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Grid Value Proposition of Marine Energy: A Preliminary Analysis

November 2021

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U.S. DEPARTMENT OF ENERGY

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Abstract

Marine energy technologies convert the energy of ocean waves, and tidal, river, and ocean currents into electricity and other forms of usable energy. The marine energy resource potential in the United States is significant and geographically diverse, with a study commissioned by the U.S. Department of Energy estimating that the nation's annual marine energy potential is approximately 2,300 TWh/year across the 50 states, or greater than 57 percent of U.S. electricity generation in 2019. However, the marine energy industry still faces hurdles to commercialization. While high costs relative to wind and solar remain a key challenge, other hurdles relate to marine energy's value streams not being well characterized and not captured by traditional energy comparison metrics like the levelized cost of energy. To address this challenge, this project undertakes several types of analyses to identify and illustrate value propositions for marine energy resources. It provides a fresh framework for considering electric system benefits based on unique marine energy attributes and provides analyses illustrating and quantifying those benefits. Although the technology remains in a development stage, the authors find many potential opportunities for the deployment of marine energy technologies both in the near term and within typical utility planning timeframes (i.e. up to 20 years). From a resource and technology perspective, marine energy resources can deliver distinct and valuable benefits to different configurations of the grid, whether the bulk system, isolated distribution systems, or remote communities, islands, and microgrids. Marine energy resources can be valuable in increasing technology diversity in a generation portfolio, providing energy where it is otherwise difficult to come by, supporting local resiliency, complementing and being complemented by other resources including solar, wind, and energy storage, and avoiding land constraints.

Summary

Introduction

Marine energy has the potential to be a key clean energy resource in the future grid and the transition to a 100% renewable energy economy. Several U.S. states have established strong renewable or clean energy targets and the U.S. Federal Government has declared a policy goal of a 100% carbon-free electricity sector by 2035.[4]

Through worldwide efforts by governments and industry, wind and solar resources have achieved grid cost parity with traditional generation and energy storage technology costs are rapidly declining. However, these resources may be insufficient on their own to ensure a reliable renewable grid at reasonable cost. Research indicates that resource diversity in time and space would reduce the overbuild of wind, solar, and energy storage to meet load by supplying energy when and where solar and wind are not available.[5] This is particularly relevant in island or remote communities that do not have land availability or transmission connections to leverage geographic diversity from solar and wind. Prevailing solutions to this challenge have vectored toward grid-scale batteries and storage, other types of hybrid electric power plants, distributed energy resources, demand response and load management practices, advanced market designs, and new natural gas development.[6] However, there is a notable gap between the character of the solutions needed in the emerging future and the limitation of currently available technologies to respond to them.

Marine energy resources are well placed to provide such diversity and meet this challenge. They are abundantly available along the country's coastlines, island regions, and in rivers or channels. They avoid land-use pressures that might otherwise limit resource development and decrease available land for other important uses. Further, they provide improved predictability over their wind and solar counterparts. This predictability will be increasingly important in ensuring grids can be operated reliably as solar, wind, and other variable renewable resources continue to grow.

While technologies that convert marine energy resources to renewable power are advancing rapidly, the industry still faces hurdles to reach full commercialization. First and foremost, marine energy technologies remain at a relatively early stage of development and validation. Second, costs are high, and devices are largely custom one-off builds. Third, and of importance to grid operators, whether ISO New England or Maui Electric, marine energy devices have not yet been proven as grid assets and their technical capabilities, characteristics, and reliability over long-term operations are not well known. Despite these challenges, the potential for marine energy as a future grid technology remains strong. Wind and solar generation resources were

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[4] Thirty U.S. States and the District of Columbia have a Renewable Portfolio Standard and 5 states have a Clean Energy Standard. Additionally, 8 states have renewable portfolio goals, and 5 states have clean energy goals. DSIRE, at *Renewable Portfolio Standards and Clean Energy Standards,* https://www.dsireusa.org/resources/detailed-summary-maps/, December 2020. and Executive Order, January 27, 2021. See Section 205 (b)(i), https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-on-tackling-the-climate-crisis-at-home-and-abroad/

[5] *See*, *for example:* Staff Report to the Secretary on Electricity Markets and Reliability, U.S. Department of Energy, August 2017, and Ioannidis, A., et al. (2019). "The case for islands' energy vulnerability: Electricity supply diversity in 44 global islands." Renewable Energy 143: 440-452.

[6] Henbest, et al. *New Energy Outlook 2019.* 2019. Bloomberg New Energy Finance. Available at: https://about.bnef.com/new-energy-outlook/

once in the same position: relatively nascent technologies that were unproven, costly, and not well understood. Batteries have recently conquered these challenges, and only in the last few years have utilities deployed battery resources in any significant capacity.

A key to overcoming challenges of high cost and unproven performance is to identify the potential value that marine energy devices present to different parts of the electric system. Without real-world deployments, this value is not well known nor captured by traditional energy comparison metrics like the levelized cost of energy. Accelerating the understanding of marine energy's value proposition among utilities and system operators will help ensure marine energy technologies are considered in energy planning. Greater awareness of marine energy's value will also help manufacturers and developers target their device designs and deployments to optimize the capture of value in delivering electricity and associated services. Finally, it will help the U.S. Department of Energy and other research institutions target their funding to optimize future marine energy demonstration and deployment efforts. To become commercially successful, the sector needs to explain why it can provide a unique contribution beyond energy decarbonization, which is otherwise readily available from other renewable resources at lower costs.

Pacific Northwest National Laboratory, working with colleagues from the National Renewable Energy Laboratory, Oregon State University, and the Pacific Ocean Energy Trust have together conducted several types of analyses to identify an illustrated value proposition for marine energy resources. This effort provides a fresh framework for evaluating electric system benefits based on marine energy's attributes and provides **a preliminary analysis to illustrate and quantify those benefits, considering the early stage of technology development.**

Approach

The goal of this work is to identify, evaluate, and measure characteristics of marine energy that may offer unique benefits to the electric grid by building a crosswalk between technology and electric grid value. Certain aspects of marine energy—location, relative predictability, generation patterns, and persistence—should be beneficial. But there has been limited research to date into analyzing and quantifying these benefits (Preziuso et al. 2019). Just as solar is not the cheapest energy resource at scale, the technology is still successful because it offers unique benefits like modularity and scaling to residential and distribution applications that make it a competitive solution. Similarly, marine energy likely has a value proposition for the electric grid under certain circumstances, where few other generating resources are feasible. For example, early research suggests that transmission investments to remote coastal locations can be deferred or avoided altogether by deploying marine energy resources. To achieve very high deployment levels of renewable energy, winter peaking resources with seasonal variation such as marine energy could be crucial. And as a predictable resource with periodicity linked to electric system needs, marine energy would require a fraction of associated integration costs of other variable resources (Preziuso et al. 2019). This project seeks further insight into this early research and provides more concrete information on marine energy's potential.

For purposes of this investigation, the term *grid value* should be broadly construed. It 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; 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 does not necessarily accrue to one entity. Even the term *grid service* has various definitions and applicable taxonomies, depending on the market environment, system operator, or utility business model.

A broad range of energy conversion device designs exist for tidal and ocean current energy and, in particular, for wave energy. While there are additional marine energy resources such as in-river hydrokinetic, ocean thermal, and salinity gradients, this project is limited to wave, tidal, and ocean current technologies.

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

To the extent possible, this work relies on representative devices for each technology category to allow for representative results. The potential for these technologies to provide electricity and grid services is substantial, so modeling them in a device-agnostic way is critical for establishing a representation of their value. **To be clear, we identify representative value and opportunities, and this work is not intended to definitively quantify value streams associated with potential deployments, rather shed light on possibility.** With nearly 40% of the United States' population living in counties on the coast and vast untapped resources available, there is a clear opportunity for marine energy technologies to play a role in the energy mix.[7]

It is important to note that we intentionally do not evaluate costs of deployment for marine energy resources nor transmission and distribution investments. Further, we do not consider environmental effects associated with device deployment. This is not because these costs are not real nor significant, but because there is a wealth of ongoing work across industry, the U.S. Department of Energy laboratories, universities, and other research institutions to improve device designs, reduce technology costs, and evaluate and mitigate environmental impacts associated with marine energy. We are focused on value.

Data, Models, and Prior Work

However, there exists a key hurdle to take advantage of this opportunity: the availability of grid quality data. Utilities and other system operators require a detailed understanding of a grid connected asset's output characteristics before they may permit interconnection to a system. High quality data describing the output characteristics of marine renewable energy devices are

[7] *See* "What percentage of the American population lives near the coast?" National Oceanic and Atmospheric Administration. https://oceanservice.noaa.gov/facts/population.html.

needed to operate the grid system within reliability limits, but these data are not available. There have not been many real-world deployments of marine energy resources to generate this information. But beyond the detailed data needed for interconnection, grid quality data are not readily available to even evaluate a value proposition for potential deployment. This is not a criticism of industry, but a recognition of the reality that more work is needed, and devices are improving and evolving. To address the gap, this project spends considerable effort in developing the electric output data necessary to evaluate marine energy's grid value proposition. We worked with resource experts to identify data in locations of interest, leveraging the Department of Energy's extensive ongoing efforts to characterize marine energy resources. We then engaged technology experts to turn that raw resource data into electric output, identifying representative wave, tidal, and ocean current devices and associated performance parameters. Finally, we engaged our grid experts and utility partners to identify grid models and data to analyze the value of the electric output. Unfortunately, detailed marine energy data are not always readily available and are particularly tough to come by at the granularity in time intervals needed for detailed grid analyses. As a result, we often had to derive new methods of analysis, though based on more typical grid analysis approaches, that could leverage the data available.

Prior work has been limited to analyses comparing marine energy development with other resources. There have been general studies that compare the levelized cost of energy of a marine device with that of solar or wind. Other more specific studies evaluate deployments and compare capital and operating costs of alternatives to deliver energy (Preziuso et al. 2019). Effectively, these studies take a cost-first approach, identifying the cost components of the technology to generate one unit of energy. However, the goal of this work is to take a value-first approach to identify, evaluate, and measure characteristics of marine energy that may offer unique or competitive benefits to the electric grid. Accordingly, we undertake analyses that are not dependent on specific technology assumptions or parameters but consider deployment from a locational perspective. That is, our analytical approach, while requiring a focus on specific locations for resource and grid characterization, is carried out in a way as to be extensible to other environments and device designs. The approach includes a combination of different types of modeling methodologies and tools, strong partnerships with technology and resource experts, and engagement with marine energy and local stakeholders.

Value Streams

In this project, we outline the landscape of marine energy attributes and their potential value streams, or benefits, into three bins: (a) spatial or locational aspects; (b) temporal or timing aspects; and (c) special applications. This structure ensures most potential benefits are captured, and finding the intersection between these benefits, available resource data, generation technology models, and grid data was a key component for enabling research. Figure S-1. Analytical approach framework identifying the suite of attributes, or value, marine energy resources can deliver to the grid organized by the characteristics of location, timing, and special applications. identifies the attributes, or values, distributed among the bins. It is vitally important to consider a broad swath of potential benefits to characterize services through a marine-energy-specific lens and develop an understanding and quantification of their value. A review of data requirements, methods, and employed models, and a range of services and values that marine energy could contribute to the grid, was informative in narrowing the services for further review and analysis. The research team identified which value streams deserved closer inquiry and downselected to the "relevant" grid services and potential benefits considered in this work. They became the focus for the case studies and illustrative valuations. These specific analyses balance the necessity of incorporating detailed resource availability,

LOCATION

System Benefits

- System Investments
- MRE as non-wires alternatives (NWA)
- Avoided or deferred distribution and transmission investments

Local support

- Local load and balancing needs
- Power quality and voltage support (volt/VAR)

Power Flow

- Reduced congestion (coastal cities and transmission corridors)
- Remote system improvements (avoided line losses and transmission and distribution loading)

Land Use

- Increased energy density of coastal land
- Avoided opportunity cost of land use for energy generation
- Provision of energy in areas where there is low to no availability (dense, remote and island regions)
- Address policy goals for intra-BA development

Portfolio effects

- Improved geographic diversity of the generation portfolio: reduced system capacity and balancing requirements and a natural resiliency effect.

TIMING

Predictability

- Reduced integration requirements and associated costs: reduction in reserve requirements, needs for gas/hydro ramping
- Enhanced market participation: bid accuracy, qualification, scheduling certainty, penalty avoidance, extended time window for decision making in forward markets

Seasonality

- Coincidence with load
- Complementary with other resource availability

Scheduled / dispatchable generation ("Tidal as baseload")

- Aggregation: resource diversity offset to create a "baseload" profile
- Dispatchability and participation in markets with storage
- Optimization of generation with storage

Portfolio effects

- Negative correlation with wind and solar at very high penetrations (e.g. winter peak)
- Thermal improvements: displacement, reduced cycling, improved efficiency, and reduced emissions
- Effective load carrying capability (ELCC) and capacity credits for MRE
- Reduction in system costs, capacity and balancing requirements with an integrated portfolio
- System reliability improvements: effects on LOLE and LOLP

SPECIAL APPLICATIONS

Enabled services

- MRE as a behind the meter resource (customer and grid benefits)
- Storage for flexibility and dispatchability
- Microgrid suitability: coastal, remote communities and islands (e.g. Barbados, Faroe Islands, Igiugig)
- Improvement in performance of other technologies (symbiotic benefits)

Resiliency

- Reduced vulnerability to electricity disruptions.
- Reduced reliance on conventional backup generation and risk from fuel availability and price volatility.
- Avoidance of sustained effects to critical infrastructure from grid disruption as a microgrid resource, in combination with microgrids, or as a backup generation resource.
- Systemwide and localized black start

Portfolio effects

- MRE modularity and array-based development allows for as-needed expansion, reducing financing risk, up-front costs and ongoing operations and maintenance costs.
- Reduced dependence on diesel and natural gas production and delivery infrastructure.
- Improvements to meeting environmental and sustainability goals.

Figure S-1. Analytical approach framework identifying the suite of attributes, or value, marine energy resources can deliver to the grid organized by the characteristics of location, timing, and special applications.

technology characteristics, and grid conditions with the desired outcome of more generalizable insights.

Findings

Our work indicates that marine energy can provide important benefits to the grid in the form of energy, capacity, and reserves, as well as baseload power that strengthens the use of energy storage systems and complements less predictable renewable generation. A strategy targeting these benefits can become central to industry efforts to reduce costs, grow to scale, and be key to the nation's grid modernization priorities.

Research and credible information are lacking on the grid value and applications of marine energy resources and technologies.

Marine energy cost and performance is currently not competitive relative to established technologies. Indeed, a review of utility integrated resource plans across the country indicates that when marine energy is even considered for deployment it is often categorized as emerging technology to be studied in detail in future plans. But this same reasoning repeats in several plan iterations without further study. In addition, costs and performance parameters vary widely (see Figure S-2) and the lack of installed grid-connected examples further limits the availability of this information and data about device performance and reliability.

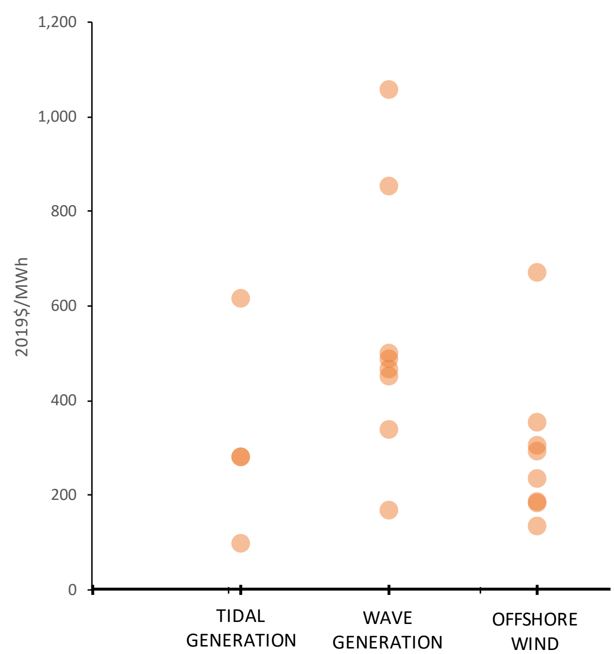

Figure S-2. Levelized cost of energy (converted to 2019 dollars) for tidal generation, wave generation, and offshore wind as reported in integrated resource plans (Cooke, O'Neil, and Preziuso 2020).

Taken together, this presents barriers for the deployment of marine energy as a grid resource: utilities and system operators are not willing to explore technology deployment when adequate information and data are not available. That said, many of these same resource plans do identify marine energy as a potential option and more recent plans from some utilities explicitly identify advantages to using marine energy devices. There is an opportunity here for the marine energy industry.

Locational Value

Deployment of marine energy resources to deliver energy to coastal loads can fulfill local energy needs and reduce transmission utilization elsewhere on the system, freeing up capacity to provide additional renewable resources.

The deployment of wave resources along the Oregon coast reduces coastal demand for eastern generation, thus opening transmission capacity from eastern Oregon and the Gorge into northwest and central Oregon, with an increasing amount of wave resource providing increased opened capacity as shown in Figure S-3. This could enable existing transmission to provide additional generation from the Columbia Gorge, eastern Oregon, and points north and east, such as solar from eastern Oregon and Washington or wind resource-rich Wyoming to West Coast loads. This may be particularly valuable given that western states have stringent renewable or clean energy generation targets and building new transmission is an expensive and logistically challenging proposition. The transmission capacity is likely to manifest in system cost savings associated with reduced transmission losses and lessen balancing reserves needed to serve load because of the added generation diversity of the coastal resource. A similar evaluation for the east coast and the rest of the west coast is likely to indicate value for marine energy and other offshore resource development, particularly in populated areas. This is evidenced by the effort underway in New England and the upper Atlantic coast to deploy offshore wind.

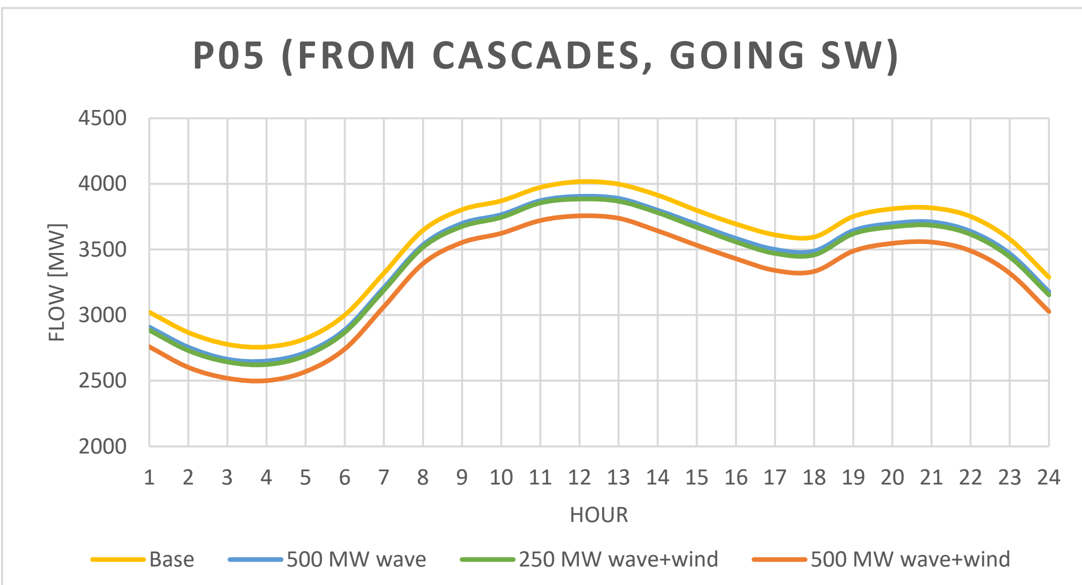

Figure S-3. Impacts to hourly average flows from wave and wind integration on Western Electricity Coordinating Council Path 05; positive direction flow is west. The base case is the Western Interconnect in 2028 as modeled by the Western Electricity Coordinating Council. Wave and wind cases represent an equal amount of each resource (i.e., 250 MW of each or 500 MW of each).

Further, wave resource deployment on the coast provides a resilience benefit in serving local loads, reducing coastal reliance on energy delivered via transmission. This benefit may be enhanced through co-deployment with offshore wind resources, which can provide similar benefits. Co-deployment with wind may also provide value in sharing infrastructure and associated costs between technologies. Beyond offshore resources, Oregon geography prevents the development of other coastal renewables. An evaluation of northern California wave and offshore wind is likely to indicate similar results with rugged terrain on the coast preventing local onshore energy development. In other parts of west coast and the east coast, land limitations in populated areas may also limit coastal generation and present a resilience value for communities associated with offshore resource deployments.

The deployment of marine energy resources on distribution grids can help deliver renewable energy to local loads while alleviating distribution system voltage issues.

In the San Juan Islands off the coast of northern Washington, the tidal energy resource correlates to winter peaking load, whereas solar energy peaks in the summer. On an hourly basis, the tidal resource is strongest during the winter evening peak. Accordingly, tidal energy has direct value for the Orcas Power and Light Co-Op system. The utility is required by Washington State's Clean Energy Transformation Act to deliver 100% of its electricity from renewable or non-emitting resources by 2045 and has an internal goal to supply 50% of its electricity from resources on the islands. It currently purchases nearly all its electricity from the mainland. These requirements and goals, in addition to limited land availability, highlight the potential value associated with deploying tidal energy, which has significant potential in the channels around the islands. Further, under its current mainland power purchasing approach, Orcus Power and Light can generate demonstrable savings by deploying incremental tidal resources. These manifest as energy purchase savings, a load shaping benefit, reduced transmission charges, and transmission line deferral benefits.

The availability of tidal energy during hours when other resources such as solar are not available helps flatten the voltage profile of a distribution grid to which they may be interconnected, such as a small island system. In such a scenario, the deployment of tidal energy eases the meeting of voltage quality requirements and results in fewer voltage regulators reaching their upper limits on tap changes, increasing regulator longevity and reliability. That said, despite the potential benefits, tidal interconnection can exacerbate voltage swings associated with strong energy output during night hours. The coupling of tidal resources with energy storage resources can help to reduce these swings. On its own, energy storage can be shown to provide relief in peak loading of the distribution system and facilitate lower system energy losses. Combining storage with marine energy can help reduce the magnitude of the storage required by complementing other renewables while delivering energy. These benefits are of value in island and remote communities where reliance on a larger grid for balancing and resource diversity is not possible.

Timing Value

Marine energy resources, when included in the generation portfolio, can be shown to reduce balancing energy requirements leading to an overall reduced reliance on dispatchable fossil generation or reduced energy storage buildout.

Our results indicate that marine resources compare favorably against proximal wind and solar in resource availability, resource persistence, and resource versatility.[8] Specifically, tidal and wave resources were observed to be more available and persistent than both solar and wind. The ocean current resource off the Florida coast, while being slightly less available than solar, has a reasonably higher availability and persistence value when compared to wind. Beyond the resource-focused metrics of availability, persistence, and versatility, we also perform a grid-specific capacity value analysis, in context of the U.S. Pacific Northwest grid. This analysis demonstrates that wave energy has a higher load-carrying capacity relative to solar and wind generation located in the same geographic area.

We also study hourly system balancing needs, that is the mismatch between generation and load, and find the annual hourly maximum balancing requirement to be reduced by 19.5% in our Pacific Northwest system, using wave energy in place of an equivalent amount of wind and solar together (deployed in equal amounts). This is particularly valid in winter during night hours when the wave resource is robust. Figure S-4 identifies this trend. We believe the trend can be attributed to (a) the relatively stable nature of the wave resource relative to wind and solar, and (b) the wave resource being typically winter-peaking energy in the Pacific Northwest. As increasing levels of wind and solar continue to be deployed to meet renewable and clean energy goals, marine technologies are likely to have value in complementing this deployment and reducing balancing requirements to meet load.

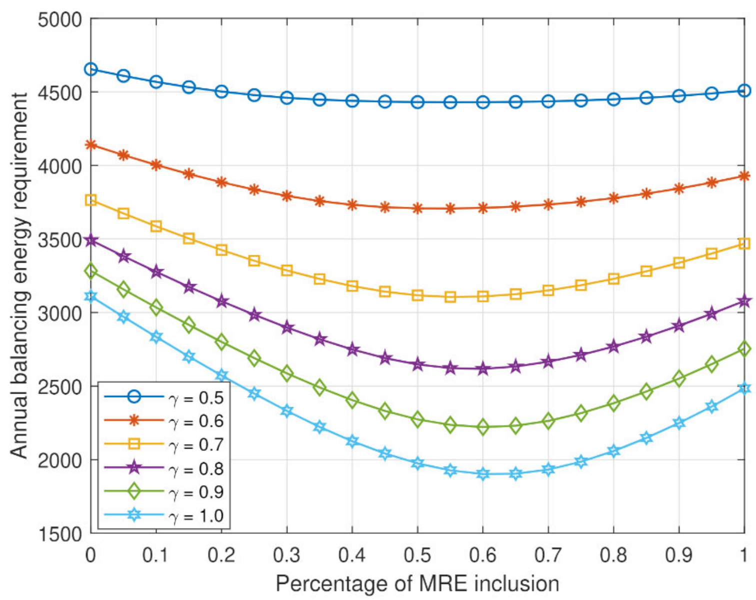

Figure S-4. Balancing energy requirements as a function of marine deployment levels under different overall renewable energy deployment levels. An increase in the fraction of marine energy, represented in the x-axis (displacing an equivalent amount of wind and solar) leads to a reduction of balancing requirements, under different levels of overall renewable penetration (γ), but there is a limit, or inflection point, after which marine energy negates its diversity value. The y-axis is in units of 10^4 MWh.

[8] Resource availability is the percent of time the resource is above a minimum generating point over a certain period. Resource persistence is a measure of resource availability across contiguous time slots. Resource versatility is a measure of the availability of alternative generation resources. The comparison between resources is made for energy output relative to the same installed capacity.

Deploying marine energy can reduce balancing requirements associated with high levels of renewable integration across both distribution and bulk power systems, which may be of near-term value to island power systems.

Our results indicate that marine energy can help alleviate energy storage capacity requirements under high renewable deployment scenarios, complementing the output of other renewable sources. The nature and extent of that benefit, however, is sensitive to several factors including location, characteristics of other energy resources, load characteristics, and characteristics of the marine resource.

Figure S-5. Required energy capacity (top) and total avoided/incurred costs (bottom) as a function of the deployment of solar, wave, and fossil energy for a hypothetical Nantucket Island system, assuming all energy is delivered with island resources. Energy storage is assumed to have a round-trip efficiency of 0.86 and deployment cost of 342 $/kWh (Kendal 2018). illustrates the required energy storage capacity and associated cost to balance the Nantucket Island grid in Massachusetts, assuming all energy is delivered from island resources. In this example, a generation portfolio with a 30% proportion of wave energy minimizes the storage capacity required to balance the system at an hourly level. Beyond this, benefits progressively diminish and eventually lead to an inflection point and increasing costs. The diminishing returns are a result of the correlation between load and the wave and solar resource profiles in Nantucket—load peaks during the summer whereas wave energy is a winter peaking resource. An analysis for the northwestern United States indicates similar benefits helping to optimize storage deployment associated with the deployment of marine energy resources.

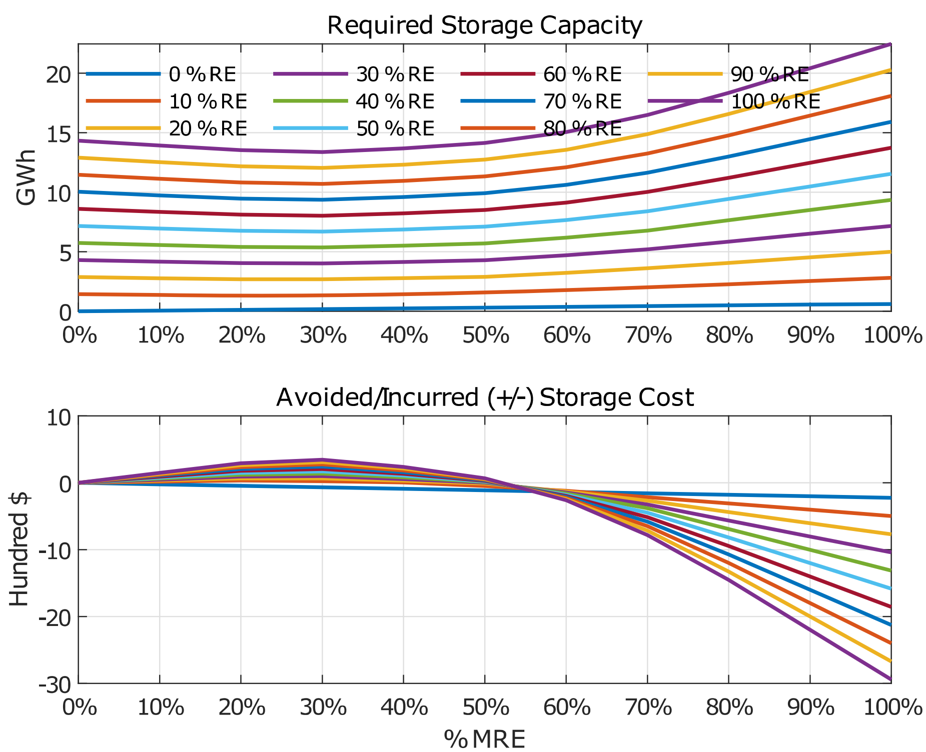

Figure S-5. Required energy capacity (top) and total avoided/incurred costs (bottom) as a function of the deployment of solar, wave, and fossil energy for a hypothetical Nantucket Island system, assuming all energy is delivered with island resources. Energy storage is assumed to have a round-trip efficiency of 0.86 and deployment cost of 342 $/kWh (Kendal 2018).

Special Applications

Marine energy can be shown to reduce capital and fuel costs associated with dispatchable generation and energy storage costs in microgrid and small grid environments while maintaining delivery of supply and supporting system resiliency.

To help achieve the island of Molokai's 100% clean energy goals, we considered the deployment of wave energy, which has a strong resource potential on Molokai's northern shore and exists on the northern shores of the other Hawaiian Islands. Incorporating wave resources into the current system, in place of solar, to meet 95% or 100% emissions-free target requires significantly lower additional capacity (about 15-47% lower) relative to adding more solar resource to the base system. Similarly, deploying a fixed amount of wave resource in place of a fixed amount of additional solar to the base system reduces the additional energy storage needed to meet a 100% emissions-free target by up to 17%. Finally, deploying a fixed amount of wave resource in place of a fixed amount of solar to the base system brings down dispatchable generation (e.g., diesel) capacity and fuel use needed to meet load by up to 66% and 62%, respectively, in place of using additional solar. In this last situation, the deployment of wave energy shows up to a 90% improvement of the sustainable ride-through energy ratio relative to the base system and a 33% improvement relative to using added solar resources.[9] Figure S-6. Dispatch for (a) the base system, (b) the base system with 5 MW of solar capacity added, (c) the base system with 5 MW of wave capacity added. The load is indicated by the gray line, solar generation in orange, wind production in purple, battery discharge energy in green, dispatchable generator production in red, and wave generation in blue. shows resource dispatch across different scenarios. It indicates that even though the same renewable energy capacity is added to the base system in plots (b) and (c), the required dispatchable generation (shown in red) is much lower with the addition of wave compared with solar.

[9] Sustainable ride-through ratio describes the fraction of load supplied over a period without consuming fuel.

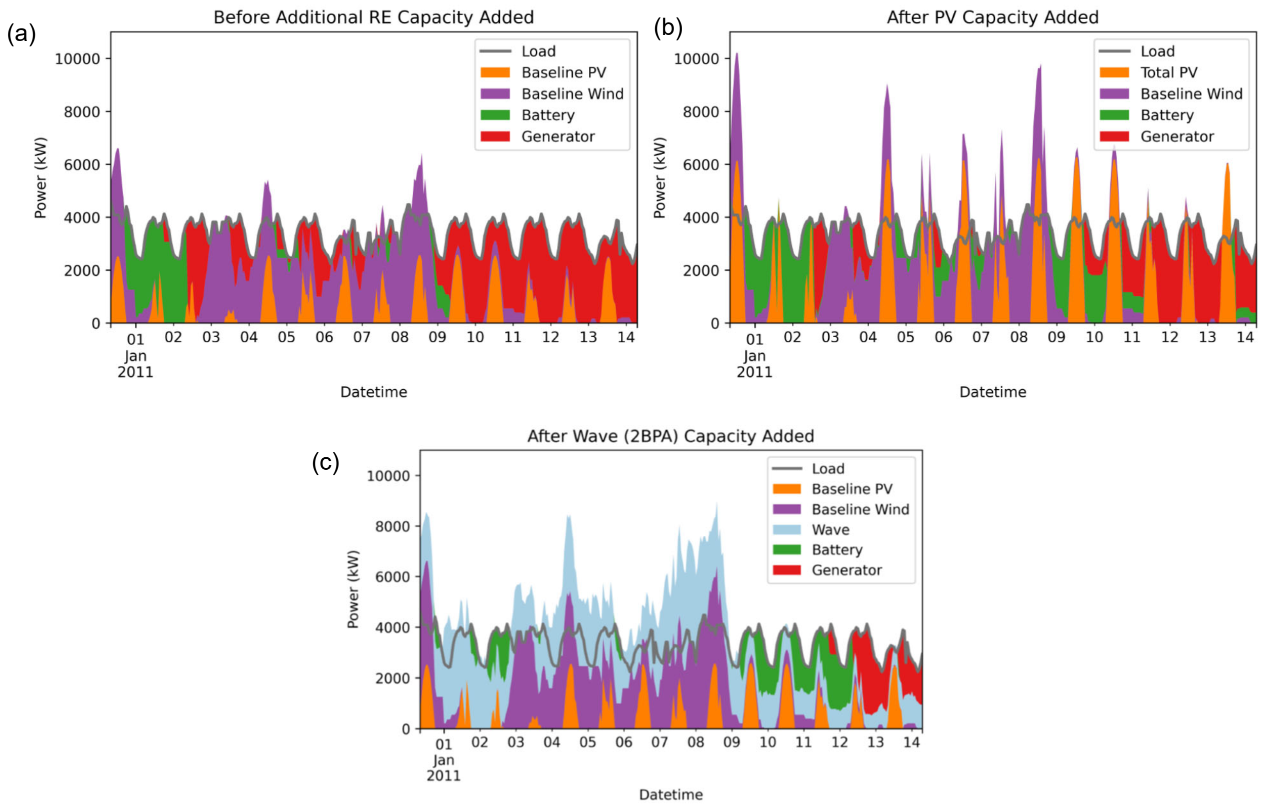

Figure S-6. Dispatch for (a) the base system, (b) the base system with 5 MW of solar capacity added, (c) the base system with 5 MW of wave capacity added. The load is indicated by the gray line, solar generation in orange, wind production in purple, battery discharge energy in green, dispatchable generator production in red, and wave generation in blue.

Similarly, for the Island of Nantucket, replacing combustion turbine capacity with tidal generation minimizes operational risk levels relative to turbine replacement by solar or wave resources in both normal operating and singular contingency conditions. The evaluation of operational risk is used as proxy for resiliency and considers both ongoing operations and contingency situations. These results stay consistent across seasons of the year and indicate that tidal resources in Nantucket may be a suitable source of local clean energy. While wind resources provide similar results, land limitations and resident pushback in a tourist and summer home destination may advantage tidal development.

These results highlight the value of marine energy as a complementary resource to other renewables: its deployment increases the likelihood that at least one resource is producing energy at any given time. These considerations are significant for remote and island grids, which cannot lean on a larger grid or readily available fuels. Accordingly, small islands and remote grids may be prime candidates for near-stage marine energy investments. Marine energy developers may find interested and willing utility partners in such locations.

Marine energy resources, when collocated with other offshore or near-shore renewable resources in hybrid systems, can bring down overall plant output volatility and generation ramp rates.

An analysis of hourly ramp rates indicates benefits in the coupling of marine energy and other renewable resources. Specifically, the coupling of wave and offshore wind resources on the Oregon coast and solar and wave resources on the Northern Puerto Rican coast show statistical reductions in hourly ramp rates. This reduction can translate to lower integration costs for renewables resources, particularly as these regions aim to meet clean energy goals. The coupling of resources may also enable mutual benefits for infrastructure investment, including ports, ships, and transmission and distribution facilities. Further evaluation considering higher a resolution resource or device output data may reveal additional value and may indicate an increased magnitude of the potential identified value.

Marine energy resources can help to relieve land-use pressures associated with renewable energy development in both populated and remote regions.

Land-use constraints are expected to increase as regions move toward higher levels of renewable deployments and climate impacts further constrain land availability for other uses. Existing land constraints already reveal the benefits of marine energy development: both the Cayman Islands and Barbados have explicitly identified land availability for renewable generation as a near-term challenge as they move toward increasing their clean energy generation portfolios. Similar situations are likely to materialize in land-constrained U.S. regions and islands.

Next Steps

Overall, we find several attributes of marine energy that point to potential opportunities for deployment, both in the near term and within typical utility planning timeframes (up to 20 years). From a resource and technology perspective, marine energy can deliver distinct and valuable benefits to different configurations of the grid, whether bulk systems, isolated distribution systems, or remote communities, islands, and microgrids. Marine energy can be valuable in increasing technology diversity in a portfolio of resources, providing energy where it is otherwise difficult to come by, supporting local resiliency, complementing and being complemented by other resources including solar, wind, and energy storage, and avoiding land constraints. The situation is ripe for marine energy stakeholders to further advance understanding of the technology in the grid planning community.

To date, there has been little work like this, even though the marine energy industry recognizes that a better characterization of the technology's value is needed. This work and similar value-focused efforts for other marine energy applications such as *Powering the Blue Economy* can help target technology design and deployment to where value is greatest.[10]

[10] LiVecchi, A, et al. 2019. Powering the Blue Economy; Exploring Opportunities for Marine Renewable Energy in Maritime Markets. U.S. Department of Energy. Available at: https://www.energy.gov/sites/prod/files/2019/03/f61/73355.pdf.

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Acronyms and Abbreviations

ADS	Anchor Data Set
BA	balancing authority
BPA	Bonneville Power Administration
BBDB	backwards bent-ducted buoy
COI	California-Oregon Intertie
DER	distributed energy resource
FPA	floating point absorber
IRP	integrated resource plan
LCOE	levelized cost of energy
LOLP	loss of load probability
MRE	marine renewable energy, or marine energy
NREL	National Renewable Energy Laboratory
NWA	non-wires alternative
OPALCO	Orcas Power and Light Co-Op
PACE	PacifiCorp East
PACW	PacifiCorp West
PV	photovoltaic
PNNL	Pacific Northwest National Laboratory
RA	resource availability
RP	resource persistence
SRE	sustainable ride-through energy ratio
WEC	wave energy converter
WECC	Western Electricity Coordinating Council

Contents

1.0 Introduction

1.1 Background and Motivation

In the last 25 years, through advances in policy, technology, and investment, wind and solar photovoltaic (PV) energy projects were widely developed in the United States. Today, costs to deploy wind and solar resources on an incremental energy basis have dropped to parity with conventional resources and levels of wind and solar production can reach significant percentages of total energy production. In some cases, when paired with hydropower, solar and wind can support large electric system-scale loads in their entirety.[11]

This has bolstered optimism for the potential of 100% clean energy-fueled electric systems while raising serious questions about operational realities, such as system reliability and stability, energy adequacy, variation in economic value and marginal costs, and the signals from market and investment structures to respond to those realities, or challenges. As dispatchable generating resources are retired, there is a new premium on resources that offer predictable generation profiles, deployment in critical locations to support weaker grids, resource diversity, and the resilience benefits of operating during grid disruptions with on-site fuel. Domestic coastal electric loads will require new solutions that support isolated grids or large loads such as cities with transmission constraints.

After wind and solar, the next generation of clean energy technologies and resources remain challenged by traditional cost metrics and commercial maturity stages. While hydropower was extensively developed between 1940 and 1980, very little development has occurred recently.[12] Still, it is expected that hydropower will play an important role in enabling system reliability into the future.[13] Prevailing solutions have vectored toward grid-scale batteries and storage, hybrid electric power plants, distributed energy resources, demand response and load management practices, advanced market designs, and new natural gas development.[14] There is a notable gap between the character of the solutions needed in the emerging future and the limitation of currently available technologies to respond to them.

Marine energy technologies convert the energy of ocean waves and tidal, river, and ocean currents into electricity and other forms of usable energy. U.S. marine energy resources are significant and geographically diverse. The National Renewable Energy Laboratory estimates that the nation's wave, tidal, and current energy potential is approximately 2,300 terawatt-hours per year across the 50 U.S. states, or greater than 57 percent of U.S. electricity generation in 2019. There are particularly high levels of wave energy in the Pacific Ocean; tidal energy across the Northeast, Pacific Northwest, and Alaskan coasts; and ocean current energy along the

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[11] See "Costa Rica generates almost 100% renewable energy in 2016." April 2017. Renewable Energy Focus. Available at: https://doi.org/10.1016/j.ref.2017.03.003

[12] Uría-Martínez, et al. *U.S. Hydropower Market Report*. January 2021. U.S. Department of Energy Water Power Technologies Office. https://www.energy.gov/sites/prod/files/2021/01/f82/us-hydropower-market-report-full-2021.pdf

[13] See "HydroWIRES Initiative." May 2020. U.S. Department of Energy Water Power Technologies Office. Available at: https://www.energy.gov/eere/water/hydrowires-initiative

[14] Henbest, et al. *New Energy Outlook 2019.* 2019. Bloomberg New Energy Finance. Available at: https://about.bnef.com/new-energy-outlook/

southern Atlantic coast.[15] The energy contained within these resources is reliable, predictable, does not generate carbon emissions, and can be developed in an environmentally friendly manner.

However, as electricity stakeholders imagine the future electric grid, marine energy is not often considered. This is evidenced by a survey-level review of utility resource plans (Cooke, O'Neil, and Preziuso 2020). The origins of this oversight can be found in traditional cost metrics such as levelized cost of energy (LCOE) and limited commissioned facilities to date.

To overcome these barriers, marine energy requires a value proposition to the electric system:

- Under what circumstances can marine energy be competitive or complementary with other generating resources?
- What unique values can marine energy contribute?
- What characteristics make marine energy resources valuable to the grid?
- How should credible information about this potential resource be developed and shared among electricity system stakeholders?

Without a better understanding of its value proposition, the electricity industry undervalues marine energy's potential and sends unclear signals about where to locate future development. To become commercially successful, the sector needs to explain why it can provide a unique contribution beyond energy associated with the lack of greenhouse gas emissions, which is readily available from other renewable resources at lower costs and risks.

The goal of this work is to identify, evaluate, and measure characteristics that may offer unique or competitive benefits to the electric grid. To reach this goal, the project must build the crosswalk between technology and electric grid value. Certain aspects of marine energy—for example, its location, relative predictability, generating profiles, and resiliency—should be beneficial. But there has been limited research to date into analyzing and quantifying these benefits (Preziuso et al. 2019). Just as solar is not the cheapest energy resource at scale, the technology is still successful because it offers unique benefits such as modularity and scaling to residential and distribution applications that make it a competitive solution.[16] Similarly, marine energy likely has a value proposition for the power system under certain circumstances, where few other generating resources are feasible. Early anecdotal research suggests that transmission investments to remote coastal locations can be deferred[17] or possibly avoided altogether. To achieve very high deployment levels of renewable energy, winter peaking resources with seasonal variation such as marine energy could be crucial. And as a predictable resource with periodicity linked to electric system needs, marine energy would require a fraction

[15] Kilcher, et al. Marine Energy in the United States: An Overview of Opportunities, NREL Technical Report. 2021. Available at: https://www.nrel.gov/docs/fy21osti/78773.pdf.

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

[17] Moazzen, et al. "Impacts of large-scale wave integration into a transmission-constrained grid." Renewable Energy 88 (2016) pp. 408-417. or, Robertson, Bryson. (2010). Ocean Wave Energy Generation on the West Coast of Vancouver Island and the Queen Charlotte Islands. Guelph Engineering Journal.

of associated integration costs.[18] This project provides further insight to this early research and more concrete information on marine energy's potential.

1.2 Vision and Outcomes

This project reviews the grid value proposition for marine energy technology development at scale over the intermediate to long-term horizon, that is from 5 to 15 years in the future. It dovetails with national valuation efforts to characterize and quantify specific services from energy resources and assess the value of those services over time. The desired project outcomes are to provide data and supporting analysis that will: (1) enable the marine energy industry to articulate value to potential investors and customers; (2) allow system planners, utilities, and decision makers to have information to evaluate marine energy when considering a suite of available generating resources; and (3) guide technology designs toward improving marine energy performance where it is likely to have competitive or unique value to the grid.[19]

Electric system planning today does not include the potential contribution of marine energy resources. This is due to several factors including lack of useful and credible data on costs, uncertainty regarding technology maturity, lack of uniformity in device designs, and limited commercial deployments. This report lays the groundwork for recognizing the value proposition of marine energy, including the many entities (e.g., customers, utilities, distribution or transmission operators, communities) and places (e.g., generation, distribution, transmission, or behind the meter) to which that value will accrue. Value is not exclusively represented in financial terms but can be expressed in measurably changed grid performance toward environmental, efficiency, or reliability goals.

Today a broad range of device designs exist for tidal and ocean current energy and especially wave energy conversion. While there are additional marine energy sources, such as in-river hydrokinetic, ocean thermal, and salinity gradients, this project is limited to wave, tidal, and ocean current devices.

- **Wave energy converters** harvest the kinetic and potential energy from ocean waves and are typically categorized by their general design or concept of the device (Drew et al. 2009).
- **Tidal current devices** harness energy from the flow of tidal currents and include tidal turbines, oscillating hydrofoils, and tidal kites (Roberts et al. 2016).
- **Ocean current energy devices** harness the horizontal flow of ocean 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 resources and device types within the marine energy industry, the project synthesizes studies and creates a basis for developing a grid value proposition that is intended to be device agnostic. Device-agnostic analysis aids in more clearly identifying the benefits and values that the marine energy industry can offer. A high tide raises all boats.

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

[19] "Value to the grid" here is intended to represent value to all grid stakeholders, whether system operators, generators, distribution utilities, customers, or others. General references to the "grid" in this report are intended to either represent the system, or subsets of grid stakeholders depending on the situation. Context within the discussion should clarify the intended meaning.

1.3 Report Outcomes and Anticipated Use

As noted above, the project is intended to illustrate the range of potential benefits of marine energy to the grid. Audiences and applications for this work include electric system planners and stakeholders who can anticipate and analyze the future grid. This community requires credible data in the face of uncertainty and reasons to consider marine energy given a range of mature energy generation competitors. Another crucial audience and user community are technology developers, who will be better positioned to design devices responsive to the development and performance needs of the future grid and engage potential offtakers.

In review of available literature, there has been very little similar work conducted to date (Preziuso et al. 2019). Most work considers a simple value, such as energy production, and attempts to maximize for this value. This is partially because power purchase agreements are structured to pay on an energy basis. Other analyses are focused on valuation for specific installations at specific locations and do not treat grid services or integration well beyond the technical electrical interconnection.

Considering the international lack of foundational material, the project is designed in an exploratory fashion to capture the full range of potential marine energy benefits, but also to improve the availability of useful data, identify critical gaps in data collection and technical tools such as grid software capabilities, and elevate the visibility of this resource to power system researchers and utility staff alike. Therefore, the technical approach started through an exercise in imagination: consider the broadest possible range of potential marine energy grid benefits. The next steps were to characterize and bound such services and benefits then organize them by marine energy attribute. This process, including a review of data requirements, methods, employed models, and a preliminary organization, are provided in the analytical approach (Section 3.3).

The project used this information to determine which values deserved closer inquiry and down-selected relevant grid services and potential benefits that became the focus for case studies and illustrative valuations of marine energy. These specific analyses balanced the necessity of incorporating detailed resource availability, technology characteristics, and grid conditions with the desired outcome of more generalizable insights. Case studies and illustrative valuations were developed as a portfolio with reasonable diversity in exploring various grid benefits. Collectively they show where site-specific analyses yield flaws in the analytical approach; provide greater sensibility about the potential range, character, or topology of values or services as applied to marine energy; and turn over new benefits that were previously not proposed to be analyzed.

The project also identified more general technology and resource attributes, investigating variable resource variability at multiple temporal and spatial scales, and extrapolating marine energy resource forecasts into market and reserve timescales, while incorporating uncertainty as compared to other variable generation. The project examined the potential for technology co-development with energy storage and other complementary technologies to smooth output and further enhance value.

1.4 Approach

Frameworks determining the total value that energy resources provide to the grid, also called resource value, are being completed for other types of energy sources but have not yet been developed for the marine energy sector. There is a need to look beyond the simple financial environment for individual devices on typical energy-revenue and capital-cost bases, beyond the asset perspective that a typical valuation exercise would yield. Research is needed to investigate whether, under what conditions, and to what degree there could be a greater grid value in developing marine energy in general.

For purposes of this investigation, the term *grid value* should be broadly construed. It 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; certain grid services or technology benefits may not be directly compensated, or the unit of value may not be the dollar. Other benefits we consider here, such as land use benefits, may not explicitly be considered *grid value*, but nonetheless can directly impact grid investment. 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 does not necessarily accrue to one entity. Even the term *grid service* has various definitions and applicable taxonomies, depending on the market environment, system operator, or utility business model.

It is important to note that we intentionally do not evaluate costs of deployment for marine energy resources nor transmission and distribution investments. Further, we do not consider environmental impacts associated with device deployment. This is not because these costs are not real, nor significant. It is because there is a wealth of ongoing work across industry, the U.S. Department of Energy laboratories, universities, and other research institutions to improve device designs and reduce technology costs and to evaluate and mitigate environmental impacts associated with marine energy.[20]

1.5 Report Organization

This report is intended to provide all major project developments and considerations conducted to date.

- Section 1, Introduction, provides the motivation and goals for the research project.
- Section 2, State of the Marine Energy Sector, offers a general context for the marine energy industry and technology development.
- Section 3, Project Approach, introduces the project foundations: the state of research within this topic; the analytical framework developed within the project; and the technical approach to working on this framework.
- Section 4, 5, and 6, Illustrative Value Propositions of Marine Energy, provides analyses of potential electric system value streams as defined in the framework (locational, timing, and special applications).
- Section 7, Next Steps

[20] *See: Tethys*: *Marine Renewable Energy*. https://tethys.pnnl.gov/marine-renewable-energy. and *About OES-Environmental*. https://tethys.pnnl.gov/about-oes-environmental.

2.0 State of the Marine Energy Sector

2.1 Current Status of Marine Energy Technology

Marine energy technologies largely remain in the research and development stage with some developers having moved into early commercialization. This poses challenges but also offers opportunities to the sector. The current state of marine energy creates a level of complexity when defining a grid value proposition since there are no commercial installations in the United States from which data can be used. Conversely, research of this type has the potential to inform model designs and decisions, aiding in the development of marketable technologies.

Current energy converters (devices that harness tidal and ocean currents) have reached a greater stage of device convergence than wave energy converters (WECs). Current energy converters most often resemble a three-blade, horizontal-axis wind turbine. Other device types also exist, including tidal kites, oscillating hydrofoils, ducted turbines, and horizontal and vertical axis crossflow turbines. Regardless of model, these devices aim to harness the horizontal flow of currents and are frequently secured to the seafloor; they can also be suspended mid-water column. Many successful installations have been deployed across the globe with one the most developed being the SIMEC Atlantis Energy's SeaGen device in Strangford Lough, Northern Ireland (MacEnri, Reed, and Thiringer 2013). The 1.2 MW system was connected to the grid in 2008 and produced over 11.6 GWh of electricity before being successfully decommissioned in 2019 (SIMEC Atlantis Energy 2019; Renewable Technology). SIMEC's MeyGen project, which consists of four 1.5 MW turbines, generated more than 24.7 GWh of electricity to the grid from the time it began exporting electricity in 2016 to January 2020. The project's 2019 performance is recognized as the longest duration of uninterrupted power from a multi-turbine tidal project in the world (SIMEC Atlantis Energy 2020). Another recent project of interest comes from SEV, the electric utility in the Faroe Islands, that has awarded a power purchase agreement to Minesto, a marine energy technology developer based in Sweden. The agreement supports the deployment of two tidal kites in an effort to help the island reach its goal of 100% renewable energy by 2030 (Minesto, 2020b). All siting permits have been approved for the tidal kites as of April 2020 (Minesto 2020a).

In contrast to current energy converters, no dominant WEC type has emerged. Several devices rely on the relative translation motion or rotational motion between a body and reference frame, such as point absorbers, oscillating wave surge devices, and attenuators. Other device types include oscillating water columns, overtopping devices, submerged pressure differential designs, and gyroscope systems. Again, although WECs are not at commercial scale, there have been notable installations across the globe. The first multi-turbine WEC system was installed in 2011 with the support of Spanish utility Ente Vasco de la Energía. The project included a 300 kW oscillating water column system integrated with the breakwater of the harbor in Mutriku, Spain (International Energy Agency – Ocean Energy Systems 2016). In 2015, the United States installed its first grid-connected WEC in Hawaii, which was an 18 kW Azura device deployed at the U.S. Navy's Wave Energy Test Site (Whitlock 2015).

Additional information about marine energy technology types and deployments can be found in *Understanding the Grid Value Proposition of Marine Energy: A Literature Review* (Preziuso et al. 2019).

The current state of technology creates cost challenges and uncertainty for the industry at large, generating a significant barrier to expansion. This is revealed in the extraordinary range of marine energy LCOE, which is currently one of the most common metrics for comparing energy technologies. As shown in a review of integrated resource plans (IRPs) in the United States, the LCOE for tidal energy technologies ranges from $97/MWh to $614/MWh, and the LCOE for wave energy technologies ranges from $165/MWh to $1,056/MWh (Cooke, O'Neil, and Preziuso 2020). This compares to recent LCOE numbers for utility scale solar at $28/MWh to $41/MWh, distributed solar at $72/MWh to $175/MWh, utility scale wind at $25/MWh to $53/MWh, and natural gas combined cycle units at $43/MWh to $71/MWh (Lazard 2020). The marginal cost of existing natural gas combined cycle ranges from $23/MWh to $32/MWh and generation -weighted average price for hydropower has been in the $40–$50/MWh range from 2012 through 2018 (Lazard 2020; Martinez, Johnson, and Shan 2021). Thirty-two IRPs were surveyed for the report, resulting in four LCOE estimates for tidal generation, eight for wave generation, and eight for offshore wind. Figure 2-1 shows the observed range of costs for the respective technologies.

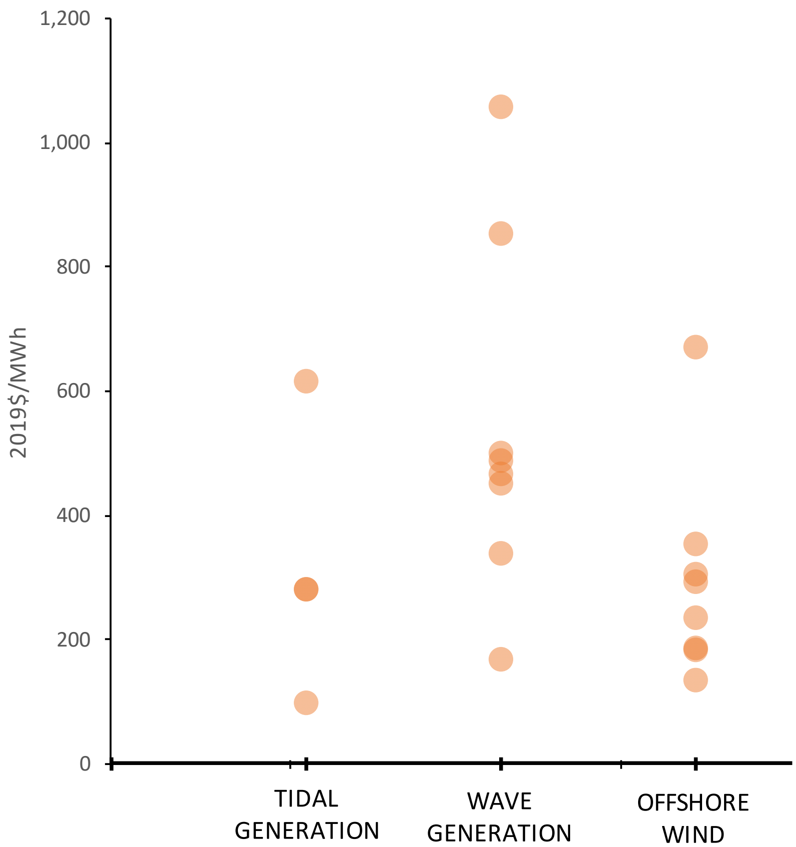

Figure 2-1. LCOE (converted to 2019 dollars) for tidal generation, wave generation, and offshore wind as reported in IRPs (Cooke, O'Neil, and Preziuso 2020).

The report also analyzes the treatment of marine energy technologies within the IRPs, acknowledging that not all inclusion is equal. Of the 32 IRPs evaluated, 21 simply included marine energy technologies in lists of potential renewable energy resources or discussed the technologies without analysis. Seven IRPs included marine energy technologies in pre-screening analyses where they were considered for inclusion in portfolio analyses. Finally, four IRPs modeled marine energy resources within their portfolio with three of those IRPs including marine energy in a preferred portfolio.

While having a small presence in IRPs, a few more utilities are considering marine energy today than they were 10 years ago, signaling that utilities consider these technologies promising but unlikely to be available within the time horizon of the IRP, which is typically the next 10–20 years. However, utilities with direct experience tend to consider marine energy more frequently (Cooke, O’Neil, and Preziuso 2020). IRPs present a window into what utilities find practical and reliable. Given the number of IRPs addressing marine energy and the treatment within those plans, their current inclusion most likely remains a demonstration of utility awareness of the technologies.

2.2 Potential of Marine Energy Resources to Provide Grid Services

The potential for marine energy technologies to provide electricity and grid services is substantial. With more than half of the United States’ population living within 50 miles of the coast and vast, untapped resources available, there is a clear opportunity for marine energy to play a role in the energy mix.

In developing a framework of value streams, we conducted an initial assessment of marine energy performance against established grid services, shown in Figure 2-2. This assessment reflects the authors’ expert view of marine energy performance against traditionally defined grid services captured in market products or reliable system operations today. This assessment offers two insights: first, marine energy must be evaluated against the new emerging future-focused set of grid services to uncover its competitive capabilities with respect to the future system; and second, incorporating storage advances marine energy capabilities against this evolving set of services.

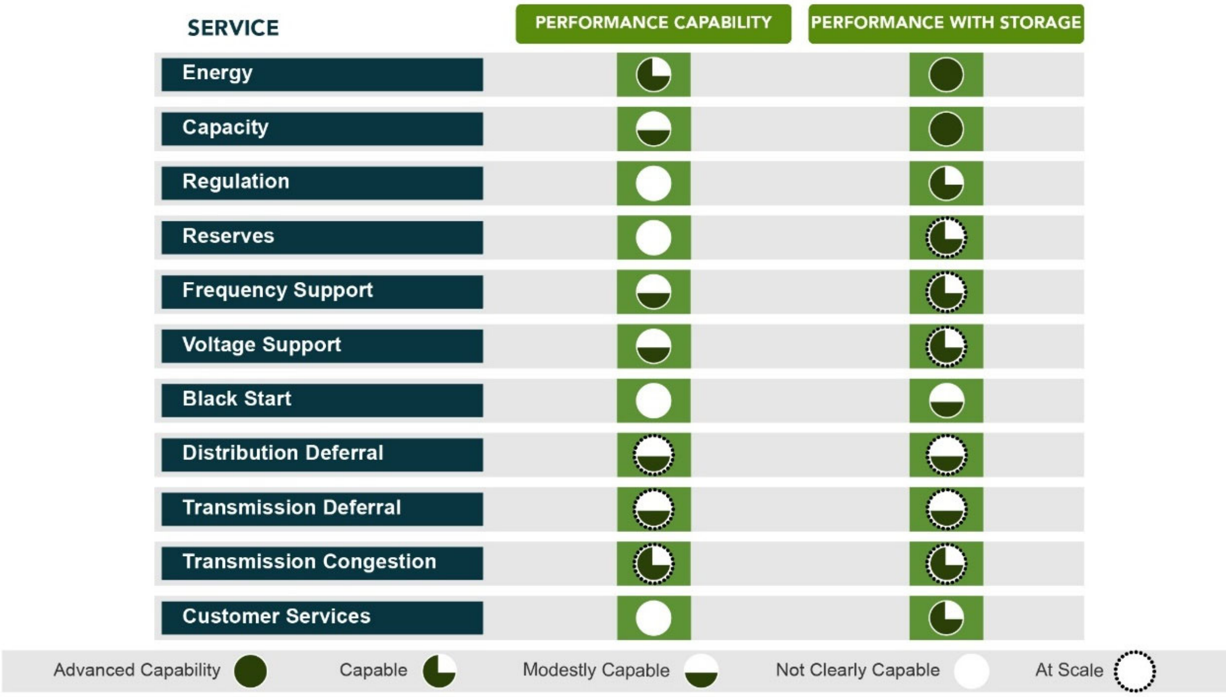

Figure 2-2. Capabilities of marine energy technologies to provide grid services with and without energy storage. Anticipated performance is based on comparisons to other resources, known equipment capabilities, and available historical analyses.

Many studies have been conducted to determine which grid services other renewable technologies, like wind and solar can provide. Market design and regulatory decisions are key to unlocking the full potential of renewable resources (Chernyakhovskiy et al. 2019; Loutan and Gevorgian 2020; Loutan et al. 2017). While this project explores the value of marine energy to the grid, there is a substantial opportunity outside of utility-scale development as well. For information on these applications, see *Powering the Blue Economy; Exploring Opportunities for Marine Renewable Energy in Maritime Markets* (LiVecchi et al. 2019).

3.0 Project Approach

3.1 Literature Review

At the start of the project, the team conducted a literature review to survey existing materials that address the interface of marine energy technologies and the electric grid. Minimal literature discusses it directly and in what exists the scope of work is rather narrow and specific, focusing on precise locations and device types. Significant research efforts have focused on the fundamentals of resource characterization, namely energetic environments, and technology development. These are addressed within the literature review and provide key insight to inform the work related to the timing benefits of marine energy. When possible, the report documented research that integrated marine energy technologies and the delivery of grid services, but the focus was in developing a repertoire of foundational research to which marine energy device-agnostic value could be linked. This approach allowed the team to cover the principal elements of the larger project to some level of detail and streamline the investigation into the value streams identified Figure 3-1 on the next page.

To develop a full collection of materials to support the project, the literature review embraced the chain of work necessary to explore the grid value of marine energy, including fundamentals of marine resources; performance and operational characteristics of energy conversion devices; grid opportunities and integration challenges most applicable to marine energy; storage coupling to fulfill grid opportunities; and competition and collaboration with other offshore resources, namely offshore wind. Through the report and associated research, the team was able to establish a knowledge baseline relevant to the project, identify research gaps, avoid redundancy in efforts, and leverage existing methods and data sources.

In addition to documenting the research to connect the grid and fundamental marine energy development, five key findings were identified:

- Aggregation of tidal generation for baseload energy 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 devices 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 across different time scales: 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.

- Collocation with other energy sources may provide 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 has been used in some utility decision making for resource selection and resulted in a portfolio selection that included marine energy: 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.

LOCATION

System Benefits

- System Investments
- MRE as non-wires alternatives (NWA)
- Avoided or deferred distribution and transmission investments

Local support

- Local load and balancing needs
- Power quality and voltage support (volt/VAR)

Power Flow

- Reduced congestion (coastal cities and transmission corridors)
- Remote system improvements (avoided line losses and transmission and distribution loading)

Land Use

- Increased energy density of coastal land
- Avoided opportunity cost of land use for energy generation
- Provision of energy in areas where there is low to no availability (dense, remote and island regions)
- Address policy goals for intra-BA development

Portfolio effects

- Improved geographic diversity of the generation portfolio: reduced system capacity and balancing requirements and a natural resiliency effect.

TIMING

Predictability

- Reduced integration requirements and associated costs: reduction in reserve requirements, needs for gas/hydro ramping
- Enhanced market participation: bid accuracy, qualification, scheduling certainty, penalty avoidance, extended time window for decision making in forward markets

Seasonality

- Coincidence with load
- Complementary with other resource availability

Scheduled / dispatchable generation (“Tidal as baseload”)

- Aggregation: resource diversity offset to create a “baseload” profile
- Dispatchability and participation in markets with storage
- Optimization of generation with storage

Portfolio effects

- Negative correlation with wind and solar at very high penetrations (e.g. winter peak)
- Thermal improvements: displacement, reduced cycling, improved efficiency, and reduced emissions
- Effective load carrying capability (ELCC) and capacity credits for MRE
- Reduction in system costs, capacity and balancing requirements with an integrated portfolio
- System reliability improvements: effects on LOLE and LOLP

SPECIAL APPLICATIONS

Enabled services

- MRE as a behind the meter resource (customer and grid benefits)
- Storage for flexibility and dispatchability
- Microgrid suitability: coastal, remote communities and islands (e.g. Barbados, Faroe Islands, Igiugig)
- Improvement in performance of other technologies (symbiotic benefits)

Resiliency

- Reduced vulnerability to electricity disruptions.
- Reduced reliance on conventional backup generation and risk from fuel availability and price volatility.
- Avoidance of sustained effects to critical infrastructure from grid disruption as a microgrid resource, in combination with microgrids, or as a backup generation resource.
- Systemwide and localized black start

Portfolio effects

- MRE modularity and array-based development allows for as-needed expansion, reducing financing risk, up-front costs and ongoing operations and maintenance costs.
- Reduced dependence on diesel and natural gas production and delivery infrastructure.
- Improvements to meeting environmental and sustainability goals.

Figure 3-1. Analytical approach framework with the suite of services marine energy resources that can deliver to the grid organized by the characteristics of location, timing, and special applications.

3.2 Marine Energy Value Streams

In this project, we outline the landscape of marine energy attributes and their potential value streams into three bins: (a) spatial or locational aspects of marine energy; (b) temporal or timing aspects; and (c) special applications. This structure ensures most potential benefits are captured. Figure 3-1 shows the attributes, or values, distributed amongst the bins. We now discuss these categorical benefits at the conceptual level to explain why marine energy has unique advantages with respect to its grid value proposition and merits a closer look.

3.2.1 Locational Value

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

Siting marine energy in constrained areas could provide both clean renewable energy and unique benefits to the system, such as a deferral or reduction of investments in the distribution and transmission system, provision of ancillary services (e.g., frequency and voltage support), and power quality benefits. A secondary benefit is economic development in an otherwise energy constrained area (Oregon Department of Energy). Depending on conditions, these locational benefits can be the anchor value for an installation.

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

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

3.2.2 Timing Value

Like most renewable energy sectors, marine will have variable production; however, marine energy is a relatively predictable resource over a time interval that mirrors the periodicity of the resource. The variability and predictability differ between types of marine energy, with tidal and ocean current resources directly tied to recurrent patterns over decades and wave resources predictable in the nearer term. Accordingly, generation can be predicted with high levels of confidence at advance scheduling periods, reducing system costs for integration. One study estimated the integration costs for 500 MW of wave energy to be 10% of the cost of integrating a comparable amount of wind on the Oregon coast (Oregon Wave Energy Trust 2013). Forecasting for solar and wind energy remains a substantial challenge in system operations today, with it being the greatest cause of real-time price spikes in the California Independent System Operator region (e.g., forecasting errors at greater than 40% deviation caused 68% of price spikes).[21]

Marine energy production is cyclical due to the periodicity of the originating oceanographic and astronomical forces. These cycles vary from short term (seconds for waves and hours for tides) to seasonal (wave, tidal and ocean current intensities) and appear to complement load variability as well as existing variable generation. Figure 3-2 illustrates the timing coincidence of the different marine resources with electric grid operations. Different forms of marine energy have periodicity that is coincident with different grid service timescales. Accordingly, resource characterization is important to ensure that device development and site deployment maximize the value of marine energy to current and future grid needs.

For example, ocean currents in the Florida Straits have dual peaking intensity over an annual period, with the greatest strength in July, a low point in October, then a second rise in January and a second low in April (Gyory et al.). This generating profile matches Florida's electric load, according to Energy Information Administration data (EIA 2020). While this seasonal matching is hardly a silver bullet, it suggests that development of ocean current technologies at scale could offer system benefits. With respect to wave energy, Pacific Ocean winter conditions, or sea states, are dramatically more energetic than summer sea states. That means that wave energy production will be seasonal, tilted toward greater production in the winter. This is advantageous as it matches load in cooler climates where heating, not cooling, is dominant. Second, winter generation complements other renewable generating profiles in the West: solar generation is at its height in the summer, and wind and hydroelectric generation ramp up strongly in the spring.

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

Even with foresight into the energy resource, the characteristics of the technologies converting the resource to electricity will be key factors in estimating generation. Further, the predictability of marine energy, including predictability in the near term, enables complementarity with other technologies, for example easier integration with energy storage relative to wind or solar as

[21] Presentation. Ascend Analytics, Oakland, CA. February 2017.

sizing of storage is simplified and likely less is required for the same resource capacity. The project looks at the potential for integration with complementary technologies and the benefits this integration can provide.

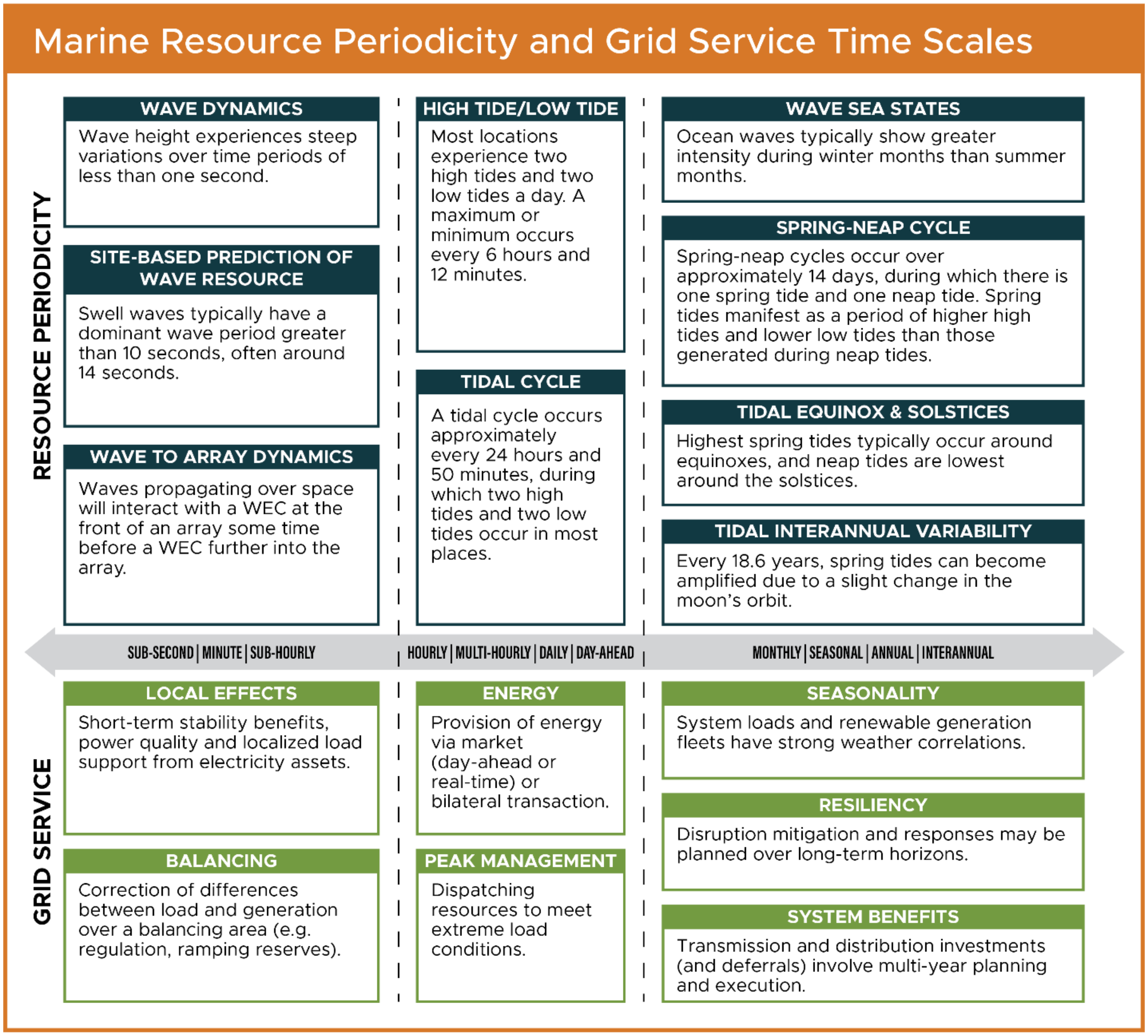

Figure 3-2. Marine energy resource periodicity and grid service timescales.

3.2.3 Special Applications

Another benefit of marine energy technology is the ability to provide services under unique contexts, which we term "special applications" in this project. For example, marine energy could provide electric resiliency for coastal communities. Weather is the dominant cause of grid disruptions and studies show that 100-year floods may be 10- to 1-year events by 2050.[22]

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

During Superstorm Sandy, one New Jersey utility reported widespread outages due to storm surge, with 4 to 8 feet of water inundating substations that had never previously experienced flooding.[23]

Distributed energy resources (DERs) can support resiliency objectives if properly enabled, to address identified vulnerabilities (LiVecchi et al. 2019; Buchanan, Oppenheimer, and Kopp 2017). Hurricane Harvey in Texas is one example that demonstrates how DER-powered microgrids can maintain electricity delivery during and after disasters (Proctor 2019). Marine energy devices integrated with coastal microgrids could support resilience improvement measures for isolated coastal communities as well as for high-priority coastal loads. Further, appropriately designed, scaled, and strategically located marine energy arrays could help power grids become more resilient by diversifying energy sources and providing essential backup and black-start services. For example, the Department of Energy funded projects in Igiugig and the Roosevelt Island Tidal Energy Project in Manhattan aim to demonstrate some of these values (LiVecchi et al. 2019).

3.3 Analytical Approach: Characterization of Value Streams

The analytical approach report was an initial review of services and system benefits that are relevant for marine energy development, including providing associated data requirements and proposed analytical methods (Bhattacharya et al. 2019). It built upon the project's literature review to assess marine energy values and services (Preziuso et al. 2019) and laid the groundwork for the next steps in this phase of the project: this technical report outlining grid service values in greater detail with value investigations and case studies to explore specific values identified as part of the analytical approach.

It is important to consider a broad swath of potential benefits through a marine energy-specific lens and develop an understanding and high-level quantification of their broad value. A review of data requirements, methods, employed models, and a range of services and values that marine energy could contribute to the grid was informative in narrowing the services for further review and analysis in the case studies and illustrative grid value analyses. The team identified which values deserved closer inquiry to downselect to "relevant" grid services that required more computationally intense modeling (e.g., distribution system or sub-hourly production cost models). This effort takes a deep dive on areas of confluence between resource availability, technology type, and opportunity to provide additional energy benefits.

The case studies are a portfolio of analyses with reasonable diversity in exploring different grid values and illustrate where site-specific analyses yield flaws in the analytical approach; provide greater sensibility about the potential range, character, or topology of values or services as applied to marine energy; or turn over new benefits that were previously not proposed to be analyzed. Concurrent with the case studies, the project team has used the analytical approach to identify non-site-specific attributes for further review. This will involve investigating variable resources variability, specifically wind and solar, at multiple temporal and spatial scales, and extrapolating marine energy resource forecasts into market and reserve timescales while

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

incorporating uncertainty as compared to other variable generation. Further, the team looks at the potential for co-development with energy storage and other complementary technologies to ease integration and maximize value.

3.4 Selected Value Streams

As previously discussed, after identifying the whole set of marine energy value streams in Figure 3-1, the project team performed an initial pass analysis to select those value or benefit streams likely to represent the most systematic advantage to the electric system. This initial pass consisted of a combination of high-level analyses based on available data or prior Pacific Northwest National Laboratory (PNNL) projects, team knowledge and experience with the power system, discussions with energy system stakeholders, and research. Accordingly, the project team has identified the following value streams for further exploration to evaluate an illustrated value proposition for marine energy. Again, this approach is not intended to develop a business case for any particular investment, but rather to illustrate value that marine energy provides to the grid. The selected value streams identified for illustrative analysis include the following (Table 3-1):

Table 3-1. Selected value streams for illustrative analysis.

LOCATION	TIMING	SPECIAL APPLICATIONS
System Benefits • Local load needs • Avoided or deferred distribution investments • Reduced transmission congestion on the West Coast coastal transmission corridor	**Predictability** • Reduced integration requirements • Coincidence with load • Complementarity with other resources	**Enabled Services** • Improvements in performance of other technologies (symbiotic benefits) • Microgrid suitability, coastal, remote communities, and islands • Marine energy as a behind the meter resource
	Scheduled/Dispatchable Generation • Optimization of generation with storage	**Resiliency** • Reduced vulnerability to electricity disruptions • Reduced reliance on conventional backup generation and risk from fuel availability and volatility
	Portfolio Effects • Negative correlation at high penetrations • Effective Load Carrying Capability/Capacity credits • Reduced integration costs	**Portfolio Effects** • Reduced dependence on diesel and natural gas production and delivery infrastructures

Marine energy technologies are at an early stage of development, but that does not mean their potential cannot be identified or illustrated. The selected value streams shown in this section highlight near-term opportunities for the deployment of marine energy resources.

3.5 Resource and Device Characterization for Analysis

As described above, the spatial and temporal attributes of wave and tidal energy resources vary from hour to hour, month to month, and year to year. As such, a general understanding of these behaviors directly influenced the team's selection of value streams that are evaluated herein. Given the complexity of wave and tidal resources, a robust and systematic methodology to quantify these resource flows is extremely important. However, with the focus of this project resting on the value that marine energy can generate for the electric grid rather than advancing the understanding of resources at specific sites, representative resource data are used throughout this work. This data consists of modeled and measured data sets to illustrate the behavior of the resources. Similarly, representative processes were used to convert resource data into power profiles with the intent to remain as device agnostic as possible and allow the team to develop representative results that could be generalized to situations beyond the specific location considered with each analysis. The data used in each value stream analysis are described in their respective sections, and further information about resource characterization and the methods used to convert resource data to power profiles is described in Appendix A.

4.0 Locational Benefits: System Benefits

4.1 Oregon Coast: Reduced Transmission Congestion

System Benefits

- Reduced transmission congestion on the West Coast coastal transmission corridor

This section considers system benefits associated with marine energy deployment at scale in the form of congestion impacts to West Coast U.S. transmission. The analysis uses the ABB GridView Production Cost Modeling (PCM) software to analyze bulk grid impacts of adding wave to the electric system near Newport, OR. GridView integrates engineering and economic analysis of the electric power grid to simulate security-constrained unit commitment and economic dispatch in large-scale transmission networks. The tool is widely used to study utilization of generators and transmission lines, production costs of generation, locational marginal pricing, transmission congestion, and more (Anderson et al. 2016).

4.1.1 Summary of Analysis Inputs and Parameters

In this analysis, PNNL uses tidal power data from the Admiralty Inlet to represent the tidal power OPALCO could harness. There are closer high-quality tidal resources in the area, particularly in the channels immediately nearby the islands; however, the Admiralty Inlet tidal resource has been actively measured over a year at high resolution. Accordingly, it represents a higher quality data source than is otherwise available for closer resources. Table 4-1 below identifies the analysis inputs and sources utilized in this Section. Section 4.2 identifies the analytical process utilized to convert the marine energy resource to an electric output.

Table 4-1. Inputs and data sources for Section 4.1.

	Type	Location	Data Interval	Source
Grid load	Bulk	WECC	Hourly	WECC; GridView 2028 ADS for WECC
Renewable resource	Wave	PacWave Test Site OR Coast	Hourly	(Yang, García-Medina, et al. 2020; Wu et al. 2020)
	Solar, Wind, Hydro, others	WECC	Hourly	WECC; GridView 2028 ADS for WECC

4.1.2 GridView Model and the WECC System

WECC currently uses GridView for production cost modeling in the region, with expected loads, resources, and transmission topology compiled and maintained for 10 years into the future. WECC's Anchor Data Set (ADS) Data Development and Validation Manual (WECC 2018) describes in more detail this data collection process and production cost modeling practices.[24]

[24] See ADS Data Development and Validation Manual. Version 1.0. System Adequacy Planning (SAP) Department. July 17, 2018. Western Electricity Coordinating Council. Available at: https://www.wecc.org/SystemStabilityPlanning/Pages/AnchorDataSet.aspx

The WECC PCM used in this analysis is the 2028 ADS V2.0 PCM base case made available as of July 2019. This case was the best available projection of new generation and transmission assets from the grid planning community within WECC at the time of release. This analysis uses the case as-is without changes to resources, transmission, or system topology aside from the addition of the marine energy resources, specifically wave, and offshore wind.

Based on data within the 2028 ADS V2.0 PCM, significant changes in generation resource mix within WECC are projected between now and 2028. There is a significant amount of additional capacity built out in California, Arizona, Colorado, Nevada, and Utah, expected to come online within the next 10 years. This new capacity is predominantly forecasted to be PV and wind. Transmission in the WECC 2028 PCM case provides the best representation of future topology and transmission capacity available. It incorporates the addition of transmission projects in the 10-year planning horizon made publicly available to the grid planning community.[25]

The WECC PCM models loads as hourly for the entire year by balancing authority. The load is based on annual load and resource data submittals that contain monthly energy and peak forecast for 1-10 years into the future. These data are then broken down from monthly to hourly by applying the historical Federal Energy Regulatory Commission Form 714 hourly load shape. The WECC 2028 PCM case currently uses a 2008 historic load shape to create the hourly load profile by applying the monthly peak load and total energy reported in the load and resource data. The historic 2008 load shape is an average load year with average weather conditions WECC-wide. For the purposes of this analysis, no changes were made to the load set by WECC in the model.

4.1.3 Analysis Results

A combination of wave and offshore wind resources were added in increments as identified in Table 4-2, scaling the available wave resource generation profile for the PacWave site, as identified in Appendix A. The offshore wind resource was pulled for wind speeds at 100 meters above the surface from the techno-economic database of the Wind Integration National Dataset (or WIND) Toolkit, a compilation of six years of wind data at 5-minute resolution and 120,000 locations across the nation (Draxl et al. 2015). The resource was tied to the nearest major (i.e., high voltage above 230 kV) transmission substation on land, that is the BPA Toledo substation near Newport, OR. The substation is a part of the BPA 230 kV transmission system.

The model runs of the different wave and offshore wind deployment scenarios were for a 1-year duration of the model year 2028. These runs were conducted using a nodal model, with load nodes within each balancing authority (or area within the model) at an hourly resolution across the entire WECC system. The analysis evaluates different levels of wave and wind integration as identified in the scenarios in Table 4-2.

Table 4-2. Evaluation Scenarios

Scenario	Wave Resource [MW]	Wind Resource [MW]
1	250	250
2	500	0
3	500	500

[25] Ibid.

The deployment of wave will have greater regional transmission impacts. Figure 4-1 identifies the WECC major transmission flow pathways for the region. This analysis looks at Path 5, that is transmission from the east and the Columbia River Gorge to the southwest into the Portland area and central Oregon; Path 14 from south central Idaho into northeast Oregon; Path 65, the DC intertie from near the BPA John Day dam in the central Columbia Gorge, directly to Southern California; and Path 66, the California-Oregon Intertie (COI) that runs from Oregon into northern California.

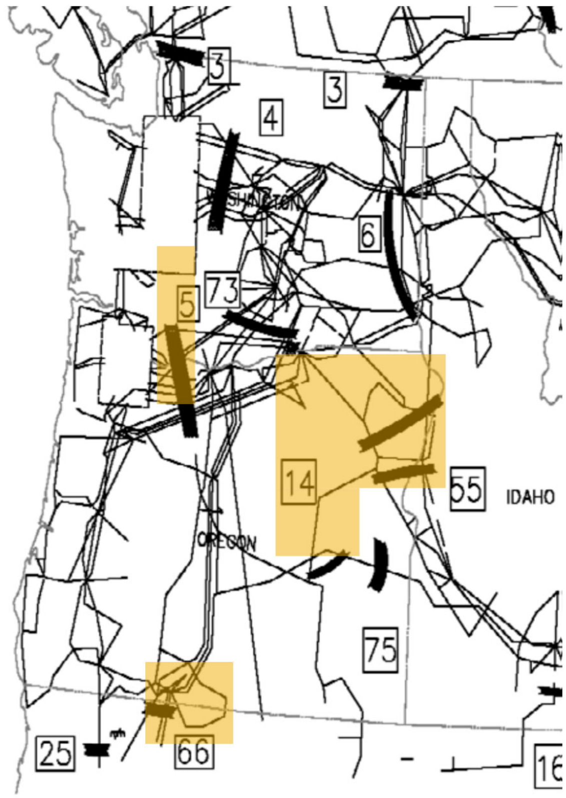

Figure 4-1. WECC paths for the Northwest. This analysis considers path 5, path 14, path 65 (not indicated on this map) and path 66 (WECC 2013). They are indicated by the black bars and highlighted in yellow.

Figure 4-2 indicates daily hourly average flow across the year for Path 5, the collection of transmission lines going from central Oregon and the Columbia River Gorge southwest into the Portland area and central Oregon. Generally, as the amount of wave deployment increases, from zero in the base case up to 1 GW (wave and wind), the transmission flows along this path decrease by about 250 to 500 MW for the deployment of 1 GW of wave and wind depending on the hour of the day. The impacts from lesser amounts of wave have a similar shape with a lesser magnitude. The wave energy and offshore wind combination cases closely track those of wave-only deployments of the same magnitude with the difference on average being immaterial. This is not surprising as, in general, the offshore wind resource has similar temporal characteristics to the wave resource off the Oregon coast.

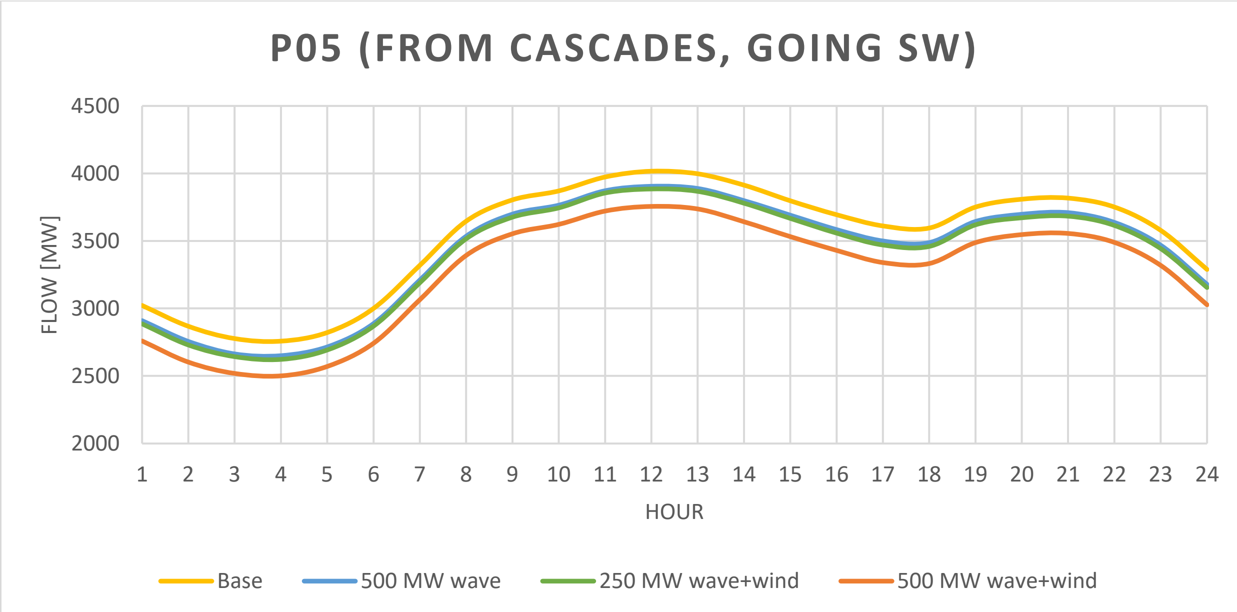

Figure 4-2. Impacts to daily hourly average flows from wave integration on Path 05; positive direction is flow west.

Figure 4-3 identifies the daily hourly average flow for Path 14, the transmission corridor between south-central Idaho into northeast Oregon. On average, each hour sees a reduced import of energy into Oregon across this corridor with increasing wave deployment.

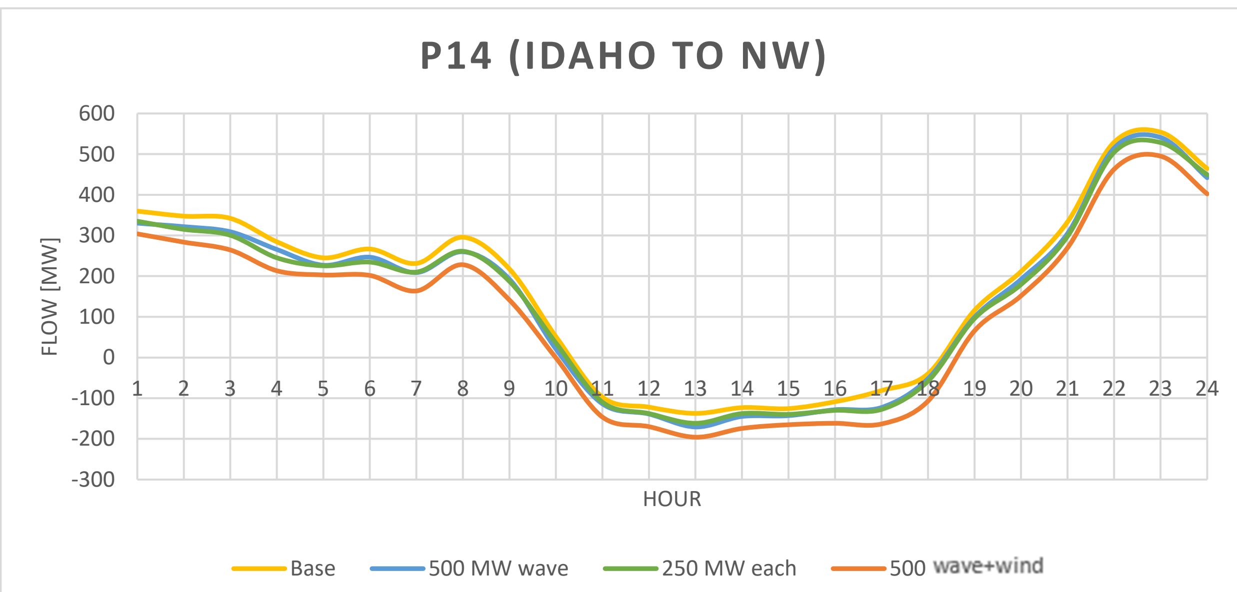

Figure 4-3. Impacts to daily hourly average flows for each hour of the year from wave integration on Path 14; positive direction is flow west into Oregon.

Figure 4-4 identifies the impact of wave integration on Path 65, the direct current intertie from near the John Day dam in the central Columbia River Gorge area, south to Southern California, without any additional interconnections along the route in Oregon. The addition of wave and wave-and-wind resources along the coast appears to permit a small amount of additional flow south into California, on average, from the resources in the John Day dam area, which are primarily hydroelectric and wind. During mid-day periods, wave specifically also appears to reduce imports north from California into Oregon. There is more differentiation on Paths 14 and 65 between wave and wave-and-wind together as compared to Paths 5 and 66. The wave-only scenario reduces flows on average at hour 13 and hour 21, increasing flows south in hour 14. This is likely a result of the less wave availability in these hours relative to wind. Regardless, the added wave resource, based on increasing flows on Path 65, serves local loads and frees up the system to provide additional resources south.

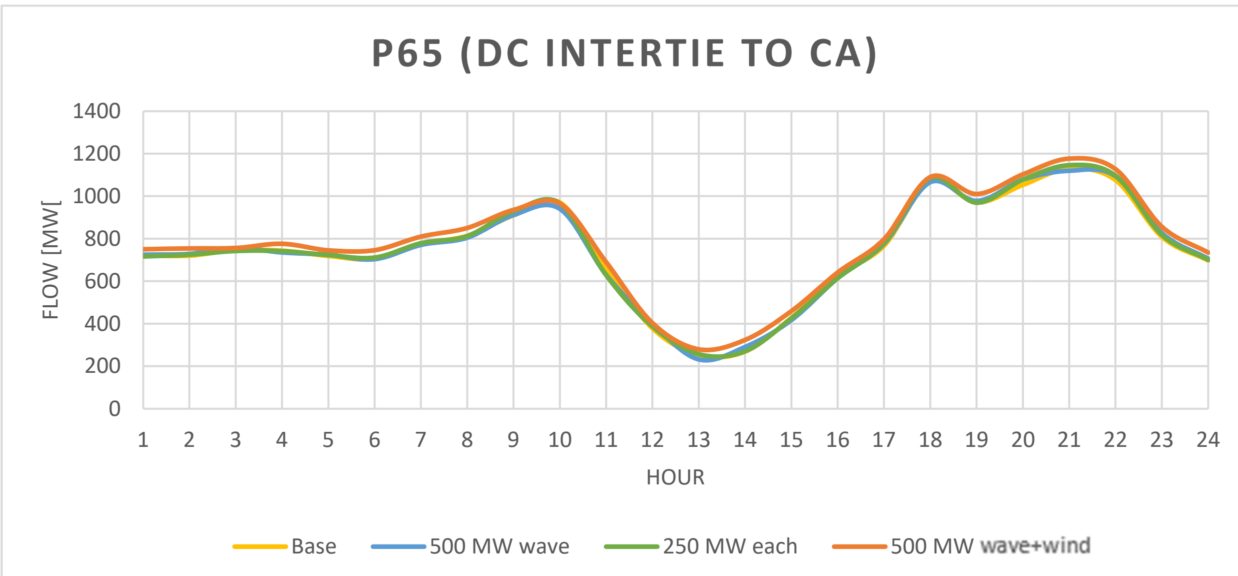

Figure 4-4. Impacts to daily hourly average flows for each hour of the year from wave integration on Path 65; positive direction is flow south into California.

Path 66 COI in Figure 4-5 is also a transmission pathway south into California that consists of three 500 kV alternating current lines and enters northern California along the Interstate 5 corridor. Here, the average impacts of the addition of wave follow a similar pattern, increasing the flow south into California most of the day. As with Path 65, the midday reversal of flow from California into Oregon is reduced. Without a detailed power flow analysis, it is difficult to determine where exactly the wave output goes. In this instance, as flows along Path 5 have decreased, it appears likely the wave resource replaces wind and hydroelectric power from the Gorge region and is not only used locally, but also transmitted south. Unlike Paths 5 and 14 and Path 65 to a lesser extent, the impact of wave integration at this scale on Path 66 appears limited. PNNL’s work on offshore wind considering deployment levels up to 5 GW indicated larger impacts with higher deployments. Larger wave deployments may indicate the same level of impact, creating additional capacity on transmission paths going east to west, and perhaps some changes in exports.

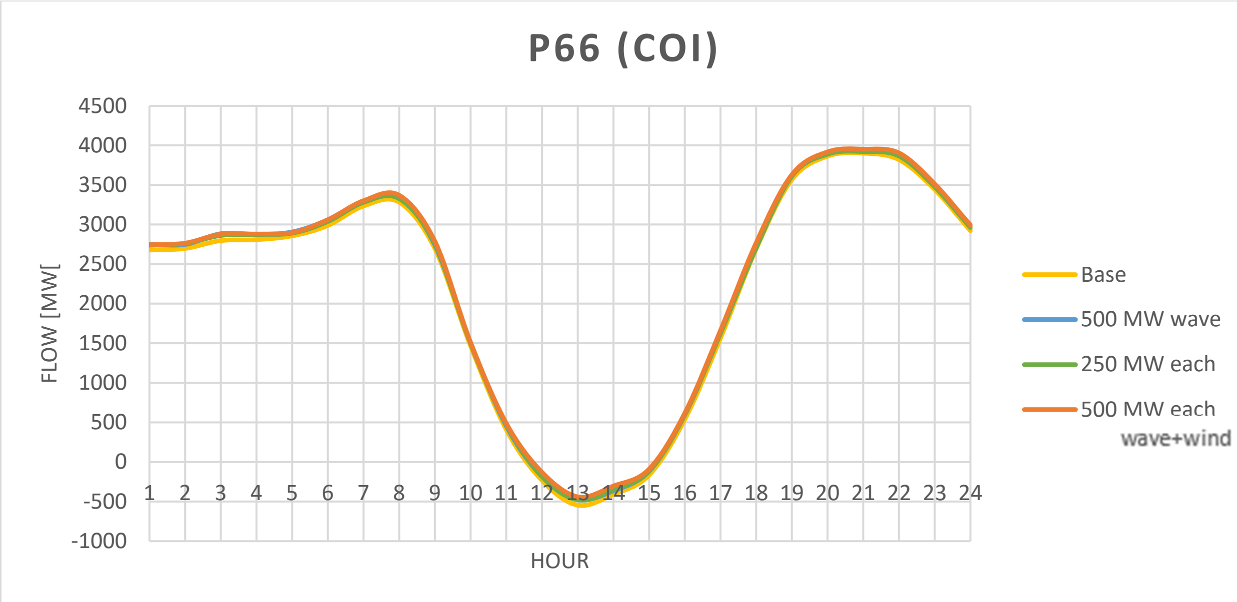

Figure 4-5. Impacts to daily hourly average flows for each hour of the year from wave integration on Path 66; positive direction is flow south into California.

4.1.4 Conclusions

These results provide some interesting insights:

- First, the deployment of wave along the Oregon coast opens transmission capacity from eastern Oregon and the Gorge into northwest and central Oregon, with an increasing amount of wave providing increased capacity along the path (Path 5). This potentially opens the existing path to provide additional generation from the Gorge, eastern Oregon, and points north and east, such as solar from eastern Oregon and Washington or wind resource-rich Wyoming. This may be a particularly valuable attribute as Oregon, Washington, and California aggressively move towards cleaner energy generation, and this additional transmission capacity may permit the delivery of additional renewable energy resources from the east without new transmission buildout.

- Second, the flows in Paths 5, 14, 65, and 66 highlight that the added wave resource is primarily being used within Oregon. Regional flows away from Oregon, that is into California and Washington, do not change significantly and imports from Idaho decrease. That said, it does appear that some of the wave resource is transmitted south into California from Oregon, displacing resources from the central Columbia Gorge region.

- Third, wave may serve as an important balance to Columbia Gorge wind, reducing reliance on Wyoming wind to provide the same balance for the Northwest, which may provide some value in reducing the cost of transmitting that wind from Wyoming into Oregon and Washington.

- Finally, PacifiCorp serves as the balancing authority and load serving entity for the PacifiCorp West (PACW) area in southwestern Oregon and the PacifiCorp East (PACE) territories in Idaho, Utah, and Wyoming, all of which have a considerable resource base. Those PACE regions are relatively remote to southwestern Oregon and accordingly there are transmission limitations between PACW and PACE. Wave integrated into southwestern Oregon may present some localized value for PacifiCorp in reducing reliance on transmission of energy from their other territories, not only opening transmission capacity, but also allowing those resources in the east to serve other loads. In addition, as discussed above, wave opens capacity on the transmission corridor along the Gorge, potentially also permitting PACE energy to be delivered to PACW. These two benefits may, of course, conflict.

There is limited divergence in transmission flow impact integrating wave-only resources and wave and offshore wind together. Where divergence does occur, it appears to be related, as might be expected, to the difference in resource availability. Overall, however, the impacts of wave only and wave and offshore wind deployment are broadly similar.

Again, it must be noted that these are modeling results and more detailed analysis will be necessary to pinpoint actual transmission flows. They do not account for existing power contracts[26] within or between regions, particularly when considering flow from the Gorge to the coast to deliver energy to public utility districts and flow south into California. Nonetheless they are insightful in highlighting the potential value to a deployment of marine energy on the Oregon coast.

4.2 OPALCO: Avoided Distribution Investments and Local Load Needs

System Benefits

- Local load needs
- Avoided or deferred distribution investments

Orcas Power and Light Co-Op (OPALCO) is a nonprofit cooperative utility delivering Bonneville Power Administration (BPA) generated electricity to 20 islands in San Juan County, WA (Orcas Power & Light Co-op 2020). In 2016 OPALCO received a $1 million grant from the Washington Clean Energy Fund, a state government initiative, to develop a community solar and energy storage system at the Decatur Island Substation, which is the point of interconnection with the mainland transmission system. With support from the fund, PNNL worked with OPALCO to conduct an economic analysis of the energy storage and community solar system, identifying benefits and costs of deployment over the lifetime of the project (Mongird et al. 2018).

Leveraging work from (Mongird et al. 2018), here we evaluate the potential and value associated with tidal generation for the OPACLCO system. The Orcas Islands have a strong tidal resource potential in their vicinity. This fact, coupled with their location in the northern latitudes of the country limiting solar resource potential, limited land availability for both solar and wind, and reliance on the mainland for delivered electricity, indicates that tidal resources could play a significant role in OPALCO’s future electric system.

[26] Several power delivery contracts exist between BPA and public utility districts along the coast as well as between other generators and other load serving entities. Neither the impacts nor implications to these contracts were evaluated.

4.2.1 Summary of Analysis Inputs and Parameters

In this analysis, PNNL uses tidal power data from the Admiralty Inlet to represent the tidal power OPALCO could harness. There are closer high-quality tidal resources in the area, particularly in the channels immediately nearby the islands; however, the Admiralty Inlet tidal resource has been actively measured over a year at high resolution. Accordingly, it represents a higher quality data source than is otherwise available for closer resources. Table 4-3 below identifies the analysis inputs and sources utilized in this Section. Section 4.2 identifies the analytical process utilized to convert the marine energy resource to an electric output.

Table 4-3. Inputs and data sources for Section 4.2.

	Type	Location	Data Interval	Source
Grid load	Local	San Juan Islands, WA	Hourly	OPALCO
Renewable resource	Tidal	Admiralty Inlet, WA	1-minute	(Jim Thomson 2009; J. Thomson et al. 2012)
	Solar	San Juan Islands, WA	Hourly	NSRDB; OPALCO

4.2.2 OPALCO System

OPALCO serves nearly all its 65 MW peak load through purchases of power from the BPA. This power is largely hydroelectric, but also consists of a small amount of nuclear and fossil resources. The power is delivered over 69 kV and 115 kV subsea transmission cables connecting Decatur Island to the mainland at BPA's Fidalgo Substation in Anacortes, WA, as identified in Figure 4-6 (OPALCO 2016). In addition to these power imports, there is a 504-kW community solar array located on Decatur island. OPALCO's distribution system includes 15 distribution submarine cables and 10 transmission submarine cables, which in all cover 22 miles between all of the islands, connected through 11 substations (OPALCO 2020).

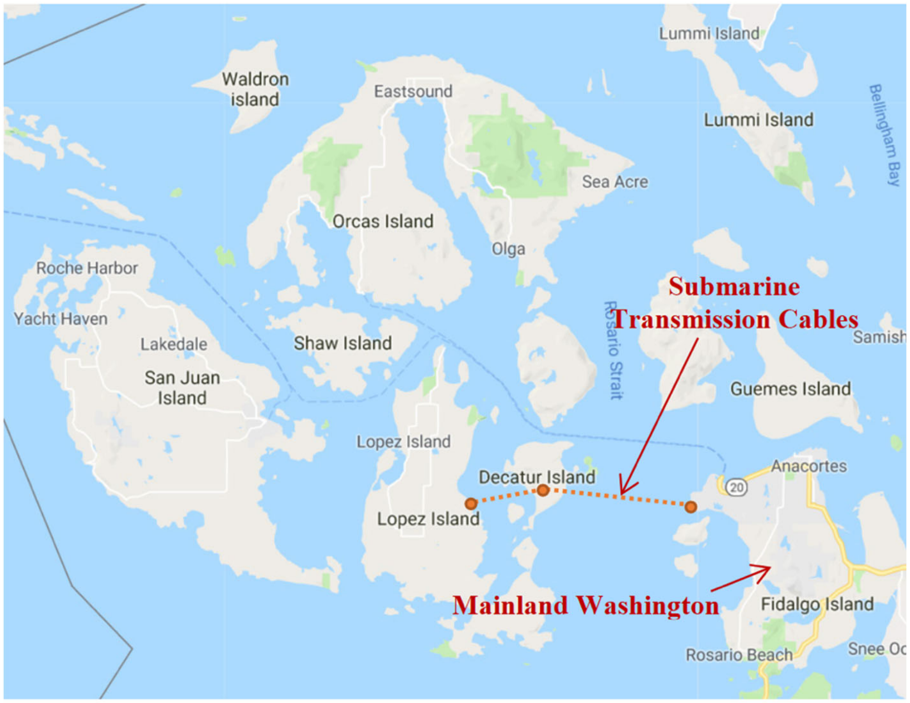

Figure 4-6. Map of the approximate path of the submarine transmission cable connecting Decatur Island to Anacortes, WA.

This work considers the value that tidal energy presents to OPALCO, namely a reduction in energy costs, load shaping costs, demand charges, and transmission charges all paid to BPA as well as estimated benefits increasing subsea transmission cable life. It is important to note, again, that we are not considering costs of deployment, merely value.

OPALCO's load has a characteristic double peak, one in the morning and one in the afternoon as indicated in Figure 4-7. These data were provided by OPALCO to PNNL for the energy storage and community solar project conducted by (Mongird et al. 2018) and leveraged for this tidal analysis.

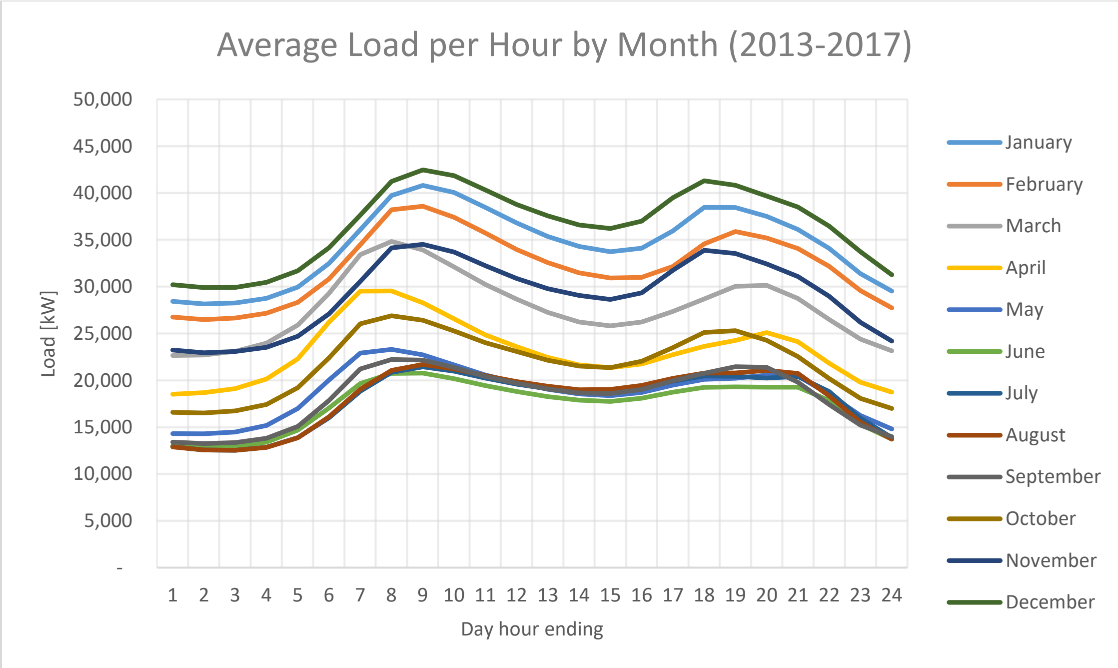

Figure 4-7. OPALCO hourly average load per hour by month from 2013 to 2017.

This average monthly load correlates to the peak hours identified in Table 4-4 below.

Table 4-4. OPALCO peak hours by month identified from average load in each month during a 5-year period (2013-2017).

Month	Peak hours
January	7-11 AM; 5-9PM
February	7-11 AM; 5-9PM
March	6-10 AM; 5-9PM
April	6-10 AM; 5-9PM
May	6-10 AM; 5-9PM
June	6-10 AM; 5-9PM
July	7-11 AM; 5-9PM
August	7-11 AM; 5-9PM
September	6-10 AM; 4-8PM
October	6-10 AM; 4-8PM
November	7-11 AM; 4-8PM
December	7-11 AM; 4-8PM
Average	7-11 AM; 4-8PM

4.2.3 Tidal Resource

The daily tidal generation by month for a 1.5 MW turbine is presented in Figure 4-8. As is evident, on an average basis the tidal resource is consistent across all months throughout the year. This is an advantage of the tidal resource over an alternative resource, such as solar, which varies significantly across months in the year. This, of course, is relatively specific to higher latitudes. Closer to the equator, the seasonal variation between solar would shift. See Figure 4-9.

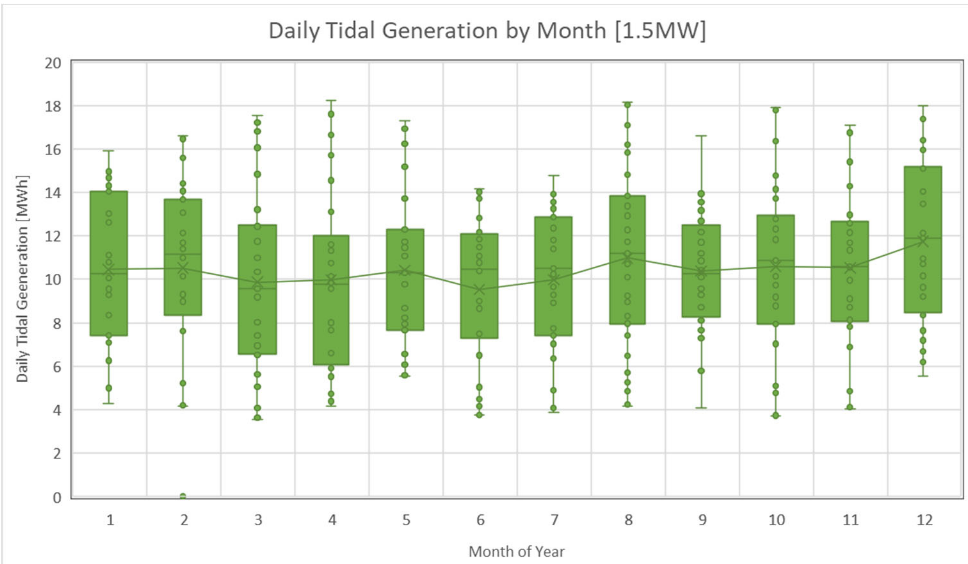

Figure 4-8. Daily tidal generation by month for a 1.5 MW tidal turbine for Admiralty Inlet.

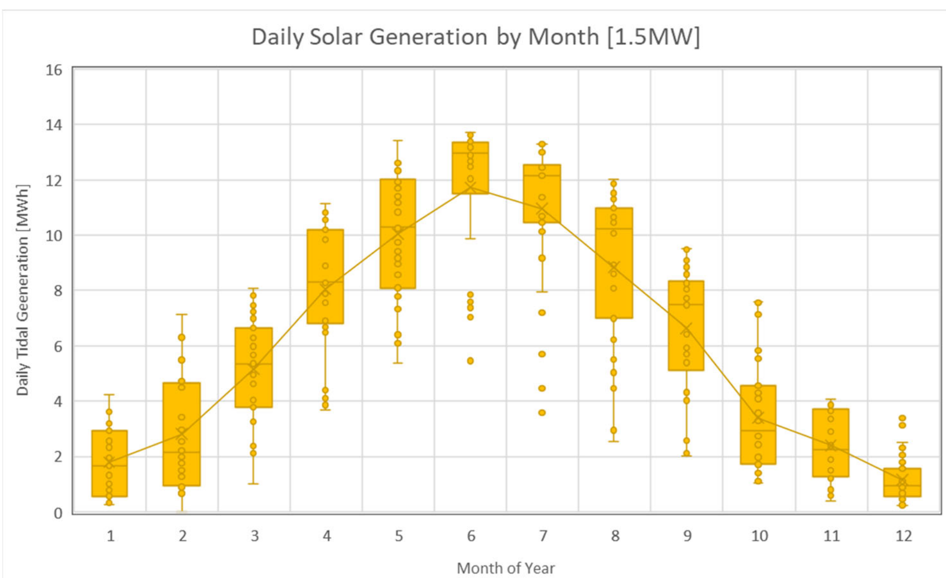

Figure 4-9. Daily solar generation by month for a 1.5 MW solar installation.

4.2.4 Value of the Tidal Resource

Value of the tidal resource availability across the year is evident in Figure 4-10, which compares the OPALCO load profile across the year to the tidal generation profile. Load is at its highest in winter months, likely a result of electric heating, and lowest in summer months where the mild climate of the San Juan islands limits air conditioning use. Clearly, the availability of the tidal resource across all months is valuable. This finding is particularly interesting considering the solar resource peaks in the summer and is significantly lower in the winter, by a factor of 8 between December and January and June and July.

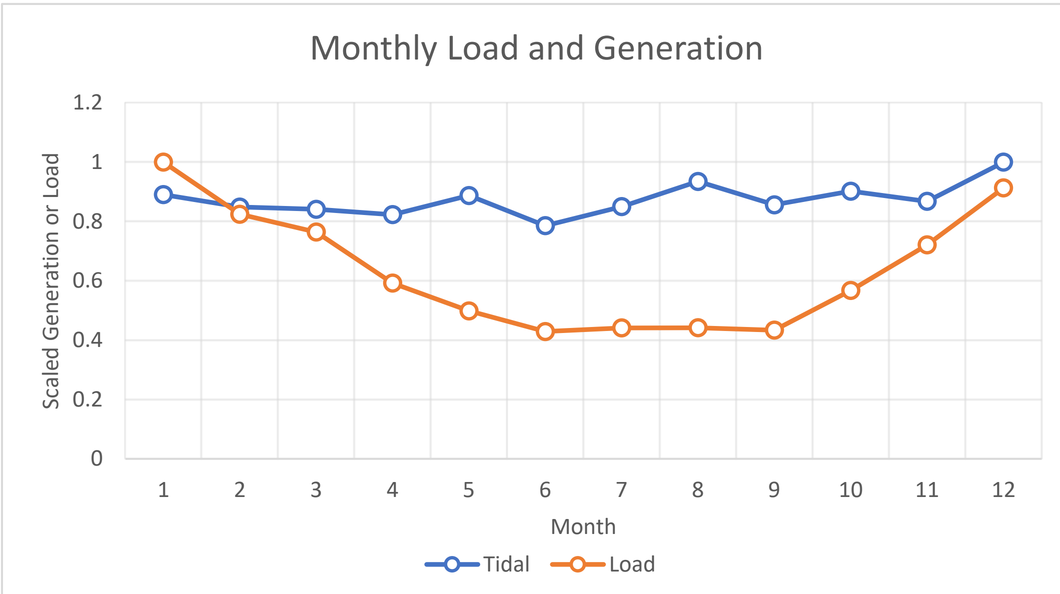

Figure 4-10. Scaled load and potential tidal generation for OPALCO by month.

Here we consider the direct value of the tidal resource to the current OPALCO system and what value it represents as a proximal resource, that is its locational or spatial value and the local needs it serves, including providing local energy and deferring transmission upgrades. Section 5 will consider the timing characteristics of the tidal and marine resources.

The monthly energy value of the tidal resource is evident. On an hourly basis, however, the situation is a bit different. Figure 4-11 identifies the hourly tidal resource profile over the year, in the peak load month of January and the low load month of July. On average the tidal resource is apparently available during both the morning and evening peak load hours, and less available in other hours, as expected with its diurnal resource characteristics. This peak hour resource availability is particularly beneficial as that is often when energy prices are highest and transmission and distribution systems most constrained. However, evaluating this availability in the summer and winter separately, indicates contradicting results. In the peak load month of January, the tidal resource, on average, is less available during the morning peak and more available in the evening. In the low load month of July, tidal is instead more available during the morning peak to early afternoon, and less available during the evening. This change may be expected with the changing characteristics of tides associated with the changing orientations of the earth and the moon throughout the year.

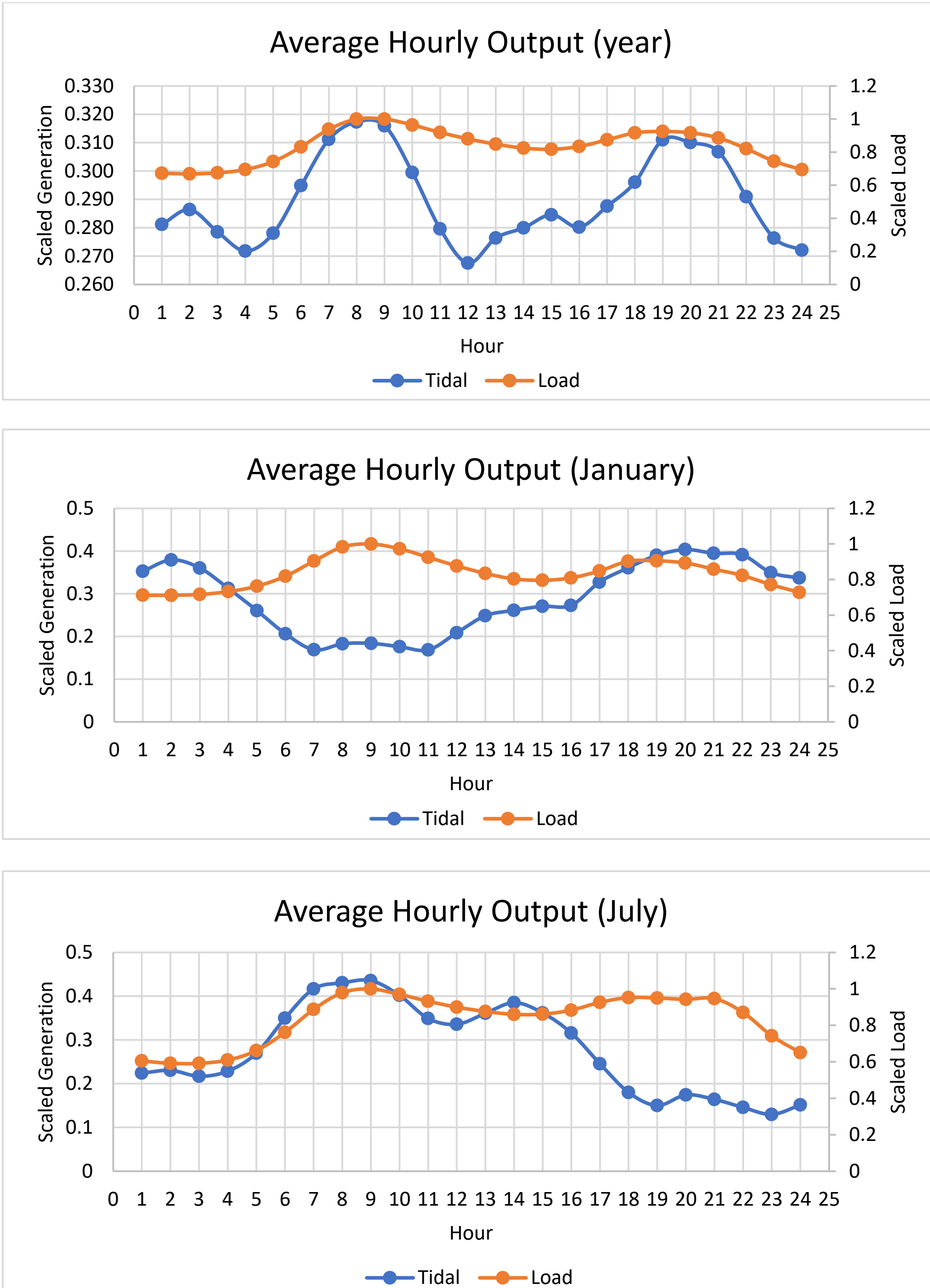

Figure 4-11. Hourly average scaled load and tidal generation over a year, the month of January and the month of July. Generation is scaled by max capacity.

Further, we explicitly evaluate tidal resource availability as a function of load requirements by considering resource capacity factors. Figure 4-12 identifies tidal resource capacity factors by month during different system peak hours. As indicated by availability above, capacity factors are best during the morning peak hours in the summer months and less available in the morning during the winter months. Conversely, they are higher in the afternoon to evening peak hours in the winter months. This finding, specific to the OPALCO system and the tidal regime in the area, is instructive in considering what other resources might complement a potential tidal resource deployment, whether it is energy purchases, new generation, demand response, or energy storage.

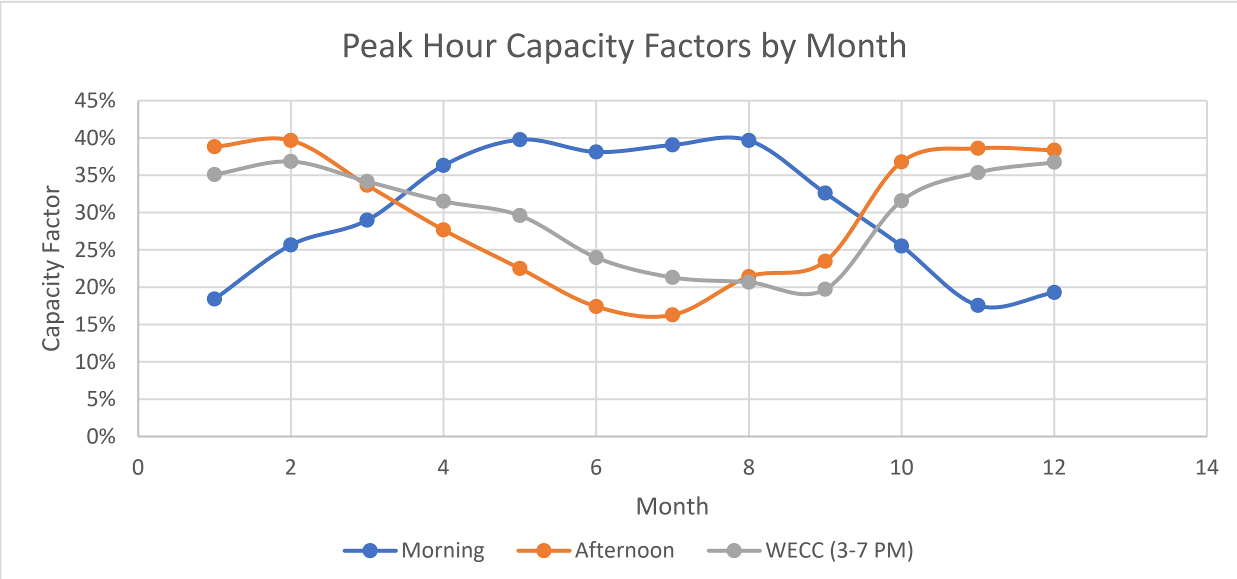

Figure 4-12. Tidal resource capacity factors during peak hours in each month for the morning OPALCO peak, afternoon OPALCO peak and the WECC-wide peak.

4.2.5 Estimation of Value

Next, we explicitly evaluate the value associated with a tidal deployment for the OPALCO system. As mentioned previously, this analysis leverages the work conducted by PNNL in (Mongird et al. 2018), which has a detailed discussion for the assumptions underlying the value stream analysis. There are several directly monetizable value streams that a tidal resource deployment could represent to the OPALCO system. These include reductions in energy costs, load shaping costs, demand charges, and transmission charges. The tidal resource also has the potential to increase cable life for the different transmission and distribution cables used by OPALCO. This benefit can be referenced as a transmission or distribution deferral benefit or a non-wires alternative benefit.

OPALCO pays for its energy to BPA through PNGC Power under a complicated multipart rate structure. Those components that can be directly impacted by the deployment of tidal resources are the following:

1. Energy import costs: This is the average energy cost paid by OPALCO to PNGC. The average rate is roughly $0.032/kWh and is estimated by taking the total energy cost divided by its total load for 2017. The tidal resource over a year generates 2,500 MWh per MW installed tidal capacity. That equates to $81,500/year/MW tidal installed in energy import cost reductions, assuming no curtailment.
2. Load shaping: This is a component of the energy bill that fluctuates monthly and is based on the change in energy purchase from the expected purchase. It is either a credit or a cost

and is broken into heavy load hours and light load hours. Heavy load hours are 6-10 PM Monday through Saturday, and all other hours are low load hours. The calculation is relatively involved and additional details can be found in (Mongird et al. 2018). For a 1 MW tidal deployment, the load shaping charge is reduced by $56,300 per year relative to no tidal deployment.

3. Demand charge: This is a typical component of retail electricity bills and is often assessed to capture distribution and transmission system usage. The calculation is usually based on a monthly peak load, either customer peak or coincident with system load, multiplied by a demand charge rate. The BPA demand charge is different in that it considers the monthly peak, the average high load hour load, and the contract demand quantity set by BPA. Accordingly, as with the shaping charge, the demand charge is not directly correlated to a straight reduction in demand. The deployment of a theoretical tidal resource on OPALCO's system does reduce peak demand, but it also reduces the peak high hour load, that is OPALCO's load at the WECC system peak hour, even further (peak demand is not always correlated with strong tidal output). As a result, demand charges increase in this situation by $7,900 per MW of tidal deployment per year. It is important to note that the increasing deployment of customer energy sources (i.e., DER) to address demand charges, in addition to providing other services, is likely to change the demand charge rate and calculation. The exact change would depend on the change in system utilization but could increase if OPALCO needs to recover the same costs across lower total demand.
4. Transmission charge: This is more straightforward based on the energy purchases during BPA's peak transmission hour in each month multiplied by the transmission charge rate of $2.103/kW. Based on 2017 load, we estimate the transmission charge benefit to be $6,800 per MW of installed tidal per year.

Finally, we estimate the value associated with increasing the life of the 69 kV transmission cable by deferring the transmission investment to replace the cable from Anacortes, WA, to the Decatur Island substation. This estimate is based on an electrochemical life model of an insulated cable subject to electrical and thermal stress from different load cycles and includes a probability of failure. Mongird et al. (2018) leverage this electrochemical cable life model along with actual cable parameters provided by OPALCO and the two-week typical cable loading cycle for December 2017 (December being a high load month). We used this model to estimate the value associated with reduced demand replaced by tidal generation. We estimate this value to be $13,047 per year per MW for 2017. This assumes, of course, that other factors do not cause a cable replacement.

Table 4-5 summarizes the quantitative evaluation of the benefit streams discussed for a 1.5 MW for the OPALCO system, represented as value per MW. The total estimated annual benefit is $148,924 per MW for a tidal system deployment.

Table 4-5. Quantification of Value Streams for a Tidal Installation for OPALCO

Annual Value Stream	Benefit per MW of Tidal
Energy Costs	$81,372
Load Shaping	$56,263
Demand Charge	-$7,941
Transmission Charge	$6,183

Cable Life Benefit	$13,047
Total Benefit	$148,924

Benefit estimation is provided here to illustrate the potential value obtainable to a deployment, but not offer a business case for deployment. We do not evaluate whether tidal is the optimal resource choice here but given that there is limited land area on the islands, and they have a 50% island-based generation target coupled with Washington’s clean energy requirements, tidal resources may provide value.

4.2.6 Conclusions

Our analysis indicates the following:

1. We consider the direct value of the tidal resource to the current OPALCO system, that is its locational or spatial value and the value of the energy it serves:
   - The average monthly tidal resource energy content correlates to winter peaking load on the San Juan Islands. Solar energy, on the other hand, the other renewable resource utilized by OPALCO on the islands, peaks in the summer, with its winter output a factor of 8 lower than the summer.
   - On an hourly basis, on average across the year, the tidal resource correlates to peak load hours in the morning and the evening. Looking specifically at winter and summer hours in the months of January and July, respectively, tidal peaks with the winter evening peak and the summer morning peak, being least available in winter mornings and summer evenings during those months. This correlates to higher winter resource capacity factors during evening peak hours and higher summer resource capacity factors during morning hours.
2. Tidal energy has direct monetizable benefits to the OPALCO system.

4.3 System Benefits: Integration of Marine Energy in Distribution Grids

System Benefits

- Avoided or deferred distribution investments

Scheduled/Dispatchable Generation

- Optimization of generation with storage

Technology Companions

- Improvements in performance of other technologies (symbiotic benefits)

This section addresses the local distribution grid impact due to integration of marine energy and how utility-scale energy storage can be operated together with marine energy and other mature renewable energy technologies such as solar PV. For fair comparison, we performed analysis on a large-scale island grid, which is located closer to a tidal power generation resource.

4.3.1 Summary of Analysis Inputs and Parameters

Table 4-6 below identifies the analysis inputs and sources utilized in this Section. Section 4.2 identifies the analytical process utilized to convert the marine energy resource to an electric output.

Table 4-6. Inputs and data sources for Section 4.3

	Type	Location	Data Interval	Source
Grid load	Island	Nantucket, MA	Hourly	National Grid
Grid topology	Distribution	Nantucket, MA	-	National Grid
Renewable resource	Tidal	Nantucket, MA	Hourly	(Yang, Wang, et al. 2020; Wang and Yang 2020).
	Solar	Nantucket, MA	Hourly	National Grid

4.3.2 Nantucket Grid

Nantucket grid data were provided by National Grid (Figure 4-13). The grid consists of eight reconfigurable feeders served with two 46 kV sub-transmission cables along with an 8 mega volt-ampere reactive shunt reactor and an adequate impedance connected to the source. The grid consists of capacitor banks, substation load tap changes, voltage regulators, reclosers, and fuses. The detail of the model can be found in (Balducci et al. 2019).

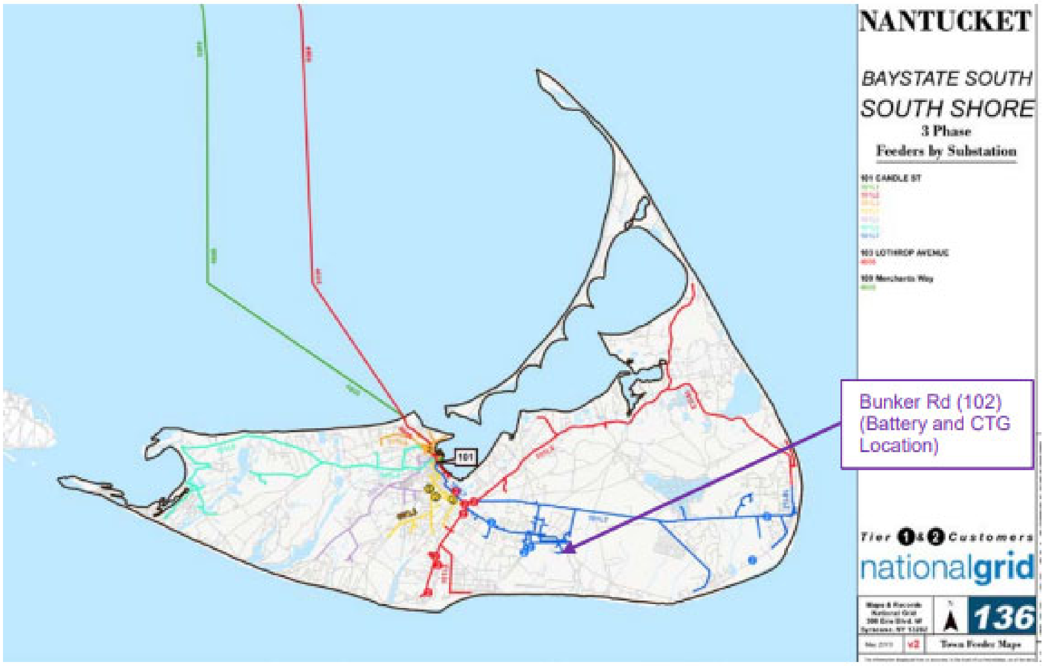

Figure 4-13. Nantucket grid area used in the case studies (courtesy of National Grid).

4.3.3 Resource Profiles

Figure 4-14 identifies the solar and tidal profiles over 200 hours for resources selected around Nantucket Island. The solar profile shows the expected daily characteristic and the tidal the expected multiple tidal currents coming in and going out. The resource profiles indicated are only for the 200 hours of peak loading time periods as utilized in the analysis in this section. The timing of the resource profiles is associated with actual peak system loading data. The complete dataset consists of whole year data of one-hour resolution.

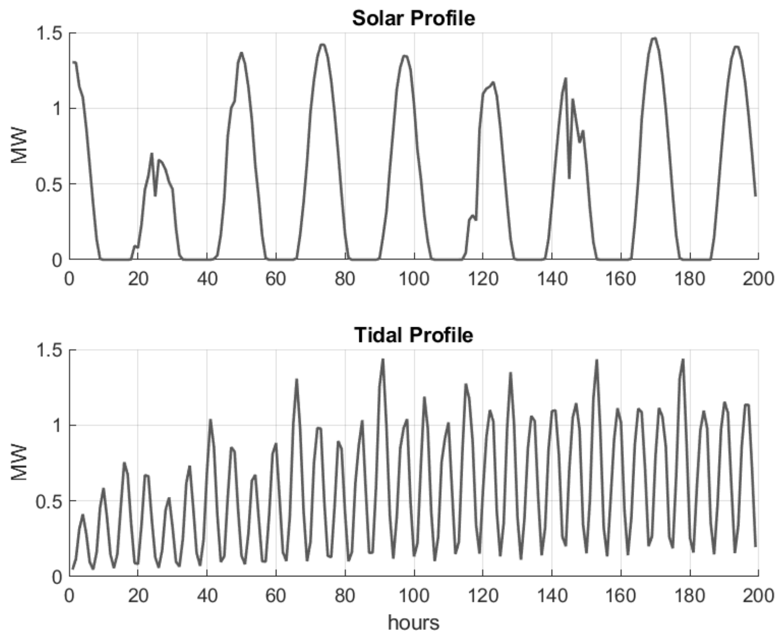

Figure 4-14. Aggregated (over multiple locations) solar PV and marine energy (tidal) power deployed in the case studies.

4.3.4 Methodology

Figure 4-15 explains the setup for analyzing distribution grid impact due to integration of marine energy. The grid data and resource data described above are the main inputs to the experiment, along with the legacy control options (e.g., tap changers, capacitor banks). A MATLAB® script was developed to automate the procedure for manipulating penetration of renewable energies (on-site distributed PV and tidal energy) and storage controller in the open-source distribution grid simulator OpenDSS, through a COM Interface.

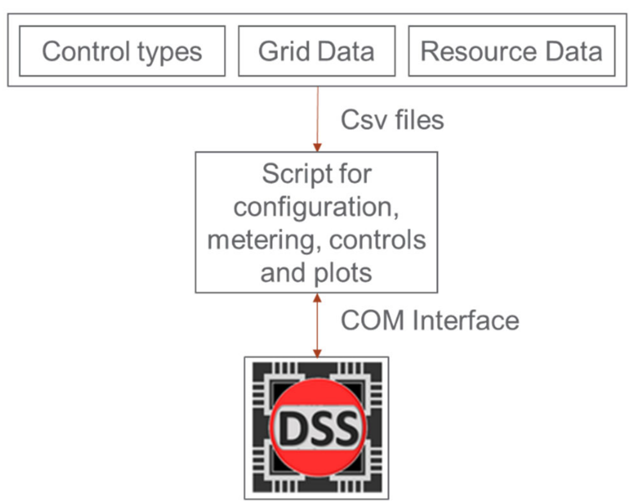

Figure 4-15. Simulation setup for conducting the impact of marine energy on distribution grids.

4.3.5 Case Studies

To demonstrate the impact of marine renewable energy (tidal in this case) as compared to solar PV the following case studies were analyzed: i) base; ii) base+PV; iii) base+marine energy; and iv) base+ PV+marine energy. The word “base” is representative of the grid having no active generation sources, that is a passive grid with load following a particular load profile for a node. For base+PV we simulate the grid with 54 distributed solar PV sites, which are customer owned and distributed across the entire grid area, this is the most accurate state of the current grid, but the exact distributed PV inverter sizes are not known. Hence the “base” case study is important for deriving the changes in grid operation as the active components in the grid increase. For base+marine energy we integrate a tidal generator in the distribution grid at one of the feeders (feeder 6 of the grid), with nameplate rating of 1.5 MW. The main reason for choosing the size 1.5 MW of the tidal turbine is to match the total PV generation existing in the grid (1.5 MW). The combined impact of both PV and marine energy is then presented in the case study of base+PV+marine energy. As a reference, the locations of these components on the grid can be seen in Figure 4-16.

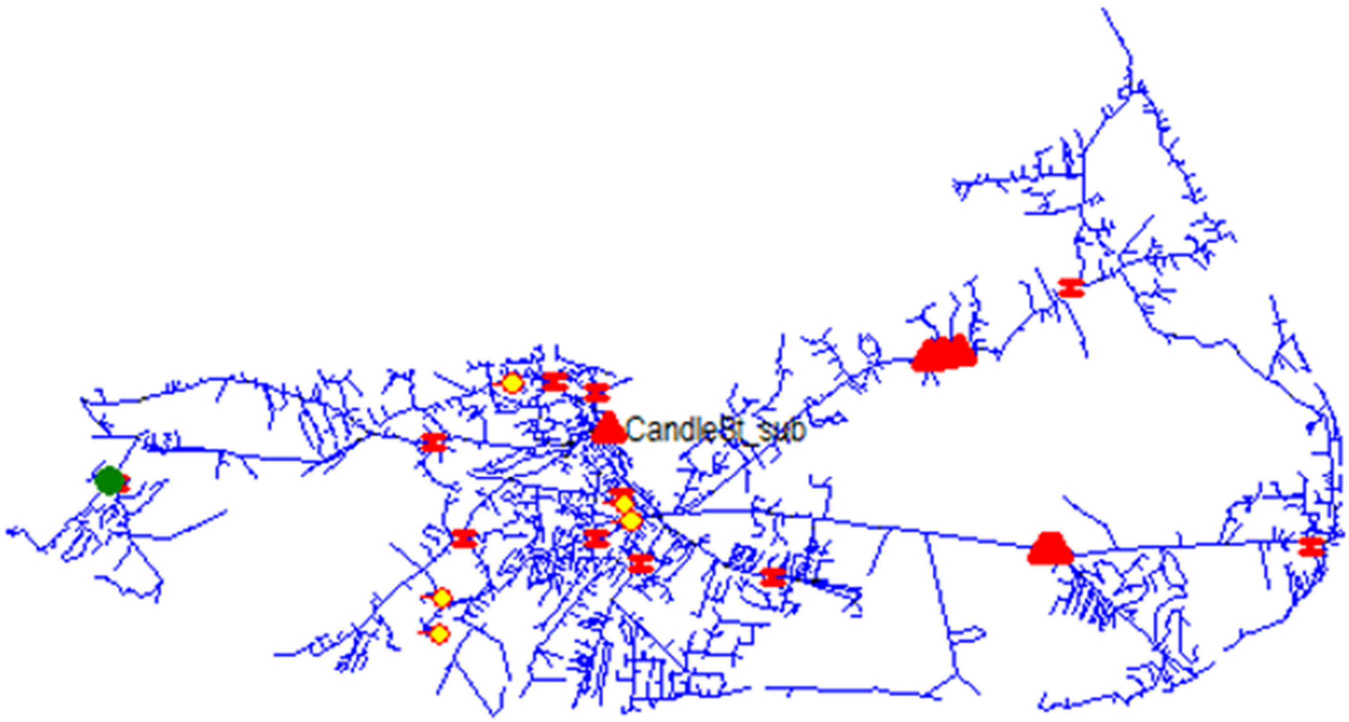

Figure 4-16. Representative grid diagram with location of substation (Candle St. sub), regulators (red triangles), selected PV sites (yellow dots), selected capacitors (red ‡ symbol), and the marine energy generator (green rectangle).

4.3.5.1 Feeders connected to Marine Energy Devices

For all four case studies, Figure 4-17 and Figure 4-18 show the currents (in amperes) and the voltages (in per unit) of feeder 6, respectively, which has marine energy connected for a peak loading week (around June) of the year.

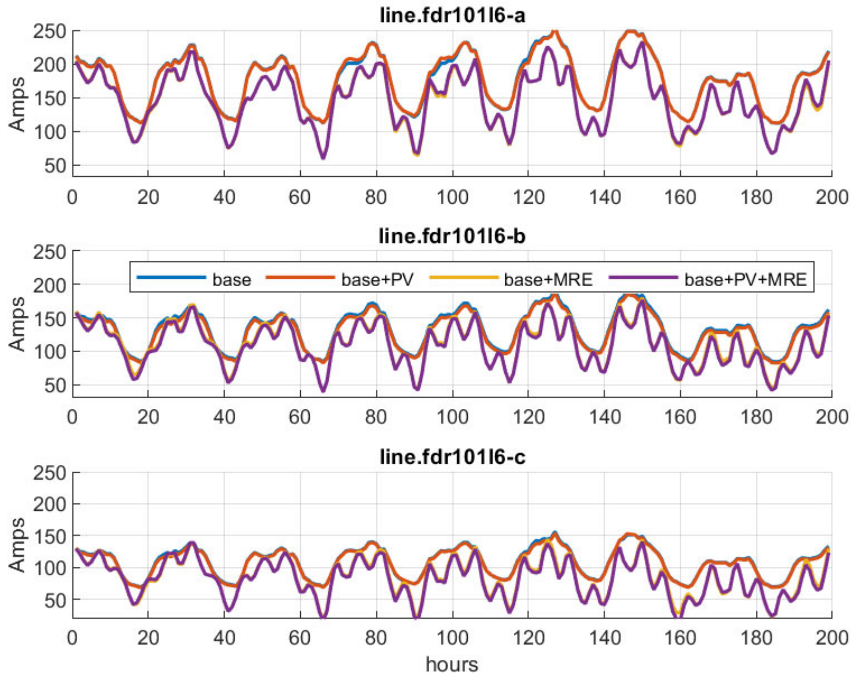

Figure 4-17 Currents of phase a, b, and c, of the feeder containing marine energy (feeder 6).

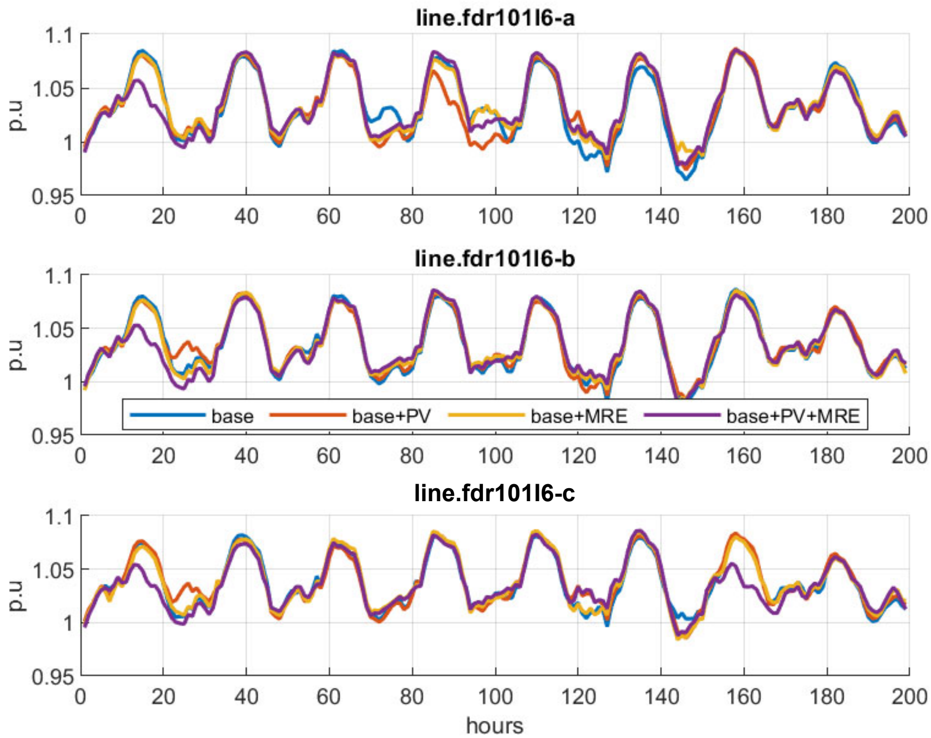

Figure 4-18. Sending end-voltages of phase a, b and c at the feeder containing marine energy (feeder 6).

From Figure 4-17 and Figure 4-18, the first observation can be made regarding the swings experienced by the current and voltage profile from local injection of tidal power. This is due to the tidal resource profile pattern which causes the current infeed in the feeder being reduced during both day and night times. This is a major change in the feed-in current as compared to the base+PV case, where the offset is only present during daytime when solar irradiation is present. This effect is translated to the voltage profiles where the voltages are lifted “up” during less loading times.

4.3.5.2 Local voltage regulators

Figure 4-19 and Figure 4-20 shows voltage profile and corresponding regulator positions at one of the regulators placed close to the marine energy generator in feeder 6. The effects seen at the feeder node (Figure 4-17 and Figure 4-18) are magnified when we move to a local node in that feeder closer to the marine energy. For example, for all cases with marine energy, the voltages at all phases of the regulator deviate from the “base” case and base+PV case. A similar effect can be observed at the tap positions, where they seem to operate at different frequencies and levels for the marine energy cases as compared to base and base+PV cases. An interesting observation can be made for the high loading hours, around hour 80, 100, and 120, where the local generation from marine energy help alleviate some of the extreme low voltages (less than 0.95 per unit) experienced at the node. At these times, even the maximum tap positions (around hour 140 for phase a and b of the regulator in Figure 4-20) for the base and base+PV cases were not able to resolve the minimum voltage violations.

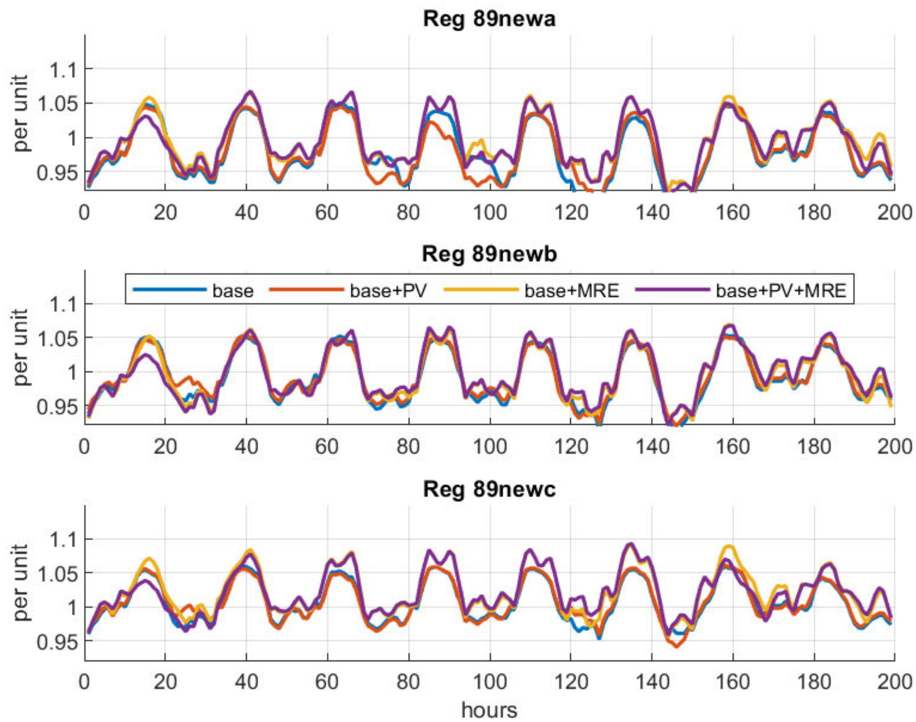

Figure 4-19 Voltage profile of phase a, b, and c at one of the local regulators in feeder 6

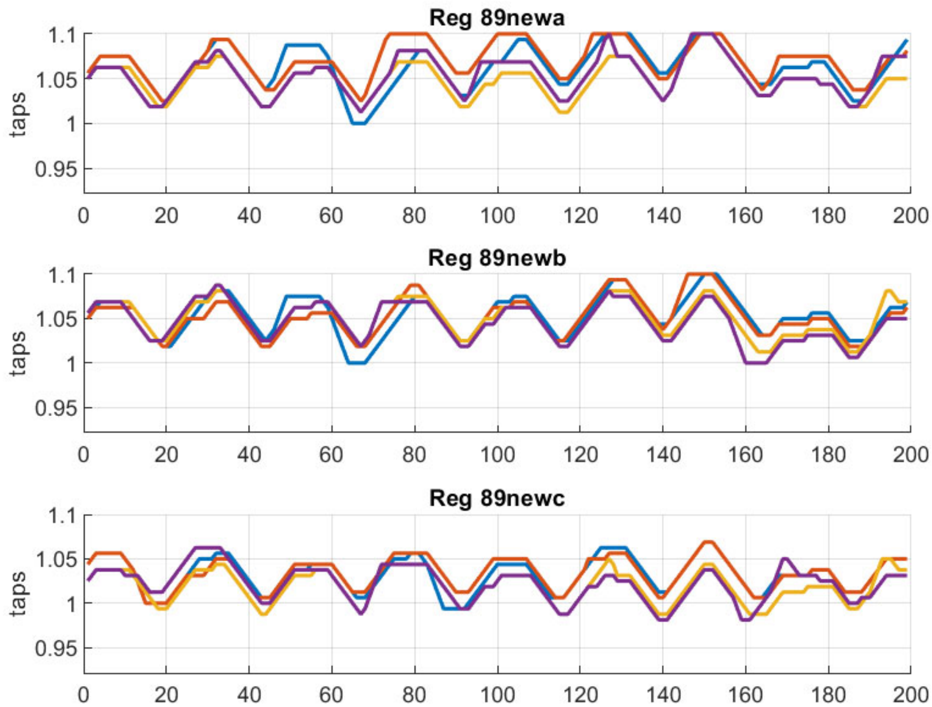

Figure 4-20 Tap positions of phase a, b, and c at one of the local regulators in feeder 6

4.3.6 Integration of Storage with Marine Energy in Distribution Grids

To demonstrate the tandem operation of marine energy with storage present in the distribution grid, we place a 6 MW, 48 MWh, and 7 MVA inverter-sized energy storage system in the grid. The storage location was selected by the National Grid's plan to install a storage system in the grid as identified in Figure 4-21.

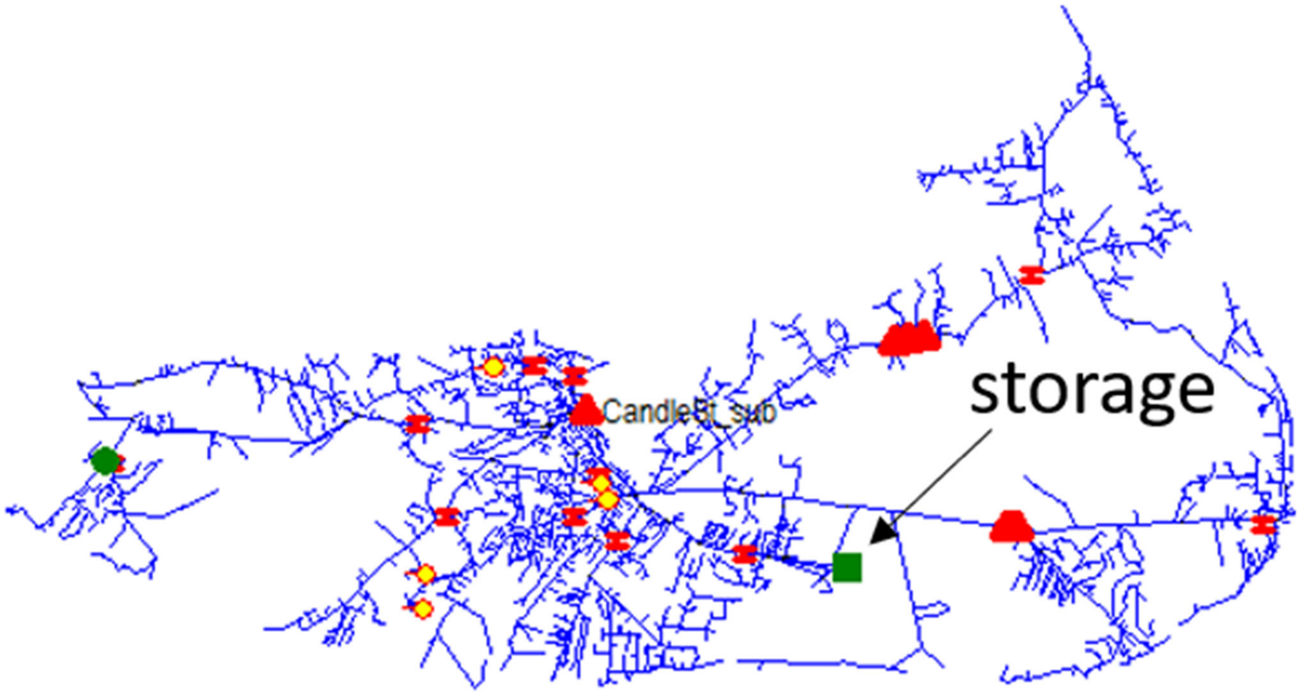

Figure 4-21. Representative grid diagram with the addition of storage.

Next, we represent the impact of including storage on the grid, which has DERs (PVs plus marine energy) with and without the installation of storage.

Yearly simulation was performed using storage with the goal to shave off the peak load experienced by the grid. The rest of the controls were kept the same as the previous section and the same resource and load data were used. Readers are referred to the last subsection, with regards to the size and location of the DERs.

Figure 4-22 presents the load profile of the power imported from the substation with the introduction of storage. The top plot shows the load profile, and the bottom plot shows the storage profile used to reduce the peak load. The storage is discharged during high loading periods while charging during off peak timings while keeping a reserve capacity of 20%. At the end, 3.8 MW of the peak load is shown to be shaved-off.

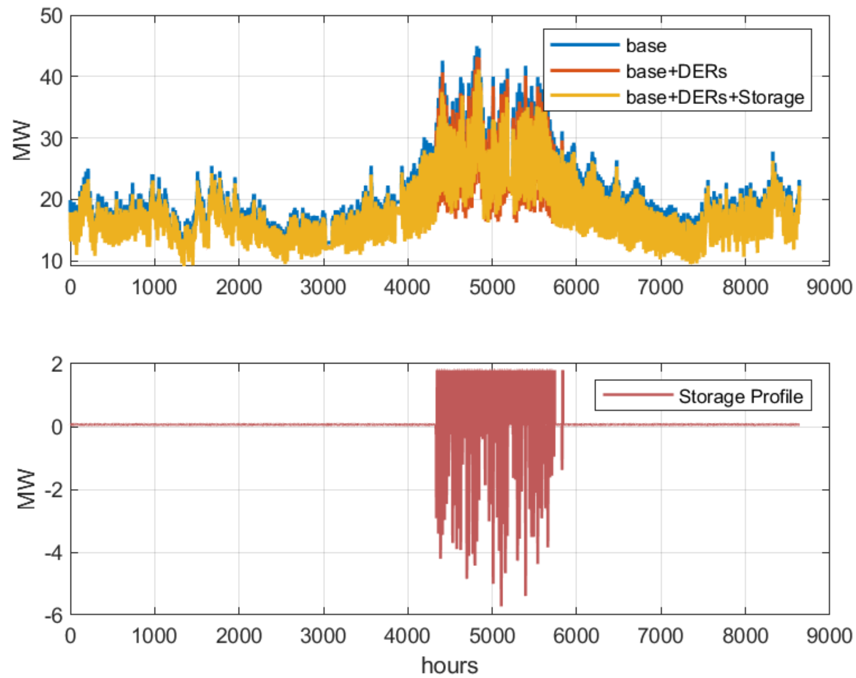

Figure 4-22. One-year power imported from the substation (top) and the storage profile (bottom) to offset the power dispatch. The case with storage shaves 3.8 MW of the peak load.

4.3.6.1 Feeder connected to marine energy

Like previous subsection analysis, we analyze the current and sending end voltages at the feeder (feeder 6) for the peak load week in a year in Figure 4-23 and Figure 4-24. Since storage is placed at the location, which is far away from the marine energy generator, it's impact on the current fed-in to feeder 6 is not much. However, since the storage helps in alleviating peak loading at the neighboring feeders, the sending end voltages (Figure 4-24) can be seen to be flattened around hours of low loads (from hour 80, 100, 120 and 140).

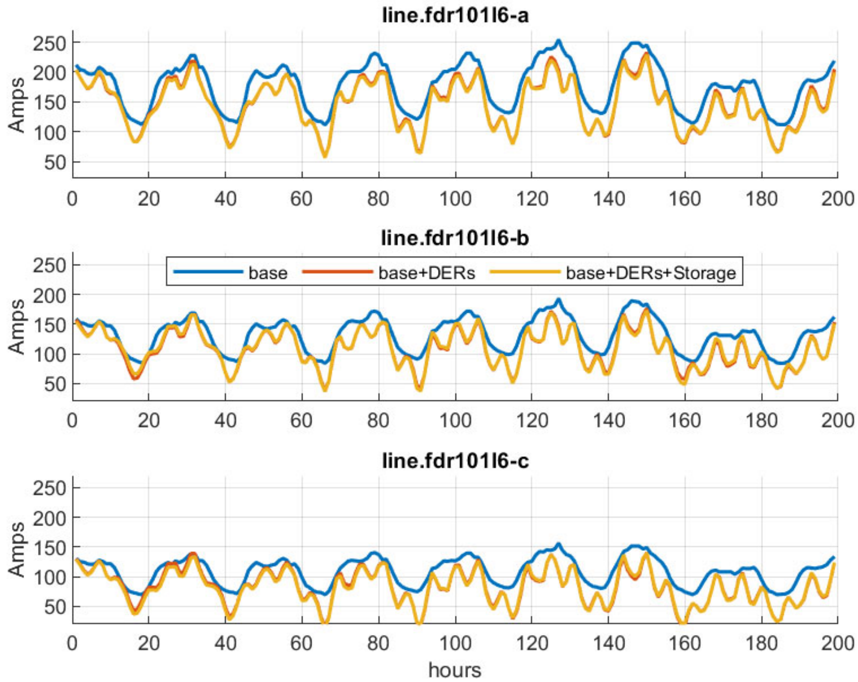

Figure 4-23 Current fed-in of phase a, b and c at the feeder containing marine energy (feeder 6).

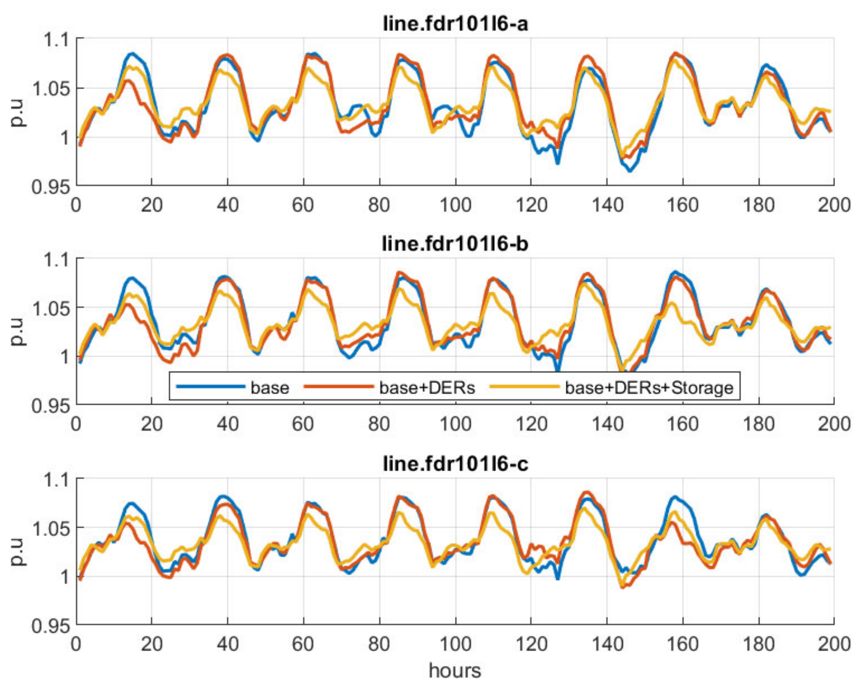

Figure 4-24. Sending end-voltages of phase a, b and c at the feeder containing marine energy (feeder 6).

4.3.6.2 Local voltage regulators

Figure 4-25 and Figure 4-26 show voltage profile and corresponding regulator positions at one of the regulators placed close to the marine energy generator in feeder 6. As the main goal of the storage controller is to reduce the peak load, it also helps to some extent on reducing the minimum voltage violations (e.g., hour 120 and hour 140). This is because the lower loading takes burden off the regulator taps position, which can be seen in Figure 4-26 to not be maximized.

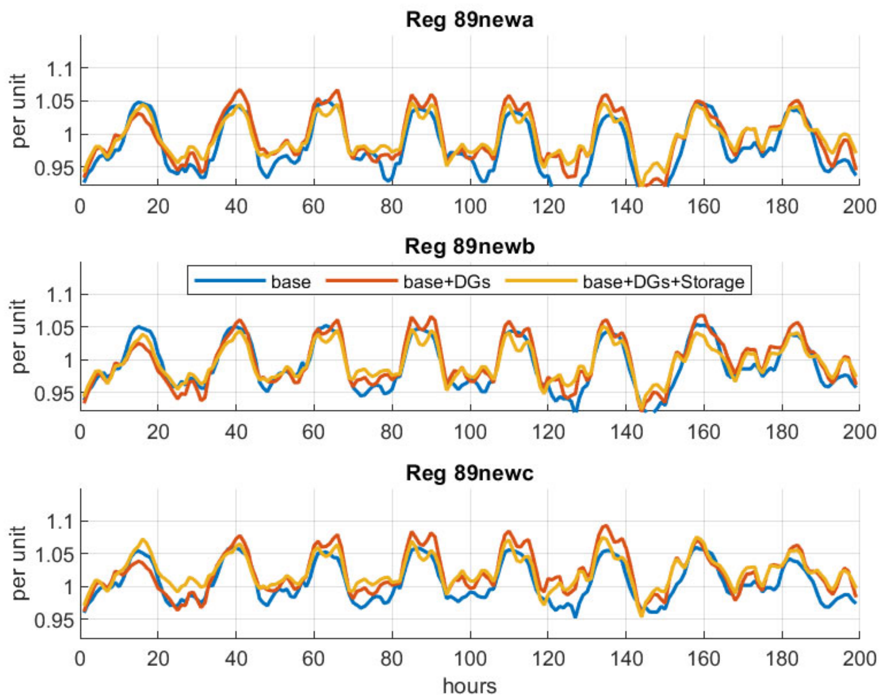

Figure 4-25. Voltage profile at one of the local regulators in feeder 6.

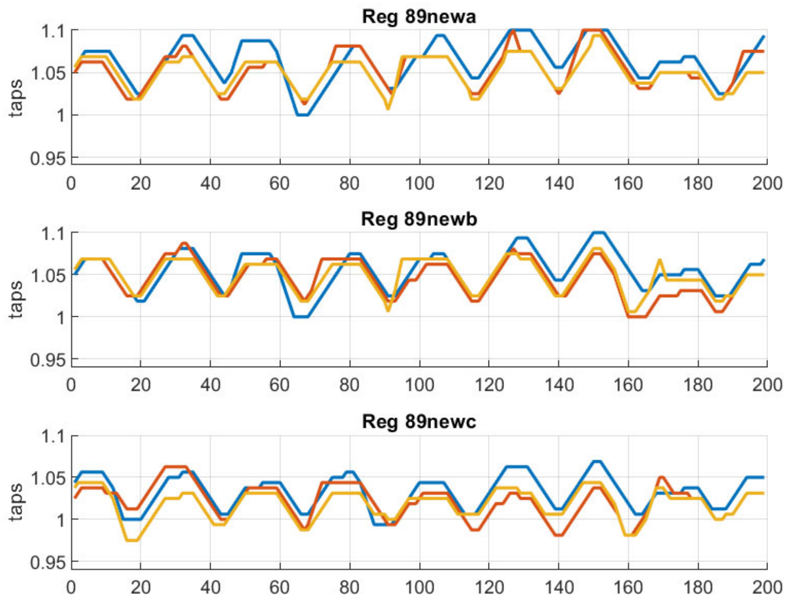

Figure 4-26. Tap positions at one of the local regulators in feeder 6.

Figure 4-27 presents statistics of the number of tap movements recorded for the whole year for all the regulators in the grid for the above shown cases. With the use of storage, 10% reduction in total tap operation is achieved. Quantification of this benefit into a dollar value can be obtained by the utility using the operation cost of the regulators; however, this may need investigation into the operation strategies of the regulators, placement, size, and ratings. Future work can target these activities.

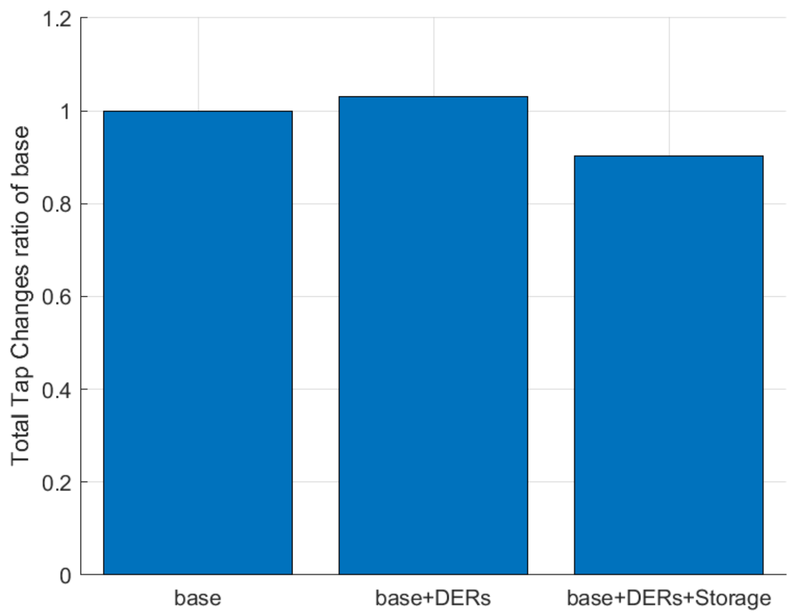

Figure 4-27. Total tap changes observed in one year, scaled to the base case taps operations.

4.3.7 Conclusions

The main takeaways from the performed analysis are:

1. Depending on the loading on the feeder injected by tidal power, cyclic voltage swings can be experienced during night times, as the usual loading during night times are low and the tidal injection has a profound impact on them.
2. Voltage regulation requirements can be off burdened significantly during the high loading periods for the feeders containing the tidal generator.
3. Storage in combination with marine energy and PV can provide relief in peak loading of the grid, facilitates lower total losses, and tap operations in the grid.

The above findings can be further refined in future investigations on different types of network models, loading conditions, control configurations (regulators/capacitors), and generation conditions.

5.0 Timing Value

5.1 Higher Relative Stability, Availability, and Persistence

Predictability

- Reduced integration requirements
- Coincidence with load
- Complementarity with other resources

Portfolio Effects

- Negative correlation at high penetrations
- Effective Load Carrying Capability/Capacity credits
- Reduced integration costs

Marine energy has been shown to be more predictable and stable than solar and wind resources (Preziuso et al. 2019). In this section, we explore some of the ways in which the higher stability and predictability of such resources may lend themselves favorably for grid operations, especially under specific spatial, temporal, or operational contexts. We first briefly describe the data used for this section, and then describe a suite of metrics devised to quantitatively characterize the timing value of marine energy resources. Subsequently, we describe the potential implications of those characteristics in the context of bulk power systems operations.

5.1.1 Summary of Analysis Inputs and Parameters

Table 5-1 below identifies the analysis inputs and sources utilized in this Section. Section 4.2 identifies the analytical process utilized to convert the marine energy resource to an electric output.

Table 5-1. Inputs and data sources for Section 4.0.1

	Type	Location	Data Interval	Source
Grid load	Bulk	WA, OR, FL	Hourly	FERC Form 714
Renewable resource	Wave	PacWave Test Site OR Coast	Hourly	(Yang, García-Medina, et al. 2020; Wu et al. 2020)
	Tidal	Admiralty Inlet, WA	1-minute	(Jim Thomson 2009; J. Thomson et al. 2012)
	Ocean Current	Florida Straits	3-hourly	(Chassignet et al. 2007)
	Solar	WA, OR, FL	Hourly	NSRDB
	Wind	WA, OR, FL	Hourly	NREL Wind Toolkit

5.1.2 Data and Models for Generation Profiles

Across the United States, three locations were selected, each representing a different type of marine energy resource: (a) Admiralty Inlet, WA (for tidal resource); (b) PacWave site in OR (for wave resource); and (c) Florida Straits (for ocean current resource). The locations can be seen on a map of continental USA in Figure 5-1 below.

Figure 5-1. Locations selected for our “timing value” case studies.

For the tidal resource, we selected Admiralty Inlet, WA as the location. From (J. Thomson et al. 2012), we obtained the velocity profile time series (in 1-minute resolution) as discussed in Appendix A. Figure 5-2 shows the time-series plot of the power generated by this representative tidal generator, at both hourly and daily resolutions.

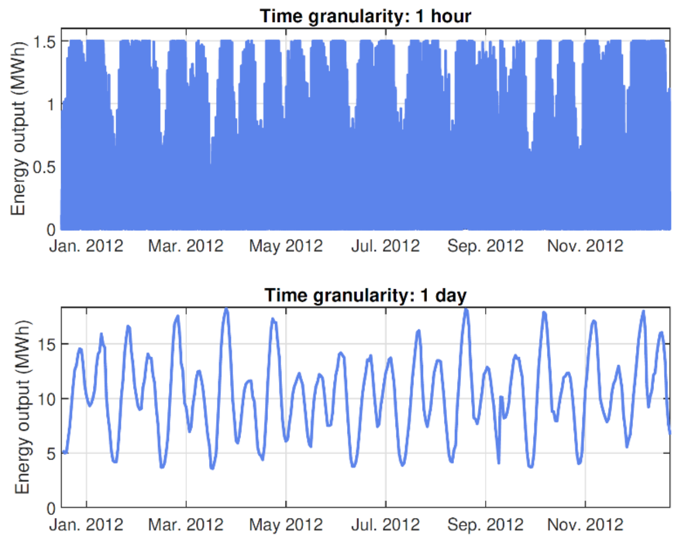

Figure 5-2. Tidal generation profile for Admiralty Inlet, WA.

Florida Straits ocean current data were selected as the candidate resource for quantitative analysis. These data were obtained at 3-hour intervals from (Chassignet et al.). The obtained velocity profiles (m/s) are converted to power output using a similar model as defined for the tidal system. Note that while the tidal generation data were obtained in an interval of 1 minute, the ocean current data were only available at a larger interval of 3 hours. Figure 5-3 shows the time-series plot of the representative ocean current driven power generator.

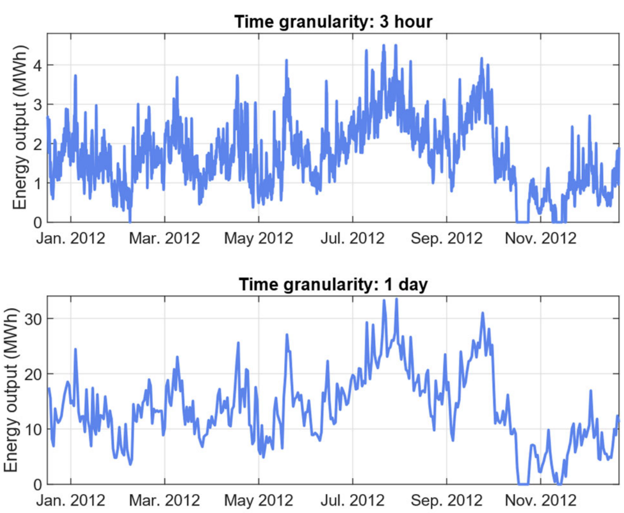

Figure 5-3. Ocean current generation profile for location in Florida Straits.

For wave resource, the PacWave site off Newport, OR, was selected as the candidate for analyses. PacWave is located at 44 deg 35’4” N 124 deg 12’45” W, which is ~7 miles (11 km) offshore and fully exposed to the Pacific Ocean. Figure 5-4 shows the time-series plot of the representative wave generation profile. The wave resource and its conversion to electric output is discussed in Appendix A. Note that the wave data granularity is 1 hour.

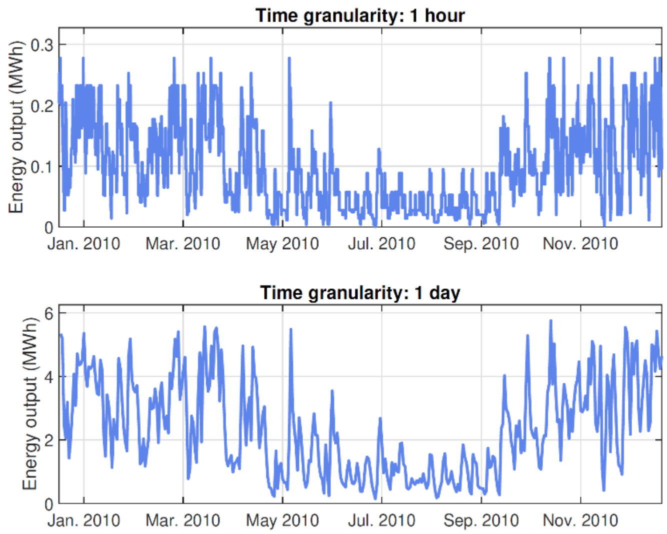

Figure 5-4. Wave generation profile (device type: BBDB) for a location in PacWave site in OR.

To complete our analysis, appropriate solar generation and wind generation data is required. We obtained solar radiation data, for locations proximal to the marine resource sites from the National Solar Radiation Database (Sengupta et al. 2018). The solar radiation data is typically available in intervals of 30 minutes. The solar radiation was converted to solar power based on the model described in Nguyen and Le (2014). Similar to the solar generation data, we obtained wind generation data from NREL's wind energy toolkit (as described in detail in Draxl et al. (2015), with an interval of 5 minutes. As one of the aims of this paper is investigating the impact of marine energy resources on balancing requirements of the utility scale power grid, we obtained the relevant load data from Federal Energy Regulatory Commission repositories for utilities in Washington, Oregon and Florida ("Form No. 714 - Annual Electric Balancing Authority Area and Planning Area Report") at an hourly time interval. One-minute resolution data was obtained for WECC through a sister project, shared by WECC for PNNL staff for comparison to tidal resource data. Unfortunately, wave data are not available at a higher level of granularity, limiting the analyses that can be conducted. Higher resolution data across all resources would enable evaluation of intra-hour balancing requirements. See Figure 5-5 for yearly profiles of the solar, wind, and utility load for northern Washington.

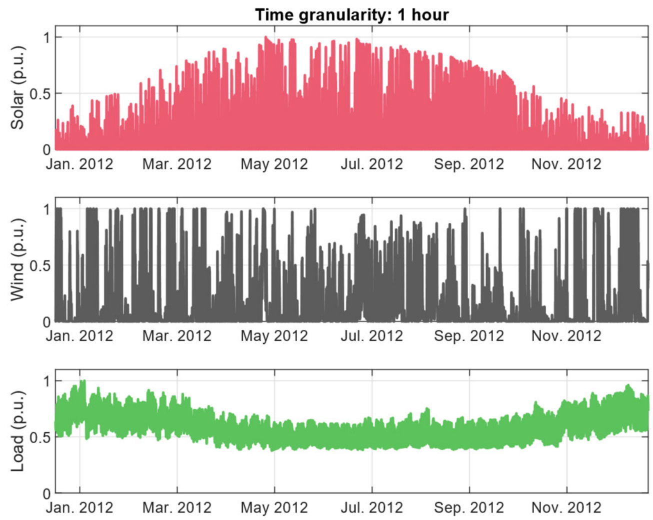

Figure 5-5. Representative solar, wind, and utility level load profiles (all normalized to their maximum values) for northern Washington state.

5.1.3 Resource Temporal Analysis: Availability, Persistence, and Versatility Metrics

In this section, we develop a suite of temporal metrics and compute the same for the marine energy resources. Moreover, we compare these metrics with wind- and solar-based resources for proximal areas in terms of the defined metrics. We also try to quantify the extent to which marine resources may be available as a generation option when solar and wind are unavailable, thereby estimating the versatility of these marine resources. Ensuing observations from this section provide a qualitative understanding of how marine resources might be helpful for potential grid applications. Note that these metrics are focused solely on characterizing the resource themselves, and do not consider specific details pertaining to their applicability for power system operation. The latter would require additional grid level specifics, in addition to the resource temporal characteristics, and would be covered separately in a subsequent section.

We define a generic time series as $x \coloneqq \{x(1), x(2), \ldots., x(T)\}$. Also, we consider a time window [0, T] with an observation interval of Δ. With these assumptions, we first define a suite of metrics that capture specific characteristics of the time-series resource data.

5.1.3.1 Resource Availability

The resource availability *(RA)* metric provides an indication of how often in a time window a generation resource is generating energy above lower threshold. Define a lower threshold $\check{x}$ such that if at any instant t, x(t)> $\check{x}$, the instantaneous availability of resource (denoted as $ra(t)$) is instantiated as 1, otherwise 0. For the total time window i.e. [0, T], the *RA* index can be calculated as,

$$RA = \frac{1}{T}\sum_{t=1}^{T} ra(t)$$

For an electrical generator feeding a power grid, the lower threshold $\check{x}$ is typically a finite value (often computed as a percentage of the rated output of the generator) to cover for different types of no-load machine losses.

5.1.3.2 Resource Persistence

The resource persistence (*RP*) metric provides an estimate of how persistently available the resource is over the considered time window. We define a sub-window of length τ such that $\tau < T$ (this sub-window is smaller than the length of the overall time window under consideration). For all sub-windows $j = 1,2,\dots,T-\tau+1$, compute the instantaneous persistence $rp(j)$ as follows:

$$rp(j) = \begin{cases} 1, if\ ra(k) = 1, \forall k \in \{j, j+\tau-1\} \\ 0, \quad otherwise \end{cases}$$

Now, for the overall duration [0, T], *RP* can be found as:

$$RP = \frac{1}{T-\tau+1} \sum_{t=1}^{T-\tau+1} rp(t)$$

5.1.3.3 Resource Versatility

Resource A (in comparison to other resources, say B and C) is defined to be versatile only if it is available in a time instant when B and C are not. This measure of instantaneous versatility can be average across the full-time window [0, T] under consideration to obtain the resource versatility metric for the resource A. Mathematically, the instantaneous versatility of resource A, relative to B and C can be denoted as:

$$rv_A^{B,C}(t) = \begin{cases} 1, \quad if\ ra_A(t) = 1\ and\ ra_B(t) = ra_C(t) = 0 \\ 0, \ otherwise \end{cases}$$

The time averaged versatility (RV) can be found as $RV = \frac{1}{T}\sum_t rv_A^{B,C}(t)$.

Next, we evaluate these metrics for the different locations selected in this study. Please refer to Figure 5-6 for the remainder of this discussion. The foremost observation we make about tidal power in Admiralty Inlet, WA, is that it is more available and persistent on an hourly time scale when compared to wind and solar in nearby areas. It is worth mentioning that there can be scenarios where wind resource is weak and potentially unavailable for extended time periods, while solar has an inherently diurnal variation pattern whereby it is unavailable during hours without daylight. In such situations, marine-based generation resources are comparatively reliable and do not suffer from as much intermittence. Similar observations regarding higher hourly availability and persistence can be made for the ocean current resource in Florida and the wave resource at the PacWave site in Oregon. In terms of persistence, we note that tidal, wave, and ocean current resources are all more persistent when compared to wind and solar at hourly time scales. In terms of hourly resource versatility, the marine energy resources were observed to be appreciably versatile over the course of one year.

Resource type (Location)	Granularity	RA	RP
Tidal (Admiralty Inlet, WA)	hourly	0.678	0.402
Solar (Northern WA)	hourly	0.403	0.313
Wind (Northern WA)	hourly	0.447	0.354
Ocean Current (Florida)	3-hourly	0.962	0.957
Solar (Coastal FL)	3-hourly	0.485	0.235
Wind (Coastal FL)	3-hourly	0.718	0.573
Wave (PacWave, OR)	hourly	0.942	0.934
Solar (Western OR)	hourly	0.423	0.337
Wind (Western OR)	hourly	0.601	0.521
Wave (Orkney Islands, GB)	hourly	0.997	0.993
Tidal (Orkney Islands, GB)	hourly	0.719	0.396
Solar (Orkney Islands, GB)	hourly	0.366	0.288
Wind (Orkney Islands, GB)	hourly	0.953	0.935
Tidal (Admiralty Inlet, WA)	daily	0.937	0.887
Solar (Northern WA)	daily	0.918	0.821
Wind (Northern WA)	daily	0.690	0.430
Ocean Current (Florida)	daily	0.961	0.947
Solar (Coastal FL)	daily	0.997	0.991
Wind (Coastal FL)	daily	0.849	0.664
Wave (PacWave, OR)	daily	0.948	0.884
Solar (Western OR)	daily	0.917	0.834
Wind (Western OR)	daily	0.813	0.578
Wave (Orkney Islands, GB)	daily	0.835	0.735
Tidal (Orkney Islands, GB)	daily	0.947	0.898
Solar (Orkney Islands, GB)	daily	0.822	0.719
Wind (Orkney Islands, GB)	daily	0.978	0.939

Figure 5-6. Resource temporal characteristics (availability and persistence) for different renewable energy resources, across U.S. and Great Britain (GB) locations.

Specifically, the RV metric for tidal, wave, and ocean current-based resources were observed to be 21%, 19%, and 14% respectively. In Figure 5-7 we show the temporal spread of the instantaneous hourly versatility values for the tidal and wave resources across all hours of the day and all days of the year. For both these resources, the versatility of the marine energy is dominant for evening and night hours and specifically over the winter months.

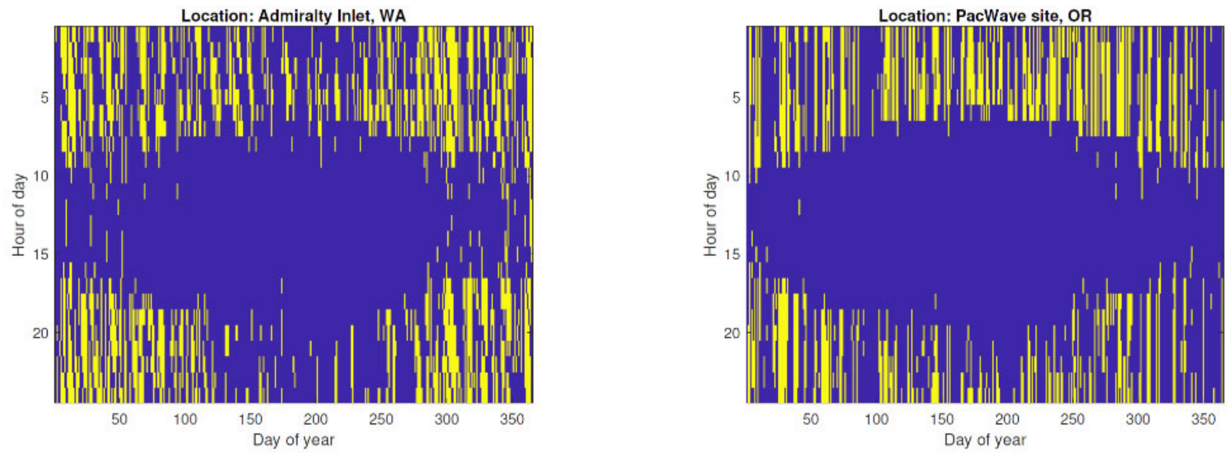

Figure 5-7. Instantaneous versatility for marine energy resources (left: tidal, right: wave) when compared to wind and solar, for U.S. locations. The yellow corresponds to instants when marine energy is available while solar and wind are not. The blue instances indicate availability of either of solar or wind (or both) resources.

Even at the daily level interval, the studied marine resources are found to be complementing the solar and wind production favorably. Specifically, for the selected U.S. sites, tidal and wave resources were observed to be more available and persistent than both solar and wind. The ocean current based resource, while being slightly less available than solar (due to seasonality in the current), has a reasonably higher availability and persistence value when compared to wind.

5.1.4 Application to Power System Operations: Reduction in Balancing Needs

In the previous section, we observed that marine energy resources in general lend themselves favorably in terms of resource availability and persistence for the selected locations in our study, when compared with solar and wind. In this section, we extend our analysis to a power system-specific paradigm, where we evaluate the potential bulk-system impacts of including marine energy resources into the generation mix.

For this analysis, we have followed a similar technique proposed in (Heide et al.) and extended it to include marine energy in the portfolio. Consider any representative power system that contains a significant amount of renewable generation in the overall generation mix. Denote the overall systemwide amount of solar-, wind-, and marine-based generation resource as $S, W, and\ M,$ respectively. Denote the load demand as L. Note that the units of S, W, L and M are kW. Consider an hourly time interval of operation. Note that for any generation type X, X_t denotes the instantaneous value at hour t and $< X >$ denotes the average (in the temporal sense) value of the time series X. For the sake of exposition, we normalize all the hourly time series with respect to their mean, such that their normalized mean value is 1. Now, denote Δ_t to be the hourly mismatch function. Also, $\alpha_S, \alpha_W,$ and α_M denote the fraction of solar, wind, and marine energy resource in the system for a given hour. Mathematically,

$$\Delta_t = \gamma(\alpha_S S_t + \alpha_W W_t + \alpha_M M_t) - L_t$$

where γ is reflective of the average amount of overall renewable generation in the system in the specific hour t. Specifically, if $\gamma = 1$ it implies that on an average the entire load can be supported by renewable generation. Note that, even though the renewables can meet the load entirely for the time-averaged data there may be specific time instances in which there is either shortfall or over-production of renewable generation. This inherent resource intermittence entails the need for quantifying the hourly balancing requirement needed to maintain stable operation of the bulk power system under consideration. Let this instantaneous hourly balancing requirement at time t be denoted as B_t. Now, like (Heide et al.), we hypothesize that under this high-renewable paradigm, the generation shortfall regimes are most critical since they require immediate ramp up from other dispatchable generators to balance the supply and demand. This can mean firing up peak power plants and fossil-fuel plants that are either expensive from an economic standpoint or non-ideal from an environmental standpoint. Therefore, we define B_t as the hourly requirement of securing generation from conventional balancing generators to meet supply-demand equilibrium under generation shortfall conditions. Mathematically,

$$B_t = -\min(0, \Delta_t).$$

B_t is also a time series and its average value, when scaled by the factor T (where T is the length of the time horizon in the study), can be considered a measure for the average balancing energy required in the time window. We have designed an experiment to study the impact of including marine energy (specifically the resource type of wave) on annual balancing energy requirements for a utility-scale power system in the Pacific Northwest. The wave resource selected for this study is the same PacWave resource described earlier. In the baseline case, the overall renewable portfolio is composed of 50% wind and 50% solar. We then start injecting finite amounts of wave resource in the generation portfolio and assume that it displaces an equivalent amount of wind and solar (cumulatively) such that the total rated capacity of renewables remains the same. In our experiments, we vary the amount of wave included from 0% (only wind and solar) to 100% (no wind and solar).

As shown Figure 5-8, as the injection of wave energy resource increases, the amount of balancing energy requirement decreases. The extent of decrease is particularly pronounced for higher overall renewable energy fraction. Note that the overall balancing energy requirements are observed to be higher for lower renewable deployment, since a lower value of γ would entail higher probability of generation shortfall scenarios and would therefore require more aggressive ramping from dispatchable resources to meet that deficit. Under such conditions, it is expected to have more dispatchable generating units in the system, which in turn may reduce the need for aggressive ramping. Such a hybrid scenario (of conventional and renewable co-generation) is beyond the scope of this present analysis. However, the authors consider this type of scenario analysis as having significant merit and will consider future work efforts geared towards this type of analysis. Also, note that beyond a certain penetration level, the balancing energy requirements starts progressively increasing with an increase in the penetration of wave energy. This denotes that for a typical energy system, there exists an optimal generation mix which reduces overall balancing requirements for the entire system. This point of optimality can be interpreted as an estimate for the technical optimum in terms of fossil fuel savings.

From the result in Figure 5-8, marine energy resources, when included in the renewable mix, has the potential of reducing balancing energy requirements, which is a tangible grid value for bulk system operations. Motivated by these findings, we proceed to characterize the temporal underpinnings of this grid-value on an hourly level through the following set of experiments. Throughout the subsequent analysis, we hold $\gamma = 1$, unless otherwise specified.

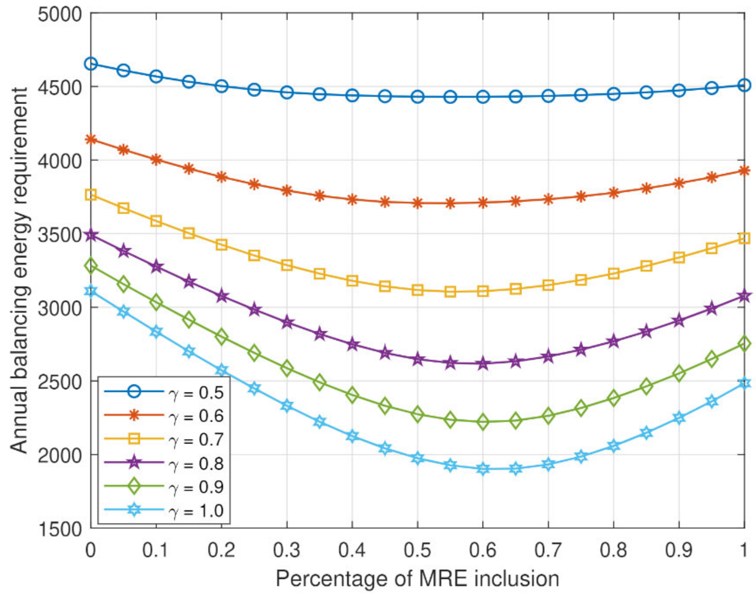

Figure 5-8. Balancing energy requirements as a function of marine energy deployment levels under different overall renewable energy deployment levels. Note that γ refers to the overall fraction of renewable energy in the generation portfolio.

In the first of these experiments, we study the hourly frequency distributions of the balancing function, under baseline conditions and with inclusion of marine energy (we select the 30% wave inclusion case for exposition purposes). In Figure 5-9 we observed that at night (hours 00:00 to 06:00) and in the evening (hours 18:00 to 23:00) the balancing needs are reduced with wave generation included in the renewable portfolio. Note that at these hours, solar energy is mostly not available, hence magnifying the value added by the marine resources on the balancing power requirements. This is identifiable from the nature of the histograms, which become significantly less right-tailed with inclusion of marine energy when compared to the baseline.

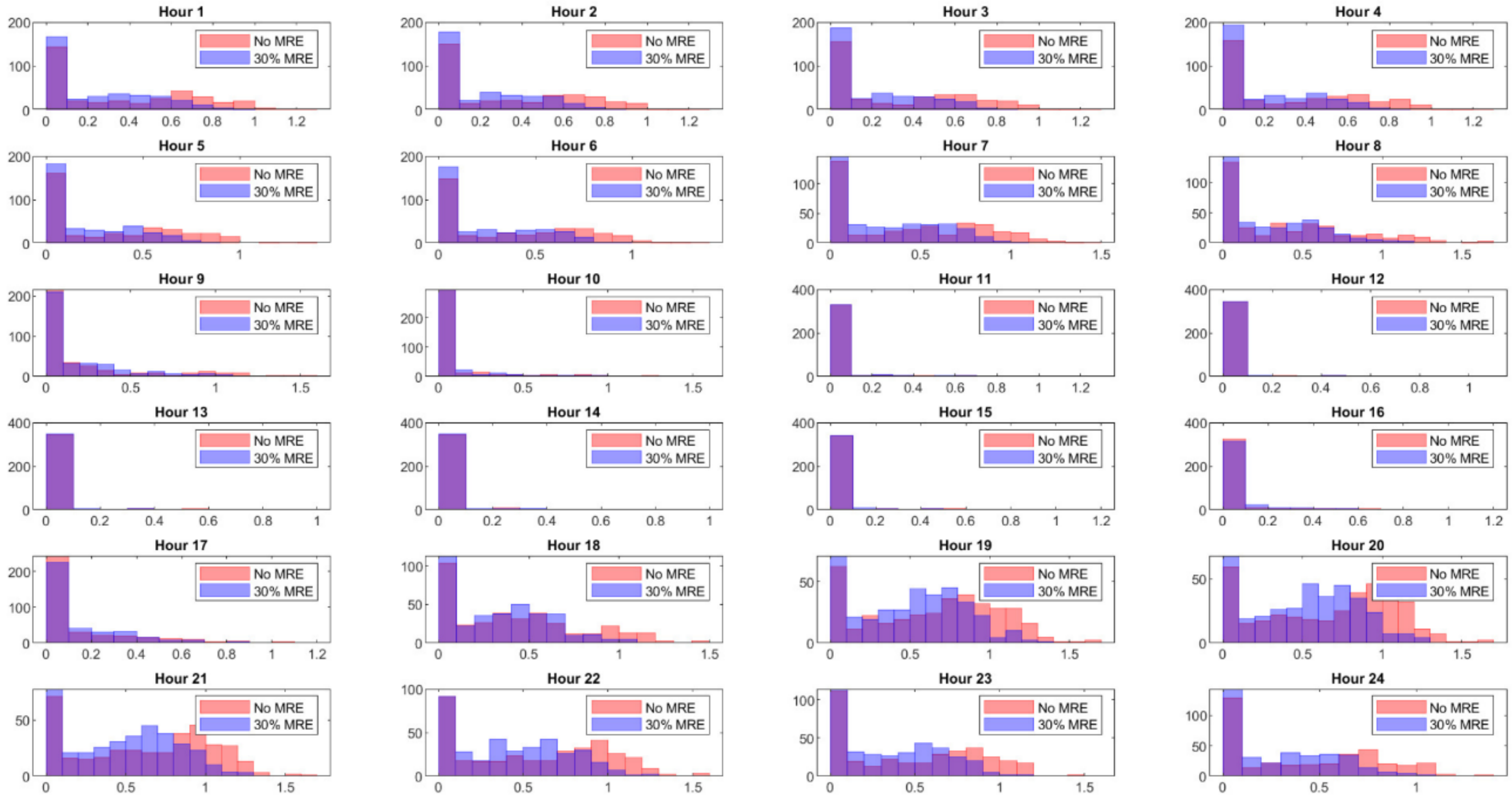

Figure 5-9. Hour-wise frequency plots for balancing energy with and without the marine energy resource included. For each of the 24 plots, the x-axis denotes the instantaneous balancing energy and y-axis denotes the frequency of observation. Note: as a function of the data, the y-axes are not consistent in each plot.

Quantitatively, the maximum balancing requirement (annual) is reduced by 19.5%, which amounts to around 0.78 GW for the entire utility-scale operation.

We now represent the nature of fluctuation of the balancing function over the 24-hour period in one day, across all 365 days of the year. This is done through fluctuation maps in Figure 5-10. From these maps without any marine energy included in the generation mix, the balancing requirements are particularly pronounced in winter evenings (hours 18:00 to 23:00) and nighttime (hours 00:00 to 06:00) for both the case studies selected in our analysis. Daytime balancing requirements (especially for summer) are comparatively lower owing to a greater availability of solar resource during the midday hours. At night, the unavailability of solar resources, coupled with the relatively lower availability of wind resources (which can sometimes be unavailable for extended duration of time) increase the probability of having higher balancing needs. When wave energy resources are included in the mix with wind and solar, that need is observed to be decreasing significantly in the winter evenings and especially during night hours.

We believe this can be attributed to (a) the relatively stable nature of the wave resource, that is the specific marine energy resource considered in this study, in comparison with wind/solar, and (b) the fact that wave is typically a winter-peaking energy resource for the locations selected in this case study. However, even though wave is a persistent resource relative to other renewables, wave (and in general marine energy resources) is inherently intermittent as well. Therefore, including it in the generation portfolio can accentuate balancing needs depending on the situation. This is reflected in our analysis during few early daytime and evening hours, especially in summer months. However, it must also be noted that this effect is far less significant than the positive effect wave resources have in the winter months (especially evening hours) in reducing balancing needs from conventional generation units.

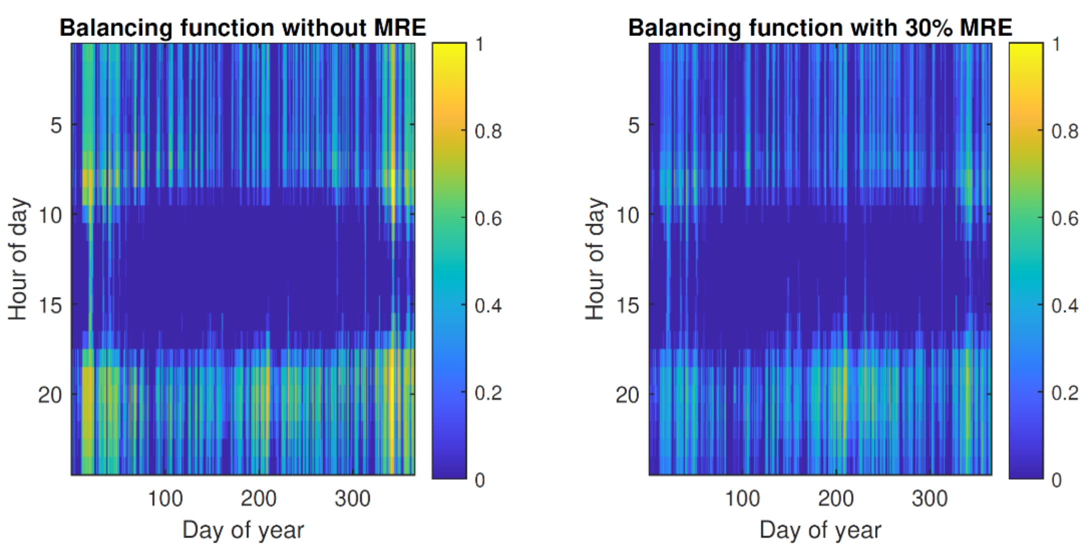

Figure 5-10. Fluctuation maps for balancing power; the x-axis represents the day of the year while the y-axis represents the hour of the day.

5.1.5 Effective Load Carrying Capability (ELCC)

Having identified the observable benefits that MRE resources might have upon inclusion in the overall generation portfolio under high renewable scenarios, we now study their potential impact on capacity value. Any generation resource, when added to a power system, should have a net positive effect in increasing the capacity adequacy of the system, and hence, enhance the reliability of operations. For this analysis, we consider the Effective Load Carrying Capacity (ELCC) metric, which is used conventionally to understand the incremental reliability of an additional generator on power system operations (Garver 1966). ELCC loosely translates to the incremental load that a power system can support with the inclusion of a new generator, without affecting reliability of operations. Accurate computation of ELCC involves the usage of several system specific parameters (such as generator forced outage rates) which makes ELCC difficult to compute without a significant amount of system-specific information. This has led researchers and planners to come up with proxies for the actual ELCC of a generator, which can be estimated with less system-specific information. One such method is the capacity factor method [2] (Keane et al. 2011). In this method, one selects the top n% (where n is a design parameter) of the peak demand hours in the year and assesses the capacity factor (i.e., the ratio of actual output to the maximum rated output) of the added generation resource in those peak-demand hours. The average output over these peak demand hours is then used to compute the average capacity factor for the resource, which in turn, serves as an approximate indicator of the added generation resource's ELCC.

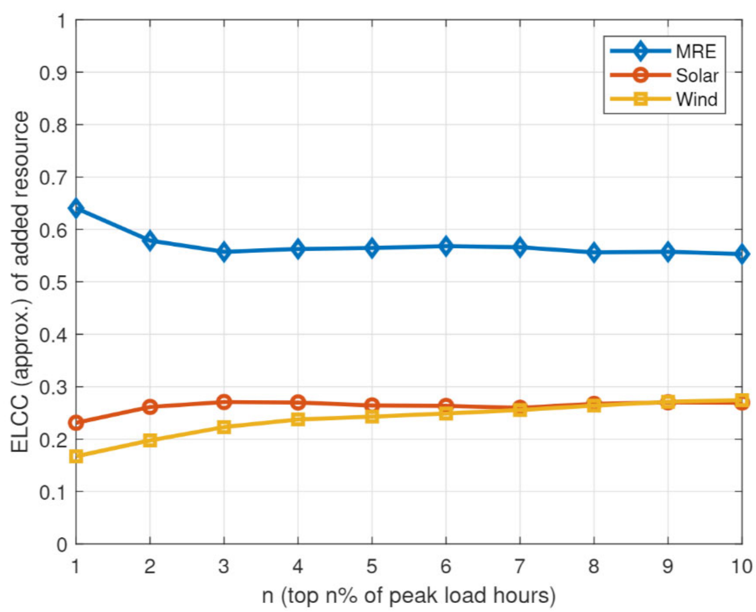

Figure 5-11. ELCC estimates using the capacity factor method versus top n% of the peak load hours in one year. Three different types of renewable resources were considered as the added generator: wave, solar, and wind.

In our work, we employ the capacity factor method to compute the approximate ELCC for a wave generation resource within a utility-scale power system under a high renewable penetration scenario. The location chosen is the Pacific Northwest case in the US (i.e., Case I), and the wave resource profiles are obtained from the PacWave site, as described in the earlier sections. The chosen power system is assumed to have a capacity of 50% (of maximum load) wind and 50% (of maximum load) solar under the baseline condition. We now describe the impact of adding 15% wave generation into the generation portfolio. We also compare this to two other cases where the added generator is solar and wind, instead of wave. These cases help us compare the effectiveness of including wave generators over wind/solar generators under the studied scenario. In Figure 5-11 we chart the approximate ELCC of the wave, solar, and wind resources versus the number of peak-demand hours selected for the analysis. The overall average (for all studied values of n, i.e., 1-10) ELCC for the wave generator is observed to be 57%, whereas the same metric for solar and wind generator are observed to be 26% and 24% respectively. The estimate was found to be a little higher for the wave resource when lesser number of peak-demand hours were considered, indicating possible coincidence of higher wave availability during peak demand hours. Overall, this study shows that wave resource can have a potentially higher capacity value when compared to wind and solar resources, especially under high renewable penetration scenarios, and for systems where the wave resource and system demand peak at approximately similar time frames.

5.1.5.1 Conclusions

Our results indicate that marine resources compare favorably against proximal wind and solar resources. We define, evaluate, and present resource metrics to characterize the marine and renewable resources, namely resource availability, resource persistence, and resource versatility Specifically, tidal and wave resources were observed to be more available and persistent than both solar and wind. The ocean current resource off the Florida coast, while being slightly less available than solar (due to seasonal variance) has a reasonably higher availability and persistence value when compared to wind.

We also study system balancing needs at the hourly level and with 30% of generation served by wave energy (assuming a 100% clean energy portfolio) we find the annual hourly maximum balancing requirement to be reduced by 19.5%, which amounts to be around 0.78 GW for the small utility-scale base system evaluated here. With marine energy in the generation portfolio, balancing needs are observed to be decreasing significantly in the winter evenings, particularly during night hours. We believe this can be attributed to (a) the relatively stable nature of the wave resource, that is the specific marine energy resource considered in this study, in comparison with wind/solar, and (b) the fact that wave is typically a winter-peaking energy resource for the locations selected in this case study.

Although this serves as an insightful platform for gauging the impacts of marine energy on power system operations, future work can incorporate more grid-specific details (such as transmission network structure, topology, and/or device-level technological details) for a comprehensive assessment.

5.2 Impact of Marine Energy on Storage Requirements for High Levels Deployment of Renewable Energy

Scheduled/Dispatchable Generation

- Optimization of generation with storage

Technology Companions

- Improvements in performance of other technologies (symbiotic benefits)

The impact of marine energy on storage requirements for high deployment of renewable energy in a certain grid area was determined using a data-driven, framework-oriented, parametric study. The methodology is presented in detail in Appendix B.

5.2.1 Summary of Analysis Inputs and Parameters

Table 5-2 below identifies the analysis inputs and sources utilized in this Section. Section 4.2 identifies the analytical process utilized to convert the marine energy resource to an electric output.

Table 5-2. Inputs and sources for Section 5.2

	Type	Location	Data Interval	Source
Grid load	Island	Nantucket, MA	Hourly	National Grid
	Bulk	Small utility NW U.S.	Hourly	WECC
Renewable resource	Wave	NW U.S.	Hourly	(Yang, García-Medina, et al. 2020; Wu et al. 2020)
	Wave	Nantucket, MA	Hourly	(Yang, García-Medina, et al. 2020; Wu et al. 2020)
	Tidal	Admiralty Inlet, WA	Hourly	(Jim Thomson 2009; J. Thomson et al. 2012)
	Tidal	Nantucket, MA	Hourly	(Yang, Wang, et al. 2020; Wang and Yang 2020).
	Solar	Admiralty Inlet, WA	Hourly	WECC
	Solar	Nantucket, MA	Hourly	National Grid
	Wind	Admiralty Inlet, WA	Hourly	WECC
	Wind	Nantucket, MA	Hourly	National Grid

5.2.2 Experiment Setup

Two case studies were performed to evaluate the impact of marine energy on the storage requirements of highly penetrated renewable energy grid. Case studies are implemented using the proposed parametric setup (See Appendix), where the penetration of renewable energy resources is made as a parameter. The geographical areas and load profiles for these two case studies are shown in Figure 5-12 and Figure 5-13, respectively. Note that while the northwestern area has a winter-peaking load, the northeastern load is summer-peaking in nature. Moreover, the northeastern load profile is more volatile (due to smaller grid area) as compared to the northwestern load profile. For both cases, the baseline model (see Appendix B for details) is obtained using the current deployment of renewable energy in the respective area, which amounts to approximately 1-2% of the total consumption. Within this baseline, the deployment of wind and solar amounts to approximately 50% each and marine energy resources (wave plus tidal) are assumed to be nonexistent.

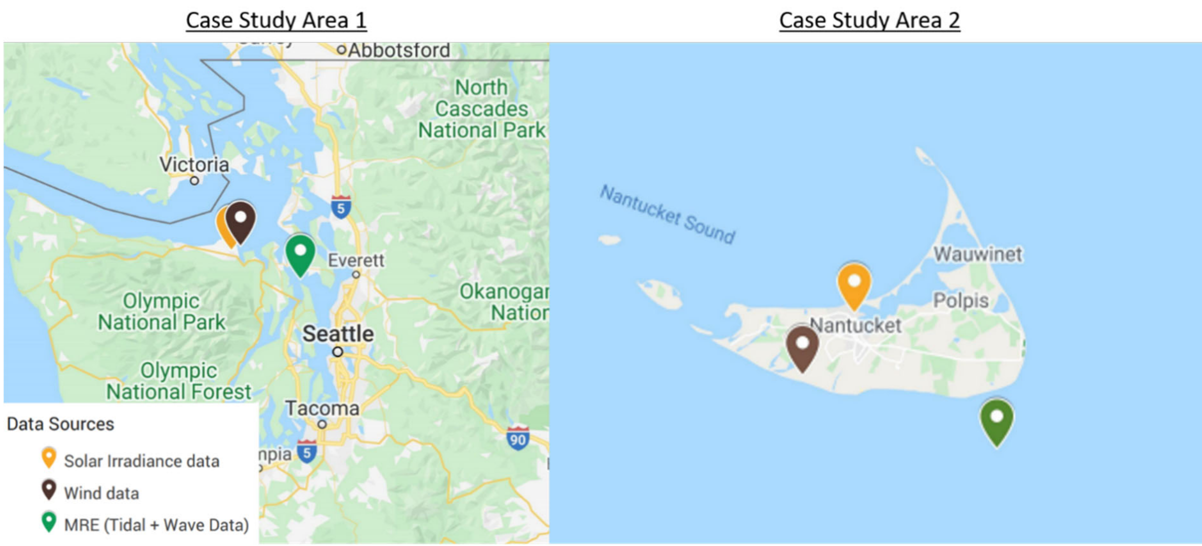

Figure 5-12. Two case studies: (left) a utility operated northwestern grid area located in the United States; (right) an island grid connected to the mainland located at the northeastern grid area.

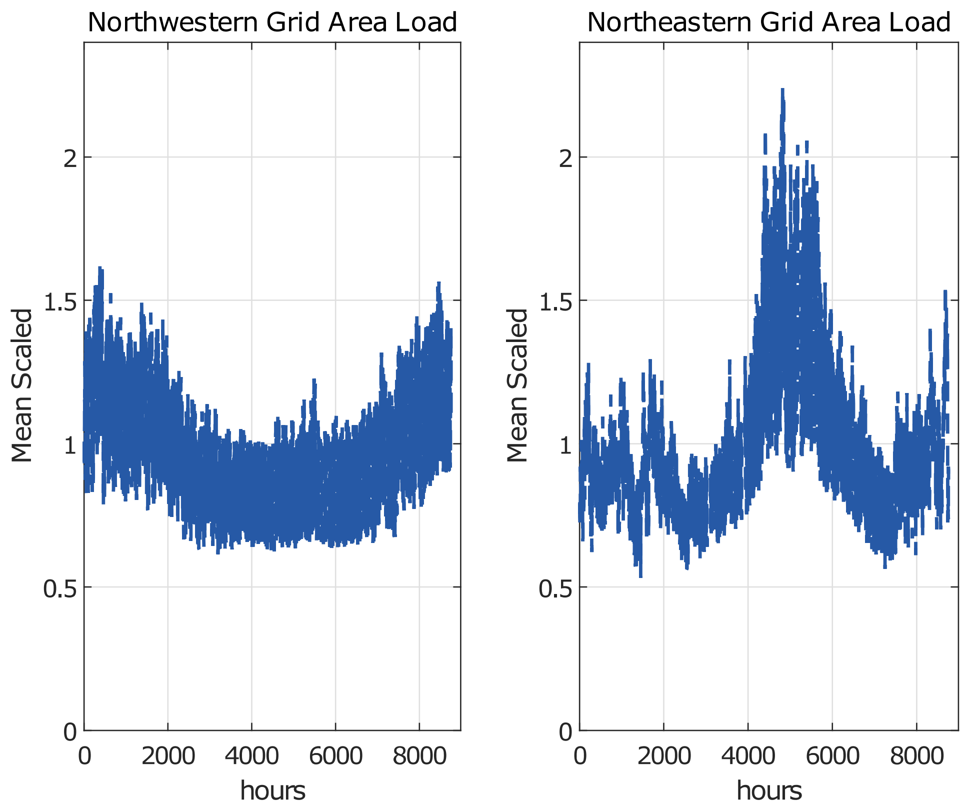

Figure 5-13. Represented load profiles for the northwestern and northeastern U.S. grid areas, with respective total energy consumption/peak load of 24.05 TWh/4.580 GW and 174 GWh/43 MW, respectively. The time series' above are scaled to their mean value observed in the time series. This helps to show variation of the time series in terms of its average value.

Figure 5-14 shows the represented renewable resource profiles, scaled to their mean generation value for the entire time-series, for the northwestern grid area. In Figure 5-14, wave energy has higher availability in winters as compared to summers, which contrasts with the solar energy. Moreover, the tidal energy despite being not widely scalable, is observed to be periodic throughout the year. Similarly, Figure 5-15 shows the northeastern grid resources. These resources represent similar characteristics (e.g. wave energy peaks in winter and tidal energy has a similar cycling period) as compared to the northwestern grid. We analyze the impact on varying renewable energy deployment, specifically marine energy (wave and tidal generation) by varying the penetration percentage of each resource and analyzing their output relative to power generation and load mismatch. Consequently, we identify storage requirements needed to support the added renewable energy. Further details are provided in Appendix C.

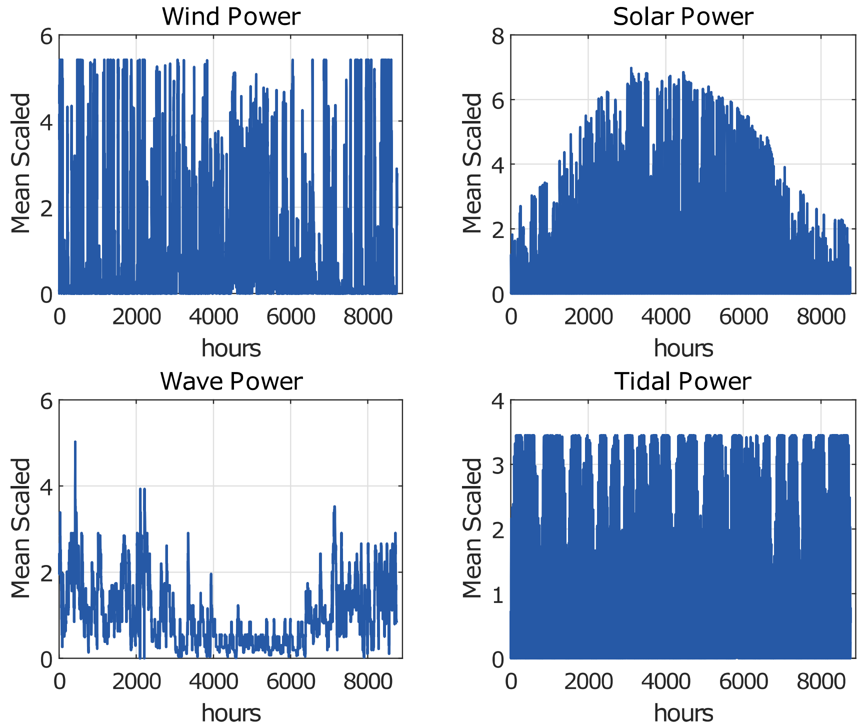

Figure 5-14. Resource data profiles for the selected northwestern U.S. location. Tidal power can be seen to show some saturation around mean scaled value of 3.5, this is because as tidal is a more local resource, power import restriction has been placed on it to reflect turbine size and power export limitation.

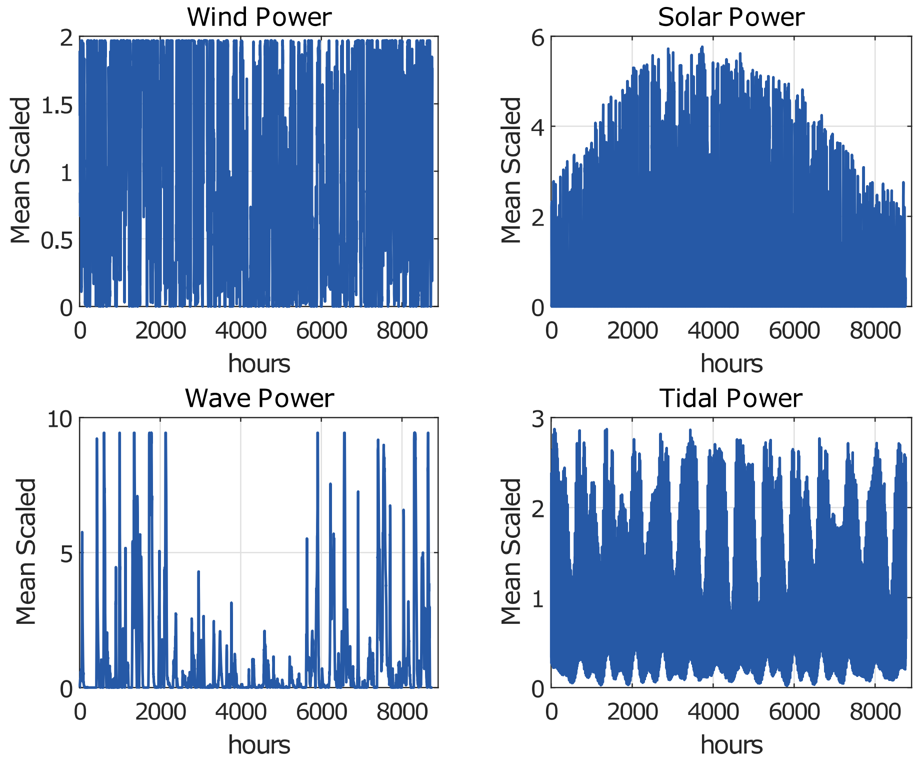

Figure 5-15. Resource data profiles for the selected northeastern U.S. location.

5.2.3 Case Study 1: Northwestern U.S. Grid Area

Figure 5-16 shows the load-generation mismatch observed with varying level of renewable energy and marine energy deployment. For the increase in marine energy, wave is deployed far more aggressively than tidal. This is done to produce realistic results by indicating the local limitations of power export by tidal. The ratio between technologies is kept variable to make the experiment generic and parameter driven. For these sets of experiments, a 1:4 ratio of tidal:wave deployment is assumed. Higher positive mismatch (excess generation) is observed during midday. This is because of the characteristics of solar energy, which has a higher mean production level during the day as compared to night. This excess energy (positive mismatch) is offset by the simultaneous increase in the share of marine energy, as both wave and tidal do not contain diurnal bias. However, for very high deployment of marine energy (see bottom right subplot of Figure 5-16), the positive mismatches (excess generation) are observed during winter along with negative mismatches in the summer. This is because of wave energy being a winter-peaking resource.

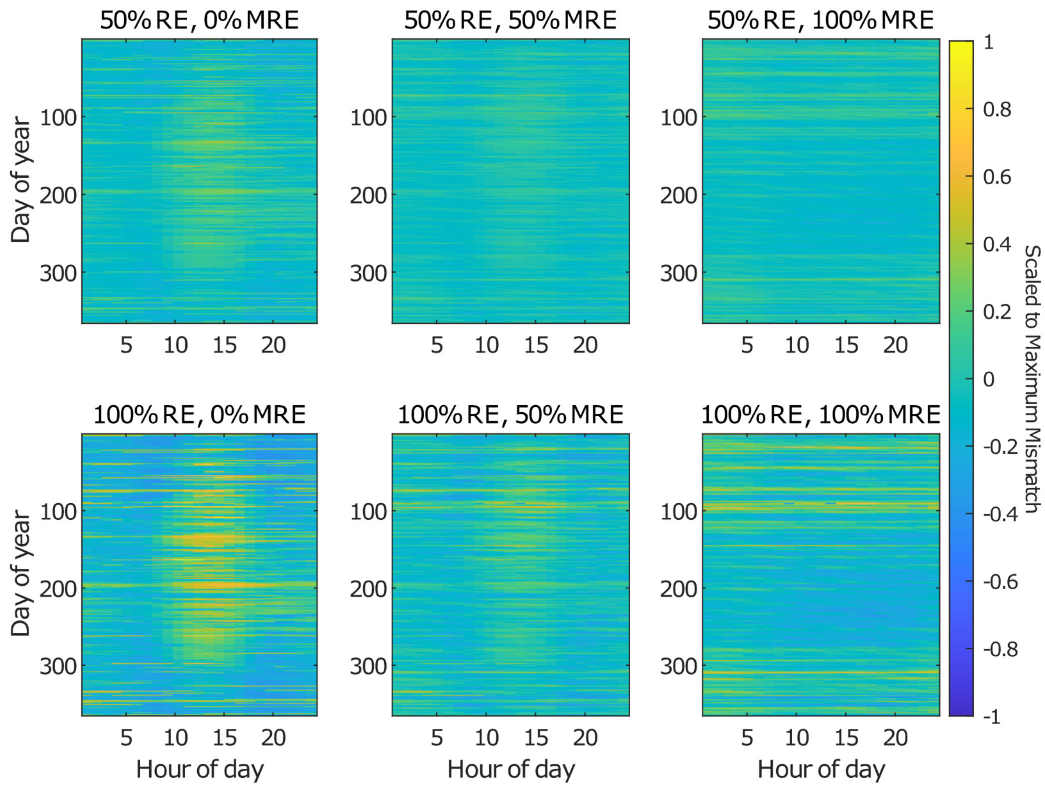

Figure 5-16. Fluctuation map of the normalized hourly mismatch generation-load mismatch quantities - scaled to the maximum mismatch observed for all scenarios of the parametric study. Dark yellow spots demonstrate high positive mismatch, whereas the dark blue spots show high negative mismatch. The increase in share of MRE reduces both positive and negative generation-load mismatch.

Figure 5-17 shows the storage profile obtained from the resultant mismatch profiles reported in Figure 5-16. Intuitively, a higher renewable energy deployment requires a higher amount of storage capacity for managing the mismatch. The observed state of charge for storage in the study can be explained as follows. Consider the case of 100% renewable energy and 0% marine energy (bottom left subplot in Figure 5-17).

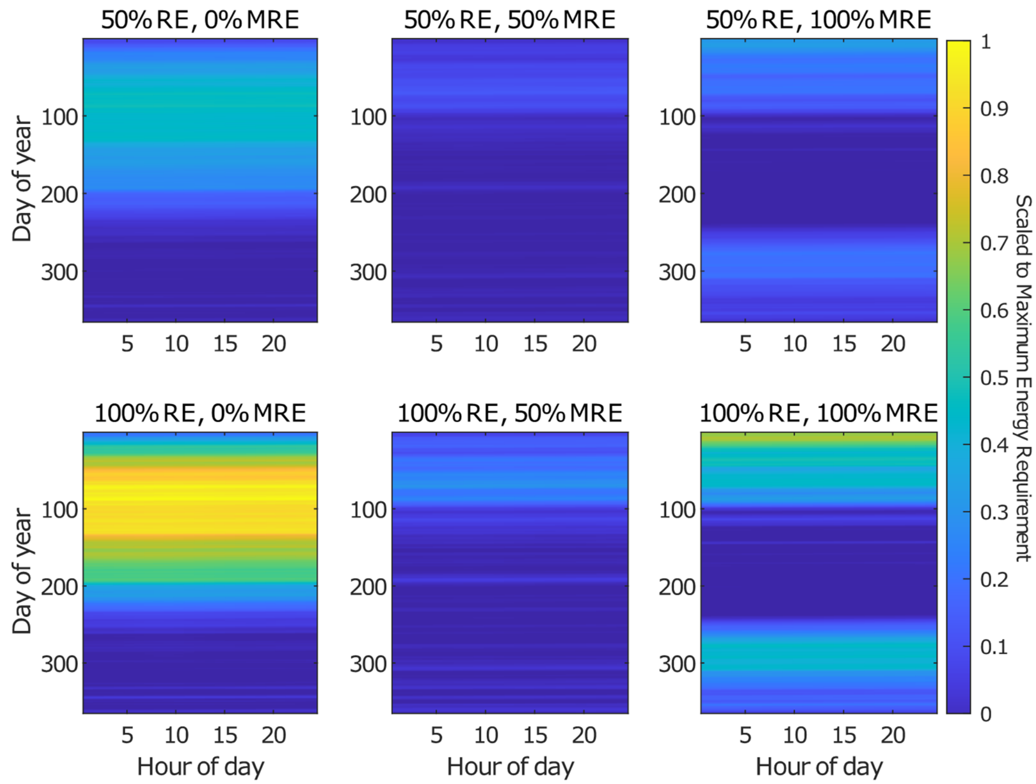

Figure 5-17. Fluctuation map of normalized hourly storage profile, scaled to maximum energy observed, for all scenarios of the parametric study.

The storage is charged during winter due to excess energy available from wind resources. This storage, along with the solar resources, is used to operate the grid for the later part of the year. As the deployment of marine energy increases, the overall mismatch observed between load and generation (and therefore, storage needs and associated costs) is reduced. However, for very high marine deployment levels (bottom right subplot of Figure 5-17), the winter has exacerbated positive mismatches due to an elevated amount of winter-peaking wave energy in the renewable energy mix. This effect can be seen when more than 60% of marine energy deployment is included, as indicated in Figure 5-18. Beyond this level, both storage capacity requirements and associated costs increase. For the cost estimate for energy storage, it is assumed that the overall cost of energy storage is equivalent to 342 $/kWh with an 86% round-trip efficiency (Mongird 2018). This is intended to be a representative number. Improved cost characterization would of course provide more applicable cost results.

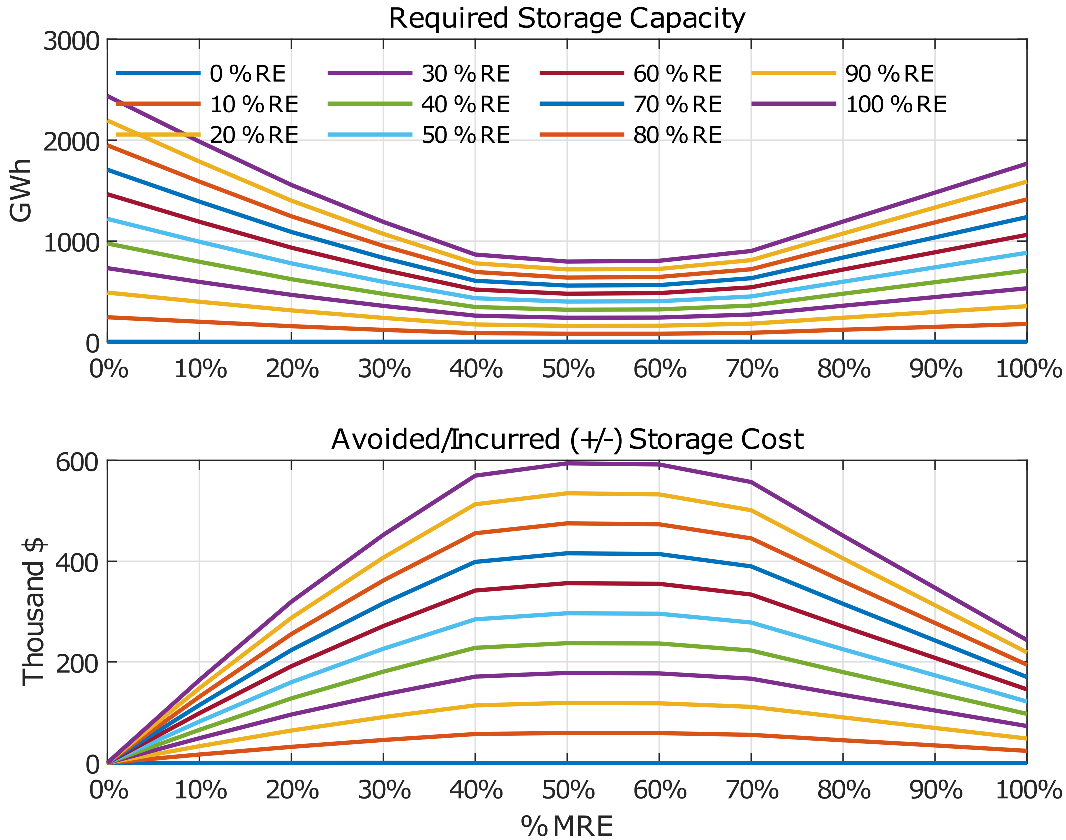

Figure 5-18. Required energy capacity (top) and total avoided/incurred (+/-) cost (bottom) as a function of deployment of renewable energy and marine energy (Kendal 2018).

5.2.4 Case Study 2: Northeastern US Grid Area

Figure 5-19 shows the load-generation mismatch observed with varying levels of overall renewable energy and specific levels of marine deployment. Again, marine energy deployment is assumed to be 50% wave and 50% tidal. Like Case 1, higher positive mismatch (excess generation) is observed during midday due to an increase in output from solar resources as renewable energy deployment increases. Another effect seen is that for higher deployment of marine energy, excess positive mismatch is seen during winter. This is because, in contrast to the northwestern U.S., the representative power system selected in northeastern U.S. has a lower load demand during winter to absorb the higher renewable generation from winter-peaking marine resources. However, for moderate levels of marine energy deployment, the overall mismatch is reduced.

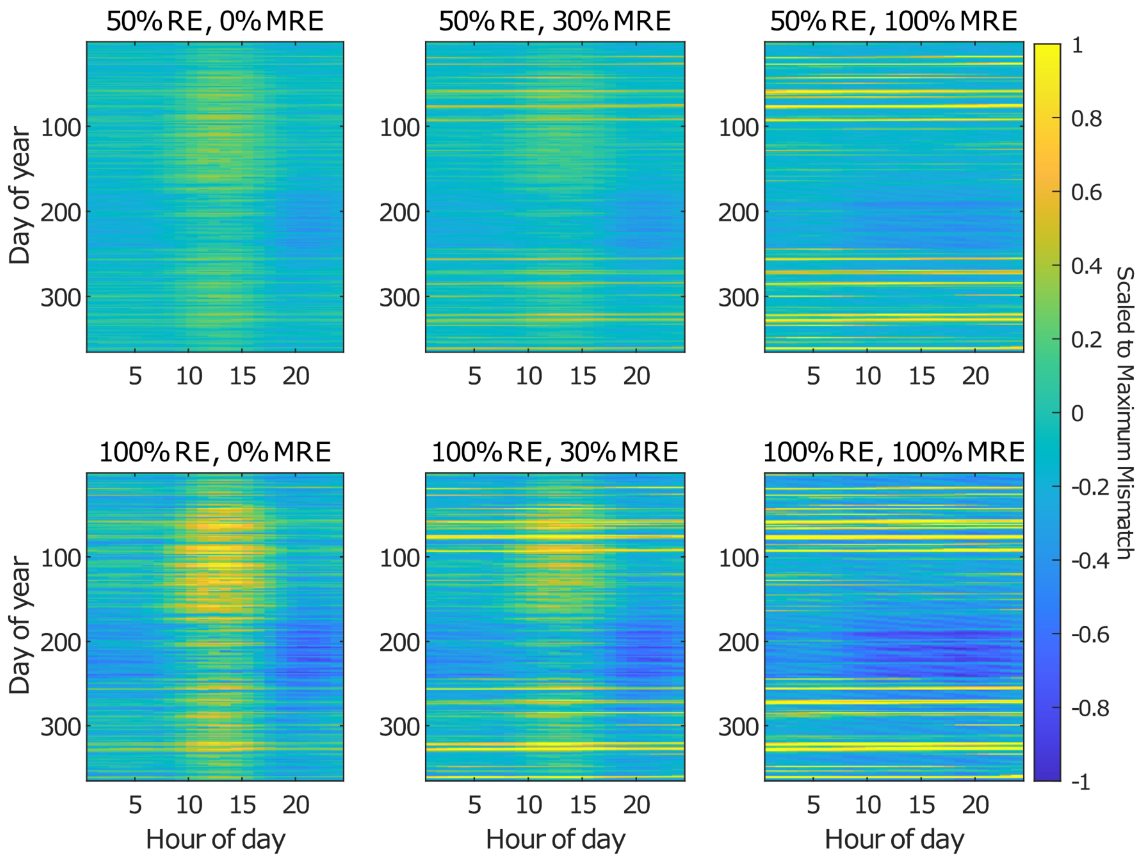

Figure 5-19. Fluctuation map of normalized hourly mismatch quantities scaled to maximum mismatch observed for all scenarios of the parametric study.

Figure 5-20 shows the storage profile obtained from the resultant mismatch reported in Figure 5-19. Like Case 1, the storage charges heavily during winter. However, in contrast to the northwestern case, this excess energy to charge storage increases for very high deployment levels of marine energy. As explained earlier, this is due to the antithetical peaking nature of load and resource (marine). Hence, the storage capacity requirement is highly exacerbated for very high levels of marine deployment, but for the moderate levels of marine deployment, the energy storage requirements are reduced as marine energy complements the energy availability of the solar resource.

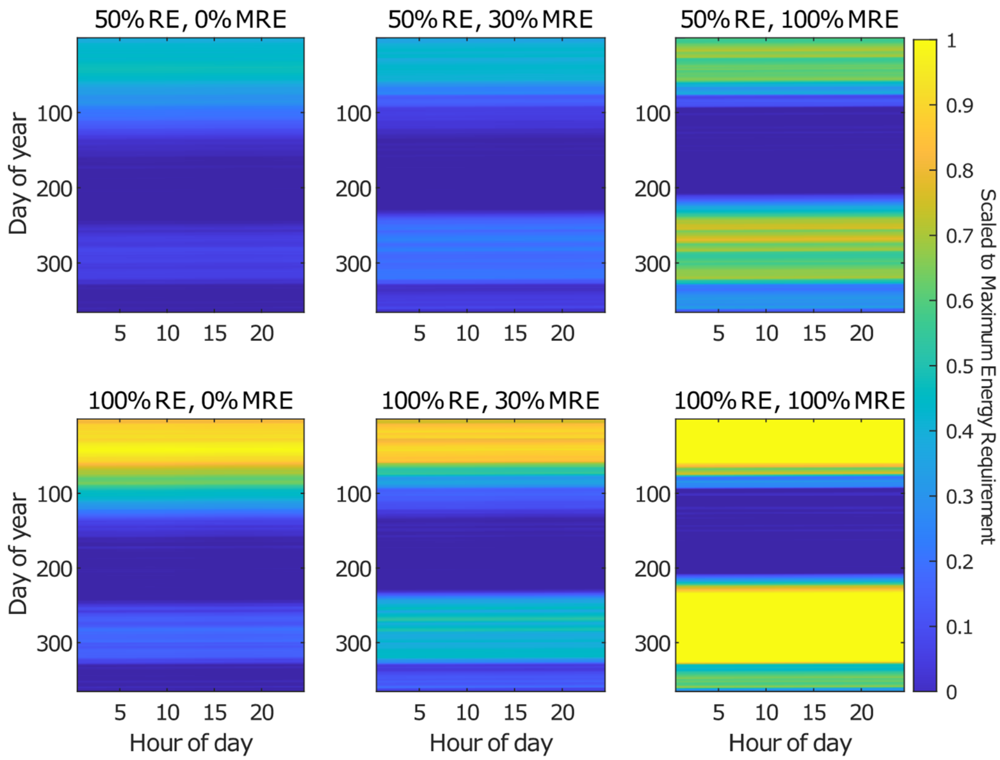

Figure 5-20. Fluctuation map of the normalized hourly storage profile scaled to the maximum energy observed for all scenarios of the parametric study.

The cost implications of this variation are captured in Figure 5-21, where we see that for this case study, marine energy deployment optimizes the storage requirements (and hence, storage costs) at around a 30% marine energy deployment level. Beyond this, one is anticipated to get progressively diminishing benefits, eventually causing an inflection and consequent increasing costs (negative).

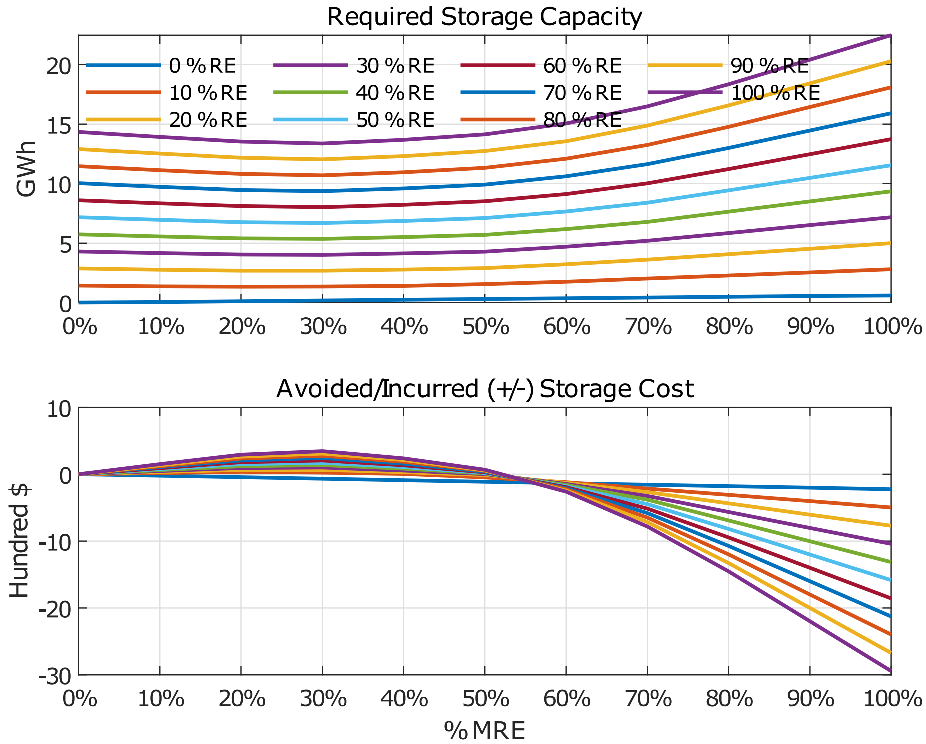

Figure 5-21. Required energy capacity (top) and total avoided/incurred cost (bottom) as a function of deployment of renewable energy and marine energy, assuming round-trip efficiency of 0.86 and cost of operation of 342 $/kWh (Kendal 2018).

5.2.5 Conclusions

Our results indicate that marine energy can help alleviate storage capacity (and hence storage costs) requirements, especially under high renewable deployment scenarios, when used in tandem with other renewable sources. The nature and extent of that benefit, however, is highly sensitive to several factors. These include (but are not limited to) location, profiles of other renewable resources, profile of the load (winter-peaking versus summer-peaking), and the inherent characteristics of the marine resources themselves (such as availability, persistence). Hence, the parametric studies were an important first step toward analyzing such grid areas to plan for an optimal renewable resource mix and storage technology.

The results are derived from generalized, grid-abstracted power system models, with all data analysis performed at hourly level interval. Although this serves as an insightful platform for gauging the impacts of marine energy on power system operation, future works can incorporate more grid-specific details (such as transmission network structure, topology, and/or device-level technological details) for a comprehensive assessment.

6.0 Special Applications

6.1 Enabled Services, Locational Benefits, and Resiliency Value

Enabled Services

- Improvements in performance of other technologies (symbiotic benefits)
- Microgrid suitability, coastal, remote communities, and islands

Resiliency

- Reduced vulnerabillity to electricity disruptions
- Reduced reliance on conventional backup generation and risk from fuel availability and volatility

6.2 A Data Driven Resiliency Formulation

Analyzing and quantifying operational risks for island power systems with diverse generation portfolios through conventional techniques can prove to be cumbersome, often requiring multiple different inputs. Therefore, in this study we investigate a novel, purely data-driven formulation that quantifies the operational reliability of island power systems using minimal data inputs. Specifically, our proposed methodology relies on hourly load and generation profiles as inputs and provides systematic measures to quantify associated operational risks. We then use the formulation to evaluate the effectiveness of marine energy resources in providing resilience benefits to island power systems.

6.2.1 Summary of Analysis Inputs and Parameters

Table 6-1 below identifies the analysis inputs and sources utilized in this Section. Section 4.2 identifies the analytical process utilized to convert the marine energy resource to an electric output.

Table 6-1. Inputs and data sources for Section 6.2.

	Type	Location	Data Interval	Source
Grid load	Island	Nantucket, MA	Hourly	National Grid
Grid topology	Distribution	Nantucket, MA	-	National Grid
Renewable resource	Tidal	Nantucket, MA	Hourly	(Yang, Wang, et al. 2020; Wang and Yang 2020).
	Wave	Nantucket, MA	Hourly	(Yang, García-Medina, et al. 2020; Wu et al. 2020)
	Wind	Nantucket, MA	Hourly	National Grid
	Solar	Nantucket, MA	Hourly	National Grid

6.2.2 Methodology

First, we define the concepts of:

a. Generation Buffer (X_1): This is the instantaneous amount of generation capability (MW) available to support a sudden incremental load change, beyond nominal operations, without changing installed capacities of generators. This depends on the amount of generation theoretically possible at any given time (e.g., a function of resource intermittence in case of renewables).

b. Demand Gap (X_2): This is the amount by which the demand can increase at any time, beyond nominal operations. Such increments may be driven by sudden operational events, extreme weather conditions, drastic changes in customer usage patterns, etc.

To maintain reliable grid operations, the generation buffer for a system should always be greater than the demand gap. Otherwise, there is a risk of losing service because of generation inadequacy. Let us define ΔX as the difference between the generation buffer and demand gap at a certain time. A higher value of ΔX would mean more generation support is available to address increased demand. Therefore, ΔX is directly indicative of the degree of operational reliability built into the system. Accordingly, the greatest possible operational security margin (i.e., ideal condition) would be achieved when the generation buffer is maximized and demand gap is minimized (i.e., there is perfect load forecasting and minimal possibility for load increments). The generation buffer is maximized when total maximum available generation is equal to rated generation capacity and demand is at a minimum. Let us consider that under such a hypothetical scenario, the generation buffer and demand gap are denoted as X_1^* and X_2^* respectively. Therefore, this ideal security condition is given as,

$$\Delta X^* = X_1^* - X_2^*$$

By extension, the extent of instantaneous operational risk (OR) (i.e., the inverse of operational reliability) in the power system can be expressed as ζ_k (unitless quantity for time stamp k) where,

$$\zeta_k = 1 - \frac{\Delta X}{\Delta X^*}$$

Note that a higher value of ζ_k would imply greater OR, and as such, less reliability. The minimum possible value of ζ_k is 0, which is realized when $\Delta X = \Delta X^*$, under perfectly ideal conditions. On the other hand, under extreme conditions, when the demand gap exceeds the generation buffer (i.e., we have a potential generation shortfall), ζ_k becomes greater than 1. From a system operator's perspective, maintaining lower levels of OR value is preferable for ensuring a smooth and reliable operation of the power system.

6.2.3 Resilience for Nantucket, MA

Nantucket island is situated in southeastern Massachusetts and has a distinctly summer-peaking load. Power is imported from the mainland using submarine power cables with the combined power carrying capacity of approximately 71 MW. There are multiple small gas combustion turbine generators (CTG). Additional details for the renewable resources specific to this area can be found in previous sections (Section 5.3.3.2).

An hourly capacity factor approximation is needed to compute the generation buffer (specifically the expected generator output) for a given time of day. The available generation from any resource for any given hour of the day can be estimated from an hourly average capacity factor

(HACF) for that resource. Owing to the seasonal nature of renewable energy resources, capacity factors vary greatly. For this study, 4 different HACF time series (each being a 24 X 1 vector) were calculated for 4 different seasons of the year using National Grid's renewable energy data for Nantucket. Figure 6-1 shows the values of HACFs for the four different seasons for all resources selected in the study. Also note that the HACF for CTG generation is season-invariant and depends purely on generator characteristics. For this study, we assume it to be 50%, unless otherwise specified.

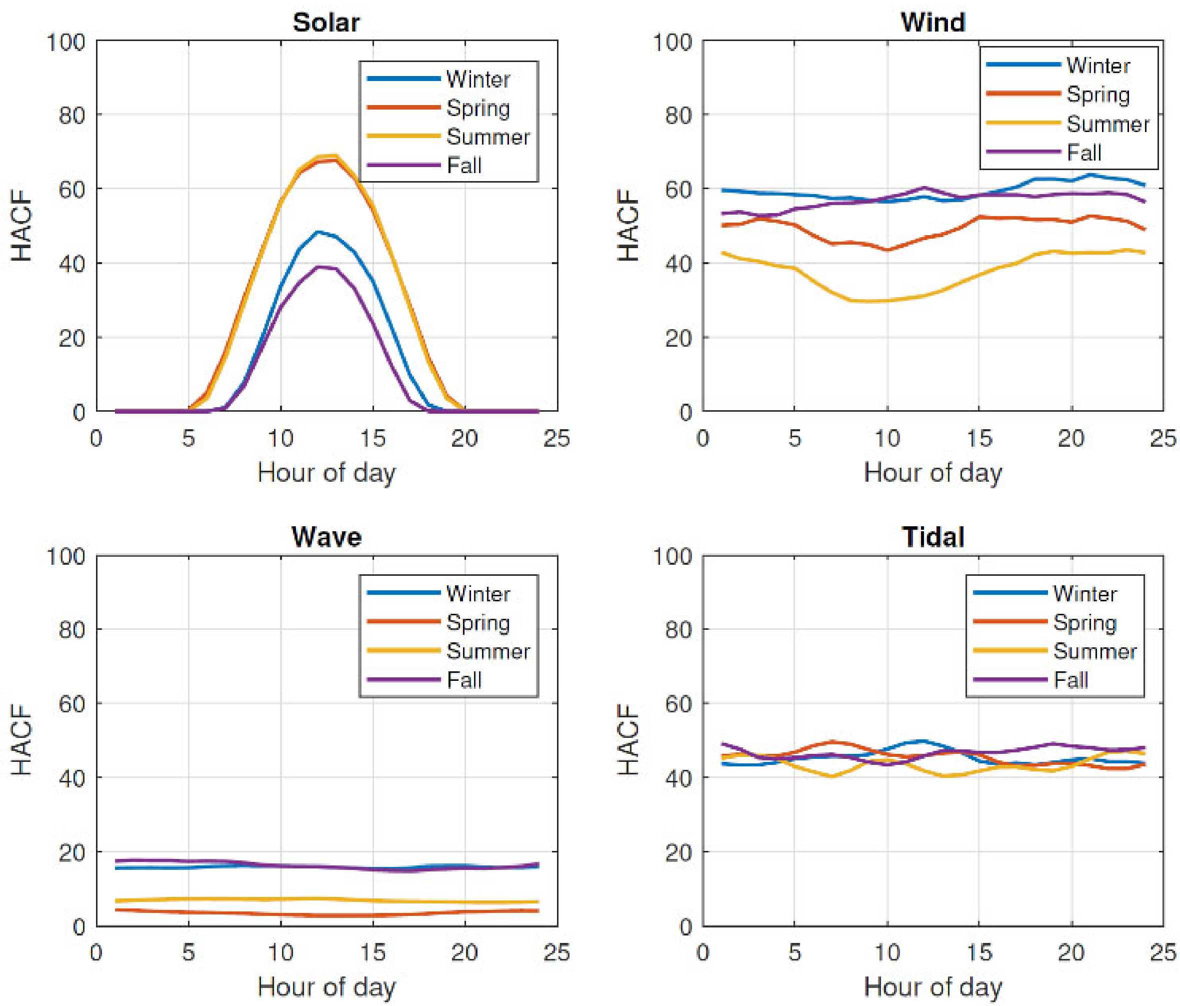

Figure 6-1: Hourly Averaged Capacity Factors (%) for all selected resources.

Scenario 1 (Impact of additional onsite generation on OR) – The addition of 40 MW of generation capacity to existing imports (~71 MW) is simulated in this scenario. This may still be insufficient for reliable operation, especially during peak summer hours. This scenario is designed to evaluate the impact of diversifying the generation portfolio on operational reliability, by adding 20 MW of other renewable resources (solar, wind, wave and tidal) in tandem with 20 MW of CTG-based generation.

Scenario 2 (N-1 contingency scenario) – Here, one out of the two cables is assumed to be unavailable for an entire day in four different months (winter-February, spring-May, summer-

August, and fall-November). During each of these four contingency days, the hourly values of ζ_k are simulated and analyzed with the remaining import cable and 40 MW of CTG capacity (base-case). Subsequently, we displace 20 MW of the CTG capacity with an equivalent capacity of renewable generation and study the consequent impacts on OR. For Nantucket, losing one of the two import cables for a full day is a high impact event, and even though it usually falls under a standard reliability event, its relative impact to the area qualifies it as a resilience event. This scenario, therefore, will evaluate the resilience level, and its deterioration during such contingencies in different seasons of the year. For both scenarios, we assume the demand profile of the representative year.

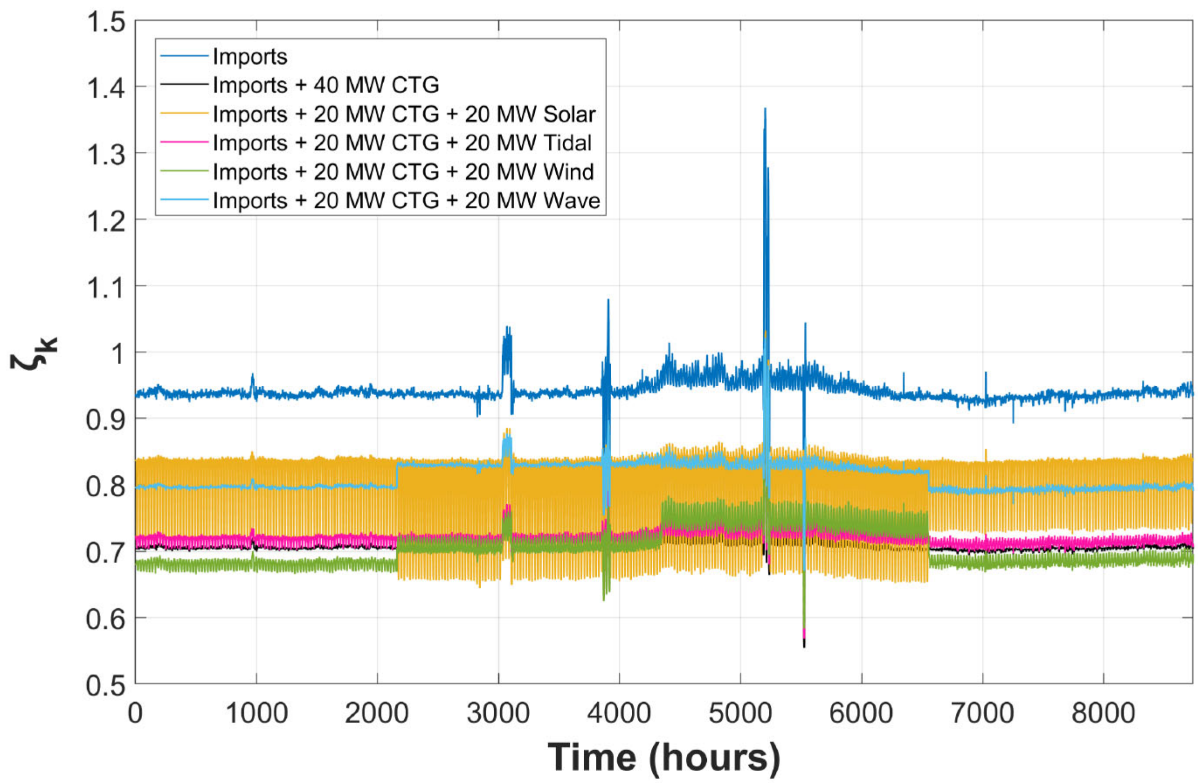

Figure 6-2. Operational risk for different generation portfolios across 8760 hours of a representative year.

Scenario 1 – The results for this scenario are shown in Figure 6-2 where the ζ_k metric is plotted for the entire year for different generation portfolios. It is observed that with only imports, the ζ_k values are just barely under 1 which means that there is minimal generation buffer to support sudden load increments. Additionally, there are several days during the representative year when ζ_k values are greater than 1, indicating a potential shortfall in generation. This indicates the necessity of adding more generation capacity to the system.

By adding additional generation capacity, it is observed that the ζ_k values are reduced when compared to only imports, indicating a reduced risk of generation inadequacy and increased reliability. Wave power around Nantucket is not a particularly strong resource, and thus, does not considerably impact the ζ_k values. The inherent variability of solar power can also be observed where the daily variation in ζ_k is the highest amongst all other resource combinations. This is numerically validated from the standard deviation values provided in Table 6-2 below. Moreover, the maximum values of ζ_k for solar and wave resources are still larger than 1, thereby highlighting the potential for generation inadequacy even with the addition of these resources. Meanwhile tidal and wind resources remain below 1 throughout the year and have the lower average values relative to other renewables. Note that this scenario is specifically important for the summer season, because of the summer-peaking nature of the system.

Table 6-2. Summary Statistics of ζ_k for summer months (July-September).

Resource Combinations	Mean	Standard Deviation	Minimum	Maximum
Imports only	0.96	4.39%	0.62	1.37
Imports + 40 MW CTG	0.71	2.06%	0.55	0.91
Imports + 20 MW CTG + 20 MW Solar	0.79	7.04%	0.65	1.03
Imports + 20 MW CTG + 20 MW Wave	0.83	2.04%	0.67	1.02
Imports + 20 MW CTG + 20 MW Wind	0.75	2.45%	0.58	0.94
Imports + 20 MW CTG + 20 MW Tidal	0.73	2.18%	0.56	0.92

Across renewable resources, the maximum ζ_k value is lowest for tidal at 0.92 and almost equal to that for an equivalent amount of CTG generation. Among renewables, the tidal resource also holds the lowest mean and minimum of ζ_k values. These observations demonstrate the resilience advantages of including tidal resources within Nantucket's generation portfolio.

Scenario 2 – In Scenario 2, N-1 contingencies are studied by simulating a day long submarine cable outage for all four seasons, assuming different renewable resources in the generation portfolio. The hourly ζ_k values for these four contingencies in the months of February, May, August, and November are calculated in Figure 6-3 from top to bottom, respectively. It can be observed that the ζ_k values for solar and wave resources are frequently greater than 1, suggesting their inadequate potential in maintaining system reliability. This observation is consistent with the observations made for solar and wave for Scenario 1. The wind and tidal resources, on the other hand, reduce the ζ_k values below 1 for all studied months. Again, this points to the advantage of tidal and wind resources as viable alternatives for CTG generation while maintaining reliability.

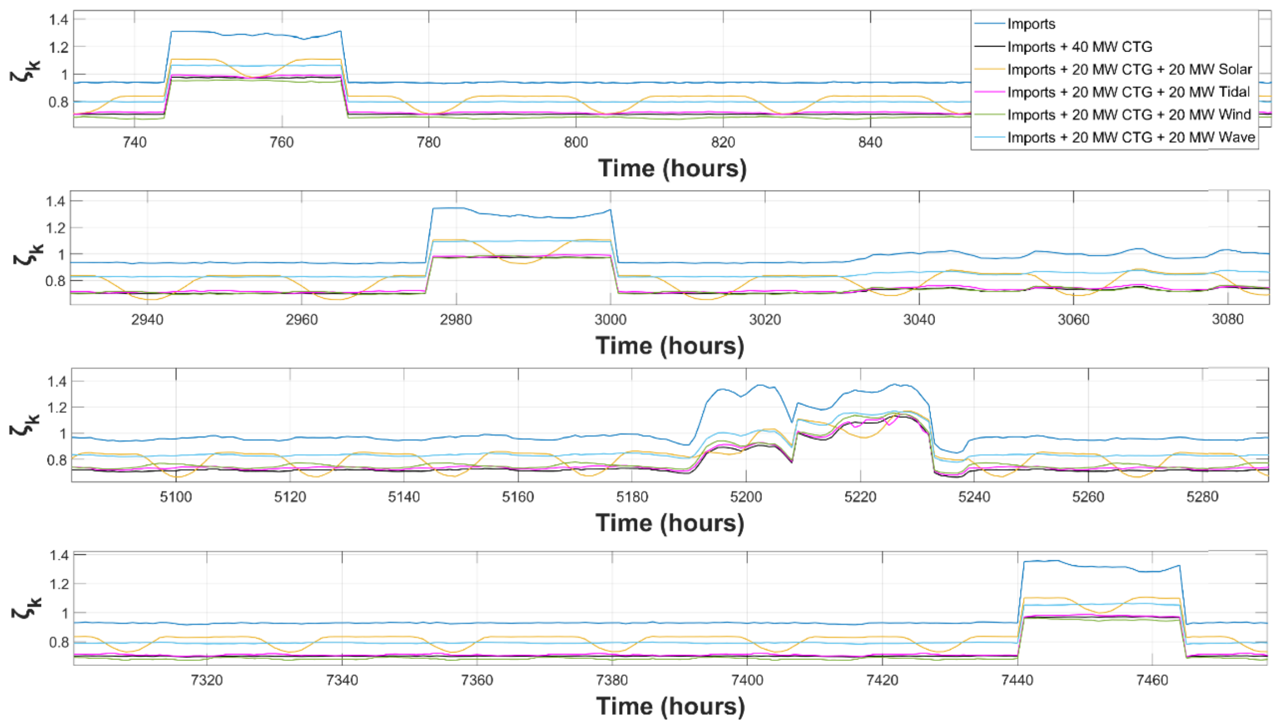

Figure 6-3. ζ_k values for different generation portfolios for 4 different contingency days, one each in the months of Feb, May, August, and November (from top to bottom respectively).

Results suggest that while considering additional generation resources, nearly half of the otherwise planned CTG capacity could be securely displaced with tidal resources, reducing carbon emissions and fossil fuel dependence with its associated price volatility. This capacity can also be replaced with an equivalent capacity of wind, but land is unlikely to be available. Further, Nantucket being a summer-home and tourist destination, may result in resident push-back to potential terrestrial or near-offshore wind development.

6.2.4 Conclusions

Our results provide several insights:

- Replacing combustion turbine capacity with tidal generation is shown to minimize operational risk levels relative to replacement by solar and wave resources in both normal operating and singular contingency conditions (i.e., a loss of 1 undersea transmission cable) for the island of Nantucket. The evaluation of operational risk here can be considered a proxy for resiliency value.
- These results stay consistent across seasons in the year and indicate that tidal resources in Nantucket may be a suitable source of local clean energy.
- Wind resources provide similar results to tidal resources, but land limitations may advantage tidal development. Further, Nantucket being a summer-home and tourist destination, may result in resident push-back to potential terrestrial or near-offshore wind development.

6.3 Marine Renewable Energy Meta-Analysis with MCOR

A set of three marine energy annual generation profiles were used to model the addition of marine energy resources to PV, battery, and diesel-generator microgrids using the microgrid planning software MCOR (Microgrid Component Optimization for Resilience). Microgrid operation during an emergency outage was simulated for a range of locations and critical load profiles, derived from real assessments of Department of Defense facilities.

6.3.1 Summary of Analysis Inputs and Parameters

Table 6-3 below identifies the analysis inputs and sources utilized in this Section. Section 4.2 identifies the analytical process utilized to convert the marine energy resource to an electric output.

Table 6-3. Inputs and data sources for Section 6.3

	Type	Location	Data Interval	Source
Grid load	Island/local	Various	Hourly	Department of Defense facilities
Renewable resource	Wave	PacWave	Hourly	(Yang, García-Medina, et al. 2020; Wu et al. 2020)
	Tidal	Admiralty Inlet, WA	Hourly	(Jim Thomson 2009; J. Thomson et al. 2012)
	Ocean Current	Florida Straits	3-hourly	(Chassignet et al. 2007)
	Solar	Various	Hourly	NSRDB
	Wind	Various	Hourly	Wind Toolkit

6.3.2 Insights

6.3.2.1 Locational benefits from the inclusion of marine energy resources

To answer the question of which locations benefit most from the deployment of marine energy resources, MCOR was run for 11 different sets of locations and accompanying load profiles for a 14-day outage period. The profiles were all normalized to have the same total annual load. The simulations were then rerun with the addition of 1 MW marine energy resources and the change was measured in the required solar capacity. This metric was chosen as it represents the reduction in critical load that must be met by the remaining microgrid components. The marine energy resources used here are: (1) wave resource near the PacWave site in Oregon; (2) tidal resource at Admiralty Inlet, WA; and (3) ocean current resource along the Florida Straits. As shown in Figure 6-4 there is only a small variation in required solar capacity with all sites experiencing a 50-60% reduction in required capacity with the addition of a 1 MW marine energy resource. Figure 6-5 explores the differences in load profile characteristics for the sites with the smallest and largest reduction in required solar capacity.

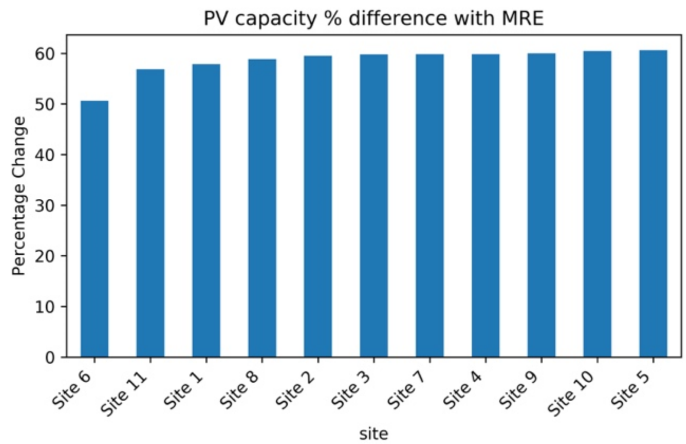

Figure 6-4. Required solar capacity after addition of marine energy resources for different sites.

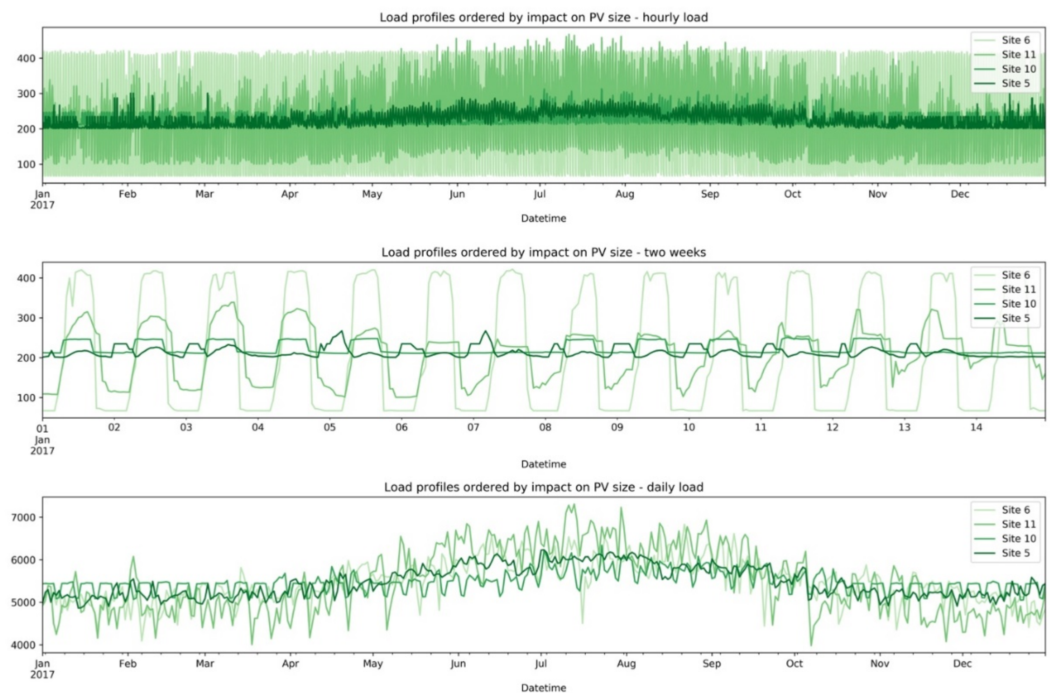

Figure 6-5. Load profiles for four sites with colors from light green to dark green ordered by reduction in solar capacity with the addition of marine energy resources. The top figure shows hourly load for the entire year, the middle figure shows hourly load for a two-week period, and the bottom figure shows daily load for the entire year.

Even though all load profiles have the same total load over the course of the year, the load profiles for which adding marine energy resources has the biggest impact on required solar capacity (e.g., Sites 10 and 5) are those with relatively constant load over the course of the day and less diurnal variation.

If the solar and battery capacities are now assumed fixed, how does the generator capacity and fuel consumption vary between locations with the addition of marine energy resources? Figure

6-6 indicates the reduction in required generator size does vary substantially between sites, ranging from 14% to 32%, although the overall reduction in fuel consumption is relatively consistent across sites. The sites with the greatest overall reduction in generator capacity are consistent with those that showed the largest reduction in required solar capacity.

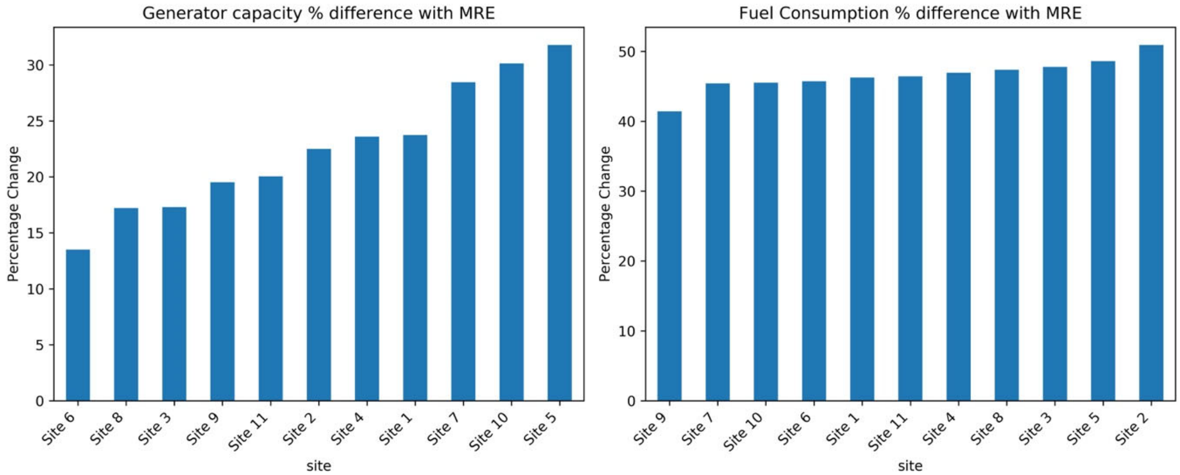

Figure 6-6. Percent change in required generator capacity (left) and fuel consumption (right) with the addition of marine energy resources for configurations with fixed PV and battery capacities.

In effect, marine energy resources have roughly the same impact on sites with varying load profile shapes, with a slightly bigger impact on sites with relatively constant load requirements over the course of day and night. This makes sense as marine energy resources can meet load at night when solar resources are unavailable.

6.3.2.2 Marine energy resources used to replace nonrenewable generation

For this analysis, Site 5 was chosen to simulate microgrid operation during a 3-day, a 7-day, and 14-day outage. Three marine energy profiles were used: tidal (Admiralty Inlet), ocean current (Florida Straits), and wave (PacWave). With a fixed starting PV and battery capacity (2 MW PV and 4 MW/20 MWh battery) based on other analysis for this site, additional generation capacity (in the form of either marine energy resources or additional PV) was added in increments of 50 kW until all critical load was met by the renewable-only microgrid or the additional capacity exceeded 10 MW. For each outage length and marine energy profile, the simulation was run 100 times to generate unique outage periods using MCOR's statistical solar profile generation model. This allows the analysis to simulate microgrid operation under a large range of outage conditions reflecting the differences in resource availability from season to season and across years. For some of the simulations, no amount of additional renewable capacity could allow the microgrid to meet 100% of the critical load with backup diesel generation, with a maximum cap of 10 MW additional capacity. The percentage of simulations where this was the case is shown in Table 6-4 for both PV and marine energy resources, all three marine energy profiles, and all three outage period lengths. It is likely that for those simulations where up to 10 MW of additional capacity was not sufficient, a larger battery is required to capture excess generation, and this is more often the case for additional PV resources as compared with marine energy resources. This results from the added complementarity of the marine resource to existing solar.

Table 6-4. Percent of Simulations where Additional Capacity was Insufficient.

	Admiralty (tidal)			**Ocean (ocean current)**			**PacWave (wave)**		
	3 days	**7 days**	**14 days**	**3 days**	**7 days**	**14 days**	**3 days**	**7 days**	**14 days**
PV	10%	17%	28%	10%	17%	28%	10%	17%	28%
marine energy	1%	2%	3%	3%	5%	9%	0	0	0

The results in Table 6-5 represent the average difference between using solar and marine energy resources for additional capacity over the 100 simulations. In those cases, highlighted above where additional capacity was not sufficient to replace nonrenewable generation, 10 MW is used as a placeholder for the additional renewable capacity, which means that many of the numbers reported may be lower limits.

Table 6-5. Percent reduction in required additional renewable energy capacity by adding marine energy instead of solar.

	3 days	**7 days**	**14 days**
Admiralty (tidal)	43%	46%	52%
Ocean (ocean current)	52%	55%	56%
PacWave (wave)	23%	31%	35%

The required additional marine energy capacity to replace nonrenewable generation sources is 23% to 56% smaller than the required additional PV capacity, with the range reflecting the type of renewable resource and length of outage period. These numbers represent averages across the 100 simulations. This can also be seen in Figure 6-7, which shows the required generator capacity (or unmet load) as a function of additional renewable capacity for both PV and marine energy resources for one of the outage scenarios and the Admiralty marine energy profile.

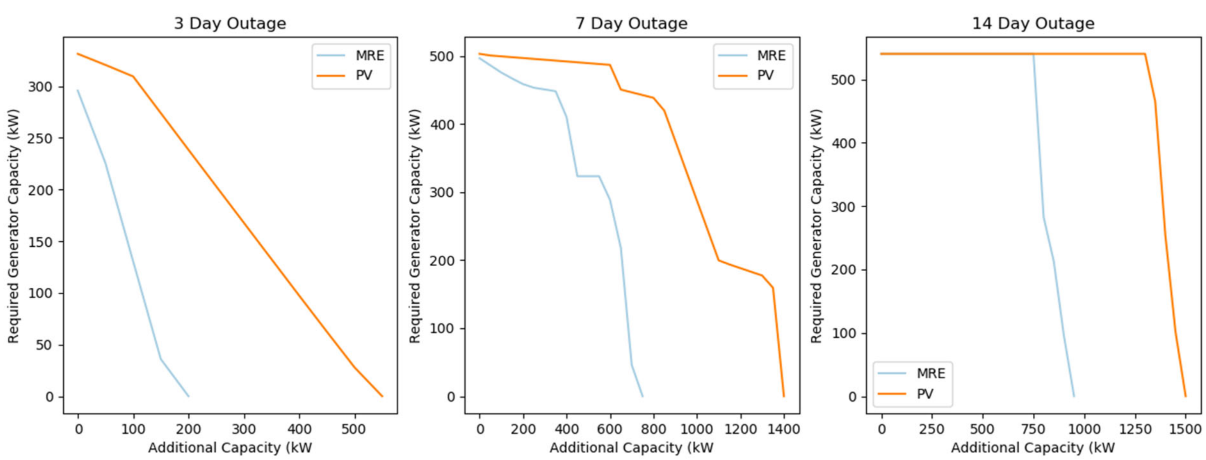

Figure 6-7. Required generator capacity (or unmet site load) as a function of added renewable capacity either in the form of solar (orange) or marine energy (blue) for one outage simulation and the Admiralty marine energy profile.

To understand how the addition of marine energy resources can offset the need for nonrenewable generation sources, the Figure 6-8 shows the 7-day resource dispatch for a microgrid before and after the addition of 1,700 kW of marine energy.

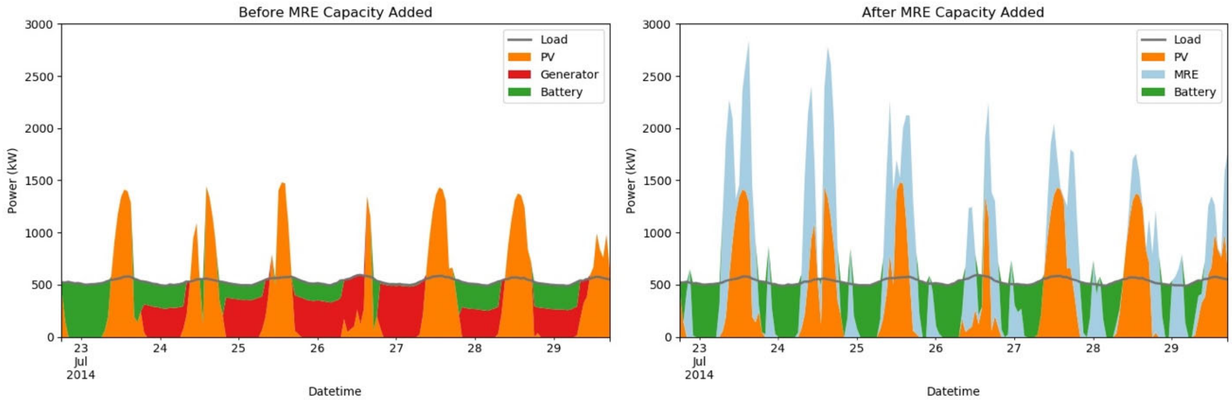

Figure 6-8. Dispatch plot before and after the addition of marine energy resources for a 7-day outage with critical load (grey line), PV generation (orange area), diesel generation (red area), marine energy generation (blue area), and battery discharge energy (green area).

6.3.2.3 Marine Energy Resources to Offset the Need for Battery Storage

A similar analysis was run to determine the required increase in battery capacity to meet all site critical load, given a 500-kW addition of PV or marine energy resources. Given the same increase in generation capacity, using marine energy in place of PV for that additional capacity can result in an average 9-38% reduction (Table 6-6) in the required battery capacity to capture that excess generation and remove the need for a backup diesel generator, with the range reflecting variable outage lengths and marine energy resource types. This results in an 8-36% reduction in battery capital costs (Table 6-7).

Table 6-6. Percent reduction in required additional battery capacity by adding marine energy capacity instead of PV

	3 days	7 days	14 days
Admiralty (tidal)	12%	22%	32%
Ocean (ocean current)	13%	27%	38%
PacWave (wave)	9%	16%	21%

Table 6-7. Average reduction in battery costs in $/kW of an installed fixed marine energy capacity required to eliminate diesel use instead of PV for a remote community in Alaska.

	3 days	7 days	14 days
Admiralty (tidal)	$229	$420	$611
Ocean (ocean current)	$248	$515	$725
PacWave (wave)	$172	$305	$401

6.3.2.4 Impacts of the addition of solar or marine energy resources to a microgrid

Finally, if the microgrid can contain nonrenewable resources, how does the required capacity and fuel use of these backup resources compare for a baseline system with 2 MW PV, 2 MW + 500 kW PV, and 2 MW PV + 500 kW marine energy? The SRE ratio introduced in Reiman et al. (2020) is also compared for these systems. This ratio quantifies the fraction of critical load met by renewable resources in a microgrid.

For the same amount of additional capacity of either PV or marine energy resources, adding marine energy instead of PV decreases the required generator capacity by 26-62% (Table 6-8) and the required fuel consumption by 11-56% (Table 6-9) on average. Using marine energy also increases the change in SRE of the system over baseline by 37-61% compared to adding more PV.

Table 6-8. Percent reduction in required generator capacity, capital cost, fuel use, and fuel cost savings by adding marine energy capacity instead of PV and fuel cost savings calculated for a remote community in Alaska

	Admiralty (tidal)			Ocean (ocean current)			PacWave (wave)		
	3 days	**7 days**	**14 days**	**3 days**	**7 days**	**14 days**	**3 days**	**7 days**	**14 days**
Generator capacity	42%	37%	26%	50%	59%	62%	40%	39%	43%
Generator cost	22%	21%	15%	27%	35%	38%	16%	21%	27%
Fuel use	41%	41%	39%	43%	52%	56%	11%	16%	32%
Fuel cost savings	$14	$32	$62	$15	$41	$88	$4	$13	$51

Table 6-9. Average SRE among simulations

	Admiralty (tidal)			Ocean (ocean current)			PacWave (wave)		
	3 days	**7 days**	**14 days**	**3 days**	**7 days**	**14 days**	**3 days**	**7 days**	**14 days**
Base system	0.87	0.80	0.77	0.87	0.80	0.77	0.87	0.80	0.77
With PV added	0.94	0.91	0.90	0.94	0.91	0.90	0.94	0.91	0.90
With marine energy added	0.99	0.97	0.96	0.99	0.97	0.97	0.98	0.96	0.95

6.3.2.5 Range in resilience metrics across all simulations for each marine energy profile and outage length

All the metrics shown above represent the average among the 100 simulations run for each test. Figure 6-9 shows the range in metric values for all the simulations. For each chart in the plots, the edges of the box represent the middle two quartiles, the whiskers represent the full range minus any outlier values, and the central line represents the median of the range.

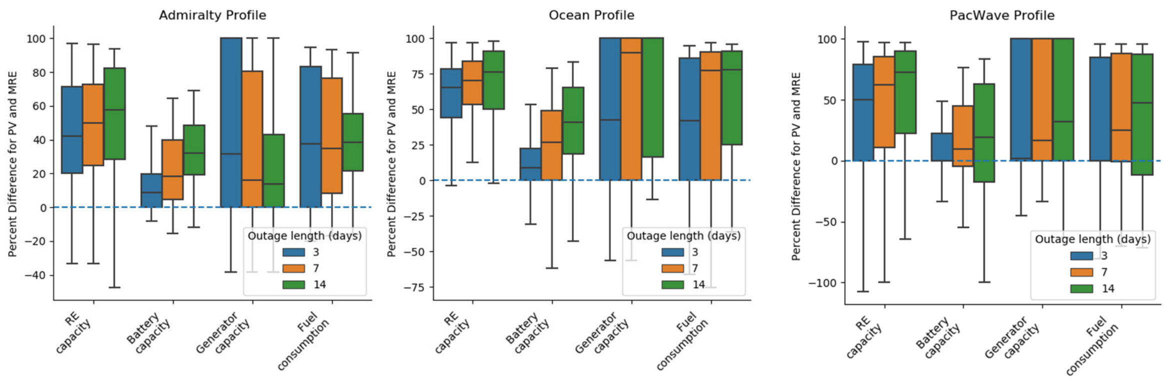

Figure 6-9. Percent reduction in the required renewable, battery, and generator capacity, and fuel use resulting from adding marine energy instead of PV across all 100 simulations.

These ranges reflect the impact that varying outage conditions can have on the choice of renewable resources. For instance, in some simulations the required PV capacity is smaller than the required marine energy capacity as seen in lower limits to the metric ranges falling below 0. However, in most cases (at least 75%), adding marine energy instead of additional PV resources results in a decrease in required renewable capacity, battery capacity, and non-renewable resource use, by up to 100% in some cases. Another way to visualize this is to look at histograms across the simulations. The example in Figure 6-10 shows the required additional capacity for PV and marine energy for all 100 simulations for the Admiralty marine energy profile and a 14-day outage period. The spike at 10 MW reflects the simulations in which the additional renewable capacity could not replace diesel generation within the allowed number of iterations.

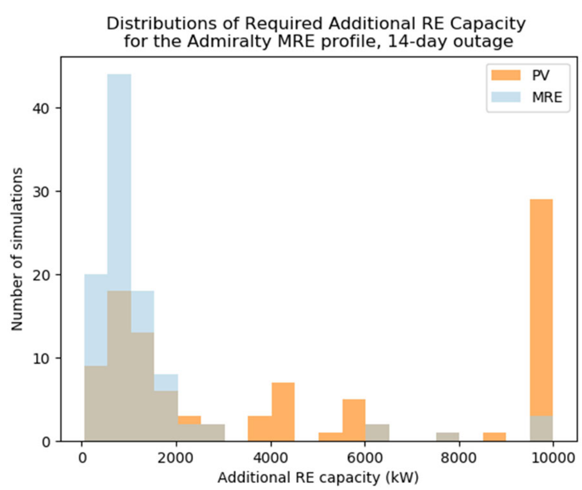

Figure 6-10. Distributions of required additional renewable capacity for the admiralty inlet marine energy profile over a 14-day outage. The brown/grey color represents the overlap of the marine energy and PV resources.

6.3.3 Conclusions

1. Marine energy resources have roughly the same impact on sites with varying load profile shapes, with a slightly bigger impact on sites with relatively constant load requirements over the course of the day and night.
2. If additional renewable capacity is added to a baseline PV+battery+diesel microgrid to replace diesel generation, the addition of marine energy resources requires 23-56% less capacity than additional PV resources, with the range reflecting different outage lengths and marine energy profile types.
3. If an additional renewable capacity is added to a baseline PV+battery+diesel microgrid to replace diesel generation and the battery is expanded to capture this excess generation, using marine energy as the additional renewable resource decreases the required battery capacity by 9-38% as compared with using PV.
4. If additional renewable capacity is added to a baseline PV+battery+diesel microgrid, adding PV resources increases the sustainable ride-through energy (SRE) ratio by 0.07-0.13 from baseline, while adding marine energy resources increases the SRE by 0.11-0.19, increasing the impact by roughly 50%.

These findings point to the complementarity value of utilizing marine energy resources in addition to existing resources such as solar. Marine energy adds an element of resource diversity that is valuable in these microgrid scenarios, particularly considering that geographic limitations would prevent adding solar diversity and reducing diesel use can represent a significant resiliency benefit.

6.4 Renewable Energy Resource Evaluation for a Microgrid on Molokai

6.4.1 Summary of Analysis Inputs and Parameters

Table 6-10 below identifies the analysis inputs and sources utilized in this Section. Section 4.2 identifies the analytical process utilized to convert the marine energy resource to an electric output.

Table 6-10. Inputs and data sources for Section 6.4.

	Type	Location	Data Interval	Source
Grid load	Island/local	Molokai	Hourly	Maui Electric Company
Renewable resource	Wave	Molokai	Hourly	(Yang, García-Medina, et al. 2020; Wu et al. 2020)
	Solar	Molokai	Hourly	NREL
	Wind	Molokai	Hourly	MERRA-2[27]

[27] The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), Ronald Gelaro, et al., 2017, J. Clim., doi: 10.1175/JCLI-D-16-0758.1

6.4.2 Methodology

Working towards Hawaii's state goal of 100% renewable energy by 2045, the island of Molokai was once projected to reach its own goal of 100% renewable energy by the end of 2020. An assessment included in Hawaiian Electric Companies' *Power Supply Improvement Plans* indicated that the island could reach this goal through distributed solar PV, utility-scale wind, and biofuel as shown in Figure 6-11. Given the near-term timeframe of the assessment, marine energy technologies were not included; however, given the dependence on biofuel within the optimal scenario, there is an opportunity to assess the role that wave energy resources might play within the mix. This was done through an assessment of renewables meeting the critical load of the island.

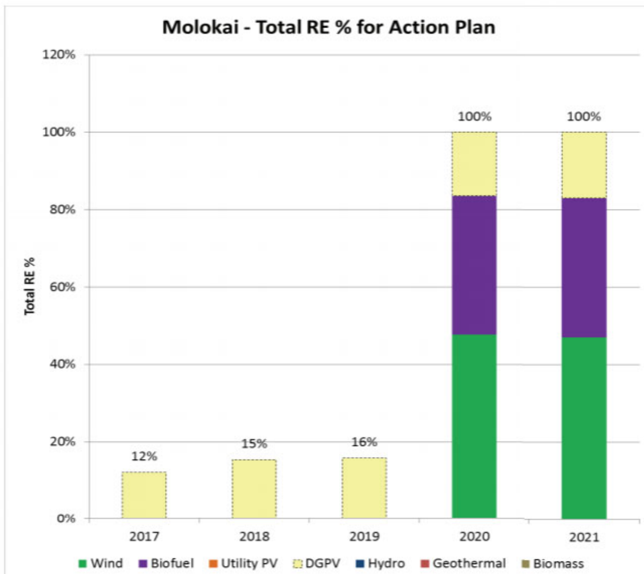

Figure 6-11. Renewable energy percentages to reach 100% renewables energy on Molokai.

To evaluate and compare the fitness of different renewable resources for inclusion in a microgrid supplying the critical load of the island of Molokai, HI, a similar simulation pipeline was established as for the previously described meta-analysis. In this pipeline, an outage of 14 days was simulated 100 times with varying solar resources using MCOR. A base microgrid system was modeled with 3.5 MW of solar capacity, 5 MW of wind capacity, a 17 MW/136 MWh battery, and a biofuel generator meeting the remainder of the critical load. Several sets of simulations were run to explore how additional renewable resources (solar, wind, marine energy) could be incorporated to reduce the reliance on biofuel.

A single profile was used based on load data provided to PNNL for Molokai from Hawaiian Electric (Yuan et al. 2019). The MERRA-2 reanalysis product at 40m height for the year 2014 was used to represent the wind resource; it was converted to a power profile with a representative 100 kW turbine power curve. A 100-kW turbine was used since a recent request for proposal from Maui Electric Company only solicited small wind turbines up through 100 kW in size for the island of Molokai.[28] Two marine energy profiles were generated (BBDB and two-body FPA). All three renewable annual generation profiles are shown in Figure 6-12 for a 1 MW system. Solar generation profiles were calculated for each outage period using MCOR's statistical profile generation model.

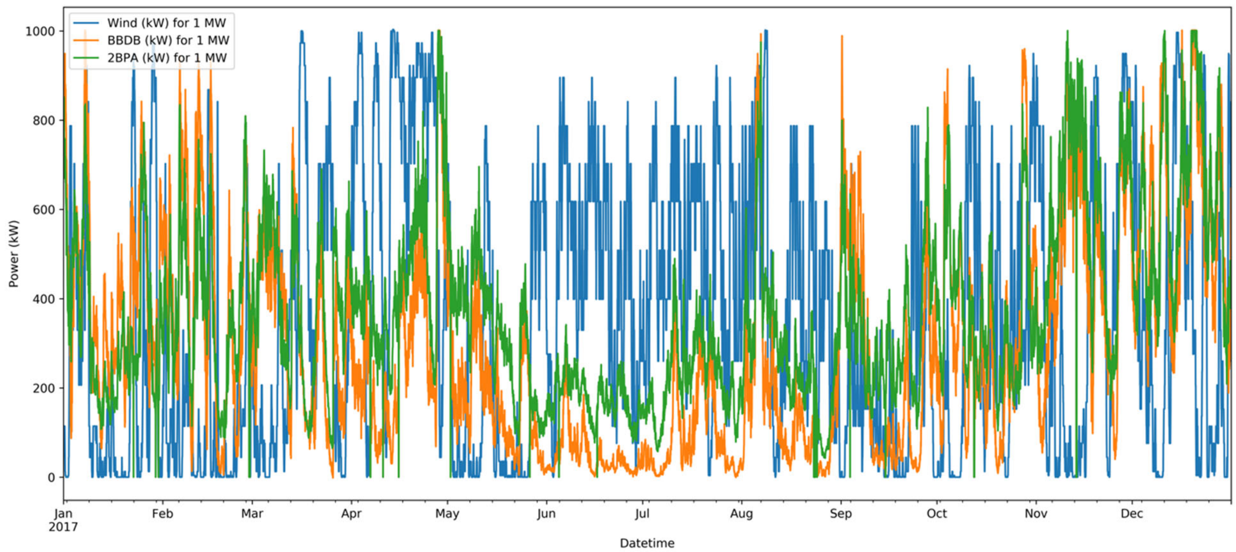

Figure 6-12. Annual hourly power production in kW for a 1 MW renewable energy system with wind shown in blue, BBDB in orange, and FPA in green.

The first simulation set determined the additional capacity required from each renewable energy resource type to increase deployment to 95% and 100%. For each resource type, capacity was added in increments of 50 kW to the baseline microgrid system until renewable deployment reached 95% and 100% or a maximum additional capacity of 10 MW was reached. The number of simulations for which 10 MW was not sufficient to meet all load with renewables was recorded as well as the average required additional capacity.

The second simulation set measured the additional battery capacity required to reach 100% renewables after 5 MW of renewable capacity was added to the baseline system for each of the different resource types. Battery power and capacity was added in increments of 500 kW/500 kWh until the threshold was met or a maximum battery capacity of 211 MWh was reached.

The third simulation set measured the impact on biofuel usage when 5 MW of additional renewable energy capacity was added to the baseline microgrid. The metrics were required generator capacity, fuel usage, fuel cost, and SRE ratio. For these calculations a biofuel cost of $40.93/MMBtu was used.

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[28] See Hawaiian Electric Company. Maui Electric issuing largest call for renewable energy projects for Molokaʻi, Lānaʻi . December 2, 2019. https://www.hawaiianelectric.com/documents/about_us/news/2019_maui_electric/20191202_maui_electric_issues_request_for_proposals_molokai_lanai.pdf

6.4.3 Results

6.4.3.1 Comparison of renewable resources required to increase renewable deployment

For this set of simulations, additional renewable capacity was added to the baseline microgrid system until a fixed deployment was achieved or a maximum threshold capacity was reached. Simulations were run for additional capacity from solar, wind, and marine resources (using both marine energy generation profiles) for 100 outage profiles each. Table 6-11 shows the percentage of simulations where the maximum additional capacity (10 MW) was reached before the microgrid was sufficient to meet 95% or 100% of the critical load without the use of biofuels. While both marine energy sources performed better than wind and PV, there was a large variation between the two.

Table 6-11. Percent of simulations where additional capacity was insufficient,

	PV	Wind	Wave (BBDB)	Wave (FPA)
95% renewables	52%	24%	18%	2%
100% renewables	65%	57%	38%	6%

This can also be seen in Figure 6-13 which compares the required additional renewable capacity to achieve 95% renewable deployment for additional solar, wind, and marine energy capacity. An additional capacity of 10 MW indicates the maximum capacity was reached before 95% of the load was able to be met by renewables. Interestingly, the required wind capacity is somewhat bimodal with either a small required additional capacity or no capacity sufficient to meet the renewables threshold, while marine energy can meet the renewables goal for a larger number of simulations but with a higher required capacity on average.

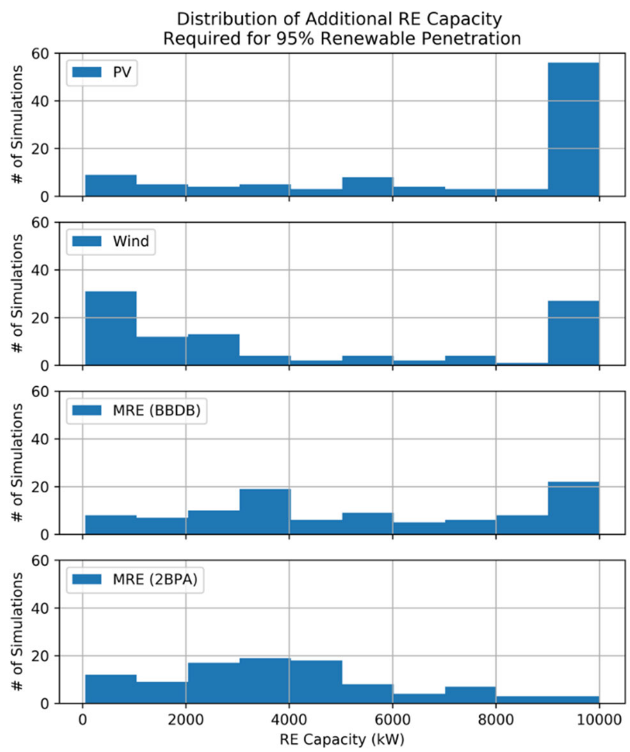

Figure 6-13. Distribution of additional renewable capacity required for the baseline system to achieve 95% renewable deployment across 100 simulations.

The percent reduction in additional capacity required for wind and marine energy to meet 95% and 100% renewable deployment as compared with PV is shown in Table 6-12. Both wind and marine energy require a significantly lower additional capacity than PV to meet the renewable deployment goal, with the two-body FPA profile performing the best.

Table 6-12. Percent reduction in required additional RE capacity by adding wind or marine energy instead of PV.

	Wind	Wave (BBDB)	Wave (FPA)
95% renewables	42%	25%	47%
100% renewables	29%	15%	40%

Figure 6-14 shows the microgrid resource dispatch operation for one of the outage profiles for (a) the baseline system and with the addition of (b) 5 MW of PV, (c) wind, or (d) marine energy capacity, using the two-body FPA profile. In all four plots, the required biofuel energy production is shown in red. Even though the same renewable energy capacity is added to the baseline in plots (b), (c), and (d), the required biofuel production is much lower with the addition of wind capacity compared with PV, and marine energy compared with both PV and wind. This is because adding a larger diversity of renewable resources increases the likelihood that at least one resource is producing energy at any given time.

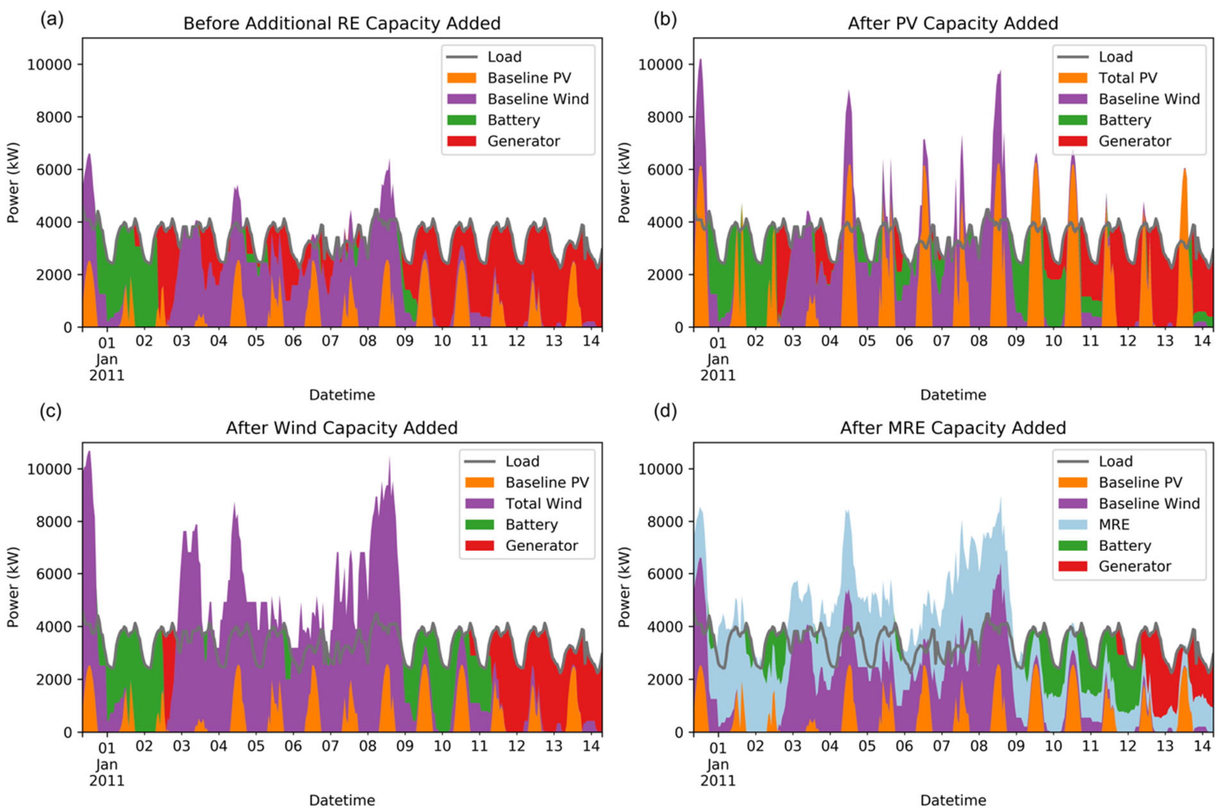

Figure 6-14. Microgrid dispatch operation for (a) the baseline system, (b) the baseline system with 5 MW of PV capacity added, (c) the baseline system with 5 MW of wind capacity added, and (d) the baseline system with 5 MW of marine energy capacity added; load (gray line), PV generation (orange area), wind production (purple), battery discharge energy (green), biofuel generator production (red), and marine energy generation (blue).

6.4.3.2 Comparison of battery capacity required to increase renewable deployment when paired with different renewable resources

For the second simulation set, a fixed amount of renewable energy capacity (5 MW) was added to the baseline microgrid system, and the battery capacity and power were increased until 100% renewable deployment was achieved, or a threshold battery capacity (211 MWh) was reached. Table 6-13 shows the percent reduction in the required overall battery capacity if wind or marine energy is added to the baseline system instead of PV. Adding wind or marine energy to the baseline microgrid instead of more PV results in a smaller required increase in battery capacity to achieve 100% renewable deployment.

Table 6-13. Percent reduction in required battery capacity by adding wind or marine energy capacity instead of PV.

	Wind	Wave (BBDB)	Wave (FPA)
100% renewables	11%	7%	17%

6.4.3.3 Comparison of biofuel requirements with the addition of different renewable resources

The last set of simulations compared the biofuel requirements of the microgrid after adding 5 MW of additional renewable capacity from the different resource types. The required biofuel generation capacity and fuel consumption for a 14-day outage were calculated as well as the SRE ratio and the improvement of that ratio over the baseline system, all shown in Table 6-14 and Table 6-15. Adding either wind or marine energy resources results in a significantly smaller required biofuel generator and fuel use as compared with using more PV resources, with the two-body FPA profile performing the best and maximizing fuel cost savings over the 2-week analysis period. And both types of renewable generation have a significant impact on the SRE ratio as compared with PV, likely due to the ability to better use the battery with more diverse resource generation.

Table 6-14. Percent reduction in required generator capacity, fuel use, and fuel cost by adding wind or marine energy capacity instead of PV (2-week period).

	Wind	Wave (BBDB)	Wave (FPA)
Generator capacity	34%	32%	66%
Fuel use	46%	37%	62%
Fuel cost savings	$14,400	$12,200	$17,900
Fuel cost savings (yr.)	$374,400	$317,200	$465,400

Table 6-15. Average SRE among simulations.

	Base System	+PV	+Wind	+Wave (BBDB)	+Wave (FPA)
SRE	0.51	0.79	0.93	0.90	0.96
∆SRE from baseline	-	+0.27	+0.42	+0.39	+0.45

6.4.4 Conclusions

Incorporating either wind or marine energy resources into a baseline microgrid requires significantly lower additional capacity (15-47% less) to meet a renewable deployment goal of 95% or 100% as compared with adding solar, demonstrating the benefits of resource diversification adding complementarity to existing resources.

The benefits of adding wind or marine energy depend on the marine energy generation profile used and the specific metric. Using more wind capacity to increase renewable deployment results in a smaller additional required capacity on average than for one of the two marine energy generation profiles but can meet the deployment goal for a smaller number of outage scenarios as compared with both marine energy resources profiles. Adding marine energy resources to a baseline PV/wind/battery/biofuel microgrid instead of more solar or wind capacity provided more certainty that critical load would be met across a large range of conditions without the need for backup biofuel generation.

7.0 Next Steps

The project has produced several foundational reports, tools, and valuation approaches to ascertain a representative value proposition for marine energy. This technical report and the other reports, journal articles and frameworks developed in this project can be used by both industry and the electric system planning sector.

The value inherent in marine energy is particularly important as traditional energy resources, namely fossil generation, are retired, leaving resource adequacy gaps. Economically meeting these gaps necessitates a diverse portfolio approach, of which marine energy is well placed to help address. There is a growing awareness in the electric sector of the significance and need for valuing location in power systems. Renewable resources vary in quality and intensity across locations, with uneven proximity to electric load and access to transmission. Clustered concentrations of renewable energy project development around high-quality resources and existing transmission have amplified the negative effects of resource volatility. These factors are driving investment and planning trends toward electric system resilience, hybrid storage power plants, and DERs. Through its predictability, marine energy can help support resilience objectives and local loads in locations that have poor renewable alternatives. The situation is ripe for marine energy stakeholders to further advance understanding of the technology in the grid planning community.

Accordingly, we identify the following key next steps to be taken by researchers, the marine energy industry and electric grid stakeholders:

- **Availability of detailed device generation data:** A challenge we faced in considering the value marine energy represents to the grid was of the lack of granular marine energy device output data. Absent granular electric generation data, electric grid operators are not able to understand the implications of marine energy device deployment, both from an electrical interconnection perspective, but also from a value perspective. Without such data (and relying on representative data like we used here), it is unlikely grid operators will consider deployment, regardless of device cost.
- **Analysis of the complementarity of marine energy with other resources and energy storage**: Although the work in this project serves as an insightful platform for gauging the impacts of marine energy on power system operations as it relates to interactions with other technologies, future work should incorporate details such as transmission network structure, topology, and/or device-level technological characteristics for more realistic assessments.
- **Potential for Delivery to coastal loads**: Further work will be needed to evaluate the real power system impacts associated with marine energy deployment and the interconnection capacity available to support such deployment. PacWave is likely to enable this work. Further, engagement with the offshore wind industry may benefit marine energy in accelerating potential development.
- **Analysis of impacts on Distribution grids and the value to remote communities and microgrids**: The potential for marine energy deployment to reduce voltage and power quality impacts should be further refined in future investigations on different types of network models, loading conditions, control configurations (regulators/capacitors), and generation conditions. Further, comprehensive, site-specific analysis will be needed before actual deployments can be considered for remote community and microgrid environments. Interconnection with existing systems and reliability of ongoing device operations will be

topics of importance. Marine energy developers may find interested and willing utility partners in such environments.

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Appendix A – Resource and Device Characterization for Analysis

A.1 Marine Energy Resource Potential

Marine energy resources are generally quantified via direct measurements and/or numerical modeling systems. Direct measurements, such as those collected via wave buoys or acoustic Doppler current profilers, provide high-resolution measurements of ocean surface and subsurface conditions via physical interactions between the body and the exciting wave, or the Doppler shift associated with the water particle velocity reflections. Direct measurements provide the best possible representation of all ocean conditions at high temporal resolution yet suffer from the fact that they only provide a point measurement for a limited deployment length. Numerical wave models such a Simulating WAves Nearshore (SWAN) or circulation models such the Finite Volume Community Ocean Model (FVCOM) may lack the temporal resolution of direct measurements but are able to numerically simulate the propagation of wave or circulation patterns over vast areas and long timeframes (decadal scale).

The marine energy resource potential data used for this project were provided from the Department of Energy funded Early Market Opportunity Hot Spot Identification and Resource Characterization project. The project is a collaboration between PNNL, the National Renewable Energy Laboratory (NREL), and Sandia National Laboratories and is focused on developing the highest fidelity assessment of U.S. wave and tidal renewable energy resources. For the wave resource, PNNL and Sandia are using the SWAN model that is driven by WaveWatch III boundary conditions and CFSR winds to develop a 32-year hindcast of U.S. wave resources (Yang, García-Medina, et al. 2020; Wu et al. 2020). For the tidal resource, PNNL is using FVCOM and local riverine, bathymetric, and tidal conditions to quantify the tidal resource in high-energy locations in Cook Inlet, AK; Puget Sound, WA; and Western Passage, ME (Yang, Wang, et al. 2020; Wang and Yang 2020). To validate these numerical outputs and provide necessary high-temporal resolution measurements, NREL is responsible for deploying a suite of in-situ wave buoys and current measurement systems around the United States. The Admiralty Inlet tidal resource was obtained from acoustic Doppler current profiler data from seafloor tripods in Admiralty Inlet, Puget Sound, (Jim Thomson 2009; J. Thomson et al. 2012). Data were collected from April 2009 through December 2012. For this effort, 2011 tidal velocity profile data time-series in a 1-minute resolution were utilized. The Florida Straits ocean current data were obtained from (Chassignet et al. 2007)).

Building on these numerical outputs and direct measurements, the marine energy resource data being used in this effort are quantified per the technical specifications of *IEC TC 114 62600-101: Wave Energy Resource Assessment and Characterization* and *IEC TC 114 62600-201: Tidal Energy Resource Assessment and Characterization*. When possible, project collaborators provided the team with provided priority access to the data outputs to ensure both project outcomes were coherent and the best available data sources were leveraged. Other modeled data and measurements were used throughout the project when appropriate and are identified in the relevant section.

A.2 Generating Marine Energy Device Output

The generation of marine energy electrical power output depends on two major time-series inputs: a resource quantified by the appropriate parameters and a marine energy technology performance representation.

A.2.1 Wave Energy Devices

In contrast to other renewable energy resource flows which require only a single variable (irradiation for solar or wind speed for wind energy), the wave energy resource assessment requires a minimum of two parameters to accurately quantify the resource: the significant wave height and energy period. These two parameters can either be calculated within a numerical program like SWAN or from the full spectral representation of the sea conditions (Robertson 2017).

Correspondingly, the power output and general performance from a WEC also need to be quantified against all expected combinations of significant wave height and energy period. The performance of WEC designs, or architectures, varies significantly across both dimensions. The WEC technologies used in this initial research is predicted based on validated ProteusDS numerical models developed by the University of Victoria, Canada.[29] Details on the technologies and associated performance matrices are presented below.

Among the wide variety of technology designs currently available, the backwards bent-ducted buoy (BBDB) and two-body floating point absorber (FPA) were initially used for this research. The BBDB comprises of a large, hollow, barge-type structure that encloses an air chamber. Incoming waves excite the barge superstructure and create pressure changes in the enclosed air chamber, which flows through a directional air turbine to generate power. The modeled BBDB, shown in Figure A-8-1, has a 17.5 m draft, a 27 m beam, and a 35 m length (Bailey, Robertson, and Buckham 2016). The performance matrix for the BBDB design is provided in Figure A-8-2. The Ocean Energy USA LLC buoy to be deployed at the Wave Energy Test Site in Hawaii in 2021 is a type of BBDB.

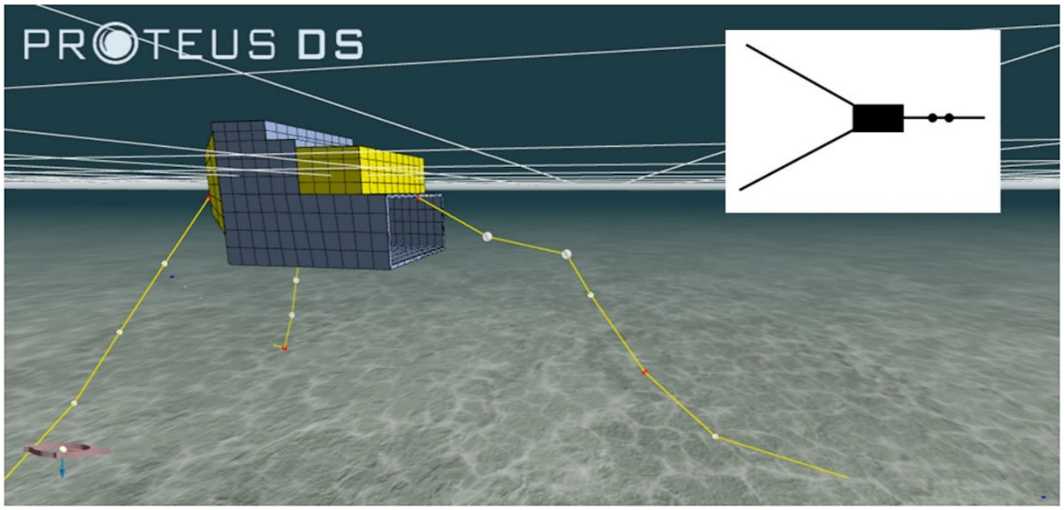

Figure A-8-1. Modeled backwards bent double-ducted buoy (Bailey, Robertson, and Buckham 2016).

[29] For a comparison of different modeling tools, *see* Beatty, Scott & Roy, André & Bubbar, Kush & Ortiz, Juan & Buckham, B. & Wild, Peter & Steinke, Dean & Nicoll, Ryan. (2015). Experimental and Numerical Simulations of Moored Self-Reacting Point Absorber Wave Energy Converters. 2015.

P [W]		Wave Energy Period [s]									
		5.50	6.50	7.50	8.50	9.50	10.50	11.50	12.50	13.50	14.50
Significant Wave Height [m]	0.25										
	0.75		838	3590	5700	8050	7390	7430	5680		
	1.25		3760	13800	19900	27300	28000	24600	20700		
	1.75		11000	31400	52500	57000	52700	51300	40400	34700	
	2.25		22700	57800	88200	94600	88200	85100	70000	64700	
	2.75		34200	83100	120000	128000	123000	117000	106000	84100	
	3.25			115000	158000	177000	165000	162000	129000	119000	
	3.75			152000	204000	203000	209000	182000	169000	147000	143000
	4.25				234000	253000	229000	232000	201000	181000	156000
	4.75					277000	272000	261000	227000	197000	180000
	5.25						303000	240000	252000	252000	
	5.75						296000	296000	279000		
	6.25										
	6.75										
	7.25										
	7.75										

Figure A-8-2. A BBDB performance matrix.

The two-body FPA uses the relative motion of two moored bodies to extract power, with these bodies being relatively small compared to the wavelength. The FPA used in this study is axisymmetric and features a 15 m diameter circular cylinder buoyant float, coaxially aligned with a 39 m tall spar, shown in Figure A-8-3 (Beatty et al. 2015). The performance matrix for the FPA design is provided in Figure A-8-4.

Ocean Power Technologies is currently developing a two-body FPA and has deployed them in numerous locations across the United States.

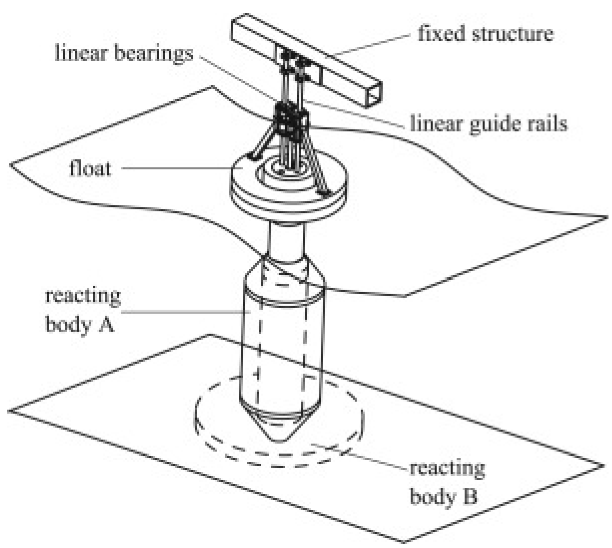

Figure A-8-3. Two body FPA (Beatty et al. 2015).

P [W]		Wave Energy Period [s]												
		5.50	6.50	7.50	8.50	9.50	10.50	11.50	12.50	13.50	14.50	15.50	16.50	17.50
Significant Wave Height [m]	0.25	696	1088	1334	1222	958	737	599	476	340	328	261	208	172
	0.75	6477	10015	11428	11770	9555	6547	5781	4291	2763	2994	2480	1967	1491
	1.25	16998	25599	31110	29358	24902	20870	16346	13796	8923	9939	6002	5113	3631
	1.75	33240	52668	52990	58153	45288	32189	28977	22427	19632	18071	12237	11711	8333
	2.25		84574	82820	99583	79710	58032	46870	40898	36048	26569	20147	14929	14583
	2.75		116455	103882	127590	121768	97884	58441	52472	46319	38176	34154	24195	19660
	3.25		155668	137440	168119	162732	128409	86810	76113	61458	56755	47213	40419	29582
	3.75		214002	195510	190137	192015	166560	142173	110692	72417	71752	71609	53110	37157
	4.25			229262	235332	255156	216426	178936	146987	127803	98797	71792	50702	49058
	4.75				308900	253597	240510	218507	142699	145985	109292	94234	92561	66746
	5.25					368152	321780	271532	212399	169601	151130	103961	93083	78872
	5.75						336041	246740	251074	180069	143292	150160	105231	84759
	6.25						394096	321218	282912	259631	202792	149217	99802	106078
	6.75						349609	356687	300026	253526	228600	162578	120928	144773
	7.25						476031	465555	286671	259860	235884	179791	153422	132911
	7.75						464001	378678	418194	291563	285077	230664	170593	142990

Figure A-8-4. A two-body FPA performance matrix.

Generating the time-series of WEC power outputs involves multiplying the hourly time-series of the significant wave height and energy period (from the previously noted SWAN numerical wave model) against the appropriate WEC performance matrices to generate the hourly power output.

A.2.2 Tidal and Ocean Current Devices

Unlike WECs, which require multiple variables to calculate power production, the power from tidal and ocean current devices can be estimated with only the current's velocity. The tidal and ocean current resource profiles were put through an axial-flow turbine model to generate electric output. Consider P_{rated}, P_{gen}, v, v_{cut-in}, and $v_{cut-out}$ to be the rated power output of the turbine (Watts), the actual power generated by the turbine (Watts), the actual tidal velocity (m/s), and the cut-in and cut-out velocities (m/s), respectively. Depending on the velocity of the tides, the turbine is assumed to be working in one of the four regions (1–4). Below the cut-in velocity, when $v < v_{cut-in}$ (Region 1), and above the cut-out velocity, when $v > v_{cut-out}$ (Region 4), the output of the turbine is assumed to be zero. We denote the maximum power generated by the turbine as P_{max}, which is computed as a function of the turbine characteristics and tidal velocity. Mathematically,

$$P_{max} = \frac{1}{2}\rho_{turb}\left(\frac{\pi d^2}{4}\right)C_{p,max}\, v^3$$

where ρ_{turb} is the density, d is the rotor diameter, $C_{p,max}$ is the maximum coefficient of performance (or mechanical efficiency), and v is the tidal velocity (m/s). Note that the cut-in and cut-out velocities depend on the size (mechanical dimensions) of the turbine. For the sake of exposition, we assume an example case where the following parametric values are chosen: P_{rated}= 1.5 MW, ρ_{turb} = 1025 kg/m^3, d= 20 m, v_{cut-in} = 1 m/s, $v_{cut-out}$ = 3.5 m/s. The $C_{p,max}$ is computed as shown in (Cavagnaro et al. 2016).

Appendix B **Case Study Details**

MCOR Microgrid Evaluation Additional Figures

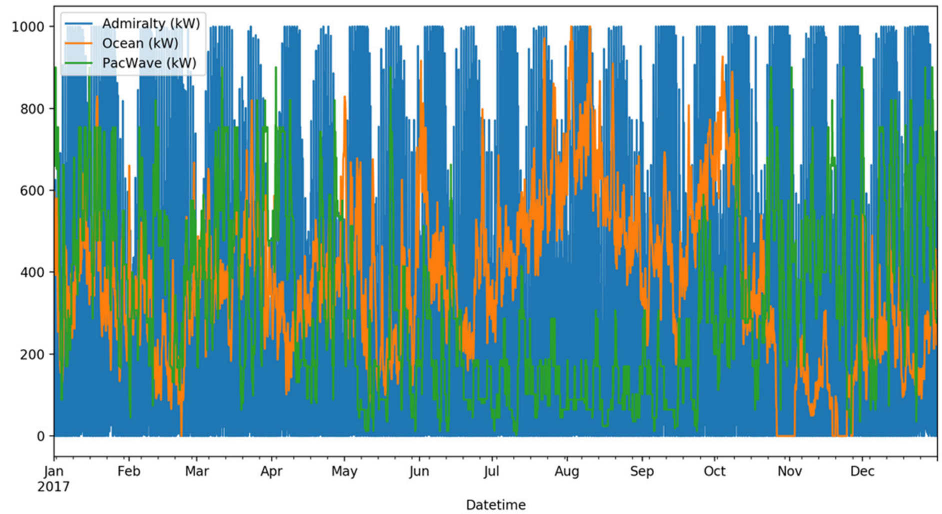

Figure B-8-5. Marine energy Resource Profiles

Figure B-8-6. MCOR Load Profiles

Appendix C – Data and Model/Methodology Derivation

C.1 Methodology Used for Section 5.7.1.

This Appendix details the procedure utilized for conducting the parametric study for evaluating storage requirements with the deployment of marine energy (marine energy). To this end, we consider a copper-plate grid model where generation, G, (from both renewables and conventional resources) meets the total demand D at all time instants (i.e. $\forall t \in [0, T]$).The models considered in this work are similar to those in [11], although unlike in [11], we consider marine energy in the resource mix and study it from a US perspective, as opposed to a European context. Also, we extend the formulation to cover a wider, more controllable range of scenarios with different levels of overall renewable energy deployment, as well as specific levels of marine energy inclusion. Let R_t^i denote the instantaneous generation at time t from renewable resource i. Similarly, let D_t and G_t be the system load and total generation (conventional and renewable combined) at time t. The amount of conventional generation required in the system at time t to account for shortfall from renewable sources is subsequently denoted as C_t, where

$$C_t = G_t - \sum_i R_t^i, \forall\, i \in [1, \dots, N].$$

Above, i are the types of renewable sources in the generation mix. Note that when there is a shortfall of renewable generation, $C_t > 0$ (i.e. positive generation is needed from conventional sources) and when there is overproduction, $C_t < 0$ (i.e. additional load/demand response needs to be deployed). Throughout our analysis, we scale the values of $D_t, R_t^i\ \forall\, i$ and C_t by the respective mean values for the ease of exposition.

Baseline conditions: The baseline conditions, i.e., the "business-as-usual" case for our study for the instantaneous mismatch function $\Delta(.)$ is given as:

$$\Delta_t = \beta_0 C_t + \sum_i \gamma_i R_t^i - D_t, \forall\, i \in [1, \dots, N] \quad (1)$$

where β_0 is the average fraction (of the total load) of conventional resources required under baseline conditions and γ_i denotes the average fraction (of the total load) of renewable resource i included in the generation portfolio. Note that $\beta_0 + \sum_i \gamma_i = 1, \forall\, i \in [1, \dots, N]$. This mismatch function provides the instantaneous mismatch between total generation (conventional and renewable combined) and the demand, under baseline conditions, reflective of present-day operations.

Parametric Setup: In this setup, we first consider the increased injection of renewable energy (by displacing conventional generation), without commenting on type-specificity. In other words, assume that for a renewable resource i, increases the amount of deployment by amount α_i, such that $\alpha = \sum_{i=1} \alpha_i, \forall\, i \in [1, \dots, N]$. The term α now denotes the total fraction of generation being displaced from conventional sources and being replaced by the cumulative effect of all N renewable resources. In such a case, the mismatch function would be denoted as,

$$\Delta_t = (\beta_0 - \alpha) C_t + \sum_i (\gamma_i + \alpha_i) R_t^i - D_t, \forall\, i \in [1, \dots, N] \quad (2)$$

Note that, for all practical purposes, $\alpha = (0, \beta_0)$. Now, we consider that the Nth renewable resource is a marine resource. We introduce a control parameter $\zeta = [0, 1)$ which denotes the fraction of reduction in generation capability from all renewable resources which are not marine, (i.e. $\forall\, i \in [1, \ldots, N-1]$) as well as compensation by an increment in the power production capability from the marine resource, i.e. the resource N. The final parametric is given as,

$$\Delta_t = (\beta_0 - \alpha)C_t + (1-\zeta)\sum_i (\gamma_i + \alpha_i)R_t^i \qquad (3)$$

$$+\left(\gamma_n + \alpha_n + \gamma \sum_i (\gamma_i + \alpha_i)\right) R_t^N - D_t\,, \forall\, i \in [1, \ldots, N-1]$$

Note that while considering the increment of marine energy in the parametric study, we must keep in mind the technological constraints which are inherent to those resources. For example, due to their locational constraints to be placed at certain locations, tidal resources are difficult to scale for large grid scale applications. Wave resources are, however, considerably more scale-able, with respect to tidal. We incorporate this fact into our consideration in the results presented in Section 5.7.1.

Energy Storage Model: The energy storage model builds upon the mismatch model presented in the above section. The positive mismatch (excess renewable generation) can be used to charge the storage whereas the negative mismatch can be used as a signal to discharge the battery by the shortfall amount. Mathematically,

$$H_t = H_{t-1} + \mathbf{I}_{\Delta_t}.\eta_{in}.\Delta_t + (\mathbf{1} - \mathbf{I}_{\Delta_t}).\eta_{out}.\Delta_t \qquad (4)$$

where H_t is the storage charging/discharging profile at time step, with generic input/output efficiency factors η_{in}/η_{out} and $\mathbf{I}_{\Delta_t}$ is an indicator variable which is 1 when $\Delta_t \geq 0$, and equated to 0 when $\Delta_t < 0$. The estimated total energy storage capacity, required for the whole window of investigation, can then be calculated as: $E_{cap} = max(H_t) - min(H_t)$

In this assumed energy storage model, the energy storage profile can exhibit positive or negative drifts [6]. This is because the scaled generation on a per-scaled level can keep getting aggregated towards positive (excess generation) or negative (inadequate generation) direction. The procedure to correct one of these positive drifts follows by continuously adapting the energy storage capacity as:

$$E_{cap} = \max\left(H_t - \min_{t'>t}(H_{t'})\right) \qquad (5)$$

which ensures that the storage capacity at step t does not fall below the $\min_{t'>t}(H_{t'})$ for all future time steps $t' > t$. The maximum of their difference then represents the required storage capacity E_{cap}. Using equation Equation (5), the new storage profile H_c (adjusting for the drift) is:

$$H_t^c = \begin{cases} E_{cap}, & if\ E_{cap} - H_t^c < \eta_{in}\Delta_t \\ H_{t-1}^c + \eta_{in}\Delta_t, & if\ E_{cap} - H_t^c > \eta_{in}\Delta_t > 0 \\ H_{t-1}^c + \eta_{in}\Delta_t, & if\ \Delta t < 0 \end{cases} \qquad (6)$$

Refer to [11, Figure 2] for an example of positive drift obtained using an unconstrained (4) and its constrained (6) storage profile.

C.2 Data Used for Section 5.7.1.

The following data has been used. The solar radiation data has been obtained from [1], after which we have used a model like that in [2] to obtain the solar energy profiles. All wind energy data has been obtained from [3]. The necessary load data for the power systems under consideration were obtained from Federal Energy Regulatory Commission [4]. For the marine energy data, the data sources are as follows. We obtained the tidal data in northwestern US from [5], and northeastern US from [6]. Details of converting to energy (kWh) are provided in [10]. The wave data is obtained from a best-in-class 32yr hindcast of wave conditions, developed using the Simulating WAves in the Nearshore (SWAN) model [7] (for northwestern US) and the National Oceanic Administrations operation WaveWatch III model [8] (for northeastern US). Parametric wave data (significant wave height and energy period) time-series were converted to wave energy converter (WEC) power profiles based on bivariate histograms of production, based on recommendations from the International Electrotechnical Commission (IEC) TC-114 [9].

C.3 Methodology Used for Section 5.7.1.

This Appendix details the procedure utilized for conducting the parametric study for evaluating storage requirements with the deployment of marine energy (marine energy). To this end, we consider a copper-plate grid model where generation i.e. (from both renewables and conventional resources) meet the total demand at all time instants i.e. The models considered in this work are similar to those in [11], although unlike in [11], we consider marine energy in the resource mix and study it from a US perspective, as opposed to a European context.

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