Pacific Northwest NATIONAL LABORATORY

PNNL-28839

Understanding the Grid Value Proposition of Marine Energy: A Literature Review

July 2019

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

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Abstract

This document is a literature review in support of a Pacific Northwest National Laboratory and National Renewable Energy Laboratory technical project to understand and quantify the potential grid value of marine energy-derived electricity generation. This review catalogs and summarizes relevant publications that indicate marine energy resource locations and availability (duration and magnitude) as relevant to evaluating grid value; the variety of energy converter devices and their performance characteristics, by marine resource; whether and to what degree marine energy installations can earn revenue or offer benefits to the electric system; and the state of research on assessing and quantifying relevant electric system benefits that do not have a traditional form of procurement or price.

The purpose of this review is to establish a knowledge baseline relevant to the project, to identify gaps, avoid redundancy, foster collaboration, and leverage methods and data to the extent possible. Key findings of the review are indicated in the Executive Summary.

Summary

In 2018, the US Department of Energy's Water Power Technologies Office Marine Hydrokinetics Program directed two national laboratories, Pacific Northwest National Laboratory and National Renewable Energy Laboratory, to investigate the potential of marine renewable resources to contribute the U.S. electric system. Due to the innovative nature of marine renewable energy and the transformation of the US electric system resource mix, there is a lack of insight about the future potential role and grid value proposition of marine energy.

An initial step in this technical project is to review available literature to inform and help characterize the portfolio of potential marine energy resource contributions. This literature review summarizes the energy fundamentals of marine resources; the performance and operational characteristics of energy conversion devices; grid opportunities and integration challenges most applicable to marine energy; storage coupling to achieve grid opportunities; and offshore wind energy competition and collaboration. It provides the context and the state of knowledge in which the grid value proposition of marine energy should be further researched and explored.

Notable findings from the review include the following:

- **Very little work has been conducted to connect the grid and fundamental marine energy development.** Few technical papers attempt to demonstrate grid value from marine energy or, conversely, illustrate how grid applications may have an effect on device size and scale, convergence of device types, and location of marine energy technologies. Those that have done so relied on numerous estimations and assumptions and target very specific potential benefits.
- **Aggregation of tidal generation for baseload—the concept of distributing tidal generators to accomplish complementary phase shifts in generation that, when summed, would provide relatively stable power—faces challenges from a cost perspective**. One study evaluated three geographically separate, complementary locations off the Scottish coast. The study concluded that aggregate power generated from sites with varying resources is sensitive to the characteristics of the individual sites and some irregularity should be expected in aggregate power output due to natural variation in successive tides. Ultimately, the study suggests that using complementary sites and limiting the capacity of the turbines, particularly during neap tides, could create baseload power, or a constant power output; but the research team expressed concerns regarding whether such a deployment would be cost effective. Decreasing the turbines' rated capacity and therefore not capturing the resource to its fullest extent would cause economic losses.
- **Tidal energy-generating profiles may be well matched for storage.** Energy storage is a fast-growing resource in the energy industry. It can provide value in a multitude of grid situations, including supporting marine energy technologies. One report suggests that because tides are predictable, tidal technologies are ideal for pairing with energy storage to create a steady output of power. In fact, Nova Innovation recently integrated a Tesla battery storage system with the Shetland Tidal Array in Scotland and expanded the generating capacity and enabled dispatchability at the site.
- **There is a potential match between resource peak and electric demand.** When considering a seasonally peaking resource, like wave energy, there is an opportunity for the generation patterns to be well matched with energy demand. For example, one study noted that British Columbia's energy consumption peaks in the winter when the available wave

resource is also at its strongest; this same characteristic is true along the rest of North America's Pacific Northwest coast.

- **Co-location may deliver grid benefits.** A study evaluating a portion of the North Sea showed that there could be significant benefits to co-locating wave devices and offshore wind turbines. When wind and waves are negatively correlated, this decreases variability and can help mitigate grid integration concerns that are sometimes associated with variable generation. Being proactive in the siting process and performing quantitative spatial planning can avoid potential conflicts between sea uses, while harnessing the most useful energy.
- **The availability and cost of land was used in utility decision-making for resource selection and resulted in a portfolio selection that included marine energy development.** In a 2017 Integrated Resource Plan for the Caribbean Utilities Company (the public electric utility for Grand Cayman in the Grand Cayman Islands), a contractor evaluated land use associated with different generation technologies and found a significant advantage to using marine energy, specifically ocean thermal energy conversion (OTEC). Accordingly, and despite a higher capital cost for OTEC relative to other resource options, the resource plan containing OTEC was among the two recommended portfolios. In the portfolio, OTEC resources replaced onshore solar development, which requires a relatively high land commitment proportional to total generation, as well as natural gas-fired backup generation and battery storage. Although OTEC is not considered in this report, connections can be drawn to the technology, and research from that field is applicable to other marine energy resources in particular instances.

As the marine energy industry grows, there is a corresponding increase in the body of literature about both the potential value of harnessing marine resources as well as the requisite technical work to integrate the resource into the grid. Due to the unique aspects of marine energy resources, especially their offshore location, volume, and predictability, there are many reasons to consider marine energy a viable potential renewable resource in the future electric system.

Acknowledgments

The authors wish to express their gratitude for the review and contributions provided by Gabriel Garcia Medina, Abhishek Somani, Genevra Harker-Kilmes, and Zhaoqing Yang (Pacific Northwest National Laboratory) and Levi Kilcher (National Renewable Energy Laboratory).

Acronyms and Abbreviations

BPA	Bonneville Power Administration
CEC	current energy converter
DEC	decremental energy
DERs	distributed energy resources
DSM	demand-side management
EMEC	European Marine Energy Centre
kW	kilowatt(s)
INC	incremental energy
LOLP	loss of load probability
LOLE	loss of load expectation
NWA	non-wires alternative
NWS	non-wires solution
OCAES	ocean-compressed air energy storage
OWC	oscillating water column
PTDF	power transfer distribution factors
PTO	power take-off
WEC	wave energy converter

Contents

Figures

1.0 Introduction

Marine energy devices have the potential to harness energy from ocean tides, waves, and currents to provide benefits to the American electric system. More than half of the population in the United States lives within 50 miles of a coast (NOAA 2019), so marine energy devices have an opportunity to operate in a way that generates unique value to coastal and near-coastal communities and the local electric grids to which they connect. However, because marine energy devices are still in the research and development (R&D) phase, the device cost per kilowatt and the capital cost of installation are much higher than more developed renewable energy technologies like wind or solar. Understanding the value and benefits of marine energy outside of conventional mechanisms like the levelized cost of electricity, which might not reflect the resource's full potential, is critical for bringing devices to market and creating a more diverse, sustainable energy mix.

In 2018, the U.S. Department of Energy's Water Power Technologies Office Marine Hydrokinetics Program directed two national laboratories, Pacific Northwest National Laboratory and National Renewable Energy Laboratory, to investigate the potential value of marine energy resources to the U.S. electric system. Due to the innovative nature of marine energy and the transformation of the U.S. electric system resource mix, there is a lack of insight about the future role and grid value proposition of marine energy.

This literature review is an initial step in a technical project designed to better understand the potential grid value[1] proposition of marine energy. While marine energy can include a range of technologies, this literature review and the larger project address wave, tidal, and ocean current energy. Due to its nascent development and device diversity, quantifying the potential grid value of marine energy requires a chain of technical work stretching from understanding the resources themselves—the fuel—to the transmission system. Figure 1. identifies the various links in this chain and the components that make up each link.

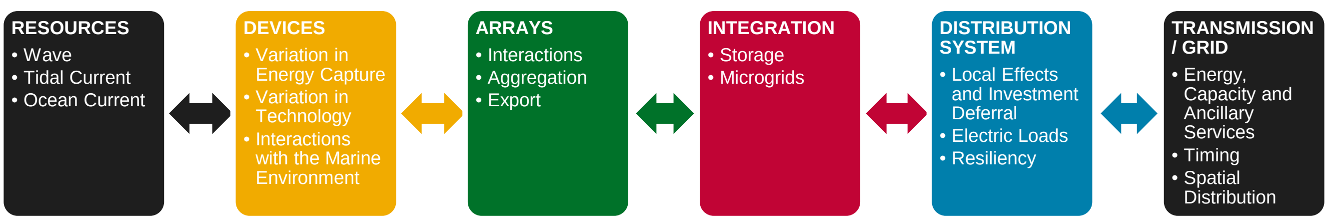

Figure 1. Technical work components for exploring the grid value of marine energy.

The purpose of this review is to compile existing literature relevant to determining what values of marine energy exist outside of conventional mechanisms, like levelized cost of electricity, and how they might be quantified. Commercially developed technologies, like solar and wind, can root their analyses in operational experiences and data, but a comparable marine energy

[1] 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., low carbon intensity). Value can also accrue to a range of entities.

analysis requires research-driven assessments based on the fundamentals of the energy resources and future development of the technologies.

For this reason, the document is organized in this order:

- Chapter 2: marine energy resources
- Chapter 3: device types
- Chapter 4: grid integration and energy storage
- Chapter 5: relevant demands of the electric grid and potential benefits of marine energy resources
- Chapter 6: resource competition and complements with offshore wind.

The bulk of marine energy research to date has been focused on the fundamentals of the sector-resource characterization with emphasis on two factors: energetic environments and technology development.[2] Chapters 2 and 3 of this review address these topics, and focus primarily on the timing of marine energy, its geographic distribution, and device performance characteristics and commercialization. Next, the literature review discusses emerging research around generating resources providing grid services, what those services may be, and how marine energy may have an opportunity to contribute. Chapter 4 provides a transition from research that focuses on specific resource-driven devices to how these devices can be integrated into a grid, and Chapter 5 discusses the potential benefits that marine energy technologies can provide, including topics ranging from congestion relief to improved system resilience.

Finally, Chapter 6 provides an emphasis on offshore wind as the generating resource best positioned to capture similar values associated with marine energy and which is further along the maturity scale, offering some insight and relevant analysis into potential grid value for marine energy.

A new program issuing from the U.S. Department of Energy's Water Power Technologies Office, Powering the Blue Economy,[3] has demonstrated that there may be many future applications for marine energy technologies beyond the provision of grid-scale energy. Although not explicitly discussed within this report, it is important to consider these applications and values as part of the sector's maturity, because they have implications for technology design and economic incentives to support development.

1.1 Scope

In compiling this literature review, the authors note that there is significant research related to marine energy device technologies and, increasingly, on grid services.[4] These two elements are essential in evaluating the potential of marine energy to competitively participate in the electric system. However, the record of research that integrates marine energy technologies with the grid through the delivery of grid services is very thin and highly specific to particular grid services and technology sub-types. While these analyses were documented whenever possible, they make up only a small portion of this report because the goal of this report is to develop a

[2] https://www.energy.gov/eere/water/marine-and-hydrokinetic-energy-research-development

[3] https://www.energy.gov/eere/water/powering-blue-economy-exploring-opportunities-marine-renewable-energy-maritime-markets

[4] Grid services are those services required for the grid to operate and deliver energy to customers. Examples are unit scheduling and dispatch, reactive power and voltage control, and frequency control.

repertoire of foundational research to which device-agnostic values generated by marine energy technologies can be linked. Thus, this review attempts to cover all principal elements of the larger project at some level of detail, while illustrating gaps, useful facts, and context.

1.1.1 Grid Value in Developing Marine Energy

Research determining the total value that energy resources provide the grid is beginning to be completed for other types of sources[5] but has not yet been done for the marine energy sector. For marine energy, there is a need to look beyond the simple financial environment for individual devices on a typical energy-revenue and capital-cost basis, beyond the asset perspective. Research should investigate whether, under what conditions, and to what degree there could be a greater grid value in developing marine energy.

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., low carbon intensity). Value does not necessarily entail money, because certain grid services or technology benefits may not be directly compensated or the unit of value may not be the dollar. Not all values are derived in a perfectly competitive manner. Certain least-cost strategies are market-based; others are circumscribed and determined by best-fit or core infrastructure solutions. Value also does not necessarily accrue to one entity. The authors note that even the term grid service has various definitions and applicable taxonomies (market ancillary services; North American Electric Reliability Corporation Essential Reliability Services; Grid Modernization Laboratory Consortium project definitions; beyond LCOE taxonomy; storage valuation taxonomy; and so forth).

1.1.2 Device-Agnostic Analysis

Today, a broad range of energy conversion device designs exist for tidal and ocean current energy and especially for wave energy. While there are additional marine and hydrokinetic energy sources, such as in-river hydrokinetic, ocean thermal, and salinity gradients, this literature review is limited to wave, tidal, and ocean current devices. These energy conversion devices are broadly understood to mean the following (and are discussed further in Chapter 3):

- **wave energy converters**: Wave energy converters harvest the kinetic and potential energy from the oceans' waves. These devices are typically categorized by their general design or concept of the device (Drew et al. 2009).
- **tidal current devices**: Tidal current, or tidal stream, devices harness energy from the flow of tidal currents (i.e., currents generated by tides). Tidal current devices include tidal turbines, oscillating hydrofoils, and tidal kites (Roberts et al. 2016).
- **ocean current energy devices**: Ocean current devices harness the horizontal flow of the oceans' currents, which are generated and affected by wind, water salinity, temperature, topography of the ocean floor, and the Earth's rotation (BOEM 2019).

To account for the diversity of energy and device types within the marine energy industry, the literature review aims to synthesize studies and create a basis for developing a grid value

[5] See *Illinois Distributed Generation Rebate – Preliminary Stakeholder Input and Calculation Considerations* at https://www.icc.illinois.gov/Electricity/workshops/DistributedGenerationValuation.aspx for an overview of work being done on valuing distributed energy resources, in addition to methodologies and approaches for determining the generated value.

proposition that is device agnostic. Device-agnostic analysis aids in more clearly identifying the benefits and values that the marine energy industry can offer as a whole.

1.2 Report Contents and Organization

This literature review presented in the ensuing chapters is organized into five categories:

- **Marine Energy Resources** (Chapter 2): the predictability, periodicity, and availability of theoretical marine energy resources.
- **Device Types** (Chapter 3): prevalent device designs, the state of development, and the characteristics of their generation and functionality.
- **Grid Integration and Energy Storage** (Chapter 4): implications of integrating marine energy into the grid and potential opportunities for coupling marine energy devices with storage to mitigate production fluctuations and enable dispatch.
- **Relevant Demands of the Electric Grid and Potential Benefits of Marine Energy** (Chapter 5): electric system challenges and requirements for which marine energy may be a suitable solution.
- **Resource Competition and Complementary Use with Offshore Wind** (Chapter 6): an overview of offshore wind energy, including potential areas of competition and opportunities for collaboration.

2.0 Marine Energy Resources

The United States has a large marine energy resource from tidal, ocean, and river currents and waves. Ocean resources are assessed in several ways, including measurements, models, and forecasts. Depending on the stage of project development, different levels of precision in the resource characterization are necessary and dictate the type of assessment that is used (Venugopal et al. 2011). Several nation-wide, theoretical assessments have been performed and published for the United States. A wave resource assessment was performed in 2011 by the Electric Power Research Institute (EPRI 2011), which estimated the theoretical ocean wave resource of the United States to be 2,640 TWh/yr. A tidal current study, also conducted in 2011, estimated that 445 TWh/yr are available from tidal resources along the United States coasts (Haas et al. 2011), and ocean currents were estimated to provide 200 TWh/yr (Haas et al. 2013). These assessments used hindcast data (i.e., data from model runs with historical information) and model-based simulations to generate estimates of the naturally occurring resources. A summary of the magnitudes and locations of the marine energy in the United States is plotted in Figure 2. Marine energy has the potential to supply a significant proportion of the nation's power generation needs.[6]

These national assessments create an opportunity to perform more detailed studies at locations that have generally favorable resources. Further resource characterization of individual sites can improve inputs to numerical models used in the development process to estimate resources and can assist in developing a classification for waves, tides, and ocean currents. Having such a classification system could guide the marine energy industry in identifying ocean resources and pairing them with suitable energy conversion technologies, determining the extent to which a resource can be developed, and informing guidelines for operating and maintaining devices. Site-specific resource characterizations, including more granular numerical models, help decrease the associated development risk (DOE 2015a).

[6] The EIA estimated U.S. electric power needs for 2017 as 4,034 TWh. See https://www.eia.gov/electricity/annual/html/epa_01_01.html.

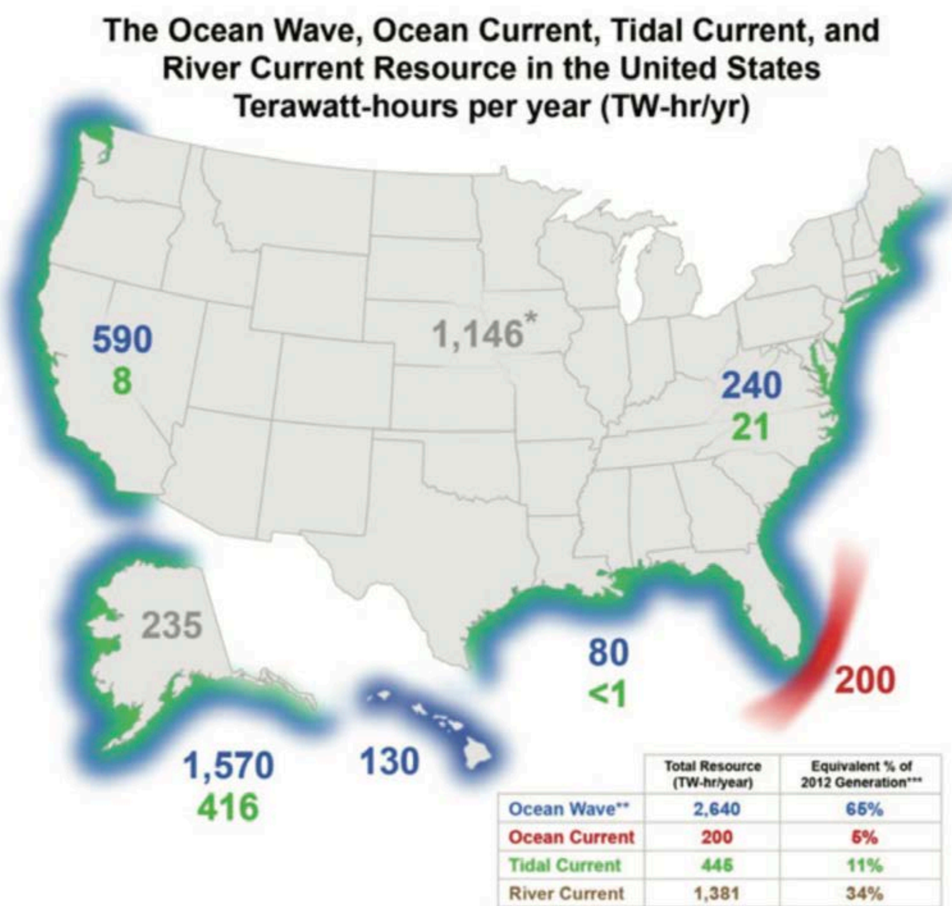

Figure 2. The theoretical marine energy resources in the United States (DOE 2015a).

2.1 Waves

Waves are a fundamentally fluctuating source of energy, for which the behavior of ocean waves is classified by amplitude, phase, and directionality. Figure 3 shows an example of amplitude and phase. Wave power is often defined as the wave power in kilowatts (kW) per meter of wavefront length. Assuming deep water, the wave energy flux is

$$J = \frac{\rho g^2}{64\pi} H_{m0}^2 T_e,$$

where

ρ = water density,
g = the acceleration of gravity,
H_{m0} = the significant wave height, and
T_e = the energy period.

Shallow water waves, however, have different implications in regard to energy flux. Wave statistics data are often represented by the percentage occurrence of each binned sea state and characterized by H_{m0} and T_e (Figure 4). This type of spectral data is important when classifying wave resources because longer, lower frequency waves carry more energy than short waves of the same wave height and because devices typically have different efficiencies relative to different wavelengths.

There are six relevant parameters for investigating wave energy resources: omnidirectional wave power, spectral width, significant wave height, wave direction, energy period, and the ratio of maximum directionally resolved wave power to the omnidirectional wave power (Lenee-Bluhm et al. 2011; Dallman and Neary 2014). Figure 5 shows an example of these parameters over a one-year period at a reference site. As shown in the figure, waves range in period from five seconds to 20 seconds, and wave power is also subject to seasonal variations; wave energy is greater in winter than in summer in the Northern Hemisphere (Parkinson et al. 2015; Dallman and Neary 2014).

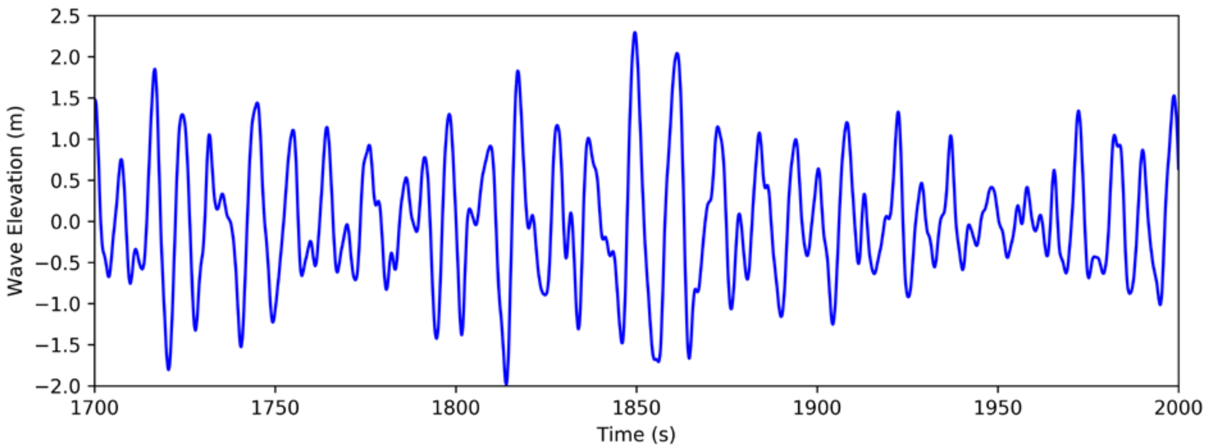

Figure 3. An exmaple of wave elevation time history (H_{m0} = 2.64 m and T_e = 8.5 sec) generated using the Bretschneider spectrum.

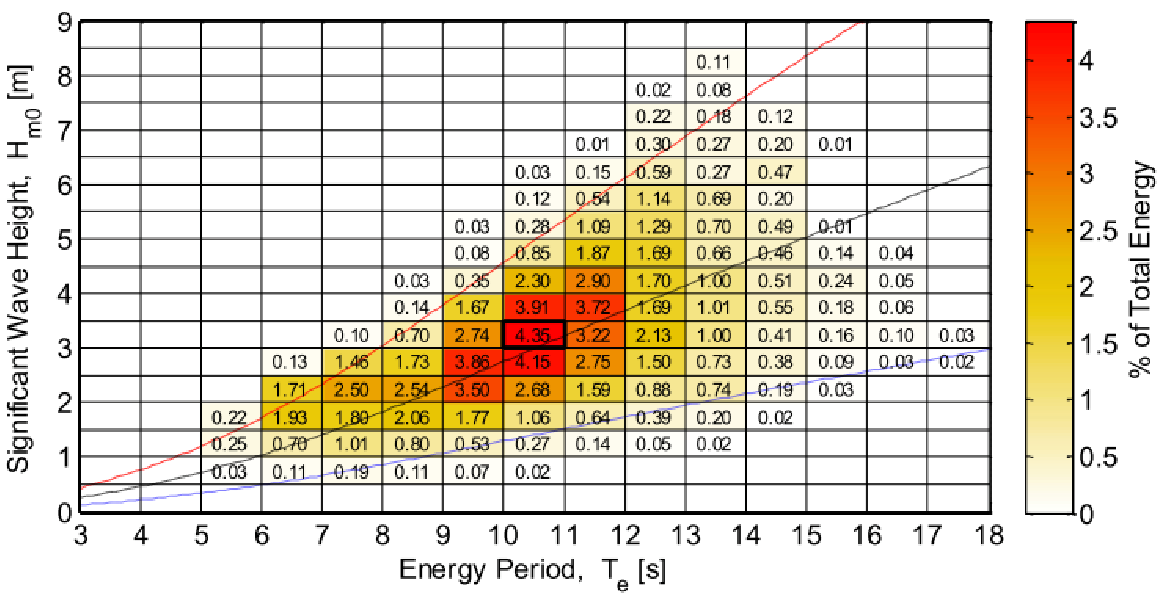

Figure 4. The percentage of total energy at Humboldt Bay, California (Dallman and Neary 2014). Lines on the graph represent the mean (black line), 5th percentile (blue line), and 95th percentile (red line).

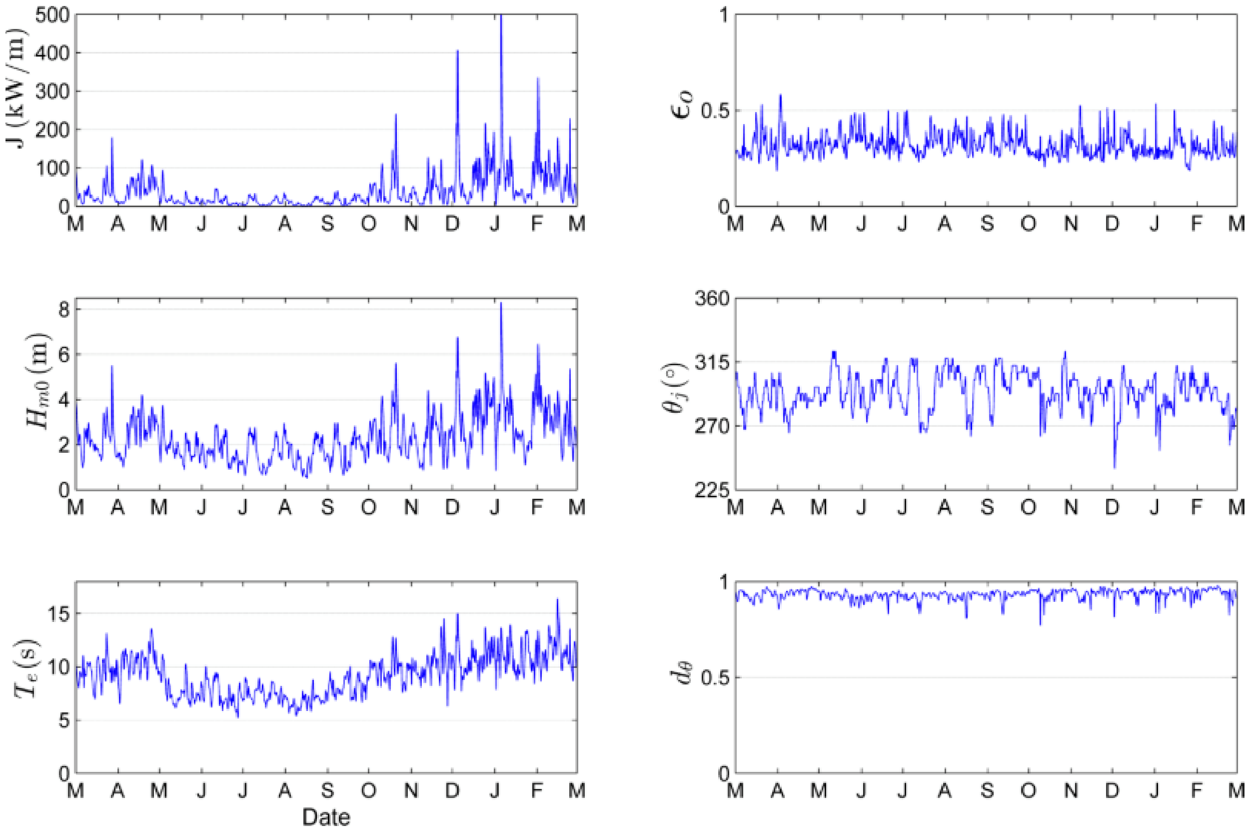

Figure 5. The six parameters of interest over a one-year period, March 2007–February 2008 at Humboldt Bay, California. J is the omnidirectional wave power, H_{m0} is significant wave height, and T_e is the time period. ϵ_0 is the spectral width that characterizes the spreading of energy along the wave spectrum, θ_j is the corresponding wave direction, and $d\theta$ is the ratio of maximum directionally resolved wave power to the omnidirectional wave power (Dallman and Neary 2014).

2.2 Tides

Analogous to the definition of power available to a wind turbine from moving air, the available power per unit area, or power density, at an individual location of a tidal or ocean current converter is defined as

$$P = \frac{1}{2}\rho V^3,$$

where *V* is the magnitude of the velocity. In contrast to the density of air, the density of seawater defined for ρ is 830 times greater. Thus, less fluid flow is required to generate a given amount of power from tides than winds, even though power density is a function of cubic velocity.

The tidal current is generally driven by the Earth's rotation, the relative positions of celestial bodies to the Earth, and local bathymetry (i.e., ocean depth and topography), and it consists of multiple constituents of varying periods. An example for the year 2011 from a location at San Francisco Bay, California, is shown in Figure 6. Typically, the dominant constituent is the "principal lunar semidiurnal," which has a period of 12 hours and 25.2 minutes with variation in extremes over 28-day cycles.

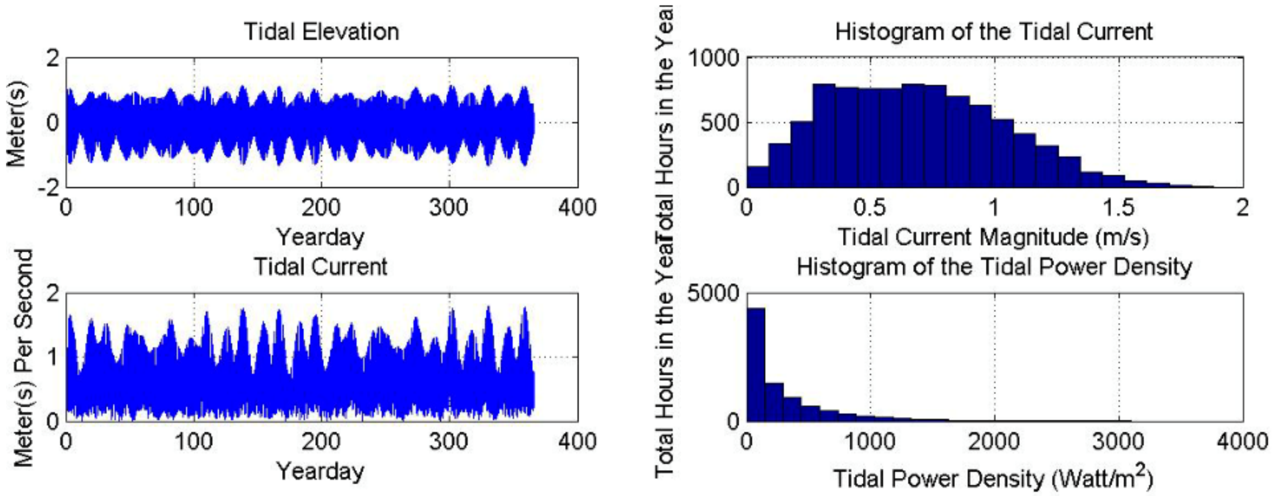

Figure 6. Time series for tidal elevation and current (left); and histograms for tidal current and power density (right) for San Francisco Bay area (Haas et a. 2011).

Due to the nature of the resource, tidal energy is typically considered predictable at a high level of certainty. The cyclical patterns created by the gravitational interaction between celestial bodies and the Earth's oceans are responsible for the associated level of predictability (Polagye et al. 2010). As tides rise and fall over time, the horizontal flow generated by that movement is understood. Extreme weather events are the exception to this predictability (Polagye et al. 2010).

Seafarers have spent significant time understanding tidal flows because ship navigation has always relied upon this knowledge to ensure safety. For example, awareness of tidal patterns allows boats entering a port to ensure they maintain safe distances between the keel and seafloor. Having knowledge of the depth of channels through which vessels pass (NOAA 2019), predicting coastal flooding during high tides (Polagye et al. 2010), and the need for fishermen to understand the level of tides (NOAA 2019) have likely driven the collection of these data throughout history. The assembly and subsequent existence of historical measured data allow for numerical models to be tested and validated because longer time series of data generate more reliable models (Polagye et al. 2010). This ultimately leads to more reliable resource characterizations during the development phase and increased confidence in any value that tidal devices might generate.

2.3 Ocean Currents

Although ocean currents use the same definition for power density as tides, the driving forces behind ocean currents differ. Ocean currents can be at the surface level or in deep water and can be driven by wind, temperature, and salinity. While tidal currents frequently change direction due to the rise and fall of tides, ocean currents are generally stable and maintain their direction over time. Although the velocity of ocean currents is slow in comparison to average wind velocities, the density of sea water generates high levels of energy for extraction (BOEM 2019).

The Gulf Stream in the northern Atlantic Ocean and the Kuroshio in the northern Pacific Ocean are the two largest ocean currents. Figure 7 shows the time series of calculated kinetic energy flux in the Florida Current, a portion of the Gulf Stream System, from 2004 to 2010 (Haas 2013). The annual mean kinetic energy flux for years 2004 to 2010 and the monthly and yearly variation throughout those years are plotted in Figure 8. These are indicators of how the available energy from ocean currents fluctuates over time and ultimately what is available for a device to harness.

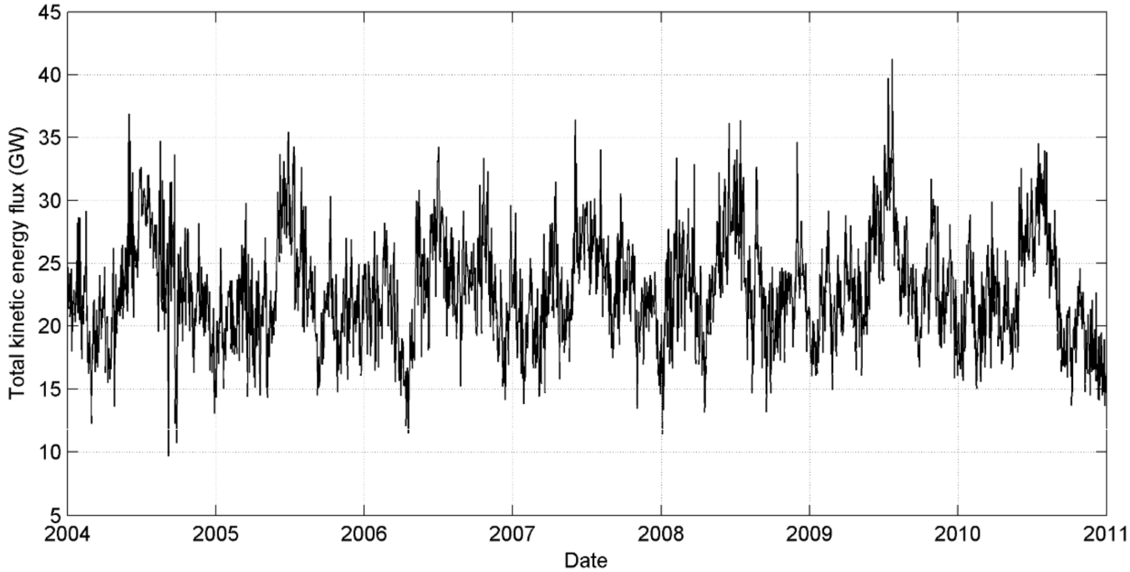

Figure 7. Time series of total kinetic energy flux in the Florida Current from 2004 to 2011 (Haas 2013).

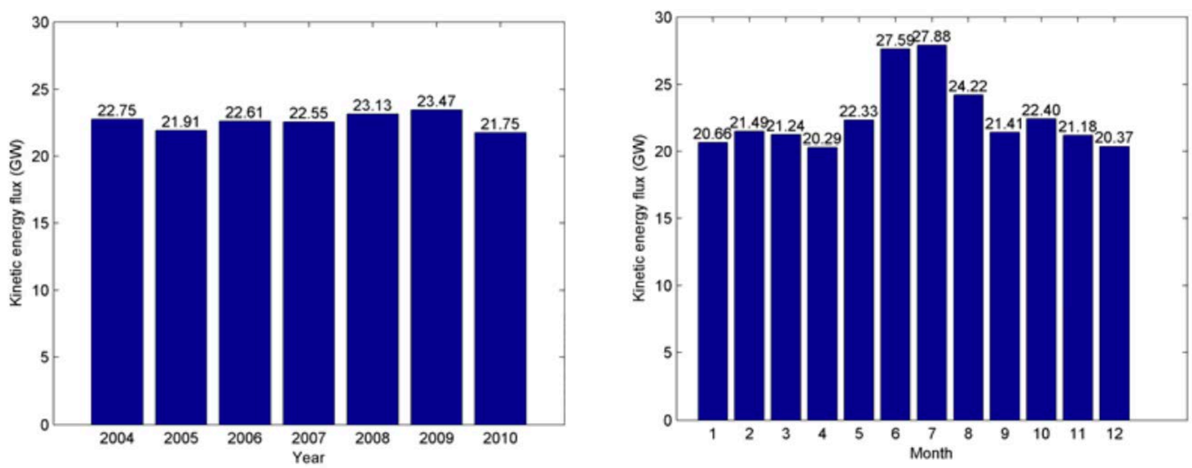

Figure 8. Mean kinetic energy flux in the Florida Current: yearly variation (left) and monthly variation (right) (Hass 2013).

3.0 Device Types

Marine energy technologies are still in the R&D stage and a range of design concepts are in development. As such, there is a need to catalog the diversity to ensure that a device-agnostic grid value is representative of the spectrum of devices or can be directly linked to particular characteristics of devices, since different device types have the potential to affect grid value and services. To accommodate diversity in devices, while working toward device-agnostic results, two general categories of devices are defined from the technology working principle: wave energy converters (WECs) and current energy converters (CECs). The latter include both tidal current and ocean current systems.

3.1 Wave Devices

WECs are developed to capture the energy within ocean waves to generate mechanical/electrical power. A wide variety WEC systems have been proposed and developed over the past decades (Falcão 2010; Drew et al. 2009). Common device types include point absorbers, oscillating wave surge devices, attenuators, and oscillating water columns (OWCs), which are shown in Figure 9. The first three types of technologies often consist of one body or multiple bodies. The power is generated from the wave-induced relative translation motion and/or rotational motion between the body and a reference frame (e.g., seabed or another body). OWCs, however, consist of a column of air trapped on top of a column of water, where the rise and fall of the water column will push the air through the air turbine to generate power. Other unique designs include overtopping devices, submerged pressure differential designs, and gyroscope systems.

An economical WEC system depends on the design concept, operation and control strategies, wave farm economics, environmental impact, and more. There is very little convergence in WEC design concepts, and WEC efficiency varies significantly depending on the design concept. An analysis of the capture width ratio (i.e., efficiency) of WECs was carried out by Babarit (2015), who found that the hydrodynamic performance significantly varies depending on the type of WEC. The study also suggested that the power take-off (PTO) efficiency and fabrication and operation costs can be essential, and the most hydrodynamic efficient design may be the least cost effective. Considering the varying WEC technologies that have been proposed, WECs are still at an early stage of development compared to other renewable energy technologies, including CECs.

While the WEC industry has not reached commercial scale, a variety of WECs have been deployed and tested. For example, Spanish utility Ente Vasco de la Energía deployed a 300 kW OWC in 2011, which was integrated with the breakwater of the harbor in Mutriku, Spain. It was also the first multi-turbine WEC system tested in the world (OES 2016). This shows growth from testing single device deployments. Carnegie Clean Energy in Australia has had several successful deployments, including the Perth project where a set of their CETO systems, fully submerged buoys, were installed and connected to the grid off Garden Island in 2014. The project operated continuously for 12 months (Carnegie Clean Energy). Northwest Energy Innovations successfully deployed its Azura device at the U.S. Navy's Wave Energy Test Site in Hawaii in 2015, making it the first grid-connected WEC test in the United States. Currently, the PacWave Test Site is being developed off the coast of Newport, Oregon. This full- scale, grid-connected test facility, founded by the DOE, is expected to begin operation sometime between 2021 and 2022 (PacWave 2019). These are only a few examples of the progress that the wave energy industry is making and indicate that any value that might be generated from these devices is future-thinking and not immediately attainable, because deployment has been limited.

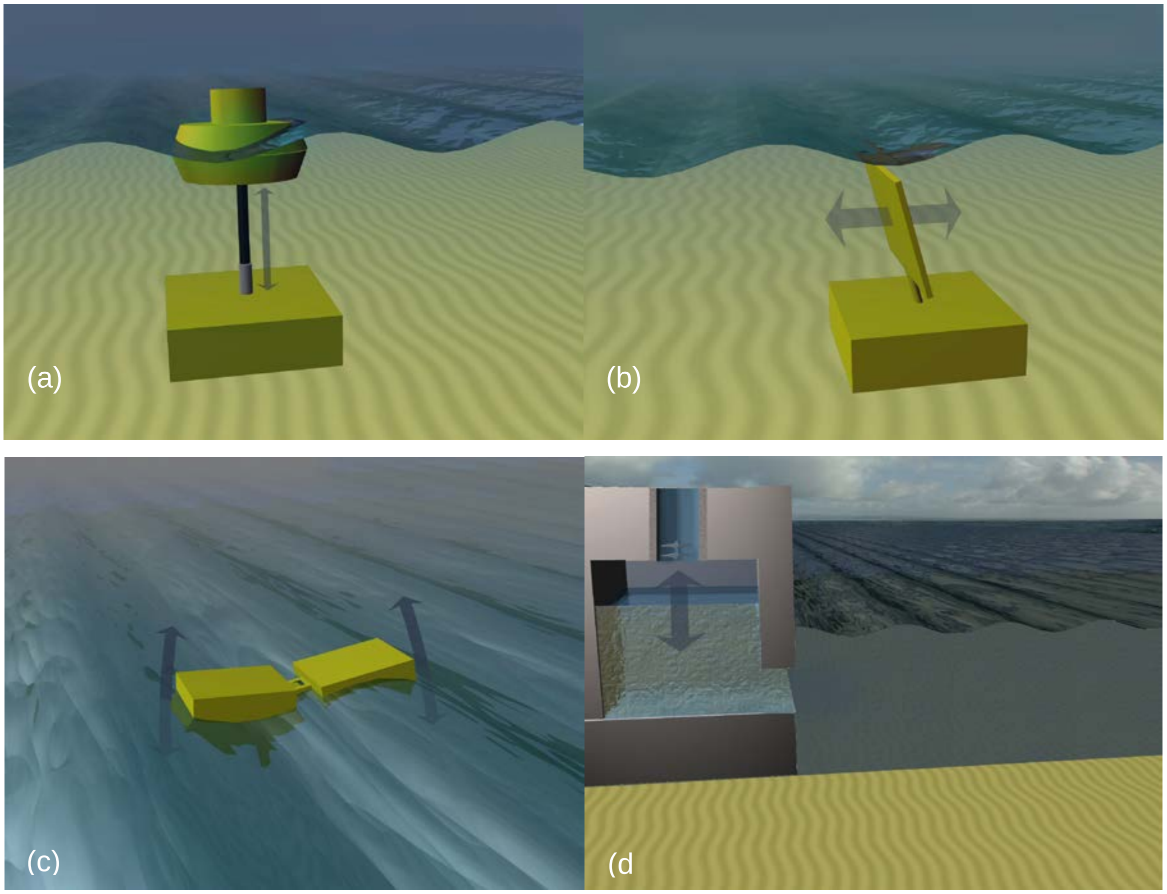

Figure 9. Schematic representation of a (a) point aborber, (b) oscillating wave surge device, (c) attenuator, and (d) oscillating water column (AQUARET 2012).

3.2 Current Energy Converters

CECs are systems designed to extract energy from tidal, ocean, and river currents.[7] Most CECs that have been developed are similar to wind turbines and marine propellers. However, they operate in the ocean environment, which has a much denser fluid (i.e., ocean water versus air), and they harness energy instead of consuming energy like marine propellers.

Types of CECs include horizontal axial-flow turbines and cross-flow turbines, as shown in Figure 10. Others include tidal kite, oscillating hydrofoil and ducted turbines (DOE 2015, Roberts et al. 2016). Overall, horizontal axis tidal turbines are the most common tidal devices. According to Magagna and Uihlein (2015), 76% of tidal energy R&D efforts across the globe focus on these devices. In addition, these turbines are most frequently secured to the seafloor to harness tidal currents, but there are also floating turbines that are suspended mid-water column. Current devices have reached greater device convergence than WECs.

[7] River currents and their devices are not considered in this study because the unique attributes of a grid value proposition have a high correlation to small-scale hydropower resources in location, scale, timing, technology considerations, and applications.

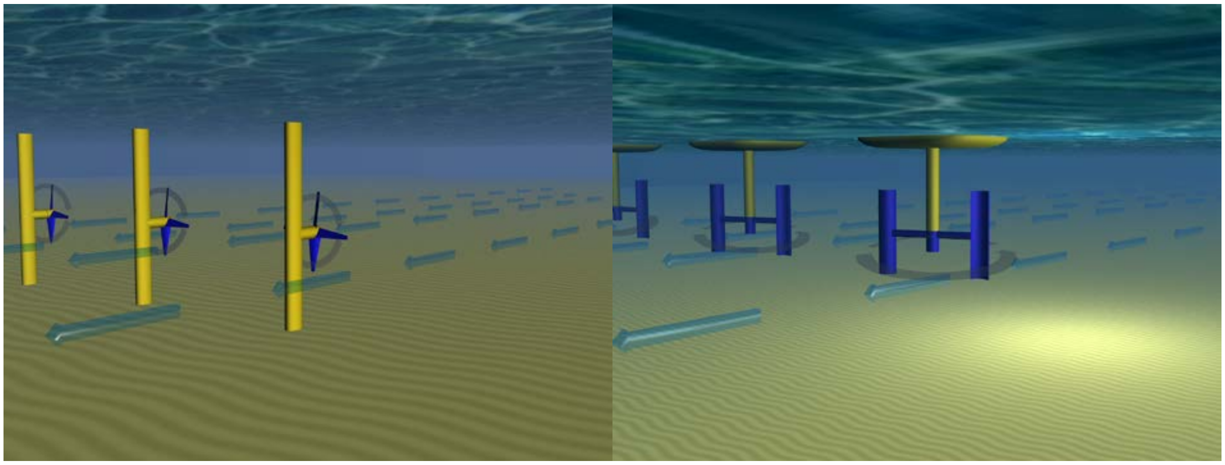

Figure 10. Schematic representation of (left) horizontal axial-flow turbines and (right) cross-flow turbines (AQUARET 2012).

Although devices have not been deployed at a commercial scale, there have been successful grid-connected deployments and successful prototype tests. SIMEC Atlantis Energy's (formerly Atlantis Resources Ltd and Marine Current Turbines) SeaGen device is arguably the most fully developed tidal stream turbine. It was installed in Strangford Lough, Northern Ireland, UK, and connected to the grid in 2008 (MacEnri et al. 2013). Various prototypes are also being developed and tested at the European Marine Energy Centre (EMEC) (Rosli and Dimla 2018). For example, in 2016 Orbital Marine Power (formerly Scotrenewables) launched its SR2000 tidal turbine with great success. The 2 MW floating twin-turbine system was able to produce over 3 GWh of electricity over its first 12-month test at EMEC (Orbital Marine Power 2019). In Canada, Sustainable Marine Energy Plat-I was tested in Grand Passage. That full-scale system was successfully deployed but not connected to the grid. While CECs have seen more deployment than WECs, the state of the industry also indicates that any substantial grid value that these devices can provide is futuristic, not existing.

4.0 Grid Integration and Energy Storage

A number of different device types are in development to harness marine energy, and shared, fundamental concepts are relevant across the industry when considering grid integration and energy storage. To varying degrees, predictability, reliability, and proximity to load centers are among the commonalities, and the energy is generated by a naturally occurring resource that dictates the timing, intensity, and production of energy. Integrating marine energy into the grid may not be trivial, but marine energy resources may also generate energy in ways unique to other energy sources, thereby providing value in critical locations. The use of various strategies, such as aggregation or energy storage can enable the provision of this value. Both challenges and favorable options for marine energy grid integration and storage coupling are related to the resource periodicity. Unlike Chapters 2 and 3, where substantial research has been completed for marine energy and the presented information was limited to the most relevant characteristics, the literature available for the topics addressed below is in more of an emerging state with regard to addressing how generating resources can provide grid services, what those services may be, and how marine energy may have an opportunity to contribute.

4.1 Tidal and Ocean Current Integration

Tidal current energy is essentially sinusoidal and predictable; variation occurs in extremes over 28-day cycles. Therefore, tidal current energy has the potential to provide a constant level of generation that could serve as baseload, a form of generation that provides a steady level of electricity production that does not vary by demand or by resource.[8] This would be achieved by providing steady power through the aggregation of multiple devices at complementary locations or through the introduction of storage. As shown in Figure 11, if the sinusoidal energy production profile of multiple devices is nearly simultaneous, the effects of ramping up to highest intensity and down to zero are amplified, thereby creating steep variation. If the production can be staggered, the ramping effects mitigate one another and theoretically result in a flat generating profile. Indeed, several studies have demonstrated that it is possible to provide smoother power output to the grid by aggregating tidal devices.

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[8] This is typically a challenge with variable renewable energy resources, such as solar and wind energy: they are variable and thus cannot provide a constant level of generation.

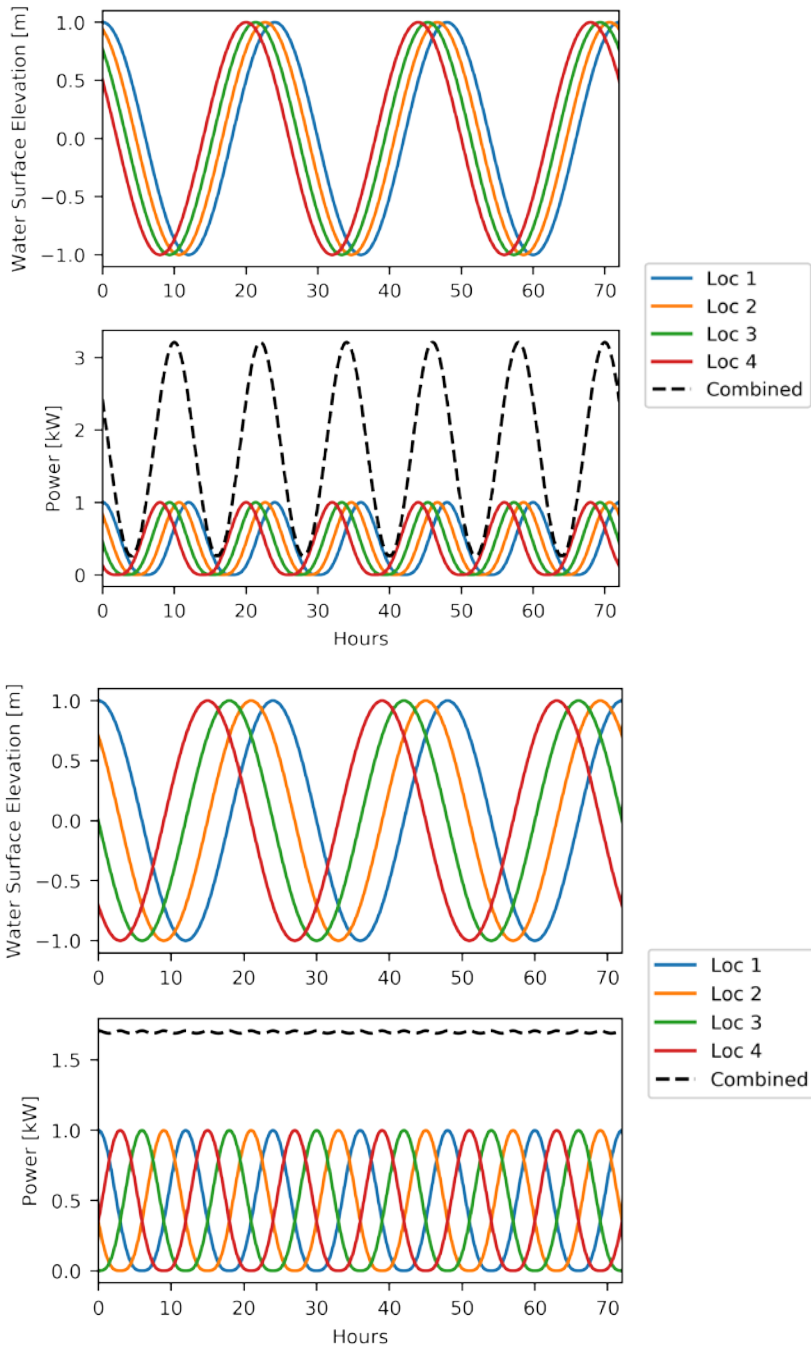

Figure 11. Simultaneous tidal energy profiles and the resulting intensity when combined (top), and staggered tidal generating profiles that mitigate high fluctuations (bottom).

However, practically, staggering generation profiles can be challenging. For example, Clarke et al. (2005) evaluated three geographically separate, complementary locations off the Scottish coast. The study concluded that aggregate power generated at varying sites is sensitive to the characteristics of the individual sites and some irregularity should be expected in aggregate power output due to natural variation in successive tides, and that accurate data are needed to generate a precise performance prediction. Ultimately, the study suggests that using complementary sites and limiting the capacity of the turbines, particularly during neap tides, could create baseload power, or a constant power output.[9] It is doubtful that this approach would be extensively pursued, however, since it is not likely to be cost effective. Decreasing the turbines' rated capacity and therefore not capturing the resource to its fullest extent would cause economic losses.

Another tidal study conducted in Ireland evaluated phase variations as a mechanism for mitigating power fluctuations and providing naturally smooth power injected to the grid (Giorgi and Ringwood 2013). The authors evaluated 11 locations around Ireland with the goal of employing a "multi-objective optimization to simultaneously minimize variance, maximize mean power, and maximize minimum power." However, these objectives often conflict with one another. Through a series of simulations using hydrodynamic models and tidal stream atlas data evaluating the varied installation of tidal devices, two interesting solutions arose from this study: the first solution, in which 1,161 devices produced an average power output of 103.7 MW to the grid throughout the year, with a minimum power of 7.8 MW and a power variance of 3.7; and a second solution, in which 254 devices produced a mean power output of 31.1 MW, with a minimum power output of 2.5 MW and a power variance of 2.4. The second solution in this study is of interest because the number of installed turbines is significantly lower than the first solution with a higher power output per turbine. The second solution would come at a significantly reduced capital investment, while still producing a considerable minimum amount of power throughout the year. The study is, however, limited by data availability and could benefit from the introduction of more accurate local information to provide more dependable solutions.

In addition to simply investigating the integration of tidal systems into the grid, a common trend when exploring the implementation of marine energy devices is coupling these systems with energy storage to smooth the power delivered to the grid. Coupling CECs with storage, specifically short-term storage, is not a new concept. A report by Bryden and MacFarlane (1998) suggests that because tides are predictable, CEC technologies are ideal for pairing with energy storage to create a steady output of power. Further, due to the cyclical nature of tides, small amounts of storage can increase the viability of tidal energy devices. Because of the relatively short time frames over which the tidal system will not produce energy, short-term storage can be an appropriate match, limiting the financial impact. For wind systems, there is the possibility of relatively long periods of time without the presence of energy production.

While energy storage can be used in conjunction with other renewable sources like wind and solar, Zhou (2013) evaluated which types of energy storage may be more appropriate for tidal current devices than others. His study compared several energy storage systems and concluded that supercapacitors and flywheels are the most appropriate for short-term, high-frequency fluctuations. In contrast, batteries are more suitable for long-term storage, particularly flow batteries, because of their relatively low-cost long-term storage capability and flexible system design. Some companies have started to implement these practices with tidal devices. Recently, a Scottish company, Nova Innovation, integrated a Tesla battery storage system with the Shetland Tidal Array in Scotland and expanded the generating capacity at the site (Renewable Energy Magazine 2018). Husseini (2018) added that although the Tesla PowerPack used at this site has been used with other renewable energy technologies, like solar

[9] Neap tides occur when the sun and moon are at right angles to each other, during the first and third quarter moons. The pull of the sun on the ocean partially cancels out the pull of the moon on the ocean, producing neap tides, where high tides are a little lower and low tides are a little higher than average. See https://oceanservice.noaa.gov/facts/springtide.html.

and wind, this is the first tidal technology to integrate this battery into its operations. In other instances, researchers have explored the coupling of non-battery storage solutions with marine energy. Though of relatively small scale, an ITM Power electrolyzer[10] with a generation capacity of 220 kg/day was implemented at EMEC with CEC prototypes (ITM Power 2017). These developments suggest that coupling marine energy devices with various types of energy storage holds likely potential for the future. This supplementary component can have a direct impact on potential grid values.

4.2 Wave Integration

Wave energy is intermittent, but unlike other renewable energy resources, it can be predicted, to a degree, several days in advance; it does not ramp up during the day like solar, nor does it experience diurnal patterns like wind; and the resource itself is much denser (Lehmann et al. 2017). However, waves also vary in terms of amplitude, phase, and directionality and are subject to seasonal variations, as shown in Figure 3 through Figure 5 above, which makes integration of this resource with the grid more challenging than for conventional energy resources. The natural fluctuation in waves requires that individual WECs have PTO capacity greater than the average power output (Yu et al. 2018). Peak power can be much higher than average power, so WEC designs need to account for this additional generating capability. Peak wave conditions are relatively short lived, so the generator associated with the device is unlikely to be built to those conditions. Instead, reducing peak power output can provide generator cost reductions.

Studies have shown that the power fluctuation from WECs can be reduced through different mechanisms, including the aggregation of WECs in an array, implementation of WEC control, and the use of energy storage systems. For example, Sjolte et al. (2013) simulated the Lifesaver point absorber as an individual device, as an array, and within a wave farm. The study assumed 48 WECs were installed, which, when individually modeled, displayed no power smoothing. However, when power was aggregated by an array, power quality significantly increased, reducing the peak-to-average ratio from 10 to 3, and when the arrays were aggregated to simulate a wave farm, the power quality increased yet again with a reduction in peak-to-average ratio to 1.56 (Sjolte et al. 2013).

Blavette et al. (2012) investigated the impact of a wave farm on a local grid system, including the impact on voltage fluctuation, peak-to-average power ratio, and flicker[11] level. The authors modeled an OWC in DIgSILENT PowerFactory, a power systems analysis software, using experimental power time series from a previous study. This simulated wave farm raised no concern regarding voltage fluctuation, but the authors determined that flicker should be evaluated in greater detail if a wave farm with larger capacity than the one studied is to be deployed.

Another approach for reducing power fluctuation and impact on the grid for WECs is the use of power smoothing, which involves the use of energy storage and the active control of the WEC PTO. Sjolte et al. (2013) showed that with minimal energy storage, the peak-to-average ratio of

[10] An electrolyzer can use an energy input to generate hydrogen gas by splitting water into its constituent elements. It can then take this hydrogen and reverse the reaction to generate electricity. This hydrogen can be stored.
[11] Blavette et al. (2016) define flicker as “visual discomfort due to the light intensity fluctuations of the lighting equipment undergoing voltage variations caused by loads and power sources having a variable power profile.”

the electricity generated from the wave farm was further reduced from 1.56 to 1.28. The use of energy storage and WEC control comes with a capital cost, however, and the effectiveness of these methods depends on the size of the storage system and how the control method is implemented. Additional research is needed.

To further understand the implications of grid-connected WECs, DOE is currently funding the development of the PacWave Test Site located seven miles off the coast from Newport, Oregon. As shown in the schematic in Figure 12, the test facility will have all the necessary grid-connection infrastructure, including cables and substations, and the capability to accommodate up to 20 WECs (DOE 2018). Noting that transmission system operators typically examine power quality through power flow and seasonal loading, capacity, voltage levels, flicker, harmonics, and short-circuit faults at the point of connection, Armstrong et al. (2015) conducted an analysis of these parameters. The study assessed the impact of the PacWave site on the local electric network using PowerWorld, a power systems simulator, and DIgSILENT PowerFactory. Results indicated that the wave facility should not have a significant impact on voltage at a transmission level, with voltage levels on the transmission network remaining well within security margins.

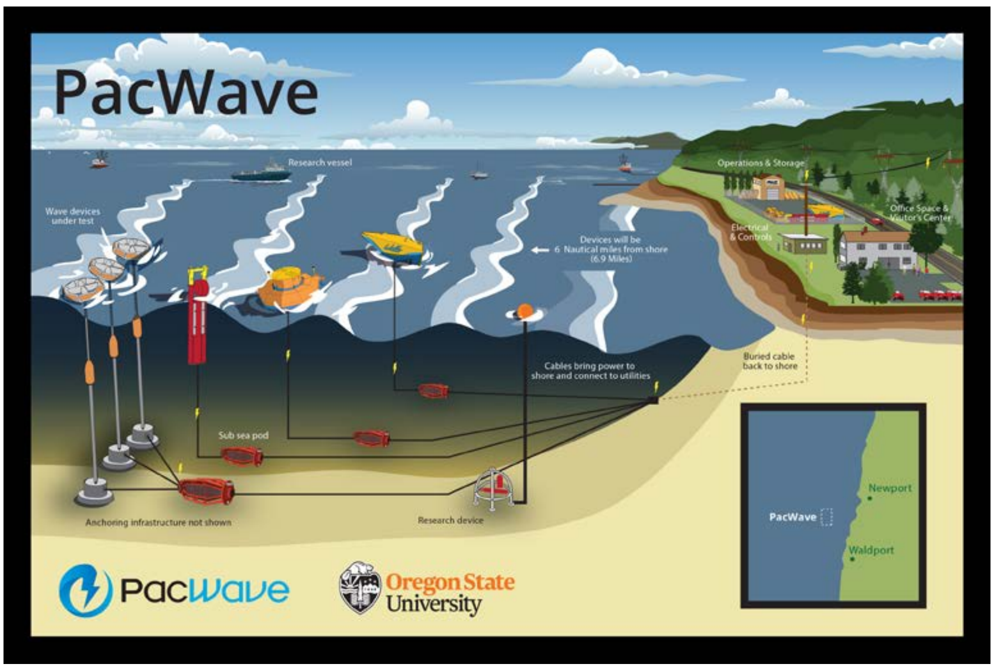

Figure 12. An illustration of the PacWave Test Site (PacWave).

Although wave technologies can present challenges to the grid, there are scenarios where they may offer benefits as well. Fernandez at al. (2012) evaluated the economic contributions that wave energy can provide to day-ahead electricity markets when combined with wind energy. The study found that the balancing costs of WECs (i.e., the cost associated with integrating intermittent renewable energy sources into markets) were 35–47% lower than those associated with wind turbines. Furthermore, system balancing costs were reduced by 35–45% when the study simulation considered a scenario combining a wind and wave energy scenario relative to a wind-only scenario. Day-ahead forecasts produced for WECs were 35–50% more accurate, in terms of normalized mean absolute error, than those produced for wind turbines.

Finally, for both wave and current energy, another key integration issue that Blavette et al. (2011) identified is the obstacle created by grid code requirements. Traditional requirements, like rated power, are not sufficient when dealing with technologies like marine energy. Phrasing will also become important in writing future grid codes: using the word *power* is not descriptive enough, given the extreme differences that can occur between peak and average power generated by marine energy devices. These issues become critical to the ability of marine energy resources to participate on the grid when considering the importance of grid codes such as the Institute of Electrical and Electronics Engineers 1547 standard, which sets the interconnection and interoperability standards for distributed energy resources with which marine energy devices would need to comply (IEEE 2019).

The wind industry had to overcome many issues regarding grid codes, and Blavette et al. (2011) recommend how to ease this process for marine energy technologies. Their recommendations include involving the marine energy industry stakeholders when developing grid codes specific to marine energy devices and creating evolutionary codes that evolve and reflect the penetration level of ocean devices. The International Electrotechnical Commission Technical Committee 114 is a technical committee created in 2007 to establish, maintain, and publish technical standards and guidelines for the marine energy industry. It consists of 26 member countries participating in standards development and conformity assessment who work toward ensuring conformity with standards (IEC 2019).

5.0 Relevant Demands of the Electric Grid and Potential Benefits of Marine Energy Resources

With the vast amount of ocean resources available and countless devices in development, marine energy has the potential to mitigate challenges that the grid is currently facing, or may face in the future, and to complement the behavior of other generators to meet grid obligations. Providing power to coastal load centers, offering congestion relief to congested transmission areas, and increasing the resiliency of the grid are among the ways that marine energy might support the electric system of the future. Furthermore, niche markets like remote communities and installations, such as research and military installations, may benefit from the use of marine energy technologies even at their current state of development and cost. While other technologies and energy-generating sources, including but not limited to offshore wind turbines and floating solar arrays, may also be capable of providing some of the projected benefits of marine energy discussed below, there are situations where marine energy may have a competitive edge in doing so. The sections below explore ideas that are relevant to the marine energy industry, but that is not to say that other resources may not also be considered.

The five topic areas identified within this space in the literature and described below include transmission congestion relief, the coincidence of peak load and resource availability, the value of marine energy in deferring or eliminating transmission investments, how marine energy can improve system resilience, and the role of marine energy in reducing land use pressures. These concepts are fundamental to the value that marine energy technologies might provide to the grid. Available literature in this space enables researchers on this project to draw the connection between theoretical work that has been done, case studies, and the operational functionality of marine technologies to values that could materialize. The literature does not intentionally indicate what the value is, but provides the information to make that determination.

5.1 Transmission Congestion Relief

Transmission congestion occurs when constraints related to a transmission asset (e.g., the power flow limit of a line) prevent the system from operating its resources to meet demand in the most economic manner. Whether constraints create congestion depends on a variety of operational parameters like demand, system state, and the presence of contingencies. For example, when a major transmission line is removed from service due to a fault or scheduled maintenance, other transmission lines may have to carry more power and therefore may reach their allowable flow limits. If the limit constrains the required energy flow, the system will not operate in the most efficient manner and, in some cases, will not be in compliance with relevant policies and standards; this is transmission congestion (DOE 2015b).

Due to their deployment locations and scalability, marine energy devices may provide an effective response to transmission congestion. Moazzen et al. (2015) performed a study of Vancouver Island, British Columbia [BC], examining the benefits that could result from the integration of ocean energy to the electric system. The island is connected to the Lower Mainland electrical grid (near Vancouver, BC) via two interties, and the Lower Mainland grid serves approximately 49% of the island's annual demand. As dependency on the mainland interties increases, transmission upgrades will be necessary to reduce transmission congestion.

Moazzen et al. (2015) used the PLEXOS Integrated Energy Model to investigate the operating costs associated with four scenarios consisting of different combinations of transmission infrastructure, existing generation facilities, and wave farms. Ten potential wave sites were identified, and a 20% conversion efficiency of the rated capacity was assumed. Each situation was evaluated to determine the optimum mix of generating facilities to meet load at the lowest operating cost, essentially using an economic dispatch model. With existing infrastructure, wave integration was demonstrated to reduce dependency on the Lower Mainland electric grid by 11% (Moazzen et al. 2015). This suggests there is an opportunity to reduce energy dependence on neighboring jurisdictions, reduce transmission congestion on that line, and avoid costs of transmission upgrades. However, given the location of the wave resource and demand across the island, a new bulk transmission line may still be necessary to accommodate the wave energy.

5.2 Peak Load and Resource Availability

Although marine energy resources may fluctuate over various time scales, peaks in energy intensity that coincide with high power demand or a decrease in production from another intermittent generator can actually produce value for the grid, rather than increasing stress.

For example, even though wave energy is intermittent, seasonal patterns have the potential to coincide with times of high power demand or generate “natural balancing” for other forms of electric generation (Möller 2018). This natural balancing, or complementary nature, of wave resources within an energy portfolio can provide a variety of benefits, and a key impact is decreased variability in the aggregate. By diversifying resources, the security of supply increases (Redpoint Energy Limited 2009). This benefit can be considered in the context of capacity credits (i.e., the amount of conventional generation that intermittent resources can replace).

The value of capacity is highest during reliability-critical and peak demand periods, and increased generation from a single type of resource has the potential to shift the generation fleet away from those periods. This shift accounts for the diminishing capacity value attributed to some forms of variable generation at high levels of penetration (Sigrin 2014). The classic example of this phenomenon is with solar energy, where high penetrations of solar can push the critical reliability or peak demand period from late afternoon into the evening, after the sun has set and when solar has no capacity value.

Adding intermittent resources that are not correlated with existing generation provides resource diversity and can help mitigate this effect. One study from Redpoint Energy Limited (2009) reports that increasing the amount of marine technologies, including ocean wave, tidal stream, and tidal range devices, in a predominantly wind generation portfolio by up to 40% would decrease the amount of backup capacity needed for the system. This results in decreased costs for backup capacity and an increased overall capacity credit for the renewable technologies (Redpoint Energy Limited 2009).

When considering a seasonally peaking resource like wave energy, there is also an opportunity for the generation patterns to be well matched with energy demand. For example, Robertson et al. (2017) note that British Columbia’s energy consumption peaks in the winter when the available wave resource is also at its strongest. Wave resources along North America’s Pacific Northwest coast also possess this trait. Figure 13 shows Vancouver Island’s potential wave energy resource superimposed on its electrical demand, illustrating the phenomenon of a winter peaking resource being well correlated with the electrical demand.

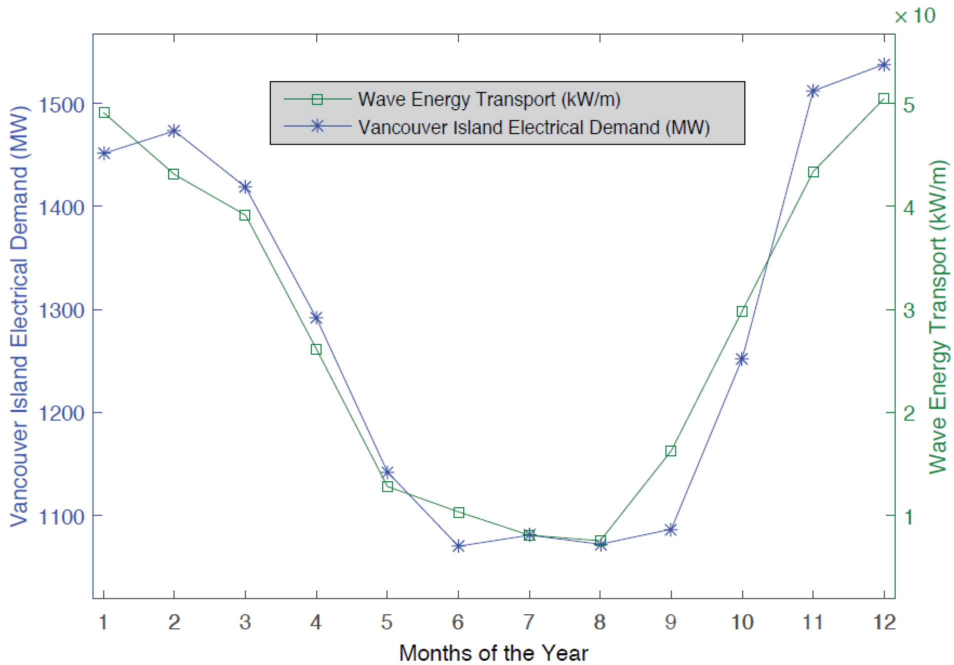

Figure 13. Annual wave energy transport and Vancouver Island electricity demand (Figure 8 from Robertson et al. 2017).

5.3 Non-Wires Alternatives

Transmission upgrades, voltage boosters, and even new line investments may be required to manage increased energy demand and connect the network to new generating sources and new loads. Non-wires alternatives (NWAs) or non-wires solutions (NWSs) are a general name for tools—storage, generating technologies, demand-side management practices, and others—that can meet the same objectives as, and complement, defer, or eliminate the need for traditional transmission investments. These alternatives are typically evaluated on a performance and bid price basis against traditional transmission investments. The value of these NWAs is often dependent upon their grid and geographic location. Marine energy resources can potentially serve as NWAs.

Bonneville Power Administration (BPA) implemented an NWA pilot project to relieve summer peak transmission congestion after the plan for an 80-mile, 500 kV transmission line was discontinued due to high costs and anticipated negative local impacts (Chew et al. 2018). BPA released a request for offers looking for bids for incremental capacity (INC) (i.e., incremental energy above existing operating levels) and decremental capacity (DEC) (i.e., decreased generation). The project, South of Allston, operated for two years, using a day-ahead, pre-scheduled basis of operations (Chew et al. 2018). The project provided 100 MW of congestion relief via third-party supplied capacity in the form of bids for INC, DEC, and demand-side management (DSM) load reduction (BPA 2019b). Figure 14 shows the five zones that were identified to match the long-term power transfer distribution factors (PTDFs) associated with the project (BPA 2016). These PTDFs illustrate the potential INC or DEC resources in each zone. In situations like this, where there are transmission congestions, marine energy technologies may be used as an NWA, providing incremental capacity, for example.

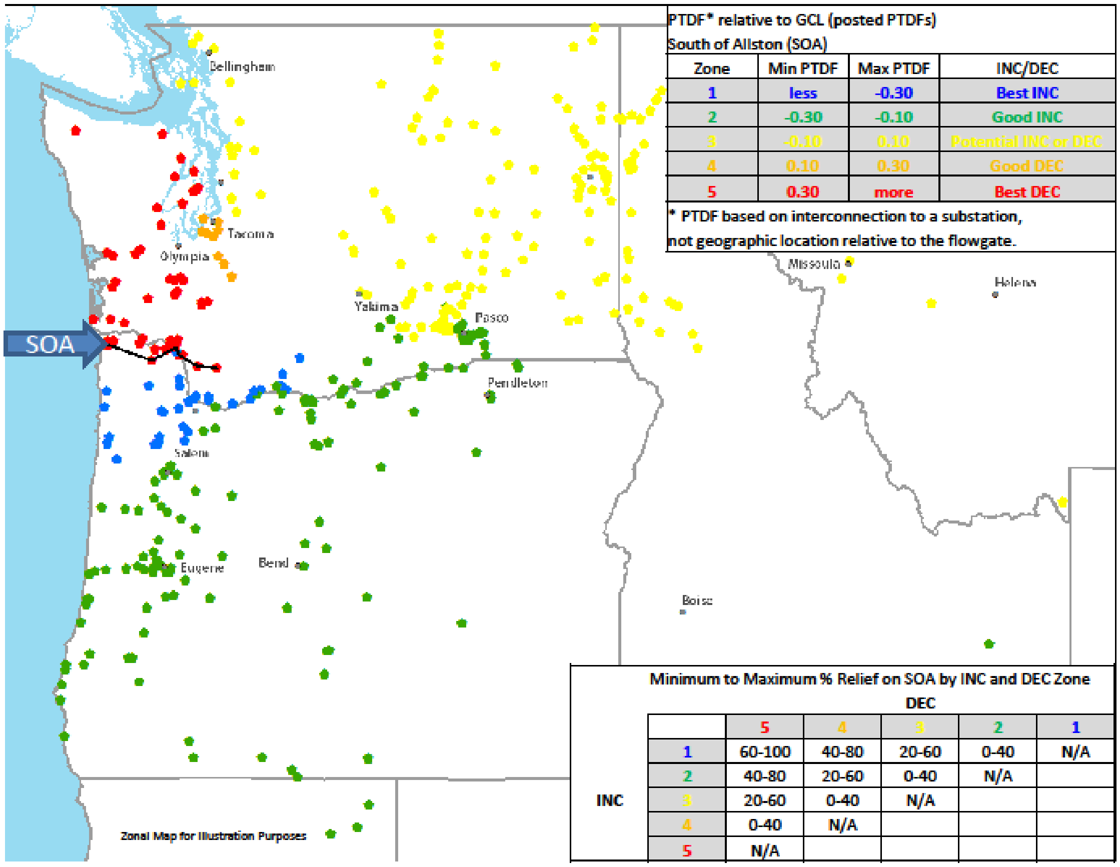

Figure 14. Zonal map for South of Allston non-wires alternative pilot project (BPA 2019a).

Other regions across the country are also exploring NWAs. The California Public Utilities Commission is leveraging the high penetration of distributed energy resources (DERs) in California, and approving a pilot regulatory mechanism to incentivize the implementation of NWAs. Utilities that deploy cost-effective DERs that can defer traditional distribution system upgrades are eligible for a 3–4% pre-tax incentive (Chew et al. 2018). In New York, demand management was implemented in 2017 as an NWA to distribution system upgrades and has seen success reducing demand more than projected and under budget (Reilly 2018). In Washington, D.C., a bill was proposed to establish an independent DER authority that would review any utility investment over $25 million dollars by evaluating NWAs as an alternative option to the utility's investment (Bade 2018). If NWAs continue to prove successful and use DERs, marine energy technologies can serve as another DER option, thereby potentially generating a grid value.

5.4 System Resiliency Improvement

The National Infrastructure Advisory Council defines resilience as a combination of four distinctive attributes: robustness, resourcefulness, rapid recovery, and adaptability (NIAC 2010). Marine energy resources can assist in increasing grid resilience in two measurable ways: (1) by reducing vulnerability to electricity disruptions, including reduced reliance on conventional generators and reduced risk from fuel price and associated volatility; and (2) in combination with microgrids or serving as backup generators for the purposes of avoiding sustained effects on critical infrastructure caused by grid disruptions.

Electric service, in general, is subject to many potential forms of service disruption, or grid contingencies, due to both natural/environmental and human factors. With the increase in severe weather events over the last few decades, these disruptions have become more frequent and longer (Melillo et al. 2014; Campbell 2012). In certain instances, the vulnerability to contingency events can be mitigated by localized power generation, thereby reducing dependence on centralized bulk generation and the associated transmission infrastructure (NASEM 2017). According to LiVecchi et al. (2019), marine energy resources may help coastal grids by serving as uninterruptible generation sources in the face of such events. At present, backup service during disruptions often relies on diesel-based generation resources, which are both expensive to operate and maintain, and are inefficient. Natural gas resources fare better in regards to operations and maintenance costs, but both are subject to the limitations of fuel availability (Robinson et al. 2006). This might be avoided through the use of marine energy resources if the technologies prove reliable (LiVecchi at al. 2019). Coupling marine energy with other distributed assets like solar photovoltaic, wind, or batteries can enhance its value, or vice versa, as a resilient resource (National Renewable Energy Laboratory 2018).

Critical infrastructure such as shelters, gas stations, and hospitals need to be kept operational during service disruptions for obvious reasons. Existing research can guide the optimal design and operation of microgrids and DERs to provide resilience, especially under contingency scenarios (Che et al. 2014; Wu 2015). Typically, significant capital investments and technical challenges are entailed in the development and operation of microgrids. If marine-based resources can provide resilience to coastal areas by offering uninterrupted generation during or immediately after contingency events, then the need to rely on microgrids to facilitate resilience in those regions may be reduced.

Further, marine energy resources may also serve as components of microgrids by providing sustained reliable and predictable power and reducing microgrid dependence on less-reliable fossil resources. As mentioned previously, in 2018, Nova Innovation integrated a grid-tied tidal energy array with a Tesla battery storage system, effectively creating a dispatchable grid resource (Renewable Energy Magazine 2018). If the grid was not available, it is easy to see this same resource providing backup capability, or, if coupled to multiple loads and additional resources, microgrid capability.

System planners use loss of load expectation (LOLE) and loss of load probability (LOLP) as metrics when determining the reliability and, used appropriately, partially estimating the resiliency of electric grids. These metrics can also be used to evaluate generation adequacy and capacity contributions. LOLP measures the likelihood that available generating capacity will not meet the system's daily or hourly peak in demand. Similarly, LOLE measures LOLP over the course of a year. LOLE is a classic reliability metric that gauges the number of days each year when it is anticipated that generation capacity will be unable to meet the daily peak demand (NERC 2016). A downside of LOLE is that the duration of the generation inadequacy is not represented by the metric, nor is the deficit in energy generation indicated, both of which are critical components of understanding system resiliency (NERC 2011).

LOLE and LOLP are used for probabilistic analyses and require an understanding of the performance characteristics of bulk power system components. They are generally based upon statistical analyses of past performance or enumeration techniques that can simulate many grid contingencies (NERC 2016). These metrics are often seen as a more accurate approach for assessing intermittent resources' capacity value than simplistic approaches that only compare a generators' output during times of particular risk for the system, like the highest periods of net load in a year (Leisch and Cochran). Since system planners depend upon these metrics for reliability purposes, there is a need to understand how marine energy may impact them.

5.5 Land Use Pressures

As the shift from conventional energy resources to renewables continues, land use pressures increase. Land-based wind and solar have a significant geographic footprint, but marine energy resources offer an offshore alternative in addition to offshore wind and floating solar technologies. One study showed that trying to reduce carbon emissions by 90% would result in a tenfold increase in land area affected by the energy devices. The study, performed by Palmer-Wilson et al. (2019), investigated the amount of land that would be necessary to reduce carbon emissions in Alberta, Canada, by 90% from 2015 levels by 2060.

The construction of renewable energy technologies on land (e.g., land-based wind and solar) can detract from competing uses—agriculture being a predominant alternative. Stevens et al. (2017) compare the space needed to generate a megawatt-hour of electricity from a variety of energy sources, including coal, natural gas, nuclear, solar, and wind. The amount of space required for these sources ranges from roughly 12 acres to 71 acres. The development of these sources could theoretically result in forgone production of staples like wheat and rice.

Furthermore, land use pressures can be driven by demographic dynamics, food consumption, energy demands, settlements and infrastructure, economic activities, zoning laws, land policy and development programs, and conservation policies (GOWA EPA 2008). Not only do these drivers dictate resource allocation, they also have environmental, economic, and social consequences (Aenunaim et al. 2018). This suggests that marine energy resources could alleviate pressure from land and generate a stream of benefits.

Land use premiums, captured by changes in the value of land, have also been on the rise. Land values for 46 metropolitan areas were collected between 1984 and 2018. Of these 46 areas, Seattle saw the largest jump in land value, increasing by 921% (AEI 2019). Figure 15 shows a comparison between the evaluated metropolitan areas, and many of the highest increases are in cities close to a coast.

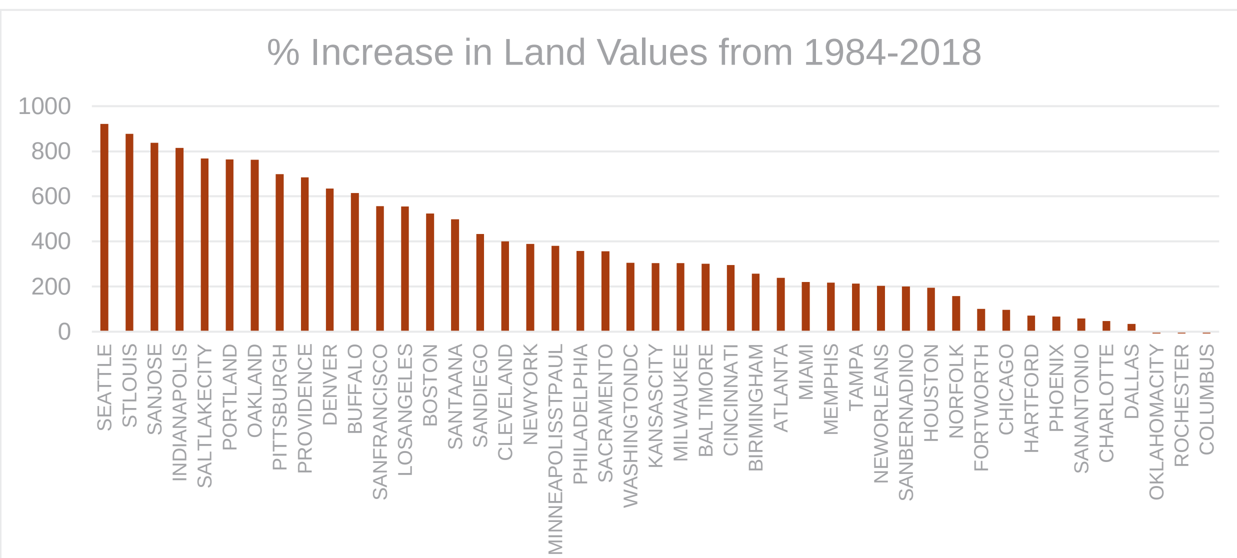

Figure 15. Increase in land values between 1984 and 2018 for 46 metropolitan areas.

With so much of the U.S. population living close to a coast and land use prices in these areas being among some of the highest in the country, offshore power generators would not only take pressure off of the land, but also offer an economically viable option. In some locations, rising land premiums are being cited as a driving force for offshore solar plant development (Trapani and Santafé 2013).

In its 2017 Integrated Resource Plan for the Caribbean Utilities Company, Pace Global (the public electric utility for Grand Cayman in the Grand Cayman Islands) evaluated land use associated with different generation technologies. Pace Global found a significant advantage to using marine energy, specifically ocean thermal energy conversion (OTEC) in this case: a much smaller area of land is required for its development relative to other technologies (Pace Global 2017). Although Pace Global did not quantify the value associated with the reduced land use, minimizing land use was a primary objective of the Integrated Resource Plan for the Caribbean Utilities Company (Pace Global 2017). Accordingly, and despite a higher capital cost for OTEC relative to other resource options, the resource plan containing OTEC was among the two recommended portfolios (Pace Global 2017). In the portfolio, OTEC resources replaced solar development, which requires a relatively high land commitment proportional to total generation, as well as natural gas and battery storage.

Pace evaluated land use as a “non-price attribute” in their analysis and although they took it into account as an objective, they did not quantify the value associated with the reduced land use of the OTEC-containing portfolio (Pace Global 2017). If they had, the overall benefit-cost proposition of that plan would have been strengthened.

6.0 Resource Competition and Complementary Use with Offshore Wind

While the potential for marine energy development is significant, tidal and ocean current and wave devices are not the only devices that can be developed offshore. The offshore wind industry offers a significantly more advanced product than tidal and ocean current and wave devices. Offshore wind turbines can also heavily rely upon the onshore wind energy industry when studying, modeling, and analyzing the resource. As Daniel et al. (2014) noted, the methods used when evaluating system impacts, generation reserve requirements, and system-wide operation costs directly transfer to the offshore wind industry. This is of particular benefit, as the report recommends that the United States consider developing up to 54 GW of offshore wind (Daniel et al. 2014).

One study evaluated the value of offshore wind along the eastern coast of the United States, focusing on energy value, capacity value, and renewable energy credit sales (Mills et al. 2018). While the study concluded that the value of energy depends upon future natural gas prices, which are uncertain, the increased wind energy penetration on the grid could eventually saturate the market and drive down the value of energy. Furthermore, capacity prices may increase in the future; offshore wind's capacity value is linked to those prices, rules governing how capacity credit is awarded, and its eligibility to participate in those markets. If offshore wind is not eligible to participate, then that value becomes void. Ultimately, the study calls for additional research to better understand these factors.

Although offshore wind energy is more developed than marine energy technologies, it does not come without its own set of challenges. Permitting, in particular, has been a significant issue for the industry (DOE and DOI 2016). Recent advances have reduced the timeline to roughly 2–4 years (Daniel et al. 2014). Furthermore, in areas where Independent System Operators and Regional Transmission Organizers do not exist, describing the large-scale system benefits that offshore wind can provide to the system may be challenging. These ideas, and the solutions that offshore wind employs, may translate well for other marine energy devices (Daniel et al. 2014). The marine energy industry has an opportunity to capitalize on lessons learned from offshore wind development as WECs and CECs come closer to commercialization.

Offshore wind does not need to be thought of as separate and exclusive from marine energy technologies, though. A study evaluating a portion of the North Sea performed by Azzellino et al. (2013) showed that there could be significant benefits to co-locating wave and offshore wind devices. When wind and waves are negatively correlated, this decreases variability and can help mitigate grid integration concerns. Being proactive in the siting process and performing quantitative spatial planning can avoid potential conflicts between sea uses, while harnessing the most useful energy (Azzellino et al. 2013).

Pérez-Collazo et al. (2014) describe three configurations for combined wind and wave systems: co-located, hybrid, and island systems. The former configuration accounts for sites that develop offshore wind turbines and a WEC array separately from one another but close enough to share grid connections and operations and maintenance. The two latter systems both combine offshore wind turbines with WECs within the same physical structure, differing mainly in size and the manner in which the resources are exploited. Hybrid systems can either be secured to the ground (an evolution of offshore wind structures that could accommodate a WEC) or floating systems, which resemble new-concept offshore wind systems. Although similar, island systems, because of their size can serve as a multi-use platform. Creating synergy in development of these resources will help generate a common regulatory framework, coordinate marine spatial planning efforts, and simplify licensing procedures.

One study evaluating wind and wave energy in California showed that aggregate power from a co-located wind and wave farm could significantly reduce the variability in power production (Stoutenburg et al. 2010). Using wave and wind data from 12 buoys and theoretical power outputs from the V90 Vestas 3.0 MW turbine and 750 kW Pelamis WECs, they showed that a co-located wind and wave farm off the coast of California would generate less variable power than two offshore wind farms located 500 km apart or two wave farms located approximately 800 km apart. According to the study, a co-located wind and wave farm would have less than 100 hours of no power output along the California coast in comparison to an offshore wind farm, which could have over 1,000 hours of no power output, and a wave farm, which could have 200 hours of no power output. Reducing variability in power output is valuable during grid integration.

7.0 Conclusions

Notable findings from this review include the following:

- **Very little work has been conducted in the intermediate stitching between the grid and fundamental marine energy development.** Few technical papers attempt to demonstrate grid value from marine energy or, conversely, illustrate how grid applications may have an effect on device scale, device convergence, and location of marine energy technologies. Those that have done so relied on numerous estimations and target very specific potential benefits.
- **Aggregation of tidal generation for baseload—the concept of distributing tidal generators to accomplish complementary phase shifts in generation that, when summed, would provide relatively stable power—faces challenges from a cost perspective**. One study evaluated three geographically separate, complementary locations off the Scottish coast and concluded that aggregate power generated from varying sites is sensitive to the characteristics of the individual sites and some irregularity should be expected in aggregate power output due to natural variation in successive tides. Ultimately, the study suggests that using complementary sites and limiting the capacity of the turbines, particularly during neap tides, could create baseload power, or a constant power output; but the research team expressed concerns regarding whether such a deployment would be cost effective.
- **Tidal energy-generating profiles may be well matched for storage.** Energy storage is a fast-growing resource in the energy industry. It can provide value in a multitude of grid situations, including supporting marine energy technologies. One report suggests that because tides are predictable, tidal technologies are ideal for pairing with energy storage to create a steady output of power. In fact, Nova Innovation recently integrated a Tesla battery storage system with the Shetland Tidal Array in Scotland and expanded the generating capacity and enabled dispatchability at the site.
- **There is a potential match between resource peak and electric demand.** When considering a seasonally peaking resource, like wave energy, there is an opportunity for the generation patterns to be well matched with energy demand. For example, one study noted that British Columbia's energy consumption peaks in the winter when the available wave resource is also at its strongest; this same characteristic is true along the rest of North America's Pacific Northwest coast.
- **Co-location may deliver grid benefits.** A study evaluating a portion of the North Sea showed that there could be significant benefits to co-locating wave devices and offshore wind turbines. When wind and waves are negatively correlated, this decreases variability and can help mitigate grid integration concerns that are sometimes associated with variable generation. Being proactive in the siting process and performing quantitative spatial planning can avoid potential conflicts between sea uses, while harnessing the most useful energy.
- **The availability and cost of land was used in utility decision-making for resource selection and resulted in a portfolio selection that included marine energy development.** In a 2017 Integrated Resource Plan for the Caribbean Utilities Company (the public electric utility for Grand Cayman in the Grand Cayman Islands),a contractor evaluated land use associated with different generation technologies and found a significant advantage to using marine energy, specifically ocean thermal energy conversion (OTEC). Accordingly, and despite a higher capital cost for OTEC relative to other resource options,

the resource plan containing OTEC was among the two recommended portfolios. In the portfolio, OTEC resources replaced onshore solar development, which requires a relatively high land commitment proportional to total generation, as well as natural gas-fired backup generation and battery storage. Although OTEC is not considered in this report, connections can be drawn to the technology, and research from that field is applicable to other marine energy resources in particular instances.

As the marine energy industry grows, there is a corresponding increase in the body of literature about the potential value of harnessing marine resources and the requisite technical work to integrate the resource into the grid. Due to the unique aspects of marine energy resources, especially their offshore location and predictability, there are many reasons to consider marine energy a viable potential renewable resource in the future electric system. Demonstrating this potential in a device-agnostic manner will provide the industry with a tool for describing the value that these technologies can provide and will promote further development.

This literature review summarizes the energy fundamentals of marine resources; the performance and operational characteristics of energy conversion devices; grid opportunities and integration challenges most applicable to marine energy; storage coupling to achieve grid opportunities; and offshore wind energy competition and collaboration. This document therefore provides the context in which the grid value proposition of marine energy should be further researched and explored.

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