PNNL-28981

Understanding the Grid Value Proposition of Marine Energy: An Analytical Approach

September 2019

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U.S. DEPARTMENT OF ENERGY

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Summary

The US Department of Energy's Water Power Technologies Office (WPTO) has tasked two national laboratories, Pacific Northwest National Laboratory (PNNL) and National Renewable Energy Laboratory (NREL), to develop an understanding of the grid value proposition for marine renewable energy (MRE): how harnessing the energy of waves, tides, and ocean currents could be a meaningful and competitive source of renewable energy in the future grid.

This work will provide insights to the conditions under which MRE technologies offer unique benefits for the electricity system. PNNL and NREL will conduct a project to comprehensively review the grid value for marine renewable energy development at scale on an intermediate- to long-term horizon. The project will dovetail with nationally-accelerating valuation efforts to characterize and quantify specific services from energy resources and assess the value of those services over time. It will capitalize on the emerging concept of *locational* value, especially for distributed energy resources (DER), referencing adopted frameworks and related laboratory analysis. And it will take advantage of laboratory expertise in a variety of disciplines – ocean physics, mechanical and electrical engineering, energy economics – chained together in order to ensure that benefits and services assessed are realistic for MRE technologies and ocean energy resources.

The purpose of the immediate analytical approach is to outline the landscape of MRE attributes and their potential value and, at a high-level, discuss methods to quantify these values. For purposes of this investigation, the words grid value should be broadly construed. The term is meant to include, but not be limited to, provision of a defined grid service, measurable benefit to grid performance, avoided costs to system investments or operations, revenue capture, and contribution to desired grid qualities (e.g. reliability or low carbon intensity). Value can also accrue to a range of entities.

The authors intend to consider use cases and system benefits where MRE may have a competitive or unique role; and where there is a distinct and measurable value additional to energy production. To do this, the authors look beyond the typical values of energy production (a payment of cents per kilowatt-hour produced) and instead to "grid services," those services required for the grid to operate and deliver energy to customers (i.e. unit scheduling and dispatch, reactive power and voltage control, and frequency control). Certain grid services are captured in the traditional suite of ancillary services that may be directly compensated in an organized market, and as a result many of these benefits already have highly competitive contributing generators or other electricity system assets. Therefore, in this initial exercise of considering competitive and unique benefits, the authors are less concerned with the energy (or grid service) production itself but the timing, the location, or the system condition that form measurable and distinct value.

In Table ES-1 below, grid values are arranged into three categories: the spatial or *locational* aspects of MRE, the temporal or *timing* aspects, and *special applications* to ensure most situational benefits are captured. For each category, the authors attempt to identify classes of value (e.g., land use, seasonality) and then identify specific ways to measure the value.

Table ES-1. Analytical approach framework: potential competitive or unique benefits from MRE.

LOCATION	TIMING	SPECIAL APPLICATIONS
System Benefits System Investments ▪ MRE as non-wires alternatives (NWA) ▪ Avoided or deferred distribution and transmission investments Local support ▪ Local load and balancing needs ▪ Power quality and voltage support (volt/VAR) Power Flow ▪ Reduced congestion (coastal cities and transmission corridors) ▪ Remote system improvements (avoided line losses and transmission and distribution loading)	*Predictability* ▪ Reduced integration requirements and associated costs: reduction in reserve requirements, needs for gas/hydro ramping or storage ▪ Enhanced market participation: bid accuracy, qualification, scheduling certainty, penalty avoidance, extended time window for decision making in forward markets *Seasonality* ▪ Coincidence with load ▪ Complementary with other resource availability	*Enabled Services* ▪ MRE as a behind the meter resource (customer and grid benefits) ▪ Storage for flexibility and dispatchability ▪ Microgrid suitability: coastal, remote communities and islands (e.g. Barbados, Faroe Islands, Igiugig) ▪ Improvement in performance of other technologies (symbiotic benefits)
Land Use ▪ Increased energy density of coastal land ▪ Avoided opportunity cost of land use for energy generation ▪ Provision of energy in areas where there is low to no availability (dense, remote and island regions) ▪ Address policy goals for intra-BA development	*Scheduled / Dispatchable Generation ("Tidal as baseload")* ▪ Aggregation: resource diversity offset to create a "baseload" profile ▪ Dispatchability and participation in markets with storage ▪ Optimization of generation with storage	*Resiliency* ▪ Reduced vulnerability to electricity disruptions ▪ Reduced reliance on conventional backup generation and risk from fuel availability and price volatility ▪ Avoidance of sustained effects to critical infrastructure from grid disruption as a microgrid resource, in combination with microgrids, or as a backup generation resource ▪ Systemwide and localized black start
Portfolio Effects ▪ Improved geographic diversity of the generation portfolio: reduced system capacity and balancing requirements and a natural resiliency effect.	*Portfolio Effects* ▪ Negative correlation with wind and solar at very high penetrations (e.g. winter peak) ▪ Thermal improvements: displacement, reduced cycling, improved efficiency, and reduced emissions ▪ Effective load carrying capability (ELCC) and capacity credits for MRE ▪ Reduction in system costs, capacity and balancing requirements with an integrated portfolio ▪ System reliability improvements: effects on LOLE and LOLP	*Portfolio Effects* ▪ MRE modularity and array-based development allows for as-needed expansion, reducing financing risk, up-front costs and ongoing operations and maintenance costs ▪ Reduced dependence on diesel and natural gas production and delivery infrastructure ▪ Improvements to meeting environmental and sustainability goals

The goal of this project is to move beyond the notional concepts of MRE predictability or offshore location to an analytical outcome and quantifiable grid value. The table above represents a range of values, but no one marine renewable energy project could possibly capture all these values (e.g. micro- and macro- scales of development are required to achieve certain values). The purpose of this exercise is to identify values but not to conduct a valuation exercise for a specific deployment. For such an exercise, which is a later part of this project in the form of case studies, a sub-set of these values might be most appropriate to analyze.

The analytical approach expresses the realm of possibility. This is an intentionally broad approach. Because we are considering several resources (e.g. wave energy, tidal and ocean current), multiple time horizons, and various situations across the U.S. and territories, some prioritization and scoping by resource will be necessary. The intent here is to identify, consider and characterize all opportunities for marine energy resources. These efforts and initial results will be captured in the next deliverable, the initial technical report. From there, these considerations can be refined and those opportunities that are most relevant with the most potential will be analyzed and evaluated further through case studies and a final technical report.

Acknowledgments

The authors wish to express their gratitude for the sponsorship and guidance of Steve DeWitt and David Hume with the Water Power Technologies Office at the U.S. Department of Energy. The authors also wish to express their gratitude for the review and contributions provided by Abhishek Somani, TJ Heibel and Mark Freshley.

Acronyms and Abbreviations

BA	balancing authority
BPA	Bonneville Power Administration
BTM	behind the meter resource
CAISO	California Independent System Operator
CUC	Caribbean Utilities Company
DER	distributed energy resource
DOE	Department of Energy
EIA	Electricity Information Administration
ELCC	effective load carrying capability
ESS	energy storage system
GDP	gross domestic product
IEEE	Institute of Electrical and Electronics Engineers
IRP	integrated resource plan
LCOE	levelized cost of energy
LOLE	loss of load expectation
LOLP	loss of load probability
MCOR	Microgrid Component Optimization for Resilience
MRE	marine renewable energy
MW	megawatt
NOAA	National Oceanic and Atmospheric Administration
NOWEGIS	National Offshore Wind Energy Grid Interconnection Study
NWA	non-wires alternatives
OTEC	ocean thermal energy conversion
PV	photovoltaic (solar)
QER	Quadrennial Energy Review
SCED	security constrained economic dispatch
VAR	volt-amp reactive
WPTO	Water Power Technologies Office

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1.0 Introduction

Marine energy technologies convert the energy of ocean waves and tidal, river, and ocean currents into electricity and other forms of usable energy. Marine energy resources, that is, waves and currents, are geographically diverse, with particularly high levels of wave energy in the Pacific Ocean; tidal energy resources located across the Northeast, Pacific Northwest, and Alaskan coasts; and ocean current energy along the southern Atlantic coastline. The energy contained within these resources is reliable, predictable, does not generate carbon emissions and can be developed in an environmentally friendly manner.

Marine energy, or marine renewable energy (MRE), is at an early stage of development as evidenced by the lack of commercial deployment. Its value proposition to the electric system is not well identified or understood, and without this understanding, the industry faces the undervaluing of its potential and unclear signals about where to site future development. To be commercially successful, the marine energy sector needs to be able to explain why it can provide a unique contribution beyond energy associated with the lack of greenhouse gas emissions, which is readily available from other renewable resources at lower costs and risks. This study seeks to answer the following questions: which attributes of marine energy technologies provide clear and competitive benefits to the electric system that make further investment and development worthwhile? And, what are the boundaries and potential benefits of realizing that value?

There is a sense that certain aspects of marine energy, for example, its location, relative predictability, generating profiles, and resiliency should be beneficial. But there has been limited research into analyzing these benefits. Certain work has been conducted for DOE Water Power Technologies Office (WPTO) purposes (levelized cost of energy (LCOE) or technology metrics), but not in such a way that fits power system planning or operational paradigms.[1]

Some of the challenges in identifying these benefits are structural, as power plants today are typically compensated for energy under a power purchase agreement with an electric load-serving entity for the provision of electricity, plus the value of any significant attributes, such as a Renewable Energy Certificates (RECs). However, there may be more value provided by MRE than its energy and RECs. Just as solar may not be the cheapest energy resource at scale, but the technology has unique benefits for modularity and scaling to residential and distribution applications that make it a competitive solution.[2] Similarly, MRE likely has a unique value proposition for the power system. Early, anecdotal research has started to scratch the surface of this challenge, suggesting that transmission investments to remote, coastal locations[3] can be deferred[4] or possibly avoided altogether;[5] that as a predictable resource, MRE would require a fraction of associated integration costs;[6] and that to achieve very high physical penetration levels of renewable energy, winter peaking resources with seasonal variation such as MRE could be crucial.

Electric system planning today does not include the potential contribution of marine renewable energy resources. This is due to many factors: a lack of useful and credible data on costs, uncertainty regarding

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[1] *See* "Marine and Hydrokinetic Technology Development and Testing." U.S. Department of Energy. Available at: https://www.energy.gov/eere/water/marine-and-hydrokinetic-technology-development-and-testing.

[2] Burger et al. *Why Distributed? A Critical Review of the Tradeoffs Between Centralized and Decentralized Resources.* March/April 2019. IEEE Power and Energy Magazine. 1540-7977/19

[3] Robertson, Bryson. (2010). Ocean Wave Energy Generation on the West Coast of Vancouver Island and the Queen Charlotte Islands. Guelph Engineering Journal.

[4] Moazzen, et al. "Impacts of large-scale wave integration into a transmission-constrained grid." Renewable Energy 88 (2016) pp. 408-417.

[5] Generation local to coastal communities could reduce or avoid the need to build transmission to inland generation.

[6] *See* "Wave Energy Utility Integration, Advanced Resource Characterization and Integration Costs and Issues." December 2013. Oregon Wave Energy Trust. Available at: www.oregonwave.org.

technology maturity, lack of uniformity in device designs, and no commercial deployments. This project will not address these challenges directly, but it will lay the groundwork and create a reference point about the value proposition of MRE, including the many entities (i.e. customers, utilities, distribution or transmission operators, communities) and places (i.e. generation, distribution, transmission, behind-the-meter) to which that value will accrue.

This project will review the grid value for marine energy technology development at scale over the intermediate to long-term horizon. The project will dovetail with national valuation efforts to characterize and quantify specific services from energy resources and assess the value of those services over time. The primary goals of this project are to provide data and supporting analysis that will (1) enable the MRE industry to articulate value to potential investors and customers; (2) allow system planners, utilities, and decision makers to have information to evaluate marine energy when considering a suite of available generating resources and (3) guide the technology investments made at the US Department of Energy toward improving MRE performance where it is likely to have competitive or unique value to the grid.

The project will produce several foundational reports, tools and valuation approaches to ascertain the value of MRE. It will recruit direct input from industry as well as from utilities and grid operators. The technical reports produced can be used by both the industry and the electric system planning sector, including case studies with diverse technologies and locations. The technology-neutral metrics developed from the project can be used by the water power program and other research organizations to benchmark, measure progress or set goals for research investments.

1.1 Marine Energy Attributes for Grid Value

The purpose of the immediate analytical approach is to outline the landscape of MRE attributes, or benefits, their potential value and, at a high-level, discuss methods to quantify this value. The attributes are organized into the spatial or locational aspects of MRE, the temporal or timing aspects, and special applications to ensure most potential benefits are captured. Table 1 below distributes these attributes, or values, amongst each category. Below we discuss these categorical benefits at the conceptual level to explain why marine renewable energy has unique advantages and merits a closer look.

Table 1. Analytical Approach Framework

LOCATION	TIMING	SPECIAL APPLICATIONS
System Benefits System Investments ▪ MRE as non-wires alternatives (NWA) ▪ Avoided or deferred distribution and transmission investments Local support ▪ Local load and balancing needs ▪ Power quality and voltage support (volt/VAR) Power Flow ▪ Reduced congestion (coastal cities and transmission corridors) ▪ Remote system improvements (avoided line losses and transmission and distribution loading)	*Predictability* ▪ Reduced integration requirements and associated costs: reduction in reserve requirements, needs for gas/hydro ramping or storage ▪ Enhanced market participation: bid accuracy, qualification, scheduling certainty, penalty avoidance, extended time window for decision making in forward markets *Seasonality* ▪ Coincidence with load ▪ Complementary with other resource availability	*Enabled Services* ▪ MRE as a behind the meter resource (customer and grid benefits) ▪ Storage for flexibility and dispatchability ▪ Microgrid suitability: coastal, remote communities and islands (e.g. Barbados, Faroe Islands, Igiugig) ▪ Improvement in performance of other technologies (symbiotic benefits)
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1.1.1 Locational, or Spatial

Coastal electricity delivery systems are spatially constrained by the presence of an ocean and, particularly on the U.S. Pacific Coast, coastal mountain ranges. Electric generation sources can be located at great distances from these areas, which means that significant transmission infrastructure is needed to assure reliable electric delivery over long distances. Accordingly, transmission services can be capacity constrained along the coasts, making it difficult to add new load to the system, inhibiting economic growth. This can be true for cities as well as remote electric loads. Installing new transmission infrastructure is an expensive and spatially constrained proposition. Coastal transmission and distribution lines may be single points of failure, providing no redundancy for these communities if a line is suddenly unavailable. These conditions present unique challenges for coastal electric service providers to assure reliability and resiliency of the system.

Siting marine energy in constrained areas could provide both clean renewable energy and unique benefits to the system, such as a deferral or reduction of investments in the distribution and transmission system, provision of ancillary services (e.g., frequency and voltage support), and power quality benefits. A secondary benefit is economic development in an otherwise energy constrained area.[7] There are existing definitions and methods for analyzing discrete locational benefits, such as distribution deferral, that can be borrowed for this project.[8] Depending on conditions, these locational benefits can be the anchor value for an installation.

Another locational benefit is the avoidance of land use, or the opportunity cost associated with not using the land for siting new generation, transmission or distribution and instead using marine resources. The infrastructure build-out required to meet renewable energy goals, especially when policy includes a proximity requirement, such as direct interconnection to the state or balancing area, may have unacceptable spatial demands on available land. This benefit becomes especially valuable where land is unavailable, for example on an island or at a remote installation.

Finally, there is a system operational effect of geographic distribution of generators, a difference between generators spread over a broad area rather than clustering generators in a single location. Notably for renewable resources, clustering of resources may be appropriate due to resource intensity or the availability of transmission. Yet this means that the operational challenges of intermittency – e.g., of a resource being unavailable, unavailability on a persistent basis, or rapid changes in the rate of availability – can be compounded. Through its ocean environment, MRE represents strong geographic diversity with the development of other renewable resources.

1.1.2 Temporal, or Timing

Like most renewable energy sectors, MRE will have variable production. However, MRE is a relatively predictable resource over a time interval that mirrors the periodicity of the resource. The variability and

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[7] Oregon Department of Energy, *Why Wave Energy*, citing BPA documentation of transmission investments required to maintain reliability and power quality on the Oregon coast. *See* https://digital.osl.state.or.us/islandora/object/osl%3A12964/datastream/OBJ/view.

[8] As part of Washington State's Clean Energy Fund, PNNL is performing technical and economic use case analyses and performance monitoring with five regional utilities that are deploying energy storage technologies. This effort is forming the framework for analysis tools to be used by utilities and regulators to capture the monetized benefits and avoided costs of deploying energy storage. *See* "Clean Energy Fund - Washington State Department of Commerce." Washington State Department of Commerce. Available at: http://www.commerce.wa.gov/growing-the-economy/energy/clean-energy-fund/.

predictability vary between the different types of MRE with tidal and ocean current resources being directly tied to recurrent patterns over decades, whereas wave resource predictability is nearer-term. Accordingly, generation can be predicted with high levels of confidence at advance scheduling periods, reducing system costs for integration. One study estimated the integration costs for 500 MW of wave energy to be 10% of the cost of integrating a comparable amount of wind.[9] Forecasting for solar and wind energy remains a substantial challenge in system operations today with it being the greatest cause of real-time price spikes in the California Independent System Operator (CAISO) region (e.g. forecasting errors at greater than 40% deviation caused 68% of price spikes).[10]

Marine energy production is cyclical due to the periodicity of the originating oceanographic and astronomical forces. These cycles vary from short-term to seasonal and appear to complement load variability as well as existing variable generation. Figure 1 illustrates the timing coincidence of the different marine resources with electric grid operations. Different forms of MRE have periodicity that is coincident with different grid service timescales. Accordingly, resource characterization will be important to ensure that device development and site deployment maximize the value of MRE to future grid needs.

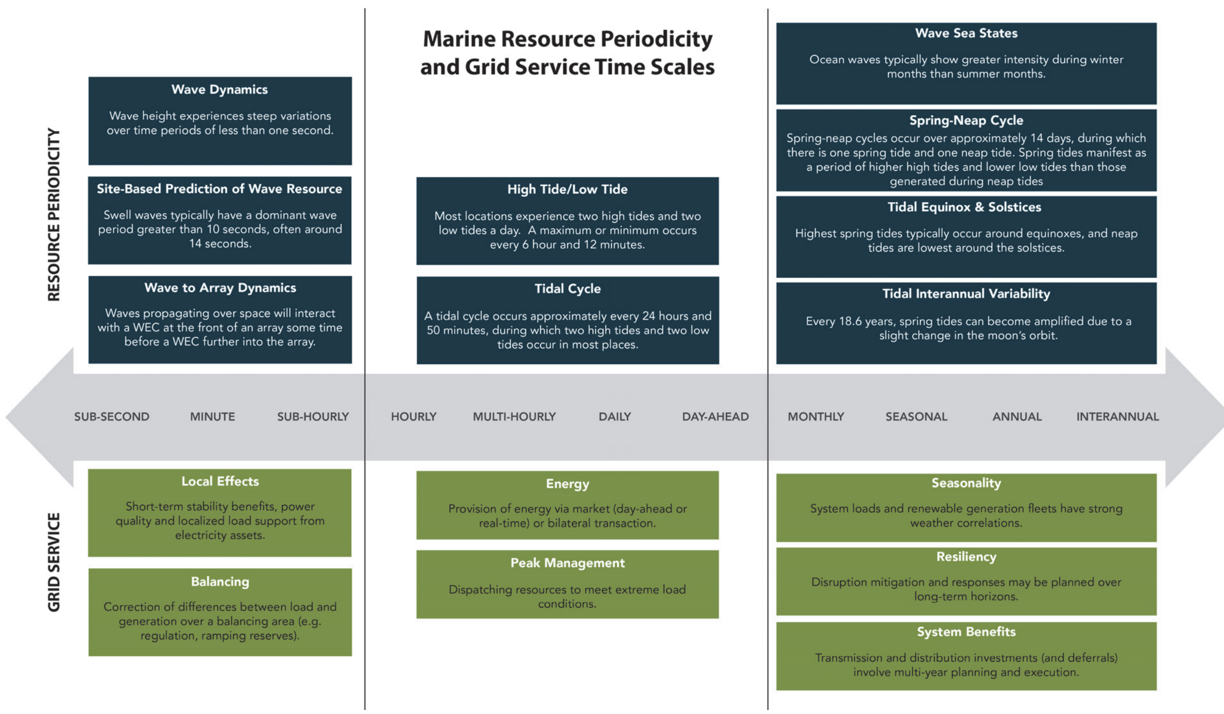

Figure 1. Marine renewable energy periodicity and grid service requirement timescales.

For example, ocean currents in the Florida Straits have dual peaking intensity over an annual period, with the greatest strength in July, a low point in October, then a second rise in January and secondary low in April.[11] This generating profile matches Florida's electric load, according to EIA data.[12] While this seasonal matching is hardly a silver bullet, it suggests that development of ocean current technologies at scale could offer system benefits. With respect to wave energy, Pacific Ocean winter ocean conditions, or sea states, are dramatically more energetic than summer sea states. That means that wave energy

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[9] *Wave Energy Utility Integration,* as cited above.
[10] Ascend Analytics, Oakland, CA. February 2017.
[11] Joanna Gyory, Elizabeth Rowe, Arthur J. Mariano, Edward H. Ryan. "The Florida Current." Ocean Surface Currents. (http://oceancurrents.rsmas.miami.edu/atlantic/florida.html).
[12] Retail sales of electricity, monthly EIA data, all sectors, August 10, 2017.

production will be seasonal, tilted toward greater production in the winter. This is advantageous as it matches load in cooler climates where heating, not cooling, is dominant. See Figure 2 below, which characterizes wave energy at a reference site in Humboldt Bay, California over a one-year period of March 2007–February 2008 (Dallman and Neary 2014). Second, winter generation complements other renewable generating profiles in the West: solar generation is at its height in the summer, and wind and hydroelectric generation ramp up strongly in the spring.

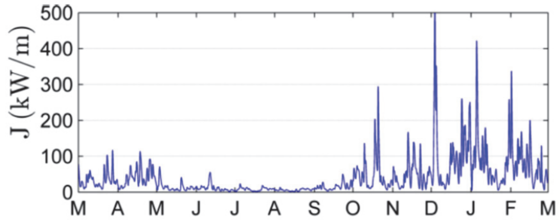

Figure 2. Wave energy over a one-year period from March 2007–February 2008 at Humboldt Bay, California. J is the omnidirectional wave power (Dallman and Neary 2014).

Further, as these resources reach higher penetrations on the system, seasonal and daily ramps of generation will be significant characteristics that pose reliability management challenges. In contrast, wave energy will maintain consistent production over seasonal periods. As the country and the world set more ambitious clean energy goals with higher renewable penetration, marine energy could help fill the production gaps to provide reliable electric service while also meeting clean energy targets.

Even with foresight into the energy resource, the characteristics of the technologies converting the resource to electricity will be key factors in estimating generation. Further, the predictability or MRE, including predictability in the near term, enables complementarity with other technologies: for example, easier integration with energy storage relative to wind or solar as sizing of storage is simplified, and likely less is required for the same resource capacity. The project will look at the potential for the integration with complementary technologies, and the benefits this integration can provide.

1.1.3 Special Applications

Another benefit of marine energy technology is their ability to provide services under unique contexts, which we term "special applications" in this project. For example, marine energy could provide electric resiliency for coastal communities. Weather is the dominant cause of grid disruptions. Studies show that 100-year floods may be 10-year to 1-year events by 2050.[13] During Superstorm Sandy, one New Jersey utility reported widespread outages due to storm surge, with 4 to 8 feet of water inundating substations that had never previously experienced flooding.[14]

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[13] *See* A. LiVecchi et al., "Powering the Blue Economy; Exploring Opportunities for Marine Renewable Energy in Maritime Markets," U.S. Department of Energy, Washington, D.C., 2019. [Online]. Available: https://www.energy.gov/sites/prod/files/2019/03/f61/73355.pdf and M. K. Buchanan, M. Oppenheimer, and R. E. Kopp, "Amplification of flood frequencies with local sea level rise and emerging flood regimes," Environmental Research Letters, vol. 12, no. 6, p. 064009, 2017/06/01 2017, doi: 10.1088/1748-9326/aa6cb3.

[14] *See* "Learning from Superstorm Sandy: PSE&G Improves Infrastructure, Communications and Logistics." PRNewswire. October 28, 2014. https://www.prnewswire.com/news-releases/learning-from-superstorm-sandy-pseg-improves-infrastructure-communications-and-logistics-280628132.html (last visited September 9, 2019) and Preston et al, *Resilience of the US Electric System: A Multi-Hazard Perspective*, August 2016. https://www.energy.gov/sites/prod/files/2017/01/f34/Resilience%20of%20the%20U.S.%20Electricity%20System%20A%20Multi-Hazard%20Perspective.pdf

Distributed energy resources (DER)[15] can support resiliency objectives if properly enabled, in particular, to address identified vulnerabilities.[16] Hurricane Harvey[17] in Texas is one example that demonstrates how DER-powered microgrids can maintain electricity delivery during and after disasters. Marine energy devices integrated with coastal microgrids could support resilience improvement measures for isolated coastal communities as well as for high-priority coastal loads. Further, appropriately designed, scaled and strategically located MRE arrays could help power grids become more resilient by diversifying energy sources and by providing essential back-up and black-start services.

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[15] Distributed energy resources (DER) are resources attached to the distribution system of an electric grid that produce electricity or modify their consumption with respect to grid service requirements and are not a part of the bulk electric system. *See* https://www.nerc.com/comm/Other/essntlrlbltysrvcstskfrcDL/Distributed_Energy_Resources_Report.pdf.

[16] See Quadrennial Energy Review, Second Installment, 2016. Chapter IV, *Ensuring Electricity System Reliability, Security, and Resilience*. (https://www.energy.gov/policy/initiatives/quadrennial-energy-review-qer) and National Academy of Sciences, *Enhancing the Resilience of the Nation's Electricity System*, July 2017. https://www.nap.edu/catalog/24836/enhancing-the-resilience-of-the-nations-electricity-system

[17] Proctor, D. "Microgrid System Keeps Houston Grocery Stores Open in Wake of Harvey." Power Magazine. August 29, 2017. https://www.powermag.com/microgrid-system-keeps-houston-grocery-stores-open-in-wake-of-harvey/.

2.0 Role of Analytical Approach in the Project Design

The analytical approach is an initial review of services and system benefits that are relevant for MRE development, including providing associated data requirements and proposed analytical methods. This approach lays the groundwork for the next steps in the project, including a literature review to assess marine energy values and services[18], an initial public technical report outlining these values in greater detail, case studies to explore specific values identified as a part of the analytical approach, a selection of relevant grid services for further analysis and the development of metrics to represent these services.

It is important to consider a broad swath of the potential benefits to characterize services and benefits through an MRE-specific lens and develop an understanding and high-level quantification of the broad value of these services. The review of data requirements, methods, employed models and a range of services and values that MRE could contribute to the grid will be informative in narrowing the services for further review and analysis in the case studies. The team can determine which values deserve closer inquiry, that is, a down-select to "relevant" grid services and potential benefits that may require more computationally intense modeling (e.g. distribution system or sub-hourly production cost models). This will take a deep dive on areas of confluence between resource availability, technology type, and opportunity to provide additional energy benefits.

The case studies will be a portfolio with reasonable diversity in exploring different grid values. The case studies will illustrate where site-specific analyses yield flaws in the analytical approach, provide greater sensibility about the potential range, character, or topology of values or services as applied to MRE, or turn over new benefits that were previously not proposed to be analyzed.

Concurrent with the case studies, the project team will use the analytical approach to identify non-site specific attributes for further review. This will involve investigating variable resource, specifically wind and solar, variability at multiple temporal and spatial scales, extrapolating MRE resource forecasts into market and reserve timescales; and incorporating uncertainty as compared to other variable generation, including auto-correlating with load to learn how well marine energy can complement wind and solar generation at scale, or otherwise help reduce reserve requirements. Further, the team will look at the potential for technology co-development with energy storage and other complementary technologies to smooth output.

From here, the team will create metrics, meant broadly in this context to represent a method to measure and indicate relative value, to represent these services. These metrics will be based in quantitative assessment and will be performance-based. This investigation is by design primarily top-down (understand the performance benchmarks that need to be achieved for value) with MRE-based operations driving the bottom-up (the likelihood of achieving that value).

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[18] *See* Preziuso, D. et al. "Understanding the Grid Value Proposition of Marine Energy: A Literature Review." Pacific Northwest National Laboratories. PNNL-28839. July 2019.

3.0 Locational Applications

3.1 System Benefits

3.1.1 Description

Marine energy resources are expected to provide several benefits for coastal energy systems. The authors categorize these benefits as system benefits.

Beyond traditional energy services, MRE technologies can provide a variety of other system benefits. Stanton defines Non-Wires Alternatives (NWA) as "electric utility system investments and operating practices that can defer or replace the need for specific transmission and/or distribution projects, at lower total resource cost, by reliably reducing transmission congestion or distribution system constraints at times of maximum demand in specific grid areas" (Stanton 2015). Coastal loads, which are often sited away from inland generation, can have high transmission and distribution costs associated with power delivery, especially under stressed grid conditions. In such cases, MRE technologies may provide transmission and distribution benefits, or NWA services. MRE device deployment may avoid or defer costly transmission and distribution upgrades needed to address congestion and deliver electricity from inland generation to coastal load. The value can be even higher if the load centers along the coastlines are remote communities and typically served by inland generation located far away from them. In situations where thermal generation assets along coastlines are used to cater to coastal communities, as is currently the situation in California, marine energy can help reduce reliance on these fossil fuel plants. Not only is there a direct benefit associated with displacing fossil fuel, there is also added benefit of not being exposed to disruptions in fuel supply.

In addition to providing system benefits, MRE technologies can also provide localized benefits, operating as distributed energy resources (DERs). DERs (including distributed PV, energy storage and others) have been looked upon as an integral component of renewable-heavy power systems to provide localized energy directly to customers. As renewable penetration increases, increasing demands on distribution systems, DERs have been looked to, to provide services such as demand response, local voltage or reactive power support, power quality support and reliable power availability. DERs can work in tandem with storage devices to extract maximal benefits (Wu et al.). Like other DERs, small scale MRE devices at the distribution level can provide local requirements in coastal areas, something that could be especially valuable in climates where other resources are limited (e.g. solar in the Pacific Northwest or Alaska).

3.1.2 Data and Analytical Methods

For system studies, techniques such as probabilistic assessments or security constrained economic dispatch (SCED) using production cost modeling can be utilized to understand the value of marine energy technologies in addressing system congestion and avoid or defer transmission and distribution investments (Koval, Zhang, and Chowdhury 2010). This analysis requires technology characteristics of MRE devices, power system specifications and the technology characteristics of other generators, as well as load data.

To evaluate the value of MRE technologies in distribution applications, power flow models can be utilized with MRE devices modeled as generation components. These load flow methods can be used for evaluating the effects of MRE DERs on distribution systems and quantifying the value they present as distribution assets, deferring other distribution service procurements or investments, and allowing for the additional integration of additional load or renewable generation. Efforts by others can provide insights into this analysis, for example, Liu et al. who evaluate impacts on voltage stability in grids for offshore winds and Chen et al. who study the effects of DERs on power quality (Liu and Sun 2014; Chen and Wu 2015).

3.2 Land Use Applications

3.2.1 Description

A potential advantage of marine energy resources is their relatively small terrestrial footprint, which is essentially an electric cable and auxiliary on-shore equipment for interconnection. This avoided land use, relative to other terrestrial generation resources, is a value stream, especially in situations where land is scarce, dedicated for other higher-value purposes, or only available at a premium.19 Land is a scarce commodity and is subject to competing uses, and accordingly, significant economic and political pressures that dictate the allocation of this scarce resource. For any allocation of its use, there is an associated opportunity cost. With the expectation that renewable resources will need to be significantly increased to meet climate goals, there may be pressure to site renewable energy resources offshore in order to meet goals in areas where available land is scarce.

A way to quantify the avoided land use value of marine energy would be to compare it to land-based generators. One can measure the land use opportunity cost of land-based generators by looking at foregone agricultural production. Since the use of land is near zero for MRE, these opportunity costs may be perceived as one of the gains that would accrue from the use of marine energy. At current (i.e. market) prices of rice and wheat, it is possible to assign a dollar value to the benefits from MRE from this one avoided land use. Add to this, the other environmental, economic and social costs of land uses, and the returns from transitioning to an offshore generation like MRE could be significant. Of course, such an analysis would require considerations of specific situations and projected alternative land use.

Land use premiums, as captured by changes in the value of land, have progressively been on the rise. Using data compiled by the American Enterprise Institute on land values for 46 metropolitan areas between 1984 and 2018, one can see that land values have increased by a maximum of (approximately and not adjusted for inflation) 921% (for Seattle).[20] See Figure 3 below.

[19] In its 2017 Integrated Resource Plan (IRP) for the Caribbean Utilities Company (CUC), Pace Global evaluated land use associated with different generation technologies. Pace found a significant advantage to using marine energy, specifically ocean thermal energy conversion (OTEC), in the much smaller land use required for its development. Although Pace did not quantify a value associated with the reduced land use, minimizing land use was a primary objective of the CUC IRP. Accordingly, and despite a higher capital cost for OTEC relative to other resource options, the resource plan containing OTEC was amongst the two recommended portfolios. The portfolio containing it replaced natural gas, solar PV and battery storage with OTEC (*2017 Integrated Resource Plan Report Prepared for: Caribbean Utilities Company* 2017).

[20] *See* American Enterprise Institute. "Land Price Indicators." Available at: http://www.aei.org/housing/land-price-indicators/

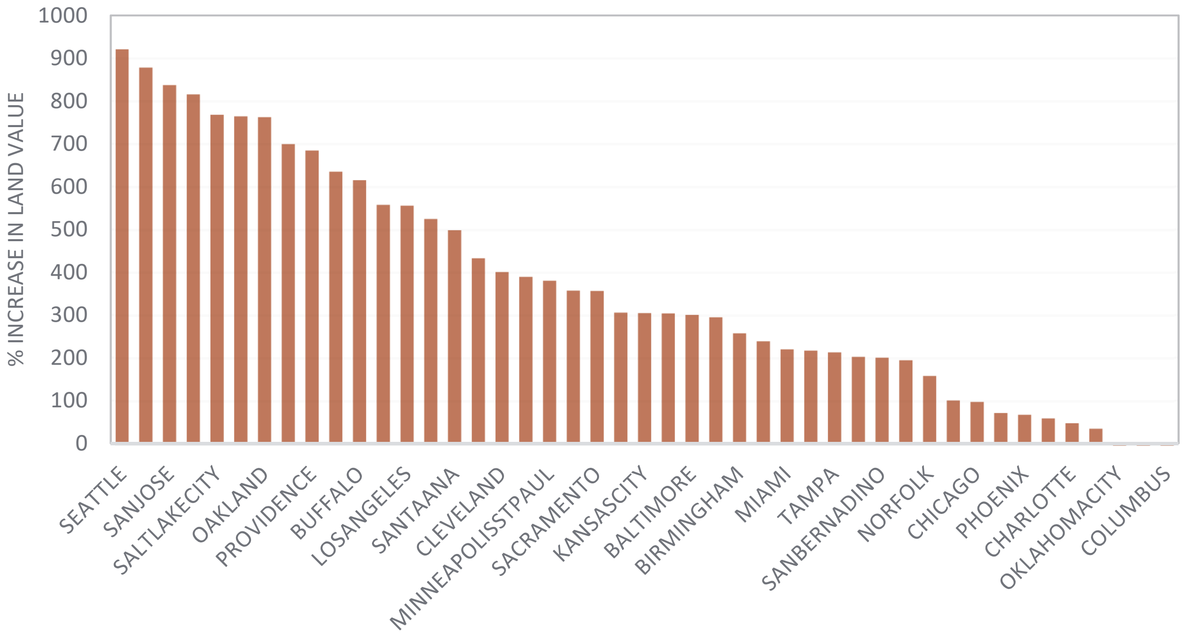

Figure 3. Changes in land value from 1984 to 2018 in major U.S. cities.

A quick visual review reveals that among these different metropolitan areas, those closer to the coast registered some of the higher increases. Since 50% of the US population lives near coastal areas, with land prices being among some of the highest around these regions, the use of offshore power generators in place of terrestrial generation may have some value.[21] In fact, rising land premiums have been cited as one of the driving forces in the development of floating solar plants (Trapani and Santafé 2015).

3.2.2 Data and Analytical Methods

Since land is a resource with multiple potential competing uses, a method to evaluate the benefit of offshore energy development is to quantify the economically foregone value for every unit of land that is used for energy production. This can be estimated in terms of foregone revenue from competing uses like industry, agriculture, forestry, or others, and this translates to an opportunity cost should that same piece of land be used for energy production. Additionally, for every unit of land that is used for energy production, there are environmental costs (e.g. loss of bio-diversity and erosion) and socioeconomic costs (e.g. quality of life) that are not insignificant. Any model that tries to accurately estimate the benefits of avoided land use will have to account for all these types of costs.

For each area under study an econometric model can be used to compute GDP from alternative production to determine economic opportunity cost. Other tools or estimates would be necessary to evaluate environmental and socio-economic costs. Given enough data points, it may be possible to perform a partial equilibrium analysis (in a panel setting) to compute estimates of the sensitivity of the different costs.

There are limitations to this effort. The unavailability of data might bias some estimates, and several variables are qualitative in nature (e.g. socioeconomic costs like quality of life) making it difficult to

[21] To understand trends in population increases in coastal vs. non-coastal communities, *see* https://www.census.gov/prod/2010pubs/p25-1139.pdf.

accurately quantify them. Importantly, such an effort may have to be very locationally specific, limiting its worth to quantify the value of avoided land use for energy production broadly.

This project will also explore other mechanisms to establish a general *land use intensity* metric that considers the availability and cost of land and other forms of land pressure (such as population density and zoning) to determine inflection points that push toward offshore development.

3.3 Geographical Diversity

3.3.1 Description

In theory, a geographically diverse generation profile is less subject to the variability that might result from localized weather and grid conditions. A solar plant may be subject to variable cloud cover or a wind plant may be subject to variable wind speeds. Where there are very large facilities or clusters of facilities, these periods of unavailability or ramping requirements can be amplified (Schwartz et al. 2012). This issue is particularly challenging in parts of the United States where alternative resources are not available (e.g. the U.S. southeastern states have little wind resource and must rely on solar development for renewable expansion). Geographic diversity for future development of wind and solar is often one of the key mechanisms in lowering the cost of integrating renewables. Still the best solar and wind resources for development have geographical limitations. Marine energy would certainly create geographic diversity as a renewable resource not located in proximity to or with co-timed resource constraints as wind and solar.

The benefit of the geographic diversity offered by marine energy manifests in several value streams. The diversity could reduce system capacity and balancing requirements by reducing the variability of the renewable energy generation profile, reducing the need for alternate resources to balance generation and load. It also provides a natural resiliency effect: the more geographic diversity of the generation profile, the less likely it is to be interrupted by contingency events. One could imagine a significant weather event requiring wind turbines to be shut down and resulting in minimal solar output due to cloud cover. Depending on the type of marine energy device, it may still function and provide a critical generation resource in such an event.

3.3.2 Data and Analytical Methods

To analyze the impact of MRE device geographical diversity and characterize its value requires several types of data. This includes MRE resource data, other generation resource output data and electric system characteristics. This information could then be fed into models to characterize and evaluate this diversity value, considering several permutations of geographic diversity. These models could include probabilistic models that characterize the overall value of this diversity. They could also include scenario analysis using production cost models, power flow models or capacity expansion models that identify system needs in specific situations. Such an effort would require careful consideration of marine energy resource and alternative resource siting to ensure representative results.

4.0 Temporal Applications

4.1 Predictability

4.1.1 Description

A key challenge of moving to a renewable electricity system stems from the inherent intermittency associated with most renewable energy resources. For solar this problem is a result of rapidly changing cloud cover as well as diurnal resource availability, while for wind it is fluctuations in wind speed. Marine energy resources can play a crucial role towards advancing clean energy goals for the domestic electricity mix because, although still variable resources, they are far more predictable compared to other renewable resources.

The following applications highlight the predictability of MRE resources:

1. Reduction in reserve requirements: In power system operation, there are several different types of reserves (Ela, Milligan, and Kirby 2011), which are used to enable reliable operations. The integration of most renewable technologies requires additional reserves to compensate for unpredictable intermittency, the lack of which may lead to significant power outages and subsequent reliability events (Papavasiliou, Oren, and Neill 2011; Loutan and Hawkins 2007; Gross et al. 2006). Having a more predictable renewable energy source such as MRE could reduce the uncertainty associated generation, potentially reducing reserve requirements as the same magnitude of reserve does not need to be kept if generation can be reliably predicted (Reikard, Robertson, and Bidlot 2015). Figure 4 below highlights this potential value. It visually compares daily generation from wind, solar and tidal in a location near Admiralty Inlet, WA. While reserves are still required for marine energy resources, tidal in this case, the magnitude may be reduced relative to wind and solar.

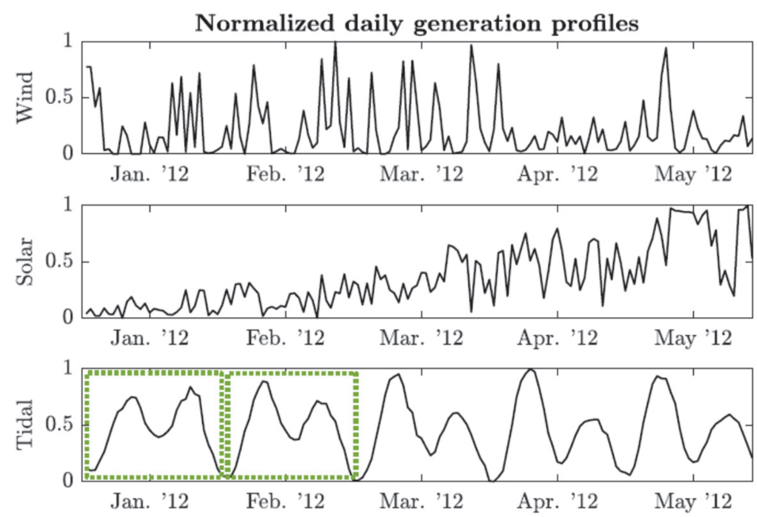

Figure 4. Daily normalized power produced by a solar, wind and tidal generator near Admiralty Inlet, WA. The green dotted rectangle in the tidal profile denotes observable periodicity.[22]

Figure 5 below shows the output of a simulated wave and a simulated tidal device over a 24-hour period at a 1-minute resolution. This shows to highlight that although marine energy resources may reduce reserve requirements, reserves are still necessary.

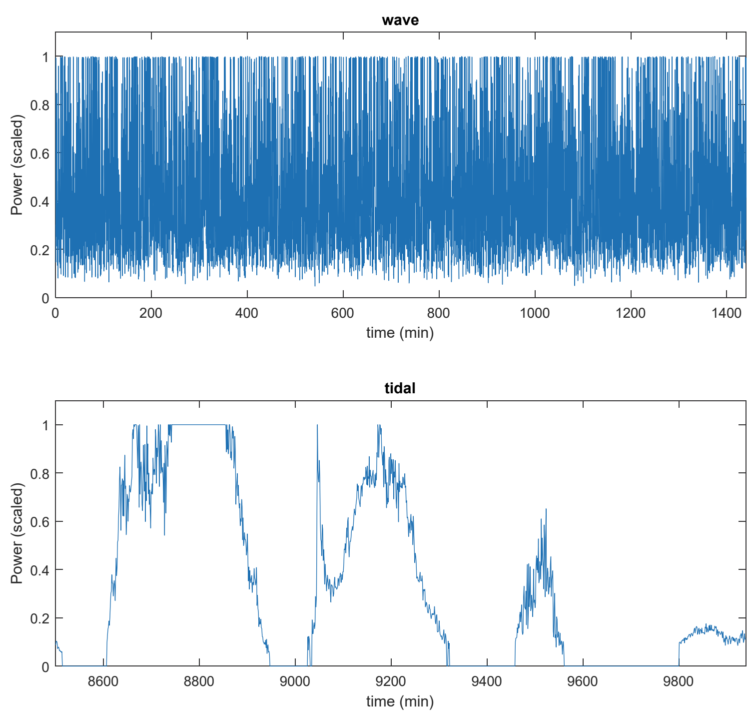

Figure 5. Simulated generation profiles over a 24-hour period from a wave device and a tidal device at a 1-minute resolution.

[22] Taken from Bhattacharya et al. "Grid Value Propositions for Tidal Generation Resources - a Temporal Analysis." *Submitted for the Oceans 19 Conference in Seattle, WA.* September 2019.

2. Reduction in the need for gas/hydroelectric resource ramping: A high penetration of intermittent renewable resources within a generation portfolio may result in generation shortfalls for extended periods of time when the resource becomes unavailable. In those cases, controllable sources of generation are dispatched (e.g. hydroelectric and natural gas units) often at high ramp rates to meet load, compensating for dropping generation. Such ramping actions may lead to increased operational expenditures, especially the for those plants that are less efficient and more expensive to operate (e.g. peaking plants). Predictable MRE resources may reduce these ramping requirements by providing an alternate energy source that is not subject to the same intermittent limitations. This value is also highlighted in Figure 4.

3. Extending the time window for decision making in markets: In situations where the generation portfolio is comprised of a sizeable fraction of renewable resources, short term load and generation forecasting becomes very important to ensure reliable operations for operational decisions such as resource dispatch to meet load requirements and optimal bid quantities in forward markets. Subsequent operational decisions of this nature are directly dependent on the quality of the forecast (of load and generation) and forecasting errors may often result in material losses (e.g. penalties and loss of revenue). Having a more predictable generation source such as an MRE directly assuages that risk arising from forecast error by lengthening the time window to take an operationally optimal decision (e.g. bidding in a day-ahead market). Again Figure 4 and Figure 5 highlight this predictability.

4.1.2 Data and Analytical Methods

At a higher level, for the case where MRE devices are used as a more predictable generation resource, reducing reserve requirements and avoiding ramping, their value stems from the avoided use of alternative resources, which are often more conventional generation resources (Moazzen et al. 2016). This value can be estimated through the modeling and identification of reserve requirements with and without MRE, or through production cost modeling for resource dispatch which can indicate costs for resources used to meet reserve requirements. For higher granularity, data-driven, learning based, time-series techniques, namely statistical techniques, might help determine the value of MRE predictability for reserve and ramping requirement reduction. This value would be directly dependent upon the forecasting accuracy of the MRE resource and hence answer the question about the value of predictability.

4.2 Seasonality

4.2.1 Description

Seasonal fluctuations occur with wave and ocean current resources such that these resources vary over the course of a year. There are periods of time where these resources experience maximums and minimums. These variations are largely the result of meteorological phenomena that generate these sources of energy (i.e. wind, solar irradiance) (Neill and Hashemi 2018). The value of seasonally peaking resources is realized when the energy resource fluctuation correlates with the load to be served. By providing energy during times of high demand, marine energy resources could alleviate pressure on other generating resources. This could also relieve transmission congestion in an area, if it exists, and avoid or defer costs of transmission and distribution upgrades.

In temperate to cold climates where heating demands rise in the winter and ocean energy intensifies, this trend can be identified, and the correlation can be measured. In locations like the Pacific Northwest, there are more energetic sea states in the winter than in the summer: this seasonal peak in wave energy intensity generally follows the load profile of the region (Robertson, Bailey, and Buckham 2017). Ocean currents in the Florida Straits, for example, experience a seasonal peak in July. The seasonal maximum in ocean current correlates with increased temperature, and ultimately parallels an increase in demand to power cooling units (Hanson et al. 2010).

4.2.2 Analytical Methods

The direct value of the seasonal coincidence of generation to load is the amount of conventional generation or power imports not needed to serve demand. This reduction can be quantified as an avoided cost. Another value would be the amount of transmission and distribution congestion that could be reduced from seasonal MRE generation devices, reducing reliance on transmission and distribution networks to provide generation from other areas during times of high demand. This again could be valued as the deferral or avoidance of costly transmission and distribution upgrades or, in a market environment, transmission congestion charges.

4.3 Tidal as Baseload

4.3.1 Description

One of the key advantages of tidal energy resources is their predictability in comparison to other renewable resources (e.g., solar, wind). Being able to plan and manage in accordance with variability patterns can create opportunities to use tidal resources to serve demands like baseload generation facilities, which could reduce the costs of integration. At present, most renewable energy technologies are unable to provide a constant or controllable power output unlike thermal power plants or hydroelectric plants.

Offsetting multiple tidal generating profiles could result in a net flat generating profile, like "baseload" operating output. This concept has been evaluated, and to date, has not been furthered (Clarke et al. 2006; Neill, Hashemi, and Lewis 2016). While it is not clear that a completely flat profile is a key outcome, this project considers two paths to a smoother profile:

1. The aggregation of multiple tidal power facilities distributed over a large geographic area can take advantage of the phase characteristics of different regions to produce a more constant power output.

2. The integration of energy storage systems (ESS) to store excess tidal energy during energy output peaks and discharge stored tidal energy during device output valleys. A 0.6 MW tidal power facility in Scotland, supported by an ESS (currently using lithium-ion, and proposed to use a flow-battery in the future), is being claimed as the world's first baseload tidal power facility ("Bluemull Sound, Shetland" 2019). Further by coupling with ESS, tidal facilities can achieve better controllability of output and could offer dispatchable generation.

4.3.2 Analytical Methods

Understanding the tidal resources' cyclic patterns, including daily, weekly, monthly and seasonal cycles, and phasing across many regions, is necessary to assess their variability characteristics and identify locations where an aggregation of tidal resources could provide constant power output. The deployment of ESS to mitigate variability of tidal resources and achieve baseload or dispatchable generation capability by doing so requires an analysis of tidal resources and a fit of potential ESS technologies to these tidal resource characteristics.

The value these potential aggregations and use of ESS presents can be quantified through several mechanisms from statistical analysis, dispatch models and even a high-level quantification of the benefits associated with thermal resource replacement (e.g. operations costs, fuel costs, capital costs and other costs).

4.4 Portfolio Effects: Temporal

4.4.1 Description

Marine energy resources have some distinct temporal characteristics which might enable them to generate unique value streams. These are classified here as portfolio effects and they include:

1. Correlation trends of MRE with respect to other renewable resources: Several researchers have investigated the potential for different renewable resources to stagger their generation profiles over time in a manner that leads to smoother generation of electrical power. For example, Widen et al. show that wind and solar resources can bear non-trivial negative correlation, thus ensuring that a combined wind-solar portfolio can act as more evenly distributed generation than standalone wind or solar units (Widen 2011). Theoretically, MRE resources could have similar correlation trends with other technologies. This is a value associated with MRE devices as system operators could take advantage of this complementary to reduce the overall capacity needed to meet load.

2. Thermal resource improvements due to MRE resources: As discussed above, the predictability of MRE resources can have value to the electric system. One way this predictability manifests is through improvements in the operations of existing thermal, namely coal and natural gas, generation units. The increased predictability relative to other renewables can lead to thermal unit displacement, reduced unit cycling, improved unit efficiency and reduced emissions.

3. Effect of MRE on reliability metrics for power systems: The use of MRE devices, and their predictable characteristics, may also improve system reliability. In order to quantify the effect of a generation resource on power grid reliability, several well-established indices can be used.[23]

4. Effect of MRE on load carrying capacity and capacity credits: MRE technologies may also show improvements in an electric system's Effective Load Carrying Capability (ELCC), that is, the amount of extra load that can be supplied while not deteriorating system reliability, and, market dependent can provide capacity credits.

5. Reduction in system costs, capacity and balancing requirements with an integrated portfolio: Elements of this have been discussed above, but the use of MRE can provide overall system benefits through its characteristics.

[23] These include: (1) the Loss of Load Probability (LOLP), that is the probability that generation will be insufficient to meet demand; and (2) Loss of Load Expectation (LOLE), that is the expected number of days in the year when the daily peak demand exceeds the available generating capacity.

4.4.2 Analytical Methods

Statistical tools can be used to evaluate correlation between MRE, other resources and load. The resource generation profiles can be applied to power flow, dispatch and system expansion models to characterize the value associated with this correlation from the perspective of distribution and transmission services, meeting load requirements and resource dispatch, and long-term resource planning. Next, dispatch tools can be used to provide insight to thermal resource improvements, the calculation of reliability metrics and ELCC, and an evaluation of an integrated portfolio. Statistical analysis coupled with market operations models can shed light into the value of capacity credits that could be associated with the use of marine energy devices.

5.0 Special Applications

5.1 Enabled Services

5.1.1 Description

Marine energy resources have a role to play as behind the meter resources (BTM), that is on the customer side of the meter rather than on the utility side. Behind the meter resources can provide customer benefits in the way of energy, often net metered and thus compensated at the higher retail rate of electricity rather than a bulk rate, potentially offsetting demand charges and reducing associated utility costs with the delivery of energy. Marine energy as a BTM resource can also potentially serve as a backup resource in case the grid becomes unavailable.

Behind the meter resources can also provide grid benefits. Smart distributed assets within the grid (including rooftop solar, small CHP generators, fuel cells and storage) often enable behind the meter services by making electricity operations more flexible (Bayram and Ustun 2017). Coordinated usage of such assets can enable an electricity prosumer to alter local load patterns in a beneficial way to the local and bulk grid. Such coordination is often driven by price signals (e.g. time of use prices, critical peak pricing, demand charges etc.) and has the potential of benefiting the grid at large by helping to achieve objectives such as peak-shaving, demand reduction and load-curve variance reduction. An MRE generating resource as a BTM resource may able to provide, in conjunction with other renewable resources and storage, a smoother generation profile and reduce the storage requirements. MRE may also enable the provision of other BTM services that were otherwise not possible. For example, more stable and predictable MRE generation might free up additional storage capabilities to participate in lucrative regulation markets, deriving an additional source of value (Bayram and Ustun 2017).

5.1.2 Analytical Methods

The straightforward method to identify the value of MRE as a BTM resource can be through scenario analysis, where marine energy is evaluated to meet a specific local load such as an industrial facility. The MRE device can offset the total energy demand and potentially eliminate peak demand charges and associated line losses, delivery charges, and local line loading. Scenarios can also consist of unique combinations of residential load profiles, DER asset portfolios, scales of deployment (e.g. individual building level to multi-building campus levels) and synchronization signals (e.g. price curves and incentives). In terms of control and operation, several different experiments which focus on different algorithms for the provision of BTM services can be used to evaluate these scenarios, including rule-based heuristics or more sophisticated optimization-based scheduling and operations modeling.

Coarser technology-agnostic and resource-data-driven studies may also help to characterize the value of generation intermittency smoothing at distribution level. These studies can be extended to understand the potential of MRE devices to free battery storage capability to participate in other grid services.

5.2 Technology Companions

5.2.1 Description

MRE technologies can be an asset to other energy system resources including energy storage, microgrids, renewables and demand response technologies.

Energy storage resources are rapidly becoming valuable electric system resources. They can provide several benefits throughout the electricity delivery lifecycle and can function as independent grid devices or support other grid devices. An example is the use of energy storage to firm and support distributed solar PV at the customer-level, a trend that is taking hold in Hawaii and California. This is especially valuable when considering limitations of the distribution system. In Hawaii, several circuits are saturated with distributed PV, according to the utility, and can no longer accept additional distributed PV. This eliminates the potential for customers who do not already have PV systems on these circuits to benefit from the technology. Recently, the Public Utilities Commission of Hawaii and Hawaiian Electric Company have established programs permitting the deployment of additional distributed PV when coupled with storage. Depending on the program and the customer's consent to participate, the utility can leverage customer systems with energy storage to deliver grid services.[24] The use of energy storage here effectively increases the value of the distributed PV resource.

With respect to marine energy, energy storage can increase the overall value of MRE by turning it into a dispatchable device. Conversely MRE, a more reliable and predictable resource relative to other renewable energy sources, can increase the value of a storage device by providing a consistent source of renewable energy. Either way this is effectively a combined MRE-energy storage resource. The combined system will have an increased capability to provide capacity, energy, ancillary services and distribution services.

Marine renewable energy resources are also well suited to be components of microgrids. In any coastal microgrid, MRE can be a suitable replacement to fossil generation, providing an alternative baseload-type resource and supporting load when implemented in conjunction with intermittent renewable technologies and energy storage. This same value is further strengthened in remote coastal communities and islands. In these areas MRE can provide significant value as a critical microgrid resource, reducing or eliminating reliance on expensive and unreliable fossil resources.

Marine energy resources also have the potential to increase the benefits of other grid technologies, including solar, wind, demand response and other devices. They can do this by shoring up the energy profiles of these other technologies and enabling, or furthering the ability of, these resources to deliver grid services.

5.2.2 Analytical Methods

At a bulk level, the additional value streams accruing to all technologies identified above in companionship with marine energy can be evaluated through production cost modeling and the insertion of MRE devices as resources in various scenarios. On the distribution system, power flow analysis tools such as GridLabD can be used to evaluate the value accruing to these systems through the manipulation of existing system resources and operational profiles and the insertion of MRE devices as companion and alternative resources.

Specific to microgrids, the above methods can be used to model a microgrid with MRE as a constituent technology to provide system services. The value accruing to a microgrid can be considered using existing techno-economic microgrid modeling tools such as DERCAM with MRE as a constituent resource displacing fossil or renewable resources.

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[24] *See* "Private Rooftop Solar." Hawaiian Electric Company 2019. Accessed: September 10, 2019. Available at: https://www.hawaiianelectric.com/products-and-services/customer-renewable-programs/private-rooftop-solar

5.3 Resilience

The National Infrastructure Advisory Council defines resilience as a combination of four distinctive attributes: (1) robustness; (2) resourcefulness; (3) rapid recovery; and (4) adaptability (III and Wallace 2010). Considering the above definition, having a resilient electricity grid is a challenge which is best met through "proactive, rather than reactive, approaches" (Preston et al. 2016). The QER 1.2 states that achieving security, resilience and reliability is one of the central objectives for electrical systems of the 21st century (*Transforming the Nation's Electricity Sector: The Second Installment of the QER* 2017). Over the years, the DOE has also paid increasing attention to making power grids more resilient to several factors which include climate change and weather disasters (Ton and Wang 2015).

To explore the different ways in which marine energy resources can assist in increasing grid-resilience, this project will investigate two measurable aspects of resilience, one of avoidance and the other of response.

5.3.1 Reduced Vulnerability to Grid Disruptions and Exposure to Fuel Price Volatility

MRE resources are geographically limited to interconnection in coastal areas and islands. This topic will explore the unique resilience challenges associated with coastal and island grids, characterize grid disruptions and the ways in which MRE resources may provide a solution to those disruptions. Electric service, in general, is subjected to many potential forms of service disruption, due to both natural and human factors. Some of these service disruption risks become more severe under extreme weather events, such as hurricanes, droughts, floods and storms. In certain instances, the vulnerability to disruptions can be mitigated by local power generation. However, at present, the requirement and, accordingly capability of resources, to fully sustain a power outage situation through local generation capabilities is mostly limited to military installations (Preston et al. 2016). MRE resources can change help coastal grids by serving as uninterruptible generation sources in the face of contingencies like floods, storms and hurricanes. Another value of using MRE resources is that of a reduced dependence on conventional fuel like diesel, which may become expensive or even unavailable during contingencies.

5.3.2 Electric Services to Critical Infrastructure

Critical infrastructure such as shelters, gas-stations and hospitals need to be kept operational during contingency events. There is extensive research to guide the optimal design and operation of microgrids and DERs to provide resilience (Che and Shahidehpour 2014; Wu et al. 2015). MRE resources can provide resilience to coastal areas by offering uninterrupted generation during events like storms and hurricanes, reducing the need to rely on microgrids to facilitate resilience in those regions. Beyond reducing reliance, MRE resources can also be critical components of microgrids enhancing their capabilities, at potentially lower costs and risk, by reducing reliance on fossil resources, batteries and other intermittent renewable resources.

5.3.3 Analytical Methods

Analyses may range from simplistic qualitative assessments to comprehensive analytics-driven quantitative approaches (including econometric and optimization studies) to determine the value proposition for MRE resources in providing resilience. A straightforward assessment is an installed-capacity study. Specifically, this analytical evaluation of the total projected installed-capacity of the MRE resources can give an indication of the maximum possible amount of load disruption prevented in the event of a contingency. Such analyses may require the use of probabilistic frameworks which model extreme weather events and subsequent grid-disruption events (such as transmission line faults and generator contingencies) to perform subsequent Monte-Carlo scenario analysis. These analyses would allow a derivation of statistical assessments of the value proposition of MRE resources in providing resilience.

To evaluate MRE and microgrids serving critical loads during contingencies, approaches such as model based optimization and multi-agent systems framework can be used (Khodaei 2014; Pipattanasomporn, Feroze, and Rahman 2012). Existing tools such as PNNL's Microgrid Component Optimization for Resilience (MCOR) tool can be utilized by adding a specific MRE-module for optimization-based resilience analysis. Co-operation value with microgrids can be measured by considering the avoided cost of alternatives, avoided fuel costs and emissions, comparable operational duration, and optimization with microgrids.

In understanding the risk reduction from fuel price volatility made possible by MRE deployment, probabilistic analysis and scenario-studies can indicate value by evaluating extents of price volatilities and differing amounts of diesel generation for back-up generator services.

MRE resources can be looked upon as means for providing uninterrupted load service in the face of contingencies, the value directly stemming from the "amount of load not lost owing to contingency event." Some researchers refer to this metric as the "avoided cost of grid outage" (Hirose et al. 2013). The value is even higher (albeit more difficult to quantify as a singular metric) if the uninterruptible service is being provided by MRE to critical loads such as hospitals, shelters or gas stations.

5.4 Portfolio Effects

5.4.1 Description

There are several value streams of marine energy technologies that are less well defined. One set of value streams is associated with the fact that marine renewable energy technologies have several characteristics that manifest as a result of their modularity. Each of these characteristics has associated value streams that can accrue to the grid through their use as energy resources.

The first of these is simply that the smaller size of marine energy devices relative to typical large-scale generation resources leads to a scaling value, a reliability value and a resiliency value. From a scaling perspective, MRE capacity can be incrementally developed, resulting in lower up-front costs, easier financing and a reduced construction timeline before the capacity is available. A developer can hedge against the uncertainty associated with future energy system requirements, not only reducing their risk, but resulting in an overall increased system efficiency and consequently, lower costs. This is all measurable value to the system. As demand expands and there are increased capacity requirements, the capacity can be further developed to meet the need.

From a reliability perspective, modular development reduces the costs associated with system down time. Unlike in a larger power plant, individual MRE devices can be repaired or replaced without shutting down the entire capacity associated with power plant. This value manifests as increased overall system efficiency, reducing reliance on peaking generation to meet demand, capacity or ancillary service requirements.

From a resiliency perspective, the modular nature of MRE devices affords a reduced risk of the impact of severe weather events as devices can be strategically placed to limit the loss of the entire array capacity during such an event. This value manifests as an amount of MRE capacity remaining available to the grid during a resiliency event. Further, as discussed above, in case of device failure during events, individual devices may be repaired or replaced without removing the entire MRE capacity from the system as a result of a resiliency event.[25]

Next, the use of MRE technologies presents value streams in the reduction of reliance on fossil infrastructure, from extraction of the fossil resource to generation of the electricity. Increased MRE use will lead to less extraction of fossil fuels, transportation to refineries, refining, transportation from refineries to electricity generators and electricity generation. It could also lead to a reduced reliance on diesel and natural gas for backup generation and microgrid applications. This reduction in fossil fuel use has many value streams that have been characterized throughout this document, but an additional one is progress on meeting sustainability goals. In addition to the progress in meeting sustainability goals through the reduction in fossil fuel use, MRE technology use may also limit the use of other technologies that strain sustainability goals. The use of MRE devices may reduce the use of silicon and other elements required in the production of PV panels and similarly, may reduce the use of rare earth elements required to produce batteries and avoid the water and land requirements of pumped storage devices. The mining of raw elements and their transportation can be avoided as can the construction of dams or holding ponds. Utilizing these technologies has these sustainability costs that may be reduced using MRE technology.

5.4.2 Analytical Methods

Estimating the value stream associated with modularity requires an analysis of each of its components: scaling value, reliability value and resiliency value. Characterizing the scaling value can be achieved by looking at the value another similar technology, wind energy, provides. Wind energy arguably has similar scaling characteristics to MRE and as a far more mature technology, reduced system costs associated with the scaling of wind can be extrapolated. This value would be associated with lower up-front costs, easier financing and reduced risks, each of which can be considered from a financing and contract evaluation of past wind farms. The aggregation of multiple wind farm financing data will allow for an estimate of the value of scaling for several different market environments, which can be extrapolated to MRE resources.

Evaluating the value associated with increased reliability from modularity can be characterized by a model that considers outages for the individual devices within theoretical MRE farm and the associated reduction in overall capacity. Modeling multiple scenarios of different device types and configurations as well as different levels of forced outages can lead to yearly capacity curves associated with different types of MRE farms. These capacity curves can then be evaluated within a representative market model to define the reliability value stream associated with modularity, which will manifest as MRE farm revenues and system operating cost reductions.

Evaluating the value of increased resiliency from modularity is more difficult. The analysis of resiliency above can be used in conjunction with a probabilistic contingency event evaluation, like the forced outage

[25] Certainly, neither the characteristic of modularity or the associated value streams are unique to MRE technologies. There are other energy generation technologies, for example wind or solar PV, that are similarly modular and can offer some of the same values to the grid. However, the marine environment of MRE devices allows some of this value to be distinct and unique. For example, a severe weather event may cause increased damage to a solar PV or wind farm, whereas the impacts to an offshore MRE array in the same event may be limited. In this document, we try to lay groundwork for further analysis as part of this project. In further work we intend to more distinctly characterize the uniqueness of value streams to marine energy.

evaluation above, to discern an incremental value of modularity. The value of black start, which is often characterized by market operators may also be added to the value of modularity.

The sustainability value can be characterized utilizing the evaluation procedures undertaken for other technologies to look at lifecycle environmental impacts.

6.0 Resource Competition

The authors recognize that marine energy resources are not and will not be competitive for all electric system purposes. For example, marine energy resources are not competitive in providing some ancillary services, such as regulation or other reserves, unless with storage, and even with storage, are not competitive in providing black start, transmission deferral or distribution deferral. See Figure 6 for a conceptual diagram of the capabilities of marine energy resources. This diagram illustrates what is possible for marine energy capabilities, based on the practical aspects of how marine energy devices will function, the state of competitive resources, current definitions of ancillary services, and available literature (as there are no commercially operating MRE developments to rely on for validation). The diagram also illustrates the potential for storage to vastly improve the performance of MRE in providing these services.

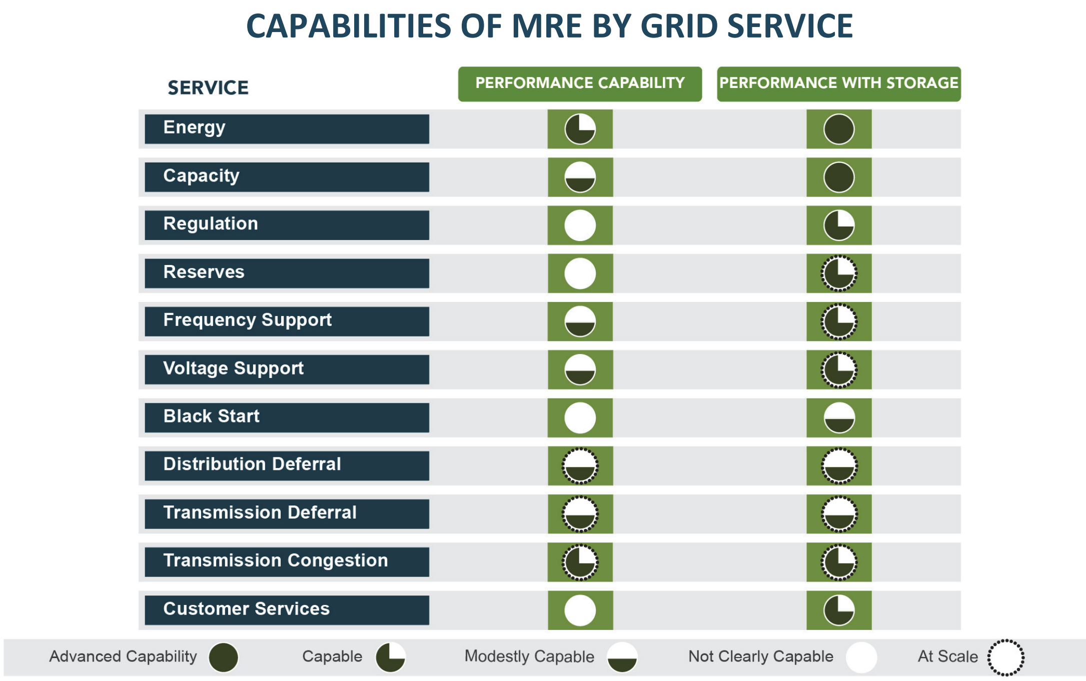

Figure 6. The capabilities of marine energy resources to provide various grid services.

Marine energy resources can be competitive in providing several electric grid services. However, several forms of resource competition need to be considered. The first is simply the availability and price of electricity, at a market clearing or hub price, which represents the general competitive price of electricity with no constraints, both terrestrial and offshore. A second category of competition is renewable energy generators, such as solar and wind facilities, which can provide renewable electricity. The last category of competition is other offshore generators, specifically, offshore wind and floating solar devices. This category of competition is significant because several benefits this project is evaluating with respect to wave, tidal and ocean current devices may also accrue to offshore wind. Each of these resources has a comparative role depending on the value examined.[26] For example, the land use benefits that may be attributed to MRE may also benefit offshore wind. For many benefits examined, a natural first question is

[26] In some instances, the "competitor" is not another power plant at all, but rather other solutions addressing a system constraint, integration challenge, or system imbalance.

why offshore wind would not be a less costly solution to capture the same value. At scale, offshore wind has clear advantages. The monopile shallow-depth offshore wind resource is already well commercialized in Europe, while the floating offshore wind technology trajectory is near commercial and sites in the Pacific Ocean are actively being evaluated.[27] The rated capacity of individual units is double the scale of terrestrial wind with both monopile and floating units installed today at 6 MW per unit and other floating offshore wind companies expressing a prospective range a greater than 8 MW per unit.[28] Due to turbulence and friction from onshore geography compared to the uniform "flat" ocean, there is a relatively consistent resource offshore. As a result, offshore wind is anticipated to have much higher capacity factors than the 35% commonly seen on land.[29]

Resource seasonality is also comparable to wave energy's seasonal intensity, as the forces driving energetics for waves in the upper portion of the water column also drive winds (Reguero, Losada, and Mendez 2015). This depends more precisely on the energy capture device utilized for wave energy conversation.

There are of course key distinctions between offshore wind and marine energy technologies:

- MRE may be deployed at an optimal level for smaller-scale solutions or at community scale, even behind-the-meter for a coastal electric load. Even one unit of offshore wind is at least 5 MW (Musial 2018). As a result, offshore wind has a minimum threshold of cost to meet in order to install any generator, while MRE may be installed at lower cost and energy levels to fit specific needs.
- Offshore wind is generally located at distance from shore in order to meet the goals of consistent resource, avoid nearshore traffic and aesthetic interactions, whereas MRE may be closer to shore and can be designed to operate completely sub-surface or with most of the device below surface. The greater the distance from shore, the greater the transmission length and associated costs.
- The peak resource locations for offshore wind are different than peak resources for wave, tidal and ocean current.
- Environmental and siting interactions will be different, making it possible for one technology to be compatible with a location while others are not. Technologies can be optimized to various ocean depths and seabed types, with various mooring and anchoring strategies.

In sum, while the project will consider competitor technologies in all three categories described above, the value and capability of one resource does not obviate the potential and value for the other.

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[27] *See* "California Activities." Bureau of Ocean Energy Management. Available at: https://www.boem.gov/California/.

[28] Block Island Wind Farm in Rhode Island operates five 6 MW units. *See* http://dwwind.com/project/block-island-wind-farm/. Statoil's Hywind Scotland Pilot Park also consists of five 6 MW turbines. *See* https://www.equinor.com/en/what-we-do/hywind-where-the-wind-takes-us.html#floating-wind. Principle Power indicates their intention to optimize scale and performance for "today's 5-8 MW and tomorrow's larger 8+ MW offshore wind turbines." *See* http://www.principlepowerinc.com/en/windfloat.

[29] Statoil indicates that its first three months of Hywind operation in Scotland achieved 65% CE from November 2017 to January 2018. *See* https://www.greentechmedia.com/articles/read/worlds-first-floating-offshore-wind-farm-65-capacity-factor.

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