and Opportunities

MHK energy is one of the most recent types of renewable energy technologies to be developed for broad commercial use. Both challenges and opportunities arise with this. The United States has a significant number of MHK device developers; many have tested early generation designs in tanks or flumes; a small number have deployed in the open ocean; and fewer still have sought or been granted FERC licenses for future grid-connected marine energy generation plants. The opportunity lies in taking advantage of early markets to demonstrate existing technologies while making fundamental and revolutionary improvements to systems to ready them for utility-scale markets in the longer term.

To date, the international community has had substantial incentives that have driven technology developers to demonstrate MHK devices in the ocean environment.[16] The same policy incentives do not currently exist in the United States, but this presents an opportunity for U.S. investments to leverage lessons learned from international experience.

The five challenges given in Table 4.N.1 highlight national opportunities for acceleration of MHK technology development and commercialization.

Activities to address these national opportunities for developing commercial-scale, reliable, and cost-effective MHK technologies for U.S. markets can be categorized as (1) technology advancement and demonstration and (2) crosscutting and supporting research. Technology advancement and demonstration activities include RDD&D efforts to directly advance the systems for energy capture, reliability, and cost. Crosscutting and supporting research activities include test infrastructure, resource characterization, and market acceleration and deployment. These priority research areas may be advanced in parallel to accelerate the sector forward. Additionally, there is significant opportunity to leverage the activities and learnings from the international marine renewables sector.

Technology Advancement and Demonstration

National technology advancement and demonstration efforts can focus on reducing the "levelized" cost of energy (LCOE) of MHK technologies through improved design, testing, and demonstrations. These efforts can be considered to advance along two parallel and complementary tracks—evolutionary innovations focused on near-term deployment in early adopter markets with high energy costs and breakthrough innovations focused on longer-term deployment in larger national markets.

Table 4.N.1 Challenges and Opportunities for MHK Development and Commercialization

Issue	Challenge	Opportunity
Resource Assessment and Characterization	Today's national resource assessments are at a low resolution, making industry decisions on technology development and deployment high risk.	Higher resolution regional assessments for MHK will support resource classification schemes and provide more detailed information. These will reduce risk for investment opportunities in technology development and deployment.
Technology Maturity	The marine and hydrokinetic energy sector is currently represented by a great diversity of technology solutions and there are limited data available to identify low-cost, high-performance solutions with high reliability, so investments are spread across all of the technology types rather than focused on the most promising technology development pathways.	There are many new players taking interest in development of what could be winning solutions in this sector, and a national effort could with entrepreneurs could develop solutions with high potential to be cost competitive and environmentally responsible. Identifying winning solutions would establish the United States as a global leader for domestic and international markets.
Cost Reduction	Significant innovation is still needed to bring costs down by more than 50% to achieve cost competitiveness of MHK devices. Devices need to capture more energy and reduce both capital and operating costs.	Innovation mechanisms and a large body of knowledge to draw from other scientific and industrial sectors are available today to accelerate the cost-reduction profile.
Demonstration	Developers who are ready to test full-scale prototypes lack access to test facilities and permitted demonstration sites. This impedes the developer's ability to validate device performance in its intended resource; test and iterate installation, operation, and maintenance logistics; and monitor device-to-environment interactions.	Access to world-class test facilities and other demonstration opportunities and associated instrumentation have the potential to accelerate technology evolution while substantially reducing technology development and demonstration costs to the industry. Specifically, early-adopter markets may present demonstration opportunities.
Deployment	The process for permitting device deployments can be expensive and time consuming, leaving fewer resources for R&D and increasing project development costs. The lack of scientific information, for example baseline environmental data, and high monitoring costs can drive environmental and regulatory expenses to 30%–50% of total early-stage MHK project cost.	By assessing and addressing potential environmental impacts now through scientific research, developing new instruments, and validating them with initial device demonstrations, this sector can avoid serious deployment barriers. National support for environmental monitoring can help reduce the monitoring cost burden for developers, allowing them to focus funds on technology development to approach cost competitiveness and facilitate more widespread deployments.

Near-term deployment in early-adopter markets—such as remote, high cost of energy locations and DOD installations—supports early successes, acting on lessons learned and iterative improvements to develop and maintain momentum for the existing MHK industry. These efforts would focus on evolutionary technology innovation to increase AEP and reliability and reduce capital and O&M expenses of current state-of-the-art MHK systems as well as provide insight into reducing environmental and permitting considerations. Activities include development of components for application in today's MHK technology solutions but also relevance to future systems as well as implementation of best practices to maximize the learning that can occur with successful technology demonstrations.

Long-term deployment in large utility-scale markets—such as the western U.S. coast—supports the high-risk, high-payoff technology advancements that are crucial to MHK realizing a significant contribution to the nation's long-term energy needs. These efforts would focus primarily on revolutionary, or breakthrough, technology innovation to develop the component and system technologies that have the attributes to be competitive with other energy technologies in large markets. The systems identified for tomorrow's large utility-scale markets in this track would benefit from the MHK design-agnostic component advancements and offshore logistics lessons learned in the near term.

Success of these efforts could be measured by the establishment of a supply chain of MHK-ready components, significant MHK technology deployment by the 2025–2030 time frame, proven technical credibility and bounded financial risk giving investors confidence in MHK technologies, and a number of concepts that have high potential for utility-scale deployment in large U.S. markets entering the pipeline for technology advancement.

Evolutionary Technology Innovation

Evolutionary innovations are continuations to existing technologies or practices. They involve extension of products already in or near the market and are generally incremental in nature. The focus would be on development of components and evolution of systems that would have applicability to today's MHK technology solutions for early-adopter markets (as well as relevance to future systems) and implementation of best practices to maximize the learning that can occur with successful technology demonstrations.

MHK developers may currently use existing off-the-shelf components when building their systems, both to reduce initial cost and take advantage of early market opportunities. In most cases, these components are not optimized for the application in which they are employed, leading to suboptimal performance and reliability. In response to this, the nation can focus on RDD&D to realize substantial performance gains through the development and application of innovative components that are designed and built specifically for MHK applications. In particular, purpose-designed and purpose-built components capable of performing within the operating ranges and under the conditions and environments specific to MHK systems would help ensure that MHK systems perform efficiently and reliably and thus improve the likelihood that these innovative technologies can cost-effectively compete in the marketplace. Example opportunities in component RDD&D to address key cost drivers[17,18,19,20] include the following:

- Advanced controls technologies: These enable devices to be tuned to extract the maximum energy from each sea state. The stated potential in the literature for controls technology to increase the energy capture from a wave energy convertor ranges from two to four times.[21]
- Universal power take-off technologies: Component solutions developed for multiple MHK applications include high reliability generators for the marine environment, compact high-torque low-speed generators, and high wear bearings.
- Structural optimization: Corrosion- and biofouling-resistant materials and coatings will reduce maintenance intervals required. Structural design informed by improved understanding of loads and material performance under loads will improve structural lifetimes. Finally, shape optimization of structures can improve energy capture (i.e. hydrodynamic performance).

In addition, there are a number of areas of overlap and opportunities for innovation to reduce costs across all MHK technologies as well as offshore wind, such as marinized components and balance-of-plant technologies, including subsea cables and offshore substations.

Opportunities also exist to rapidly advance technology development through development, improvement, and validation of advanced engineering and physics-based design and optimization tools. These tools reduce uncertainty and risk in technology performance, and reduce time and costs for device developers by minimizing the number of design iterations necessary. Furthermore, validation data sets and design tools that are made open source will facilitate continuous improvement in these design tools to match the pace of rapidly evolving MHK systems.

Success of these efforts can be measured by resulting incremental technology developments having the potential to be broadly applicable, supporting cost reductions for several different MHK energy conversion system solutions, and beginning the establishment of an MHK supply chain.

Near-Term Demonstrations

Opportunities for demonstration of MHK technologies in the near term include demonstrations at controlled test facilities and open water demonstrations in early adopter markets. Demonstrations are useful for evaluating the ability of MHK technology concepts to succeed in the practical aspects of deployment and to identify any technical, market, and policy challenges not revealed through laboratory system and component testing. MHK technology demonstrations are used as follows:

- Gain experience with O&M strategy
- Gather environmental data under actual operating conditions
- Assess advanced component technologies through their integration with MHK systems available today
- Assess device reliability, maintainability, and survivability
- Assess device energy capture

Lessons learned through demonstrations lead to reduced cost of electricity via the following mechanisms:

- Reduced project and operational costs
- Advancement on the learning curve with increased cumulative deployment
- Improved device reliability, maintainability, and survivability
- Improved device energy capture efficiency

In addition to cost reduction, deployment in early-adopter markets can do the following:

- Allow technology developers to help investors gain confidence by seeing proven, reliable technologies in longer-term deployments
- Earn confidence in MHK technology by showing it works as promised in the relevant operational environment and over relevant timelines
- Provide a revenue stream (if grid connected) to help a technology developer fuel further investment and advancements
- Gain exposure and public acceptance of MHK technologies and allow regulators to observe actual environmental impacts over relevant timescales
- Allow technology developers seeking to be original equipment manufacturers a chance to demonstrate a track record of delivering on commercial contracts

Breakthrough Technology Innovation

Breakthrough innovations are generally considered to be game-changing solutions, employing new technologies that cannot be compared to any existing practices or techniques. Such innovations can occur at any stage of development, but tend to be most successful during the early stages of development for new technologies when the preferred configuration for devices is still in question, which is currently the case for all MHK technologies. Innovative companies have learned that mainstream business and marketing structures significantly constrain blue-sky thinking, while technology incubators allow creation of new value where none previously existed.[22] An early example of this is the development of interchangeable parts, which revolutionized manufacturing. These were developed at public armories, originally for rifles, under President George Washington.[23] A more recent example is the X Prize Foundation, a nonprofit organization founded in 1995 that designs and manages public technology incubator competitions intended to encourage technological development that could benefit mankind.[24]

Elements required for spurring game-changing innovation include the following:

- Teams that bring together diverse expertise and skill sets
- Willingness to take a fundamentally different approach with little to no commitment to retaining initial early concepts
- Ability and incentive to attempt high-risk innovations
- Strong focus on the end goal and a clear understanding of what is needed to meet it

An example of such innovation efforts to drive MHK technology cost down rapidly is the Wave Energy Prize.[25] This prize-based challenge, sponsored by DOE and beginning in April 2015 and ending in November 2016. The prize is designed to increase the diversity of organizations involved in WEC technology development while motivating and inspiring existing stakeholders. It is meant to encourage the development of more efficient WEC devices that, for example, might double the energy production or use new low-cost lightweight materials to capture energy from ocean waves, which in turn would dramatically reduce the cost of wave energy, making it more competitive with traditional energy solutions. Through this effort, developers will conceptually design their game-changing WEC devices, build them, and then test them at the U.S. Navy's NAVSEA Carderock Division facility in Maryland—the nation's premier wave-generating basin. With this initiative, the federal government funds only performers who exceed the target metrics and stimulate investment many times greater than the cash value of the prize.

Crosscutting and Supporting Research

In addition to opportunities for technology advancement and demonstration, crosscutting and supporting research activities can help the nation realize MHK's potential. These activities include the following:

- Developing device-testing infrastructure to provide opportunities for component and system demonstration
- Conducting regional-scale resource modeling and characterization to help developers understand where to site devices and design to those resource conditions
- Conducting research to resolve potential environmental and siting issues, thereby reducing the cost and time associated with permitting MHK projects and accelerating deployment

These crosscutting portfolio activities are generally technology agnostic, helping to inform the technology advancement strategy and reduce barriers for all device types.

Test Infrastructure

The ability to test and iteratively improve on MHK concepts is critical to successful innovation. With growing U.S. interest in ocean energy technology development, test facilities are needed to support a wide range of R&D needs, including the following:

- Providing validation data for design codes and standards
- Performance testing of scale to full-sized prototypes
- Gaining practical experience of installation and maintenance operations
- Testing new environmental instrumentation and monitoring methodologies under development
- Providing insight into reducing environmental and permitting barriers

Without easily accessible and well-instrumented national test facilities, entities are left to individually establish the elements needed for conducting these iterations. It is tremendously costly and time consuming for individual developers to undertake this disciplined testing regime independently, a burden that detracts from the focus on technology innovation.

When the critical role of test facilities is considered in accelerating the commercialization of emerging MHK technologies, a direct comparison can be made to U.S. experience in wind energy. Test facilities established by the Federal government played, and continue to play, a critical role in improving wind turbine system and component designs and in developing wind turbine design codes and standards prior to large-scale deployment of new technologies.

The nation could enable the innovation cycle for MHK technology through establishment of and/or provision of access to facilities for testing as well as proven instrumentation and methods for gathering data from each test. Such efforts could be designed to maximize learning from the testing of device energy capture, loads on the device, and reliability, all of which are critical to reducing the number of iterations of design that are necessary to achieve commercial success.

The United States has many existing assets available for testing at the low to mid stages of technology readiness (i.e., model scale testing wave tanks and basins, flumes, and water tunnels) but very limited options for higher technology readiness level (TRL)[26] open-water grid-connected testing. A TRL 7/8 open water test facility with multiple berths has been identified by the MHK stakeholders as a high priority need and, if established, would enable U.S. MHK developers to perform grid-connected testing without the expense of supporting infrastructure, permits, licensing, and monitoring. Although international open-water, grid-connected locations exist where U.S. developers could perform international testing (such as the European Marine Energy Centre), this option entails substantial challenges for U.S. companies and lost opportunities for the U.S. MHK industry and R&D community. Insufficient test berth availability at foreign locations and significant additional cost for transporting a U.S.-manufactured device overseas often deter domestic MHK device developers from testing at full scale in fully energetic ocean conditions, which is necessary to validate device design and numerical models.

National opportunities for open-water testing currently exist with the U.S. Navy at its wave energy test site (WETS) in Kaneohe, Hawaii.[27] WETS offers grid-connected test berths in a partially sheltered open-water location appropriate for devices at TRLs of 5–7. MHK systems at TRLs of 8–9 require higher energy wave conditions for full validation, which will enable commercialization. WETS is permitted for testing of point absorbers and oscillating water columns; however, all remaining device types are unable to undergo testing at a grid-connected, open-water site in the United States. It is noteworthy that in Europe, MHK developers of any device type have access to grid-connected, open-water testing infrastructure suitable for completing the TRL 9 validation testing required to reach commercialization.[28]

Similar opportunities for testing of current energy devices exist, with U.S. test facility capabilities ranging from small-scale laboratory testing to large-scale open-water testing. Examples include the following:

- Open ocean current device testing with performance and environmental data acquisition at the Southeast National Marine Renewable Energy Center[29]
- A site on the Tanana River suitable for testing instream river current devices developed by University of Alaska Fairbanks's Alaska Center for Energy and Power[30]
- A 90-foot-long tow tank at the University of New Hampshire and an additional open-water test site for large-scale testing of tidal current systems[31]
- A 48-inch-diameter water tunnel facility at the Penn State Advanced Research Laboratory for high-fidelity testing of blades or small-scale turbines[32]

Affordable access to well-instrumented world-class test facilities for emerging MHK components and systems would directly accelerate development and deployment of U.S.-developed technologies by reducing technical and financial risks, reducing the cost of testing for individual developers and the industry as a whole, and reducing the time-to-market of commercially ready systems.

Resource Characterization

As with any renewable resource, identifying, characterizing, and accessing higher quality and greater quantities of the resource provide potential for LCOE reduction. Additional research by MHK stakeholders is needed to identify the practical resource potential at specific sites of interest to achieve commercial development of these resources. There is an opportunity to create classification schemes for MHK resources to inform and allow device designs for resource classes that balance energy capture while reducing the risk of unexpected resource loads on the device.

Several national-scale resource assessments have been published to inform strategic decisions on where MHK resources may be economically viable to pursue. These assessments included wave, tidal, ocean current, river current, and ocean thermal resource assessments. Building on the information from these assessments, there is an opportunity to focus on more specific (e.g., regional-scale, characterization of wave, tidal and ocean current) resources in hot-spot areas throughout the nation where there is high resource potential. Clearly the resource assessments demonstrate a large wave resource potential—more so than other potential MHK resources throughout U. S. waters. With this information and refined numerical models of hotspot resources, a classification system for the wave resources (for example) could be established, much like existing wind energy resource classification schemes.

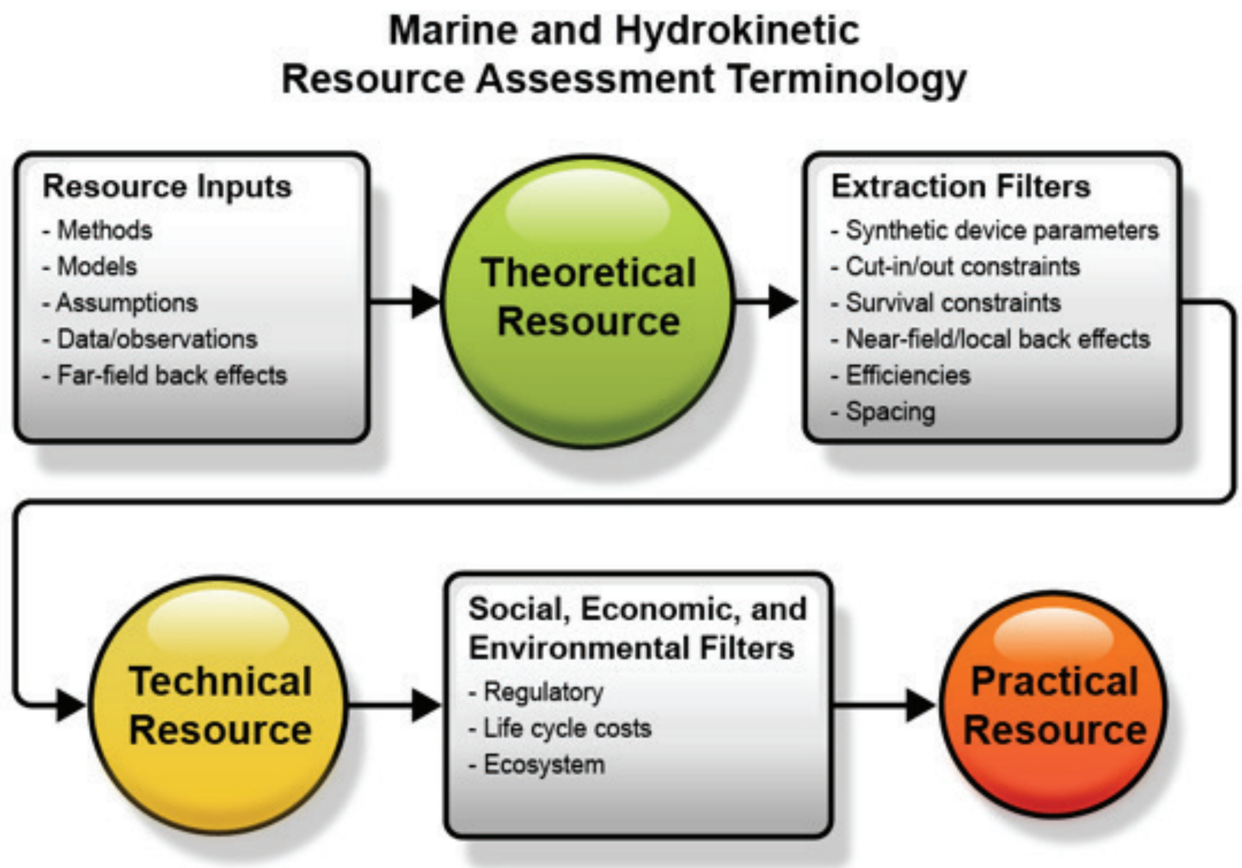
A wave energy resource classification system would allow the WEC industry to determine whether an ocean wave site is suitable for energy conversion and to what scale on the range from micro-grid to commercial, to select the WEC archetype and power-class appropriate to the resource, and to inform O&M schedules and costs.

Because there are limited data for MHK technologies, techno-economic assessments leverage national resource assessments and European cost of energy data, adjusting to reflect resource intensity in the United States. While development of quantitative analysis techniques and modeling capabilities has allowed for some scenario projections of wave energy deployment in the contiguous United States,[33] national opportunities exist to better define MHK cost and deployment metrics by using measurements and data gathered from actual deployment-based monitoring. These include opportunities to update scenario projections on the basis of updated cost of energy estimates for wave devices and to further analysis efforts to determine tidal or ocean current deployment projections in states that have high potential for these renewable energy sources.

Assessing the available resource for MHK technologies is a difficult and complex task. Each MHK technology involves a distinctly different technical discipline and requires estimating different physical variables in the natural environment. For devices that extract energy from tidal, ocean current, and river flows, the quantity of interest is the velocity field and its time history. For wave devices, the time history of the wave height and the wave period are the quantities of primary interest. Most of these quantities are not well documented historically. For example, tidal flows have always been of great interest to seafarers, but generally, the range of tidal heights was recorded with the time of occurrence and not the velocity field.

Marine and hydrokinetic (MHK) resource estimates are often organized in a hierarchical fashion, from theoretical to technical to practical resources, as illustrated by Figure 4.N.3. First, the available naturally occurring kinetic plus potential energy in the wave or water current resource is estimated at a particular location. Water current resources are typically calculated through cross sections of river, tidal estuary, or ocean current flows, whereas wave resources are calculated over a length of coastline at some distance from shore or along a specific water depth contour. Instantaneous and yearly average water current "local power densities" at specific locations are measured in kW/m^2, and wave resources are measured in kW/m^2 of wave crest length. Integrating the power density over the whole year (or multiplying time-averaged local power density by the number of hours in a year) for a specific wave or water current resource will yield the "local available energy" from that resource in a year (measured in kWh/year). Summing the local available energy over a geographical area (e.g., region, country, or world) provides an estimate of the "total available energy" for that resource in the region.

Figure 4.N.3 The Relationship between the Theoretical, Technical, and Practical Resources



The total available energy for a resource provides an estimate of the amount of energy that is present in the natural environment, and this quantity is frequently referred to as the theoretical resource, gross potential, or potential resource. Herein, it will be referred to as the "theoretical resource." Estimates of the local available energy for a given resource provide insight into geographic locations of high potential for MHK technologies to be employed and an estimate of the spatial extent and quality of these resources. Generally, the theoretical resource is estimated by using complex numerical fluid flow simulation models.

A second resource quantity of interest is the amount of the MHK theoretical resource that can be technically extracted by an MHK device or array of devices. The National Academy of Science (NAS) defines the "technical resource" as the portion of the theoretical resource that can be captured by using a specified technology. Estimating the theoretical resource is complex, but estimating the technically extractable resource is even more complex, and in most cases, the technically extractable resource cannot be directly calculated from an estimate of the theoretical resource alone. This is because the amount of extractable resource can be changed by the introduction of the energy extraction device into the flow. Generally, it is expected that the introduction of the device will reduce the amount of energy that can be extracted from the flow. Furthermore, the energy extraction efficiency of the devices themselves can significantly affect estimates of the technical resource.

The third resource quantity of interest is the amount of technical resources that can be practically extracted after consideration of all other constraints. Examples of filters that could impact the practical MHK resource are environmental, regulatory, and social and economic considerations as follows:

- **Environmental filters:** Potential impacts on marine species and ecosystems, bottom disturbance, and altered regional water movement
- **Regulatory filters:** Federal and state regulations (such as the Marine Mammal Protection Act and the Coastal Zone Management Act) and federal agency jurisdictions
- **Social and economic filters:** Spatial conflicts, interconnection to the power grid, and capital and life-cycle costs

The basis of many of the critical environmental, regulatory, and social and economic filters is the need to meet multiple management objectives from the shared coastal, ocean, and riverine environment.[34] With a growing number of uses, users, and demands, there are increasing spatial and regulatory conflicts in meeting these management objectives. Planning for multiple uses can maximize the achievement of multisector goals while reducing conflict. However, at this early stage of development of MHK technologies, there are insufficient experimental data to accurately estimate the impact of these filters to make a reliable estimate of the practical resource.

Theoretical Resource Estimates

The Department of Energy (DOE) sponsored a series of resource assessment studies that estimated the theoretical resource potential of ocean wave,[35] ocean current,[36] ocean tidal,[37] river current,[38] and ocean thermal gradient energy[39] in the Unites States. Figure 4.N.4 shows the magnitudes and locations of the hydrokinetic resources and indicates that wave energy is the most abundant hydrokinetic resource in the United States.

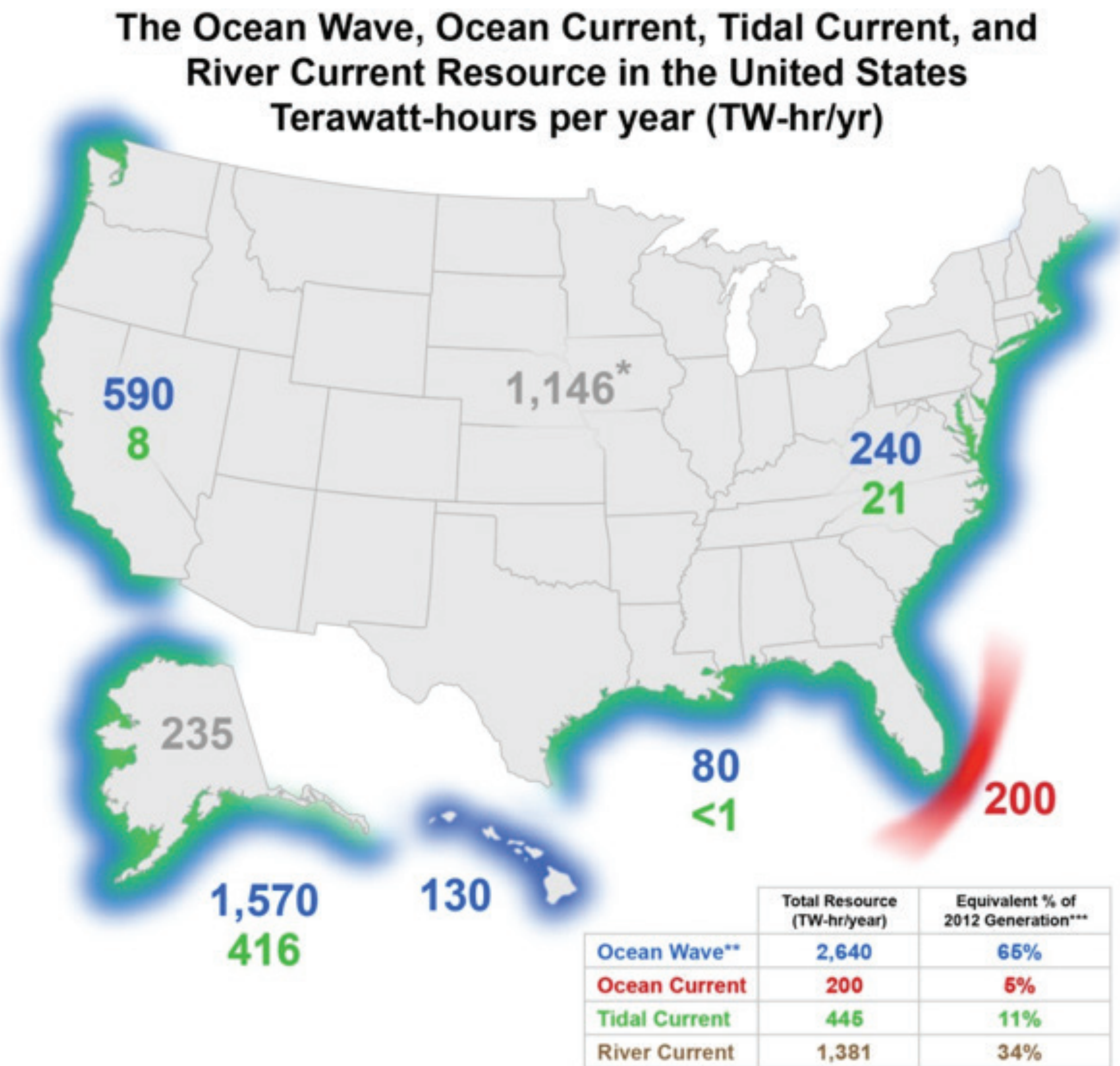
The MHK resource potentials listed in Table 4.N.2 summarize results from ocean wave, tidal current, ocean current, and river current resource assessment studies mentioned above and commissioned by DOE for the entire United States. Table 4.N.2 also includes MHK resource estimates for the contiguous United States (CONUS), where the electricity output can be fed into the electrical grid to supply regional markets. The National Academy of Sciences (NAS) National Research Council (NRC) performed an impartial review of these studies and raised several potential issues with the methods used to estimate the theoretical MHK resource and the technical resource.[40] Nevertheless, the committee concluded that the overall approach taken by the wave resource and tidal resource assessment groups is a useful contribution to the understanding of the distribution and possible magnitude of energy sources from waves and tides in the United States.

Owing to a lack of operational data on MHK technologies, none of the DOE-sponsored resource assessment studies attempted to evaluate the practical resource potential. The unknown impacts of MHK technologies did not make it possible to account for social, economic, regulatory, environmental, and competing resource use restrictions. However, it is important to note that in all cases, practical considerations will significantly reduce the potential contribution that the MHK resource can make to the U.S. energy portfolio. The text box Wave Energy Resource Estimates provides an example of a more in-depth look at an MHK resource characterization completed by DOE, a characterization of the wave energy resource.

National opportunities exist for accurate and high quality ocean resource characterization and forecasting research. Effective MHK resource characterization relies on measuring at the multiple pertinent spatial and temporal scales to assess the energy available to the devices and on physical and temporal scales for specific device design within specific water regimes (e.g., from national scale resource assessments of total energy available annually to characterizing the extent of variability of mean tidal current speeds and turbulence across a strait over a period of minutes). In the longer term, application by the project developer of resource characterization and methodologies to characterize specific sites could further enable devices to be tailored to the intensity of the resource, thereby increasing the lifetime of the devices.

Figure 4.N.4 The theoretical MHK resources in the United States

Credit: National Renewable Energy Laboratory



Ocean Wave: P. Jacobson, G. Hagerman, and G.Scott, "Mapping and Assessment of the United States Ocean Wave Energy Resource," Electric Power Research Institute, Report Number 1024637, 2011.
http://www.epri.com/abstracts/pages/productabstract.aspx?ProductID=000000000001024637
Ocean Current: K.Haas, H.Fritz, S.French, and V.Neary, "Assessment of Energy Production Potential from Ocean Currents Along the United States Coastlines," Georgia Tech Research Corporation, 2013.
http://energy.gov/sites/prod/files/2013/12/f5/energy_production_ocean_currents_us_0.pdf
Tidal Current: K.Haas, H.Fritz, S.French, B.Smith, and V.Neary, "Assessment of Energy Production Potential from Tidal Streams in the United States," Georgia Tech Research Corporation, 2011.
http://energy.gov/sites/prod/files/2013/12/f5/1023527.pdf
River Current: T.Ravens, K.Cunningham, and G.Scott, "Assessment and Mapping of the Riverine Hydrokinetic Resource in the Continental United States," Electrical Power Research Institute, Report Number 1026880, 2012.
http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001026880

*Resource distributed throughout the river systems in the United States.
**Resource data for the 200-m depth contour
***The size of the resource with respect to total U.S. electricity generation in 2012, which was 4,054 TW-hr (U.S. Energy Information Administration, "Electric Power Monthly," May 2013)

Note: National resource assessments indicate that wave energy accounts for more than 80% of U.S. marine theoretical resources (excluding river current) and over 55% of U.S. total MHK theoretical resources.

Table 4.N.2 United States MHK Energy Resource Estimates[3,4,5,6]

MHK Energy Potential by Resource						
Resource	Theoretical Resource		Technical Resource		Technical Resource	
	Total US		Total US		CONUS	
	TWh/year	%U.S. Annual energy production (AEP)(1)	TWh/year	%US AEP(1)	TWh/year	%US AEP(1)
Wave Energy (2, 3)	1594–2640	39–65	898–1229	22–30	378–472	9–12
Tidal Current Energy (4)	445	11.0	222–334	5.5–8.2	15–22	0.4–0.5
Ocean Current Energy (5)	200	4.9	45–163	1.1–4.0	45–163	1.1–4.0
River Current Energy	1381	34.1	120	3.0	100	2.5
Total:	**3620–4666**	**89–115**	**1285–1846**	**31.6–45.2**	**538–757**	**13–19**

Note: (1) 2012 U.S. annual electrical energy consumption 4054 TWh/year; (2) the wave resource varies as a function of water depth; the wave resource is larger in deeper water further from shore; depending on location, contours used to calculate lower and upper bounds on resource potential are different; where the continental shelf has steep inclination, contours used are 50 m and 200 m depth contours; where the continental shelf has shallow inclination, contours used are 20 m depth and 50 miles distance from shore; (3) technical resource on the basis of on a wave device installation packing density of 15 MW per kilometer of wave front; (4) technical resource estimate of 50% to 75% of theoretical resource on the basis of an assumed range for energy extraction potential and mechanical to electrical conversion efficiency; (5) theoretical resource on the basis of 30-year mean kinetic energy flux in the flow.

Wave Energy Resource Estimates

Wave resources are the most abundant MHK resources in the United States. For this reason, a more in-depth analysis of the wave resource has been undertaken by DOE. This text box discusses the wave energy technical resource estimate, a wave energy conversion model, wave energy practical resource estimates, and the potential contribution of regional wave resources.

Technical Resource Estimate—Wave Energy

As shown in Table 4.N.2, the theoretical wave energy resource along the outer contour of the U.S. coastline was estimated to be approximately 2640 TWh/year. The 200-m depth used in the West Coast of the United States (e.g., to calculate the upper bound of theoretical resource) is an appropriate depth for systems of the future. However, the first generations of wave energy converter (WEC) devices will likely be deployed in shallower water depths of 50–100 m because of mooring, export cable, and maintenance access costs. Accordingly, to determine the technical and practical resource in the near term, the theoretical wave resource data[41] were reanalyzed at the 100 m water depth. Results from this analysis estimate that the theoretical wave energy resource at 100-m depth in the United States is 1851 TWh/year. For CONUS the theoretical wave resource is estimated to be 780 TWh/year, which represents 19.2% of 2012 U.S. generation, and the majority of the wave resource is on the West Coast.

Wave Energy Resource Estimates

The average West Coast wave resource is 27 kW/m of wave crest, which is approximately three times more energetic than the East Coast, where the resource is 9 kW/m, making the use of wave energy much more technically and economically challenging in that resource. The NAS listed "extraction" filters that should be considered when moving from theoretical to technical resource potentials, and "social, economic and environmental" filters when moving from technical to practical resource potentials, as illustrated in Figure 4.N.3, above. The extraction filters are driven by technical capabilities (e.g. cut-in/out constraints, survival constraints, near-field/local back effects, efficiencies). The following section details DOE efforts to consider all of the technical "extraction" filters recommended by the NAS except for survival constraints and near-field/local back effects, which are not well quantified at this time and therefore could not be applied.

To evaluate the technical wave resource in a straightforward manner that is adaptable and technology agnostic, the analysis employs a conceptual technology wave converter deployed in arrays, where only the overall energy conversion efficiency of the array is considered. The methodology assumed that WECs will be installed in large arrays that are several rows deep in the direction of wave propagation. As waves pass through the rows of the array, energy is absorbed from the wave front, and therefore downstream rows are exposed to reduced incident wave energy. If an array consists of an arbitrarily large number of rows, it is theoretically possible to extract almost all incoming wave energy. In practice, however, there will be a point of diminishing returns, where installing additional rows of devices will provide only marginal increases in absorbed energy. Accordingly, there will be a point where deploying additional rows of WECs is not economically beneficial. To evaluate the technical wave resource, it is assumed that once the resource has been depleted to 8 kW/m as it passes through an array, it is not economical to deploy additional rows. In addition, the analysis assumed that the array has an overall mechanical to electrical conversion efficiency of 90%, predicated on eventual use of wave devices that are more advanced than today's technologies having mechanical to electrical power conversion efficiencies between 65% and 80%.[42] This model can be written as a simple energy conversion formula as follows:

$$\frac{Wave\ array\ output}{meter} = \left[\frac{Inflow\ energy}{meter} - \frac{Outflow\ energy}{meter}\right] * Conversion\ efficiency$$

Using this simple model, the energy that would be generated by an advanced wave technology converter array was calculated to assess the future technical potential of wave energy.

The technical resource for each region, as presented in Table 4.N.3, was calculated using the method described above. The total U.S. technical resource is on the order of 900 TWh/year, representing 22.2% of 2012 U.S. net electric power sector generation. It is, however, worth noting that 57% of the technical resource is located in Alaska, and even if the Alaska resource is harnessed, transmission to electricity demand in the CONUS is not feasible in the near term. The CONUS technical resource is 359 TWh/year, representing 8.8% of 2012 generation. On the East Coast, the technical resource potential is low and represents only about 0.6% of 2012 generation and for this reason does not seem like a near-term opportunity.

Wave Energy Conversion Model, continued

Table 4.N.3 Theoretical, Technical, and Maximum Practical Wave Energy Resource Breakdown at 100-m-Depth Contour

Region	Quantity	Theoretical Resource	Technical Resource with 8 kW/m Outflow	Maximum Practical Resource
U.S.	TWh/year	1851	899	522
	% 2012 U.S. generation	45.6%	22.2%	12.9%
CONUS	TWh/year	780	359	264
	% 2012 U.S. generation	19.2%	8.8%	6.5%
West Coast	TWh/year	502	333	240
	% 2012 U.S. generation	12.4%	8.2%	5.9%
AK	TWh/year	973	508	233
	% 2012 U.S. generation	24.0%	12.5%	5.8%
HI	TWh/year	98	32	24
	% 2012 U.S. generation	1.8%	0.6%	0.5%

Practical Resource Estimates—Wave Energy

It is not feasible to extract all the technical wave resource for two main reasons: (1) certain regions of the U.S. coastline are precluded from WEC deployments owing to exclusion zones, including marine sanctuary and shipping lanes, and (2) some of the wave energy resource is stranded more than 600 kilometers from on-shore substations that provide an interface to the electrical grid. The right column in Table 4.N.3 shows how removing the exclusion zones and the resource far from on-shore substations reduce the available wave energy resource. Specifically, Table 4.N.3 shows that the maximum practically extractable CONUS wave energy resource is 264 TWh/year, representing 6.5% of 2012 generation. This estimate of the practical resource does not account for social constraints and additional filters, as recommended by the NAS,[43] and thus the practical resource numbers presented in Table 4.N.3 should be considered an upper limit to the practical wave energy resource. For example, although national marine sanctuaries and shipping lanes were removed from the areas where WECs could be deployed, it was not possible to consider restrictions on deployment due to recreational or local environmental concerns that have not yet been assessed. Although the Hawaii and Alaska wave resources cannot contribute to electricity generation needs in the CONUS, there is a significant opportunity for the resources to make large contributions to the individual state generation needs.

Opportunity: Potential Contribution of Regional Wave Resources

Wave energy has the potential to make a significant contribution to low carbon electricity in all of the West Coast states as shown in Table 4.N.4. In addition, states with relatively high electricity prices, like Alaska with an average of 16.3 cents/kWh and Hawaii with 34 cents/kWh, could serve as early niche markets for a new commercial generation of wave energy converters.

Wave Energy Conversion Model, continued

Table 4.N.4 Potential contribution of wave energy to west coast states low carbon electricity

Region	Quantity	Region Electricity Sales(1)	Theoretical Wave Resource	Technical Resource with 8 kW/m Cut-in Filter	Maximum Practical Resource
West Coast (CA, OR, WA)	TWh/year	398.4	502	333	240
	% 2012 region generation	–	Over 100%	84%	60%
AK	TWh/year	6.4	973	508	233
	% 2012 AK generation	–	Over 100%	Over 100%	Over 100%
HI	TWh/year	9.6	98	32	24
	% 2012 HI generation	–	Over 100%	Over 100%	Over 100%

Note: (1) State Electrical Profiles 2012 from http://www.eia.gov/electricity/state/.

Market Acceleration and Deployment

National market acceleration and deployment opportunities exist to minimize key deployment risks to reduce the cost and time associated with permitting MHK projects. These include undertaking research and developing tools identifying, mitigating and prioritizing environmental risks; providing accurate and objective data to accelerate permitting time frames and drive down costs; increasing opportunities for MHK researchers, regulators, and policy makers to be informed on these issues; and engaging in ocean planning processes to ensure that MHK is considered in the nation's evolving marine spatial plans.

A strategy to address the critical market acceleration and deployment opportunities can be thought of as containing at least three major elements as follows:

- Data collection and experimentation
- Development of monitoring and mitigation technologies and techniques
- Information sharing and international collaboration

Implementing the first two elements of such a strategy, as with the technology advancement and demonstration activities, requires the ability to execute controlled and field experiments and testing. The data collected from these efforts is critical to answer key questions that would expedite the permitting process of future projects. MHK stakeholders have conducted analyses to identify the greatest MHK environmental uncertainties and identify gaps remaining from previous efforts. Opportunities to address these gaps include measurements of acoustic output (both operational and construction noise sources) as well as organismal impacts, effects on marine animals from direct and indirect interactions with devices (e.g., blade strike, entanglement, collision, attraction, and avoidance), effects of electromagnetic fields, and effects of energy removal in coastal systems.

Environmental research for MHK can be undertaken to develop new monitoring instrumentation that would more accurately and cost-effectively gather data to understand potential technology impacts to the environment and to develop methods and techniques to avoid or mitigate any impacts. Test facilities can be used as environmental laboratories to collect data to drive down the environmental uncertainties as well as to test and prove the efficacy and cost of new environmental instrumentation and monitoring methodologies under development. Without this research, millions of dollars could be invested in devices that convert marine energy into electricity, but they may prove difficult to deploy owing to the practical demands of environmental compliance for new energy technologies today.

Ensuring that accurate and objective information is easily accessible to decision makers is extremely important to the third strategy element. Targeted workshops allow state and federal regulators to become more familiar with MHK technologies and hear updates from leading researchers on the current state of scientific understanding around potential environmental impacts. The ultimate goal is to reduce regulatory uncertainty and accelerate permitting timelines. The U.S.-developed Tethys database is a knowledge management system to gather, organize, and provide access to information on research into the potential environmental interactions of all ocean energy technologies.[44,45] The primary functions of Tethys are to facilitate the exchange of information and data on the environmental effects of marine and wind energy technologies and to serve as a common information portal for marine and offshore wind energy practitioners and therefore enhance the connectedness of the renewable energy community as a whole.

Involvement in National Ocean Council activities, regional planning bodies, and U.S. Bureau of Ocean Energy Management state task forces is important to help ensure that marine renewable energy technologies are considered in marine spatial plans and policy decisions.

International Collaboration

The international community broadly recognizes the need for collaboration to accelerate this newest renewable energy technology to be competitive in the market. The International Energy Agency's Ocean Energy Systems (OES) Technology Initiative was created for the specific purpose of information sharing related to MHK technologies.[46] OES is an intergovernmental collaboration bringing together 22 countries to advance research, development, and demonstration of conversion technologies to harness energy from all forms of ocean renewable resources, such as tides, waves, currents, temperature gradient (ocean thermal energy conversion and submarine geothermal energy), and salinity gradient for electricity generation as well as for other uses, such as desalination, through international cooperation and information exchange. Participants in the OES are specialists from government departments, national energy agencies, research or scientific bodies and academia, nominated by the contracting parties.

The United States has been an active member of OES since 2005 and is actively participating to gain insight and experience from the global community. The United States provides management and leadership for the following two collaborative OES tasks:

- Annex IV—Environmental Issues; Assessment of Environmental Effects and Monitoring Efforts for Ocean Wave, Tidal, and Current Energy Systems: One of the primary goals of the Annex is to ensure that existing information and data on environmental monitoring (and, to the extent possible, practices for environmental mitigation) are more widely accessible to those in the industry; national, state, and regional governments; and the public.
- Annex V—Project Information Exchange; Exchange and Assessment of Ocean Energy Device Project Information and Experience: The sharing of project data and computational assessment methods will allow the participants to determine the most promising approaches for analysis, design, testing, cost estimation, and operation of these devices on the basis of the collective experience of the group.

Summary

National opportunities exist to develop commercial-scale, reliable, and cost-effective MHK technologies for U.S. markets over the medium and long term. There is great promise for reaching this goal through pursuing investments on the technologies with the most abundant resources, supporting next-generation game-changing technologies, and ensuring that needed testing and verification infrastructure is in place to accelerate commercialization. With more than 50% of the American population living within 50 miles of the coast, MHK energy could provide a substantial amount of electricity for the nation in areas where it is needed most.

Endnotes

1 National Oceanic and Atmospheric Administration (NOAA), "Oceans and Coasts," Accessed February 11, 2015: http://www.education.noaa.gov/Ocean_and_Coasts/.

2 Technical resource potential refers to the portion of a theoretical resource (annual average amount of physical energy that is hypothetically available) that can be captured by using a specific technology.

3 Jacobson, P.; Hagerman, G.; Scott, G. "Mapping and Assessment of the United States Ocean Wave Energy Resource," Electric Power Research Institute, Report Number 1024637, 2011. http://www.epri.com/abstracts/pages/productabstract.aspx?ProductID=000000000001024637.

4 Haas, K.; Fritz, H.; French, S.; Neary, V. "Assessment of Energy Production Potential from Ocean Currents Along the United States Coastlines," Georgia Tech Research Corporation, 2013. http://energy.gov/sites/prod/files/2013/12/f5/energy_production_ocean_currents_us_0.pdf.

5 Haas, K.; Fritz, H.; French, S.; Smith, B.; Neary, V. "Assessment of Energy Production Potential from Tidal Streams in the United States," Georgia Tech Research Corporation, 2011. http://energy.gov/sites/prod/files/2013/12/f5/1023527.pdf.

6 Ravens, T.; Cunningham, K.; Scott, G. "Assessment and Mapping of the Riverine Hydrokinetic Resource in the Continental United States," Electrical Power Research Institute, Report Number 1026880, 2012. http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001026880.

7 On basis of average annual U.S. residential electricity consumption of 10,837 kWh in 2012 (EIA).

8 Reikard, G.; Robertson, B.; Bidlot, J. R. "Combining Wave Energy with Wind and Solar: Short-term Forecasting." Renewable Energy (Volume 81), September 2015; pp. 442–456. http://www.sciencedirect.com/science/article/pii/S0960148115002141.

9 Parkinson, S.; Dragoon, K.; Reikard, G.; García-Medina, G.; Özkan-Haller, H. T.; Brekken, T. K. A. "Integrating Ocean Wave Energy at Large-scales: A Study of the U.S. Pacific Northwest," Renewable Energy (Volume 76), April 2015; pp. 551–559. http://www.sciencedirect.com/science/article/pii/S0960148114007538.

10 National Renewable Energy Laboratory (NREL). "Navy Installation Resource Characterization" (pending publication).

11 For example, the "Alaska Energy Authority Power Cost Equalization Program Guide" (July 2014) states that the charge for electricity in rural areas of Alaska can be three to five times higher than the average rate of 14.8 cents/kWh in Anchorage, Fairbanks, or Juneau. Accessed June 4, 2015: http://www.akenergyauthority.org/Programs/PCE.

12 Clement, A.: McCullen, P.: Falcao, A.: Fiorentino, A.: Gardner, F.: Hammarlund, K.: Lemonis, G.: Lewis, T.: Nielsen, K.: Petroncini, S.: Teresa Pontes, M.: Schild, P.: Sjostrom, B.: Sørensen, H.: and T. Thorpe. (2002). "Wave Energy in Europe: Current Status and Perspectives." Renewable and Sustainable Energy Reviews 6 (5), 2002; pp. 405–431. http://www.sciencedirect.com/science/article/pii/S1364032102000096.

13 "Niagara's Power from the Tides." Popular Science Monthly, May 1924.

14 OpenEI (2014). "The Open Energy Information Website." OpenEI partners with a broad range of international organizations to provide energy information and data. Available at: http://en.openei.org/wiki/Marine_and_Hydrokinetic_Technology_Database.

15 IEA-OES (2014). 2014 Annual Report, "Implementing Agreement on Ocean Energy Systems, Executive Committee of Ocean Energy Systems." Available at: http://report2014.ocean-energy-systems.org/.

16 Jeffrey, H.; Sedqwick, J.; Gerrad, G. Public Funding for Ocean Energy: A Comparison of the UK and U.S. Institute for Energy Systems, School of Engineering, University of Edinburgh, 2013. http://www.sciencedirect.com/science/article/pii/S0040162513001741.

17 Bull, D.; Ochs, M. E.; Laird, D. L.; Boren, B.; Jepsen, R. A. "Technological Cost-Reduction Pathways for Point Absorber Wave Energy Converters in the Marine Hydrokinetic Environment." Sandia National Laboratories, 2013. http://energy.sandia.gov/wp-content/gallery/uploads/SAND2013-7204.pdf.

18 Bull, D.; Ochs, M. E. "Technological Cost-Reduction Pathways for Attenuator Wave Energy Converters in the Marine Hydrokinetic Environment." Sandia National Laboratories, 2013. http://energy.sandia.gov/wp-content/gallery/uploads/SAND2013-7207.pdf.

19 Laird, D. L.; Johnson, E. L.; Ochs, M. E.; Boren, B. "Technological Cost-Reduction Pathways for Axial-Flow Turbines in the Marine Hydrokinetic Environment." Sandia National Laboratories, 2013. http://energy.sandia.gov/wp-content/gallery/uploads/SAND2013-7203.pdf.

20 Bull, D.; Ochs, M. E. "Technological Cost-Reduction Pathways for Oscillating Water Column Wave Energy Converters in the Marine Hydrokinetic Environment." Sandia National Laboratories, 2013. http://energy.sandia.gov/wp-content/gallery/uploads/SAND2013-7205.pdf.

[21] Li, G.; Weiss, G.; Mueller, M.; Townley, S.; Belmont, M. "Wave Energy Converter Control by Wave Prediction and Dynamic Programming." Renewable Energy (vol. 48, no. 0), December 2012; pp. 392–403. http://www.sciencedirect.com/science/article/pii/S0960148112003163.

[22] Townsend, C. "The Case for Breakthrough Innovation." September 2013. Accessed December 5, 2014: http://www.wired.com/2013/09/the-case-for-breakthrough-innovation/.

[23] Jenkins, J.; Swezey, D.; Borofsky, Y. "Where Good Technologies Come From: Case Studies in American Innovation." The Breakthrough Institute. Oakland, CA. December 2010. Accessed December 5, 2014: http://thebreakthrough.org/archive/american_innovation.

[24] See XPRIZE Foundation Web site: http://www.xprize.org.

[25] See the Wave Energy Prize Web site: http://www.waveenergyprize.org.

[26] DOE, "Technology Readiness Assessment Guide, DOE G 413.3-4A." U.S. Department of Energy, Washington D.C., 2011. Accessed July 8, 2015: https://www.directives.doe.gov/directives-documents/400-series/0413.3-EGuide-04a/@@download/file. Westwave, "Appendix 2 Technology Readiness Levels for Supply Chain Study for WestWave, ESBloe-WAV-11-027," Dublin, undated. Accessed July 8, 2015: http://www.westwave.ie/wp-content/uploads/downloads/2011/12/Appendix-2.pdf. "Marine and Hydrokinetic Technology Readiness Level." Open Energy Information. Accessed July 8, 2015: http://en.openei.org/wiki/Marine_and_Hydrokinetic_Technology_Readiness_Level.

[27] "Navy Seeks Renewable Ocean Energy Technology at Industry Forum." Story Number NNS120402-13. Accessed April 15, 2015: http://www.navy.mil/submit/display.asp?story_id=66173.

[28] The European Marine Energy Centre (EMEC) Ltd. http://www.emec.org.uk/facilities/

[29] The Southeast National Marine Renewable Energy Center at Florida Atlantic University. Available at: http://snmrec.fau.edu/.

[30] The Tanana River Hydrokinetic Test Site at the Alaska Center for Energy and Power (ACEP), University of Alaska. Available at: http://acep.uaf.edu/.

[31] The Jere A. Chase Ocean Engineering Laboratory at the University of New Hampshire (UNH) School of Marine Science and Ocean Engineering. Available at: http://marine.unh.edu/.

[32] The Garfield Thomas Water Tunnel at the Penn State Applied Research Laboratory (ARL). Available at: https://www.arl.psu.edu/.

[33] Previsic, M. "The Future Potential of Wave Power in the United States," Re Vision Consulting, 2012. http://www.re-vision.net/documents/The%20Future%20of%20Wave%20Power%20MP%209-20-12%20V2.pdf.

[34] National Research Council. An Evaluation of the U.S. Department of Energy's Marine and Hydrokinetic Resource Assessments, The National Academies Press, 2013. http://www.nap.edu/catalog/18278/an-evaluation-of-the-us-department-of-energys-marine-and-hydrokinetic-resource-assessments.

[35] Jacobson, P.; Hagerman G.; and G. Scott. (2011) "Mapping and Assessment of the United States Ocean Wave Energy Resource," Electric Power Research Institute, Report Number 1024637, 2011. http://www.epri.com/abstracts/pages/productabstract.aspx?ProductID=000000000001024637.

[36] Haas, K.; Fritz, H.; French, S.; and V. Neary. (2013). "Assessment of Energy Production Potential from Ocean Currents Along the United States Coastlines," Georgia Tech Research Corporation, 2013. http://energy.gov/sites/prod/files/2013/12/f5/energy_production_ocean_currents_us_0.pdf.

[37] Haas, K.; Fritz, H.; French, S.; Smith, B.; and V. Neary, (2011). "Assessment of Energy Production Potential from Tidal Streams in the United States," Georgia Tech Research Corporation, 2011. http://energy.gov/sites/prod/files/2013/12/f5/1023527.pdf.

[38] Ravens, T.; Cunningham, K.; and G. Scott. (2012). "Assessment and Mapping of the Riverine Hydrokinetic Resource in the Continental United States," Electrical Power Research Institute, Report Number 1026880, 2012. http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001026880.

[39] Ascari, M.; Hanson, H.; Rauchenstein, L.; Van Zwieten, J.; Bharathan, D.; Heimiller, D.; Langle, N.; Scott, G.; Potemra, J.; Nagurny, J.; and Jansen, E. Ocean Thermal Extractable Energy Visualization - Final Technical Report. (2012) U.S. DOE. DOE/EE0002664-1. http://www.osti.gov/bridge/purl.cover.jsp?purl=/1055457/1055457.pdf

[40] Jacobson, P.; Hagerman, G; Scott, G. "Mapping and Assessment of the United States Ocean Wave Energy Resource." Electric Power Research Institute, Report Number 1024637, 2011. http://www.epri.com/abstracts/pages/productabstract.aspx?ProductID=000000000001024637.

[41] Previsic, M. "The Future Potential of Wave Power in the United States," Re Vision Consulting, 2012. http://www.re-vision.net/documents/The%20Future%20of%20Wave%20Power%20MP%209-20-12%20V2.pdf.

[42] National Research Council. An Evaluation of the U.S. Department of Energy's Marine and Hydrokinetic Resource Assessments. The National Academies Press, 2013. http://www.nap.edu/catalog/18278/an-evaluation-of-the-us-department-of-energys-marine-and-hydrokinetic-resource-assessments

[43] Ibid.

[44] See Tethys Knowledge Management System. Available at: http://mhk.pnl.gov/.

[45] Copping, A.; Hanna, L.; Whiting, J.; Geerlofs, S.; Grear, M.; Blake, K.; Coffey, A.; Massaua, M.; Brown-Saracino, J.; Battey, H. "Environmental Effects of Marine Energy Development Around the World for the OES Annex IV." 2013. Available at: www.ocean-energy-systems.org.

[46] The Ocean Energy Systems (OES) Implementing Agreement is an intergovernmental collaboration among countries, which operates under framework established by the International Energy Agency in Paris. Available at: http://www.ocean-energy-systems.org/.

Acronyms

AEP	Annual Energy Production
CONUS	Contiguous United States
DOD	Department of Defense
DOE	Department of Energy
EIA	Energy Information Administration
FERC	Federal Energy Regulatory Commission
FOA	Funding Opportunity Announcement
IEA	International Energy Agency
LCOE	Levelized Cost of Energy
MHK	Marine and Hydrokinetic
NOAA	National Oceanic and Atmospheric Administration
NAS-NRC	National Academy of Science - National Research Council
NAVSEA	Naval Sea Systems Command
OES	Ocean Energy Systems
TRL	Technology Readiness Level
WEC	Wave Energy Converter
WETS	Wave Energy Test Site

Glossary

OpenEI Hosted through NREL's OpenEI web portal, the U.S. Department of Energy's Marine and Hydrokinetic Technology Database provides up-to-date information on marine and hydrokinetic renewable energy, both in the U.S. and around the world. http://en.openei.org/wiki/Main_Page

Tethys database Tethys is a web portal developed and hosted by DOE's Pacific Northwest National Laboratory to facilitate the exchange of information and data on the environmental effects of marine and wind energy technologies; and to serve as a commons for marine and wind energy practitioners and therefore enhance the connectedness of the renewable energy community as a whole. In Greek mythology Tethys was an archaic Titaness and aquatic sea goddess, the daughter of Uranus and Gaia. http://tethys.pnnl.gov/

See also: Marine and Hydrokinetic Technology Glossary
http://energy.gov/eere/water/marine-and-hydrokinetic-technology-glossary