CHAPTER 12

Power Generation from Tides and Waves

Dhruv Bhatnagar, Danielle Preziuso, and Rebecca O'Neil with contribution by Jan Alam, Saptarshi Bhattacharya and Sarmad Hanif

1 Introduction

Ocean waves and tides have the potential to supply a significant portion of the world's energy needs. Water is denser than air, ocean forces are powerful, and significant population density and corresponding electricity loads occur near ocean environments around the world. Yet commercial development of energy capture technologies from marine resources has been limited to date, generating only 1.2 TWh of electricity across the globe in 2018 while global electricity demand was 23,000 TWh (International Energy Agency 2019a, b).

Currently, cost and technology uncertainty of marine energy devices remain the primary barrier to expansion. However, as renewable energy technologies mature and become more viable through policy intervention, economic development, generation incentives, and robust research and development programs, marine technologies increasingly hold promise of commercialization.

This chapter discusses the development of marine energy projects to date, economic factors for deployment and operations, and commercialization pathways for the future. While marine renewable technologies include a range of devices such as ocean thermal conversion technologies and ocean current devices, the chapter focuses on the wave and tidal energy sectors.

D. Bhatnagar • D. Preziuso • R. O'Neil (✉)
Pacific Northwest National Laboratory, Richland, WA, USA
e-mail: Rebecca.ONeil@pnnl.gov; https://www.pnnl.gov/marine-energy; https://www.pnnl.gov/projects/marine-energy-grid-value

M. Hafner, G. Luciani (eds.), *The Palgrave Handbook of International Energy Economics*, https://doi.org/10.1007/978-3-030-86884-0_12

2 Resources, Technologies, Deployments

Tidal current energy capture devices and wave energy converters (WECs) can vary greatly in design, scale, stage of development, and technology readiness level. Given this range, the most useful common references for economic potential are tidal and wave energy resource characteristics and occurrence.

2.1 Tidal Current Devices

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). Tidal currents are bi-directional but generally one-dimensional, as a given tide typically ebbs and flows along one vector. Tidal devices may be mounted to the ocean floor and elevated to the current or may be suspended from the surface. Ultimately, the amount of energy that can be harnessed is dictated by the velocity of the tidal current.

The simplest and most dominant form of a tidal current device is the horizontal axial-flow turbine, which roughly resembles a horizontal axis wind turbine and operates in a similar manner. A variety of other device types are being developed, including tidal kites, oscillating hydrofoils, ducted turbines and screw turbines (Roberts et al. 2016; U.S. Department of Energy 2015). All of these technologies differ from tidal barrages, which are configured to extract energy from changes in tidal elevation rather than the horizontal current of tides, and have been in commercial use for decades.

Due to the nature of the resource, tidal energy is considered variable but highly predictable in its variability, unlike other renewable resources (e.g., wind and solar), which require extensive short-term forecasting and energy reserves to compensate for weather conditions. Tidal patterns are generally sinusoidal but can show great variation in intensity and pattern within short distances. Less than 20 miles apart, the maximum velocity at Admiralty Inlet, Washington (Northwest USA) can be more than double the maximum velocity at Sequim Bay, Washington over the course of a day and display significantly different resource patterns over time as shown in Fig. 12.1.

2.2 Tidal Current Device Deployment

Although tidal devices have not been deployed at utility scale, there have been successful grid-connected deployments and prototype tests. The most developed tidal stream turbine installation to date, SIMEC Atlantis Energy's SeaGen device, was installed in Strangford Lough, Northern Ireland, United Kingdom and connected to the grid in 2008 (MacEnri et al. 2013). Over the course of its lifetime, the 1.2 MW system produced over 11.6 GWh of electricity, which ESB Independent Energy bought through a power purchase agreement before the device was fully decommissioned in 2019 (SIMEC Atlantis Energy 2019; Renewable Technology 2017).

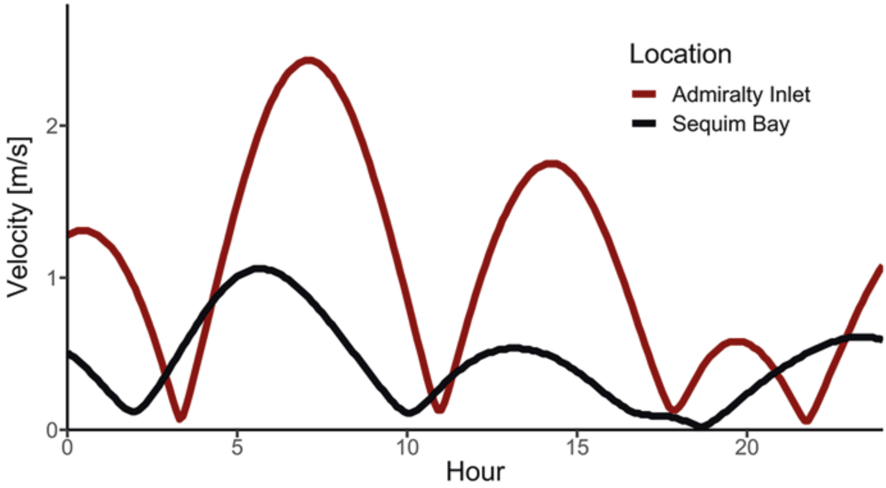

Fig. 12.1 Tidal current velocity [m/s] at Admiralty Inlet and Sequim Bay in Washington, USA. Data are from the Assessment of Energy Production Potential from Tidal Streams in the United States (Haas et al. 2011)

The European Marine Energy Centre (EMEC) has hosted and tested several prototypes in recent years, including Orbital Marine Power's SR2000 tidal turbine, which was launched at the facility in 2016. During its first 12 months of operation at EMEC, the 2 MW floating twin-turbine system produced over 3 GWh of electricity (Orbital Marine Power 2020). Pilot projects have also taken place in North America, with Sustainable Marine Energy testing its 280 kW PLAT-I tidal energy platform in Grand Passage, Nova Scotia in February of 2019. The project has successfully generated electricity with no noticeable negative marine wildlife impacts to date. It is however not connected to the grid (Sustainable Marine Energy 2019a).

In September 2019, Sustainable Marine Energy announced that it had been awarded a license by the Nova Scotia Department of Energy and Mines to sell power via a power purchase agreement to Nova Scotia Power. The company anticipates the development of 9 MW of tidal capacity in the Bay of Fundy in a joint venture with Minas Tidal LP (Sustainable Marine Energy 2019b). The Faroe Islands' electric utility, SEV, awarded a power purchase contract to Minesto in November 2018 to deploy two installations of its tidal kite devices. The European Commission's SME Instrument Programme in June 2019 issued a €2.5 million grant to Minesto and SEV to support the installation of the devices (Minesto). As of April 2020, all siting permits have been approved for the two tidal kites in Vestmannasund as part of the Deep Green Island Mode Project (Minesto 2020a).

2.3 Wave Energy Converters

Waves are a fundamentally fluctuating energy source. Ocean surface waves are created by the movement of wind over the ocean. Once produced, they can travel large distances. When they arrive at a location far from the area of production, they are called swells. While waves express high variation between their peak intensity and average intensity, they also display seasonal patterns. The behavior of ocean waves is classified by amplitude, phase, and directionality.

Unlike tidal energy devices, there is a variety of WEC designs (Falcão 2010; Drew et al. 2009). Point absorbers, oscillating wave surge devices, attenuators, and oscillating water columns are among the most common device classifications, with the first three technology types often consisting of one or more bodies that generate power from the wave-induced relative translation motion and/or rotational motion between the body and a reference frame (e.g., seabed). Oscillating water columns differ from these devices in that they instead consist of a column of air trapped on top of a column of water; the rise and fall of the water column due to incident waves pushes the air through a turbine, thus generating power. Most devices are wave-to-wire, generating power within an individual device, then aggregating within an array and sending power to shore via an export cable. Other hydraulic devices are designed for near-shore environments and they pump water to onshore power generation equipment.

2.4 Wave Energy Converter (WEC) Deployment

As with tidal current devices, WECs have not yet reached commercial development, yet a variety of WECs have been deployed and tested around the world, many of which have been connected to local grids. In 2011, the Spanish utility Ente Vasco de la Energía supported the deployment of a 300 kW oscillating water column system integrated with the breakwater of the harbor in Mutriku, Spain. The system was also the first multi-turbine WEC system tested in the world (International Energy Agency—Ocean Energy Systems 2016). In Australia, Carnegie Clean Energy has deployed several successful pilots. The Perth project off Garden Island included three fully submerged buoys that were connected to the grid and operated continuously for 12 months. The project incorporated a desalination plant to produce freshwater (Carnegie Clean Energy), and the Australian Department of Defence contracted for the electricity generation under a power purchase agreement (Sawyer 2017). North America has also seen grid-connected WEC deployments. The first grid-connected device in the United States was an 18 kW Azura technology deployed by Northwest Energy Innovations at the U.S. Navy's Wave Energy Test Site in Hawaii in 2015 (Whitlock 2015).

3 Cost Drivers

3.1 Technology Cost Drivers

Anticipated deployment costs for wave and tidal devices are relatively high to other existing generation technologies. As described above, deployments have consisted of small-scale projects or pilots intended to test technologies in the water, their electricity production, interaction with the marine environment and integration into power systems. Device development for projects is a custom process, introducing construction costs and delays without manufacturing standardization, supply chain alignment, or cross-over with maritime sector applications for economies of scale and availability.

The marine operating environment introduces specialized hazards, which accordingly introduces novel and unavoidable costs. Saltwater contains minerals that can corrode materials and coatings. Aquatic life will interact with the deployment, raising environmental concerns and triggering regulatory requirements. Wave energy devices are intentionally mobile with exposed mechanics and changing levels of submersion. Tidal and wave devices will require special protections with advanced coatings, corrosive resistant materials, or protective casings. Deployment in the ocean can be limited due to customized supply chain, specialized vessels and equipment, and limited operational windows. Technology developers must design devices to withstand strong and multi-directional forces. Research and development programs across the world have promoted strategic investments to drive down these costs (U.S. Department of Energy 2019b; International Energy Agency 2019b). Individual wave energy conversion devices must be built for a significantly higher power output capacity than their average power output to handle the natural fluctuation in wave intensity (Yu et al. 2018).

3.2 System Costs: Levelized Cost of Electricity

The levelized cost of electricity (LCOE) is the most common metric for comparing the cost-benefit of different energy generation technologies. For example, the often-cited Lazard estimates compare technologies on an LCOE basis (Lazard 2019). Compared to simple representations like installation cost per unit of rated power, LCOE offers a more holistic representation of an energy project by considering actual generation.

The LCOE metric creates a ratio between the present value of a project's lifetime costs and the amount of energy that the project will produce throughout the project's lifetime. LCOE is in units of currency per amount of energy, or in the United States, dollars per kilowatt hour. It is calculated as (Fig. 12.2):

The metric recognizes that project costs vary over time and that the siting of renewable energy projects dictates resource strength and energy available. The differences in energy production impact the denominator of the LCOE equation: the more energy the project can produce each year, the lower the cost of

$$LCOE = \frac{cost\ to\ generate\ (capital\ and\ O\&M\ over\ project\ lifetime)}{total\ amount\ of\ energy\ generated}.$$

Fig. 12.2 Simple formula for Levelized Cost of Energy

electricity becomes. LCOE has largely been the metric of choice when governments consider incentivizing new technologies and it is a primary screen for gauging which innovative technologies are nearing commercial viability and if they can be considered for out-year investment.

LCOE estimates for small and early developments of tidal current and wave energy projects are within the range of \$400/MWh to \$800/MWh for tidal (Jenne et al. 2015; IEA-OES 2015) and \$250/MWh to \$2000/MWh for wave (IEA-OES 2015). This can be compared to \$49/MWh for solar, \$57/MWh for wind and \$119/MWh for combined cycle natural gas power plants sited in California (Neff 2019).

The highly variable range of wave and tidal LCOE values is mirrored in the estimates used by the electric utility sector in planning documents. From a review of U.S. utility integrated resource plans (IRPs), with values escalated to 2019\$ U.S., tidal and wave sectors both have over 6-to-1 cost ratios from the lowest to the highest. The range for offshore wind is lower at 5-to-1. This range is still expressed with very few data points: tidal values only have 4 observations from which to generalize, while there are 8 observations for offshore wind and for wave energy. See Fig. 12.3.

Estimated LCOE for tidal and wave devices is higher by an order of magnitude relative to other generating resources. As tidal and wave devices are not yet commercially available, and as evidenced by the broad range in value, these cost estimates remain guesswork and are not considered reliable comparators or gages for future levelized costs. Both solar panels and wind turbines in the early stages of development had similarly high levelized costs. In 2010, the global weighted average LCOE of utility-scale solar photovoltaic (PV) was approximately \$370/MWh. Since that time, the levelized cost has dropped by 77% (IRENA).

Research has shown potential for wave energy devices to be co-located with offshore wind plants, as the generating resources can be complementary and co-location reduces the cost per energy generation for both resources (Reikard et al. 2015; Chozas et al. 2012). Similarly, energy storage is particularly well suited for pairing with tidal energy projects. Tidal energy's inherent predictability and periodicity lend itself well to coupling devices with a limited amount of storage. Hybridization with energy storage has the potential to change the competitiveness of a tidal project by decreasing the fluctuation in power output over time; however, introducing storage increases project costs and slightly reduces the net energy produced onsite due to round-trip efficiencies (Zhou et al. 2013; Ben Elghali et al. 2019).

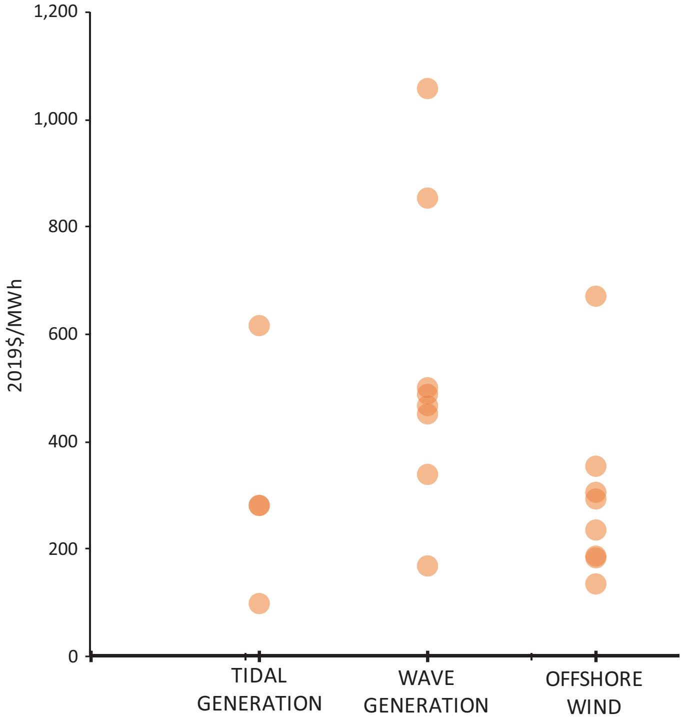

Fig. 12.3 LCOE (converted to $2019) for tidal generation, wave generation, and offshore wind as reported in U.S. utility integrated resource plans (IRPs). Points are partially transparent such that darker points represent more than one IRP reporting an LCOE of the indicated value. (Cooke et al. 2020)

While LCOE is widely used and covers a renewable energy project's economic lifetime, it represents an incomplete picture of the *value* of a particular energy project. LCOE fails to capture a range of other potential value streams that generators supply, most notably services critical to the operation of the grid (The University of Texas at Austin Energy Institute 2020; Ueckerdt et al. 2013). In the past, when the energy system was composed of entirely dispatchable resources—where output could be modulated to meet load and technology attributes varied little (i.e., large central scale power plants that operated for decades and required similar amounts of land and fuel supplies)—LCOE was an appropriate metric to directly compare across technologies. Today, there is an increased recognition of the range of technology attributes and differentiators, as well as contributions to grid reliability beyond simple energy that need to be measured and accounted for.

On a simple cost basis, an energy project in the ocean will always be challenged to appear competitive with a land-based energy project. The economic competitiveness of tidal and wave energy resources to future electric grid conditions is better evaluated, then, by these resources' unique values and attributes rather than its costs alone. In order to review potential future development markets and economic opportunities, the remainder of this chapter discusses unique or competitive value that tidal and wave energy devices can provide to global energy systems.

4 Economic Value: Relevant Markets and Applications

While operation in a marine environment has cost implications, in certain markets this attribute of wave and tidal resources may provide a competitive edge. Opportunities for development may exist in a wide variety of markets, particularly remote and island communities, military bases, and constrained grids and grids with high contributions from renewable energy sources. Further, maritime applications, may also provide market opportunities.

4.1 Remote and Island Communities

Tidal and wave development are more promising in locations where the cost of electricity is high and access to a consistent fuel supply (e.g. diesel fuel) is challenging. These are often remote and island communities with small grids.

Island and coastal communities are often at the forefront of climate impacts and have a strong driver to move to cleaner energy sources (Dornan and Shah 2016). Beyond providing clean energy, the development of renewable resources in remote communities can have benefits in job creation, economic development, and emissions reductions (Shirley and Kammen 2013). Tidal and wave resources can help avoid the impacts of fossil fuel use and address challenges associated with other renewable technology integration (i.e., solar or wind variability, intermittency and a lack of predictability). Research suggests that marine energy resources can avoid transmission investments to remote, coastal locations (Robertson 2010; Moazzen et al. 2016); that as a predictable resource, marine energy would require a fraction of associated integration costs and support the integration of other resources; and that to achieve high physical penetration levels of renewable energy, winter peaking resources with seasonal variation such as marine energy could be valuable. The use of marine energy in a portfolio increases resource diversity, reducing vulnerability to grid and fuel supply disruptions and exposure to fuel price volatility.

The following examples highlight the unique value associated with tidal and wave devices and illustrate broader potential market opportunities.

4.2 Faroe Islands (Resource Complementarity)

The utility in the Faroe Islands, SEV, has evaluated the use of tidal energy as part of its approach to achieve a 100% renewable energy generating portfolio. SEV finds that tidal energy can provide a consistent and predictable output, complementing other seasonally variable resources of wind, hydroelectric generation, and solar photovoltaic. These resources, in combination with pumped storage and batteries, SEV predicts, can enable it to successfully and reliably achieve a 100% clean generation portfolio. Doing so otherwise would require a significant overbuild of wind and solar resources (Katsaprakakis et al. 2019). The utility is presently working on the pilot project previously mentioned to showcase the use of tidal energy, and if successful, intends to expand this effort with larger tidal turbine units (Minesto 2020b).

4.3 Alaska (Fuel Supply and Resource Availability)

The U.S. state of Alaska has several remote communities. Many of these communities are not connected to a large electric grid and are self-sufficient for their energy, reliant mostly or entirely upon diesel generation for electricity (Beatty et al. 2010). There is significant interest in the use of renewables to provide reliable and fuel-independent electricity to these communities in order to lessen the high costs of using diesel generation that result from high fuel costs (due to transportation) and supply chain uncertainty. Shipped diesel fuel may be disrupted due to weather or other factors, creating a potential resilience benefit from the use of local, reliable, and available resources. The community of Igiugig in Alaska has deployed a river current device, similar to tidal energy, and the community of Yukatat is evaluating the potential for a wave energy converter to test the provision of electricity from these resources and reduce their use and dependence on fossil generation (Alaska Center for Energy and Power 2016; ORPC 2020).

4.4 Caribbean & Indian Ocean Islands (Land Use)

Another advantage of wave and tidal devices is their small terrestrial footprint, which is limited to an electric cable and auxiliary on-shore equipment for interconnection. Land is a scarce commodity on islands and subject to competing uses. With the expectation that renewable resources will need to be significantly increased to meet climate goals, there is increasing benefit to siting renewable energy resources offshore in areas where available land is scarce. In its 2017 Integrated Resource Plan for the Caribbean Utilities Company, Pace Global found an advantage in utilizing marine energy, specifically ocean thermal energy conversion (OTEC), as significantly less land was required for its development relative to other resources (Pace Global 2017). Similarly, the Seychelles Energy Commission approved a 25-year power purchase agreement for a 4 MW floating solar development in a lagoon off Mahé island, with the African Legal Support Facility citing that the plant provides clean energy generation while avoiding the challenge of land constraints on the island (Bellini 2020).

4.5 Military Bases

There are several remote military bases around the world: remote outposts within a nation's mainland borders that are not grid-connected, or remote outposts on islands or another nation's territory. Energy is a critical need for military operations and these bases must have reliable power at all times, especially during severe weather events and military conflicts, which is problematic when these bases are heavily reliant on imported diesel (Defense Science Board 2016). Similarly, there are numerous grid-connected bases that are reliant upon grid-delivered electricity that is susceptible to interruption in contingency events (Samaras et al. 2019). For example, in April 2011, a tornado left the U.S. Army's Redstone Arsenal base in Huntsville, Alabama without power for eight days, leading to a base closure and a reliance on diesel backup generators for critical activities. By the end of the outage, the generators had almost emptied their fuel reserves (Marqusee et al. 2017).

Recently militaries have explored the use of alternative resources, particularly renewable resources with energy storage, to reduce reliance on diesel, which not only avoids costs and emissions but also achieves their primary goal of ensuring continued operations if diesel supplies are no longer available (Samaras et al. 2019). Tidal and wave energy devices can act as a replacement to fossil generation as a result of their improved predictability and periodicity, supporting load when implemented in conjunction with intermittent renewable technologies and energy storage, in a microgrid, for example. Further, tidal and wave devices can provide resilience by offering an improved level of uninterrupted generation relative to solar or wind (Newman 2020). Figure 12.4 below highlights this value using the output of a microgrid dispatch model. The box and whisker plot indicates the percentage reduction in renewable energy capacity, battery capacity, diesel generator capacity, and diesel fuel consumption for a microgrid ensuring the delivery of energy during different electric grid outage lengths using the addition of a tidal energy resource instead of a solar PV resource across 100 simulations.

4.6 Constrained Grids and Grids with High Renewable Energy Contributions

Electric generation sources can be located at great distances from both large and remote coastal electric loads, which means that transmission infrastructure is needed to assure reliable electric delivery over these long distances. Transmission services can be capacity constrained along the coasts, making it difficult to add new electric loads to the system, inhibiting economic growth. Installing new transmission infrastructure is an expensive and spatially constrained proposition (ScottMadden 2020). Further, coastal transmission and distribution lines may be single points of failure, providing no redundancy for these communities if a line is suddenly unavailable (Hasan et al. 2013).We see examples of this in coastal cities of North Carolina, USA, where extreme

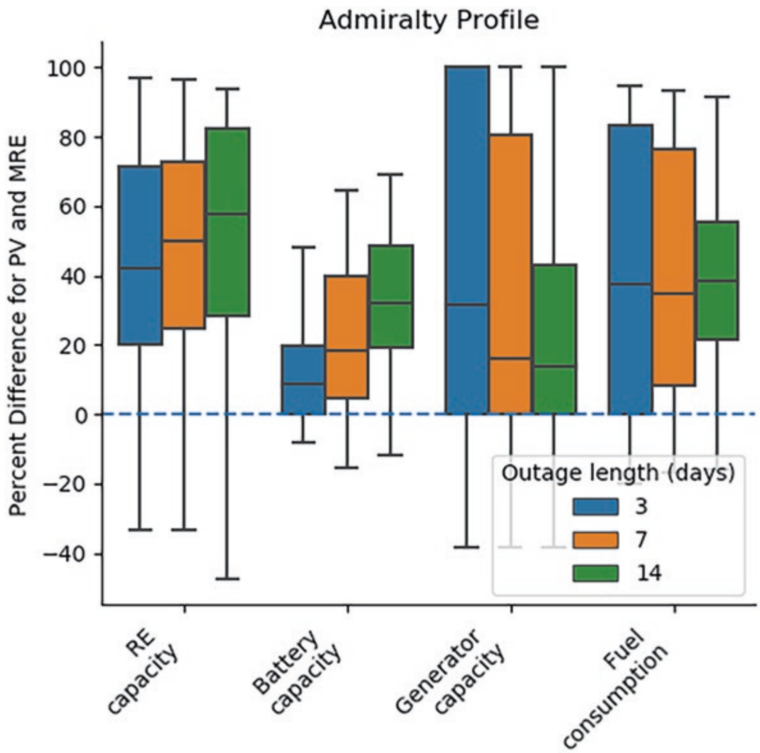

Fig. 12.4 Percent reduction in the required RE capacity, battery capacity, generator capacity, and fuel use resulting from adding additional MRE instead of PV capacity to meet 100% uptime during different outage lengths, across 100 simulations for a hypothetical load served by a microgrid with a diesel generator, battery, solar PV and tidal energy. (Newman 2020)

weather events, like hurricanes, and unforeseeable contingencies result in widespread power outages in major tourist locations (Bohatch 2017; Dalesio 2014).

Siting tidal and wave energy devices in such 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 local power quality benefits. Another benefit could be supporting economic development in otherwise energy constrained areas (Oregon Department of Energy 2012). Finally, the infrastructure build-out required to meet renewable energy goals, especially when policy includes a resource proximity requirement, such as direct interconnection to a state or particular utility's electric system, may have unacceptable demands on available land, creating another opportunity for tidal and wave resources (ScottMadden 2020).

Wave and tidal device output will be more predictable than their solar or wind renewable counterparts. This advantage enables tidal and wave resources to provide benefits to the grid in several other ways, including accommodating optimal amounts of complementary resources, distribution and transmission system management, and reduced costs in holding fewer operating reserves. Wave and tidal energy have electricity generation profiles that complement wind and solar resource availability over annual, seasonal, and daily periods. These resources fill critical resource timing gaps in grids with increasingly high levels of renewable energy generation. A wider portfolio of diverse contributing renewable energy brings geographic diversity, supports resource adequacy, and reduces reliability risks.

4.7 Scotland (Energy Storage Integration)

In 2018, 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). The system allows for storage of excess tidal energy during energy production peaks and then discharges stored tidal energy during low to no device output periods. The facility is claimed as the world's first "baseload" tidal power facility (Nova Innovation 2019) due to its relatively flat net production.

By coupling with storage, tidal or wave facilities could achieve better controllability and offer a scaled version of dispatchable generation. Researchers have explored the coupling of non-battery storage solutions with marine energy. Though of relatively small scale, an electrolyzer, which splits water using electricity to generate hydrogen gas (H_2), with a generation capacity of 220 kg of H_2/day was developed using tidal current device prototypes for its electric input (ITM Power 2017). The resulting hydrogen from this system could be used to generate electricity when demand increases, potentially for much longer timeframes than the typical four-hour limitations that standard commercial battery technologies currently allow. Such a system could also be used to supply fuel cell-based vehicles and additional transportation systems (U.S. Department of Energy 2019a). These developments suggest that coupling marine energy devices with various types of energy storage can enable new value streams.

4.8 Australia (Renewables Integration)

As Australia deploys more renewable resources on its electric system, the country has recognized a need for supporting technologies and resource diversity to help integrate this renewable energy. Wave and tidal energy use could reduce system capacity and balancing requirements by reducing the overall variability of the energy generation profile. The diversity could also provide a natural resiliency effect: the more geographic diversity of the overall generation profile, the less likely it is to be interrupted by contingency events. As renewable resources reach higher levels of deployment, seasonal and daily ramps of generation will cause significant reliability management challenges. In contrast, wave energy will maintain consistent production over seasonal periods and could fill the production gaps to provide reliable electric service. Australia's Commonwealth Scientific and Industrial Research Organization has evaluated Australia's wave energy potential and finds that the southern coastline of the country has a wave resource that could contribute up to 11% of Australia's total energy needs (CSIRO 2020).

4.9 Powering the Blue Economy

One strategy to advance commercialization of wave and tidal energy technologies in the near-term is to develop these technologies for electric demands within existing and emerging maritime sectors, called the "blue economy." Meeting the electricity needs of maritime sectors requires targeted technology development at small scales with specialized characteristics to fit the demands of the maritime environment. These markets include ocean observation, desalination, seawater mining, and aquaculture (LiVecchi et al. 2019). While this approach may advance commercialization of marine energy technologies, the largest economic opportunity still remains in serving traditional electric grids under the circumstances described above.

5 Conclusion

Considering the magnitude of tidal and wave resources and the policy drive toward a cleaner, decarbonized electricity system, it is reasonable to anticipate that tidal and wave energy will be able to commercialize and deploy around the world. This may be especially true in environments where there are limited clean energy resource options, the marine nature of these deployments provides additional value, or grid conditions require the unique attributes of tidal and wave energy resources.

Acknowledgments Research described in this article was sponsored directly by the U.S. Department of Energy's Water Power Technologies Office.

References

Alaska Center for Energy and Power. 2016. "Yakutat Wave Energy Resource Assessment." Alaska Center for Energy and Power. Accessed May 18. http://acep.uaf.edu/projects-(collection)/yakutat-wave-energy-resource-assessment.aspx.

Azzellino, Arianna, Vincenzo Ferrante, Jens Peter Kofoed, Caterina Lanfredi, and Diego Vicinanza. 2013. "Optimal siting of offshore wind-power combined with wave energy through a marine spatial planning approach." *International Journal of Marine* Energy 3–4: e11-e25. https://doi.org/10.1016/j.ijome.2013.11.008, http://www.sciencedirect.com/science/article/pii/S2214166913000349.

Beatty, Scott J., Peter Wild, and Bradley J. Buckham. 2010. "Integration of a wave energy converter into the electricity supply of a remote Alaskan island." Renewable

Energy 35 (6): 1203–1213. https://doi.org/10.1016/j.renene.2009.11.040, http://www.sciencedirect.com/science/article/pii/S096014810900528X.

Bellini, Emiliano. 2020. "Quadran International wins Seychelles tender for large-scale floating PV with bid of $0.095/kWh." PV Magazine. Last Modified January 10 2020. Accessed May 18. https://www.pv-magazine.com/2020/01/10/quadran-wins-seychelles-tender-for-large-scale-floating-pv-with-bid-of-0-095-kwh/.

Ben Elghali, Seifeddine, Rachid Outbib, and Mohamed Benbouzid. 2019. "Selecting and optimal sizing of hybridized energy storage systems for tidal energy integration into power grid." Journal of Modern Power Systems and Clean Energy 7 (1): 113–122. https://doi.org/10.1007/s40565-018-0442-0.

Bohatch, Emily. 2017. "No light in sight: North Carolina barrier islands could be without power for weeks." USA Today. Last Modified July 28, 2017. Accessed September 23. https://www.usatoday.com/story/news/2017/07/28/north-carolina-barrier-islands-without-power-no-timeline-restoration/519972001/.

Bryden, I. G., and D. M. Macfarlane. 2000. "The utilisation of short term energy storage with tidal current generation systems." Energy 25 (9): 893–907. https://doi.org/10.1016/S0360-5442(00)00020-7, http://www.sciencedirect.com/science/article/pii/S0360544200000207.

Carnegie Clean Energy. "CETO 5—Perth Wave Energy Project." Carnegie Clean Energy. Accessed June 17. https://www.carnegiece.com/project/ceto-5-perth-wave-energy-project/.

Chozas, Julia Fernandez, H. C. Sørensen, and N. E. Helstrup Jensen. 2012. Economic Benefit of Combining Wave and Wind Power Productions in Day-Ahead Electricity Markets.

Cooke, A.L., R.S. O'Neil, and D.C. Preziuso. 2020. Review of Marine Renewable Energy in Integrated Resource Plans. PNNL-29862. Richland, WA: Pacific Northwest National Laboratory. (Anticipated.)

CSIRO. 2020. "Wave Energy in Australia." CSIRO. Last Modified April 29 2020. Accessed May 18. https://www.csiro.au/en/Research/OandA/Areas/Marine-technologies/Ocean-energy/Wave-energy.

Dalesio, Emery. 2014. "Arthur hits North Carolina coast just before holiday." Associated Press. Accessed September 23. https://krcgtv.com/news/local/arthur-hits-north-carolina-coast-just-before-holiday-08-14-2015.

Defense Science Board. August 2016. *Task Force on Energy Systems for Forward/Remote Operating Bases: Final Report*. Defense Science Board (Washington, D.C.: Defense Science Board). https://dsb.cto.mil/reports.htm.

Dornan, M., and K. U. Shah. 2016. "Energy policy, aid, and the development of renewable energy resources in Small Island Developing States." Energy Policy 98: 759–767. https://doi.org/10.1016/j.enpol.2016.05.035. <Go to ISI>://WOS:000387300300073.

Drew, B., A. R. Plummer, and M. N. Sahinkaya. 2009. "A review of wave energy converter technology." Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 223 (8): 887–902. https://doi.org/10.1243/09576509JPE782.

Falcão, António F. de O. 2010. "Wave energy utilization: A review of the technologies." Renewable and Sustainable Energy Reviews 14 (3): 899–918. https://doi.org/10.1016/j.rser.2009.11.003, http://www.sciencedirect.com/science/article/pii/S1364032109002652.

Fernandez, JC, HC Sorensen, and NE Helstrup. 2012. *Economic benefit of combining wave and wind power productions in day-ahead electricity markets*. (International Conference on Ocean Energy). https://www.icoeconference.com/publication/economic_benefit_of_combining_wave_and_wind_power_productions_in_day_ahead_electricity_markets/.

Fraunhofer ISE. 2020. Recent Facts about Photovoltaics in Germany. Fraunhofer ISE (Fraunhofer ISE). https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/recent-facts-about-photovoltaics-in-germany.pdf.

Haas, K.A., Fritz, H.M., French, S.P., Smith, B.T., and Neary, V. 2011. Assessment of Energy Production Potential from Tidal Streams in the United States. Georgia: Georgia Tech Research Corporation.

Hasan, Kazi Nazmul, Tapan Kumar Saha, Mehdi Eghbal, and Deb Chattopadhyay. 2013. "Review of transmission schemes and case studies for renewable power integration into the remote grid." Renewable and Sustainable Energy Reviews 18: 568–582. https://doi.org/10.1016/j.rser.2012.10.045, http://www.sciencedirect.com/science/article/pii/S1364032112005965.

International Energy Agency—Ocean Energy Systems (IEA-OES). 2015. *International Levelised Cost of Energy for Ocean Energy Technologies: An analysis of the development pathway and Levelised Cost of Energy trajectories of wave, tidal and OTEC technologies*. IEA Technology Collaboration Programme for Ocean Energy Systems (OES) (IEA Technology Collaboration Programme for Ocean Energy Systems (OES)).

———. 2016. *Ocean Energy Systems Annual Report*. (International Energy Agency The Executive Committee of Ocean Energy Systems). https://report2016.ocean-energy-systems.org/.

International Energy Agency. 2019a. "Global energy demand rose by 2.3% in 2018, its fastest pace in the last decade." International Energy Agency,. Last Modified 28 March 2019. https://www.iea.org/news/global-energy-demand-rose-by-23-in-2018-its-fastest-pace-in-the-last-decade.

———. 2019b. Tracking Power. (Paris, France: International Energy Agency). https://www.iea.org/reports/tracking-power-2019.

IRENA. 2019. Future of Solar Photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation: paper), International Renewable Energy Agency, Abu Dhabi. https://irena.org/-/media/Files/IRENA/Agency/Publication/2019/Nov/IRENA_Future_of_Solar_PV_2019.pdf.

ITM Power. 2017. "World's first tidal-powered hydrogen generated at EMEC." Accessed May 2. http://www.itm-power.com/news-item/worlds-first-tidal-powered-hydrogen-generated-at-emec.

Jenne, D.S., Y.-H Yu, and V. Neary. 2015. "Levelized Cost of Energy Analysis of Marine and Hydrokinetic Reference Models." 3rd Marine Energy Technology Symposium, Washington, D.C. NREL/CP-5000-64013.

John, Jeff St. 2020. "Transmission Emerging as Major Stumbling Block for State Renewable Targets." Greentech Media. Last Modified January 15 2020. Accessed May 19. https://www.greentechmedia.com/articles/read/transmission-emerging-as-major-stumbling-block-for-state-renewable-targets.

Katsaprakakis, Dimitris Al, Bjarti Thomsen, Irini Dakanali, and Kostas Tzirakis. 2019. "Faroe Islands: Towards 100% R.E.S. penetration." Renewable Energy 135: 473–484. https://doi.org/10.1016/j.renene.2018.12.042, http://www.sciencedirect.com/science/article/pii/S0960148118314733.

Lazard. 2019. “Levelized Cost of Energy and Levelized Cost of Storage 2019.” Lazard. Last Modified November 7 2019. Accessed May 18. https://www.lazard.com/perspective/lcoe2019.

Lehmann, Marcus, Farid Karimpour, Clifford A. Goudey, Paul T. Jacobson, and Mohammad-Reza Alam. 2017. “Ocean wave energy in the United States: Current status and future perspectives.” Renewable and Sustainable Energy Reviews 74: 1300–1313. https://doi.org/10.1016/j.rser.2016.11.101, http://www.sciencedirect.com/science/article/pii/S1364032116308164.

LiVecchi, A., A. Copping, D. Jenne, A. Gorton, R. Preus, G. Gill, R. Robichaud, R. Green, S. Geerlofs, S. Gore, D. Hume, W. McShane, C. Schmaus, and H. Spence. 2019. *Powering the Blue Economy; Exploring Opportunities for Marine Renewable Energy in Maritime Markets*. U.S. Department of Energy (Washington, D.C.: Office of Energy Efficiency and Renewable Energy U.S. Department of Energy). https://www.energy.gov/sites/prod/files/2019/03/f61/73355.pdf.

MacEnri, J, M Reed, and T Thiringer. 2013. “Influence of tidal parameters on SeaGen flicker performance.” *Philosophical Transactions of the Royal Society A*. https://doi.org/20120247, https://royalsocietypublishing.org/doi/10.1098/rsta.2012.0247.

Magagna, Davide, and Andreas Uihlein. 2015. “Ocean energy development in Europe: Current status and future perspectives.” International Journal of Marine Energy 11: 84–104. https://doi.org/10.1016/j.ijome.2015.05.001, http://www.sciencedirect.com/science/article/pii/S2214166915000181.

Marqusee, Jeffrey, Craig Schultz, and Dorothy Robyn. 2017. Power Begins at Home: Assured Energy for U.S. Military Bases. Reston, VA: Noblis. https://www.pewtrusts.org/~/media/assets/2017/01/ce_power_begins_at_home_assured_energy_for_us_military_bases.pdf

Minesto. “Faroe Islands—tidal energy to reach 100% renewable by 2030.” Minesto. https://minesto.com/projects/faroe-islands.

———. “Faroe Islands—tidal energy to reach 100% renewable by 2020a. “Minesto secures all permits for Faroe Islands’ installations.” Minesto. Last Modified April 1 2020a. Accessed May 18. https://minesto.com/news-media/minesto-secures-all-permits-faroe-islands%E2%80%99-installations.

———. “Faroe Islands—tidal energy to reach 100% renewable by 2020b. “Minesto signs PPA with electric utility SEV for utility-scale tidal energy installations.” Minesto. Last Modified February 19 2020. https://minesto.com/news-media/minesto-signs-ppa-electric-utility-sev-utility-scale-tidal-energy-installations.

Moazzen, I., B. Robertson, P. Wild, A. Rowe, and B. Buckham. 2016. “Impacts of large-scale wave integration into a transmission-constrained grid.” Renewable Energy 88: 408–417. https://doi.org/10.1016/j.renene.2015.11.049. <Go to ISI>://WOS:000368563900039.

Neff, Bryan. 2019. Estimated Cost of New Utility-Scale Generation in California: 2018 Update. (California Energy Commission). https://ww2.energy.ca.gov/2019publications/CEC-200-2019-005/CEC-200-2019-005.pdf.

Newman, S. 2020. “Marine Renewable Energy Meta-Analysis with the Microgrid Component and Optimization for Resilience (MCOR) Tool.” Richland, WA: Pacific Northwest National Laboratory. (Anticipated.)

Nova Innovation. 2019. “Bluemull Sound, Shetland.” Nova Innovation Ltd. Accessed September 10. https://www.novainnovation.com/bluemull-sound.

Orbital Marine Power. 2020. “Orbital Marine Power Takes Final Lessons from SR2000 Tidal Turbine and Brings Prototype Programme to a Close.” August 12, 2020.

https://orbitalmarine.com/orbital-marine-power-takes-final-lessons-from-sr2000-tidal-turbine-and-brings-prototype-programme-to-a-close/.

Oregon Department of Energy. 2012. "Why Wave Energy?: Why wave energy is good for Oregon's energy systems" https://digital.osl.state.or.us/islandora/object/osl%3A12964/datastream/OBJ/view

ORPC. 2020. "RivGen® Power System." ORPC Inc. Accessed May 18. https://www.orpc.co/our-solutions/scalable-grid-integrated-systems/rivgen-power-system.

Pace Global. 2017. 2017 Integrated Resource Plan Report Prepared for: Caribbean Utilities Company. (Pace Global).

Reikard, Gordon, Bryson Robertson, and Jean-Raymond Bidlot. 2015. "Combining wave energy with wind and solar: Short-term forecasting." Renewable Energy 81: 442–456. https://doi.org/10.1016/j.renene.2015.03.032, http://www.sciencedirect.com/science/article/pii/S0960148115002141.

Renewable Technology. 2017. "Strangford Lough Tidal Turbine, Northern Ireland." https://www.renewable-technology.com/projects/strangford-lough-tidal-turbine-northern-ireland/.

Renewable Energy Magazine. 2018. "Tesla Battery Storage Successfully Integrated with Tidal Energy Array." Accessed November 6. https://www.renewableenergymagazine.com/ocean_energy/tesla-battery-storage-successfully-integrated-with-tidal-20181031.

Roberts, A; Thomas, B; Sewell, P; Khan, Z; Balmain, S; Gillman, J. 2016. "Current tidal power technologies and their suitability for applications in coastal and marine areas." Ocean Engineering and Marine Energy. https://link.springer.com/content/pdf/10.1007%2Fs40722-016-0044-8.pdf.

Robertson, Bryson. 2010. *Ocean Wave Energy Generation on the West Coast of Vancouver Island and the Queen Charlotte Islands.* Vol. 3.

Samaras, Constantine, William J. Nuttall, and Morgan Bazilian. 2019. "Energy and the military: Convergence of security, economic, and environmental decision-making." Energy Strategy Reviews 26: 100409. https://doi.org/10.1016/j.esr.2019.100409, http://www.sciencedirect.com/science/article/pii/S2211467X19301026.

Sawyer, Tim. 2017. "Perth Wave Energy Project." Tethys. Last Modified January 24 2017. Accessed May 18. https://tethys.pnnl.gov/project-sites/perth-wave-energy-project.

ScottMadden. 2020. Informing the Transmission Discussion. WIRES (WIRES). https://wiresgroup.com/wp-content/uploads/2020/01/ScottMadden_WIRES_Informing-the-Transmission-Discussion_2020_0113_FINAL.pdf

Shirley, R., and D. Kammen. 2013. "Renewable energy sector development in the Caribbean: Current trends and lessons from history." Energy Policy 57: 244–252. https://doi.org/10.1016/j.enpol.2013.01.049. <Go to ISI>://WOS:000318530300029.

SIMEC Atlantis Energy, 26 July 2019. "Atlantis Successfully Decommissions 1.2 MW SeaGen Tidal System in Industry First," https://simecatlantis.com/2019/07/26/meygen-operational-update-3-2/.

Stoutenburg, E. D., N. Jenkins, and M. Z. Jacobson. 2010. "Power output variations of co-located offshore wind turbines and wave energy converters in California." Renewable Energy 35 (12): 2781–2791. https://doi.org/10.1016/j.renene.2010.04.033. <Go to ISI>://WOS:000280379400020.

Sustainable Marine Energy. 2019a. "Results of First Phase PLAT-I Testing at Grand Passage." Sustainable Marine Energy Ltd. Last Modified June 6th, 2019. https://sustainablemarine.com/news/plat-i-testing-1-1.

———. 2019b. "SME reveals plans for 9MW Pempa'q Tidal Energy Project." Sustainable Marine Energy Ltd. Last Modified September 30th, 2019. https://sustainablemarine.com/news/pempaq-project.

The University of Texas at Austin Energy Institute. 2020. "The Full Cost of Electricity." The University of Texas at Austin. Accessed May 19. https://energy.utexas.edu/policy/fce.

U.S. Department of Energy. 2015. "Advancing Clean Electric Power Technologies: Technology Assessments." In *Quadrennial Technology Review 2015*.

———. 2019a. *H2@Scale: Enabling Affordable, Reliable, Clean, and Secure Energy across Sectors*. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (Washington, D.C.). https://www.energy.gov/sites/prod/files/2019/09/f67/fcto-h2-at-scale-handout-2019.pdf.

———. 2019b. *Water Power Technologies Office 2019 Peer Review Final Report*. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (Washington, D.C.). https://www.energy.gov/eere/water/2019-water-power-program-peer-review-report-and-presentations.

Ueckerdt, Falko, Lion Hirth, Gunnar Luderer, and Ottmar Edenhofer. 2013. "System LCOE: What are the costs of variable renewables?" Energy 63: 61–75. https://doi.org/10.1016/j.energy.2013.10.072, http://www.sciencedirect.com/science/article/pii/S0360544213009390.

Whitlock, Robin. 2015. "Azura wave energy device deployed at US Navy test site." Renewable Energy Magazine. Last Modified 18 June 2015. Accessed May 19. https://www.renewableenergymagazine.com/ocean_energy/azura-wave-energy-device-deployed-at-us-20150618.

Yu, Yi-Hsiang, Nathan Tom, and Dale Jenne. 2018. "Numerical Analysis on Hydraulic Power Take-Off for Wave Energy Converter and Power Smoothing Methods." ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering.

Zhou, Zhibin, Mohamed Benbouzid, Jean Frédéric Charpentier, Franck Scuiller, and Tianhao Tang. 2013. "A review of energy storage technologies for marine current energy systems." Renewable and Sustainable Energy Reviews 18: 390–400. https://doi.org/10.1016/j.rser.2012.10.006, http://www.sciencedirect.com/science/article/pii/S1364032112005485.