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Exploring the Grid Value Potential of Offshore Wind Energy in Oregon

May 2020

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Pacific Northwest National Laboratory
Richland, Washington 99354

Executive Summary

The wind resource on Oregon's Outer Continental Shelf (OCS) presents an opportunity for renewable energy deployment at scale. Offshore wind energy (OSW) may convey value to an evolving electric grid beyond the relative costs of energy production. This study explores and broadly characterizes, from existing databases and literature, the Oregon OSW grid value potential that could be spread through electricity transmission systems in the context of regional generation and load compositions. Three types of grid value potential were considered—(i) resource complementarity, or the inherent match of Oregon OSW resources to existing intermittent renewable energy and dispatchable hydropower resources, (ii) load complementarity commensurate with hourly power consumption patterns and the sub-hourly variability of the intermittent resource, and (iii) locational value to support coastal grids and increase regional grid reliability.

Grid value potential is influenced by the de-carbonization of power supply across the western United States. Washington and California have adopted 100% clean energy by 2045 requirements, contributing to early thermal plant retirements. Executive orders, cap-and-trade systems, and other renewable portfolio standards at the state level, combined with the significant cost declines of utility-scale renewable generation are other factors driving the transition. The surge of variable renewable resources and recession of conventionally-dispatchable power sources heighten the need for alternative clean energy sources which can smooth power supply and reliably anchor the grid. In Oregon, ongoing efforts to define capacity value to the grid correspond to this need. Several observations from this study are relevant to these capacity considerations.

Oregon offshore wind shows hourly complementarity with other utility-scale renewable resources, especially Columbia Gorge wind and southern Oregon solar, and some seasonal complementarity with Northwest hydropower resources.

Viable energy resources which are complementary to hydroelectric and variable renewable energy (VRE) generation will enable a robust Pacific Northwest (PNW) grid and can contribute to the optimization of additional transmission and energy storage investment. To evaluate this grid value potential, OSW generation complementarity was considered relative to other VRE resources, namely onshore (or "terrestrial") wind (TW) resources in Oregon, Washington, and Wyoming and solar resources in central and southern Oregon. While dispatchable hydropower, like dispatchable fossil fuel generation, can theoretically provide nearly perfect complementarity with load (i.e., correlation coefficient, r, approaching 1.0) or near perfect complementarity with generation (i.e., r approaching -1.0), VRE generation is subject to intermittency of renewable resources. Wind resources approximately 30-40 kilometers offshore of Port Orford, Reedsport, Newport, and Astoria were investigated. Hourly correlation calculations were conducted over six years and the following seasonal trends were observed:

- OSW complementarity with Columbia Gorge wind is shown primarily in the summer ($r \approx -0.20$) and to a lesser extent in the spring ($r \approx -0.13$).
- OSW complements central and southern Oregon solar in the winter ($r \approx -0.15$), indicating some potential for balancing solar generation when the region sees most significant loads due to heating. This relationship is observed at lower correlations in the fall ($r \approx -0.11$) and spring ($r \approx -0.10$).
- TW complementarity with Oregon solar resources in the summer ($r \approx -0.20$) exceeds that of OSW ($r \approx 0$).

Complementarity with the hydropower system was also characterized. Hydropower, which supplies the majority of loads in the PNW, differs from other renewable energy resources in that it is controllable. However, there are seasonal variations in the hydropower resource which limit this dispatchability, typically in late summer. Climate change is exacerbating these late summer constraints due to changes in both precipitation and temperature. The seasonal consistency of OSW could help to meet these late summer pinch points, and complementarity with other resources would reserve hydropower flexibility to supply a range of balancing, load following, and other services within the power generation stack.

Offshore wind could provide greater load complementarity than Northwest onshore wind and could help meet system peak loads.

Complementarity between OSW and load also indicates grid value potential. Hourly correlations between VRE generation and load profiles from the four balancing authorities with territory in Oregon were analyzed over seasons in 2012 (a recent year with readily available load data), and appended to the resource correlations, as shown in Figure ES.1.

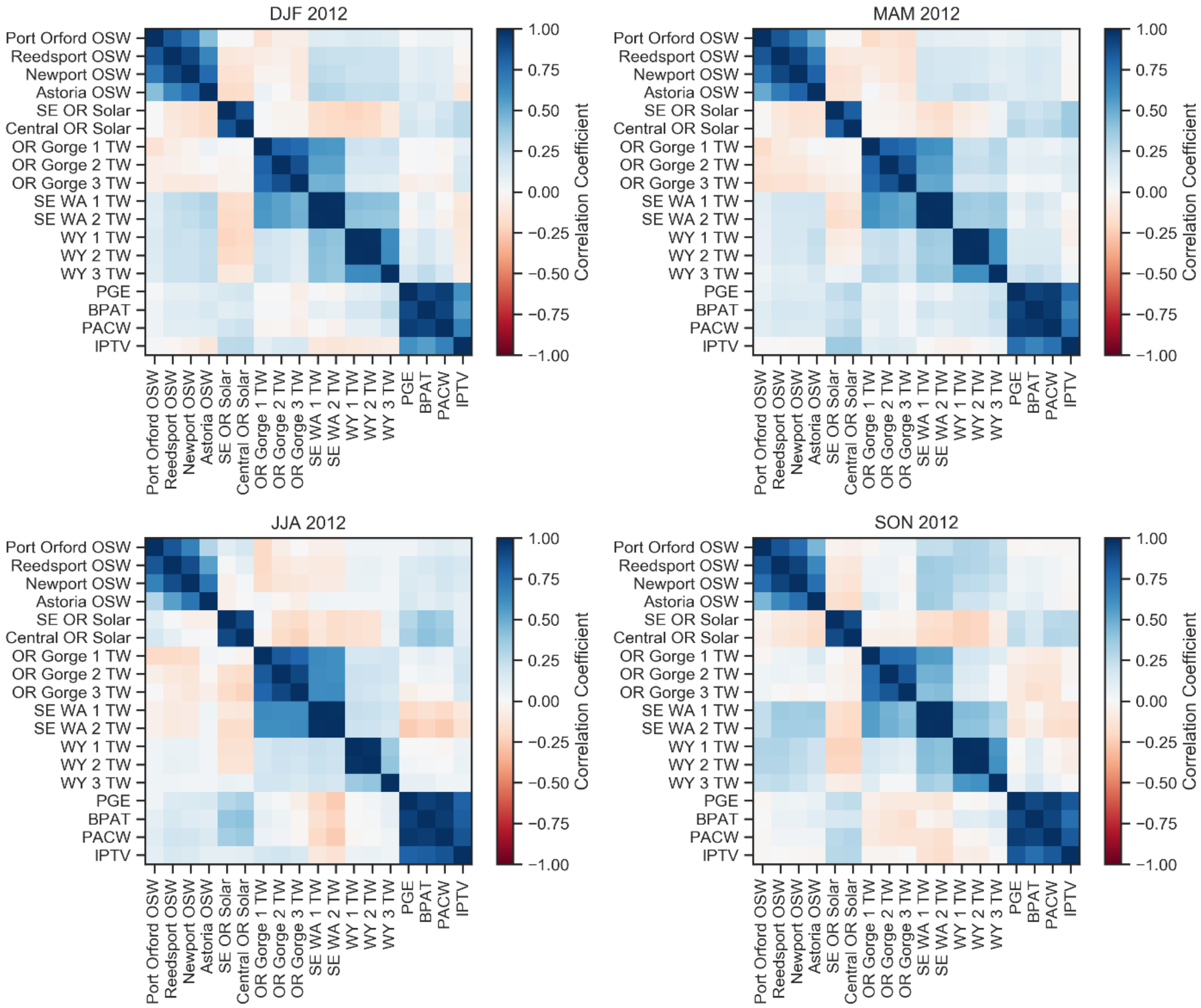

Figure ES.1. Seasonal resource (OSW, Solar, TW) and load (PGE, BPAT, PACW, IPTV) complementarity in 2012: December, January, February (DJF); March, April, May (MAM); June, July, August (JJA); and September, October, November (SON).

Solar generation, naturally timed with daytime activities, provides the best match to load, as expected over all seasons (i.e., r as high as 0.4 over summer hours in 2012). However, OSW has a moderate positive correlation with load in the winter ($r \approx 0.15$), spring ($r \approx 0.17$), and summer ($r \approx 0.18$). Modest winter correlation may impart load-balancing grid value when PNW loads are highest. Overall, the OSW resource has greater complementarity to the load than terrestrial wind resources in the region.

Load-balancing capabilities of OSW were also verified through analyses of generation capacity factors by month and at specific peak hours. These factors indicated that the OSW generation has the potential to be relied upon to deliver energy during daily peak hours relative to other renewables. Finally, the OSW resource showed smoother ramp rates compared to those of TW resources in Wyoming and eastern Washington, which would necessitate less system resources devoted to balancing the variable generation of power.

Over 2 gigawatts of offshore wind can be carried by current transmission to strengthen coastal grids, allow for additional renewable energy integration from the east, and reduce power flows into Oregon without exporting significant power.

By providing a strong generating resource on the coast, OSW may be able to provide grid value by improving local power quality, mitigating the risk of failed or interrupted power delivery to coastal communities, addressing transmission insufficiency in delivering power to high load locations, and/or allowing the expansion of industries with stringent power quality requirements.

Transmission of hypothetical OSW power output was considered using a production cost model (PCM) of the western interconnect electric grid with primary focus on impacts of OSW integration in the PNW. Modeled coastal power flows indicated that OSW generation would serve substantial amounts of coastal loads, on the order of 1 gigawatt (GW). In addition to improved power reliability, the modeled results showed improved resilience to the coast through less reliance on transmission infrastructure crossing the coastal range and the medium voltage transmission infrastructure in Southern Oregon.

The model does not indicate significant transmission limitations on the larger transmission system, finding that 2 GW of OSW generation could be accommodated across the coast before the system experienced minimal wind curtailments.[1] Without significant transmission development, OSW curtailments increase once 3 GW of OSW are interconnected, as summarized in Table ES.1. Modeling also indicates annual generation cost savings due to replacement of fossil fuel plants totaling near $86 million for 3 GW of OSW deployment. This savings is associated with significant emissions reductions.

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[1] Wind curtailment is defined here as the percent of energy not delivered, or spilled, to the electric grid relative to the possible output of the OSW site.

Table ES.1. Wind curtailment due to transmission constraints associated with different penetration levels of OSW

OSW Penetration	Port Orford	Reedsport	Newport	Astoria
1 GW	0.2%	0.1%	0.0%	0.1%
2 GW	2.0%	7.2%	0.2%	3.1%
3 GW	20.5%	28.1%	10.3%	14.6%
4 GW	36.8%	42.2%	26.1%	30.1%
5 GW	47.3%	51.5%	37.3%	40.9%
3 GW + Electric Vehicles	19.5%	27.6%	9.3%	14.0%

Analysis of regional transmission flows indicates positive benefits for the region. The deployment of OSW from the coast eastward to loads along the I-5 corridor reduces the predominant East-West power flow to these load centers, and thus opens transmission capacity from eastern Oregon and the Columbia River Gorge into northwest and central Oregon as indicated in Figure ES.2. In this manner, the existing corridor may provide additional generation from the Gorge, eastern Oregon and points north and east.

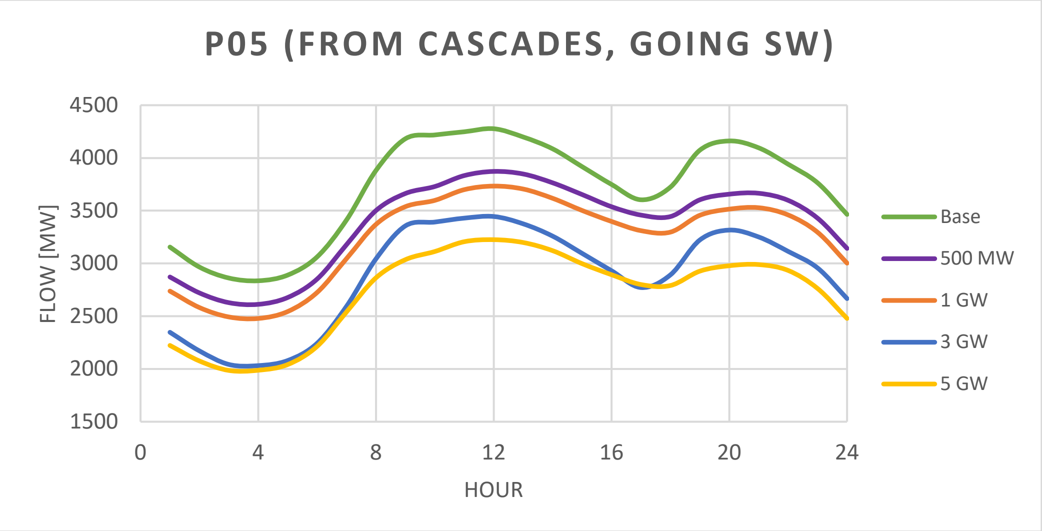

Figure ES.2. Impacts to hourly average flows across the year from OSW integration on Path 05, the transmission path from the Cascades and the Columbia River Gorge southwest into north/central-west Oregon. Positive direction is flow west.

Through 3 GW of OSW development, transmission flows into California are largely unchanged, and power flow into Oregon from Idaho is reduced.

The results of this study suggest that OSW provides an array of potential values including but not limited to the production of energy. Complementarity of OSW with load patterns reserves the flexibility of the hydropower system for the most critical system needs, which provides a significant capacity benefit to the region. A direct benefit is posed to coastal communities by way of more robust power supply and decreased reliance on east-west transmission. Finally, transmission flows are opened to facilitate the transmission of additional power generation in a timeframe when the PNW grid is likely to see greater interconnection of VRE generation.

Acknowledgments

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Any errors or omissions are the sole responsibility of the authors.

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1.0 Project Overview

The wind resource on Oregon's Outer Continental Shelf (OCS) presents an opportunity for renewable energy deployment at scale. Offshore wind energy (OSW) may convey value to an evolving electric grid beyond the relative costs of energy production. Though the estimated levelized cost of energy (LCOE) for floating offshore OSW technology currently exceeds the LCOE for onshore wind or solar energy, the pace and trajectory of the technology's cost reductions are similar to those of onshore wind energy in the last several decades (Musial et al. 2019). The value that OSW may provide to the electric grid and its stakeholders is not captured by LCOE. An understanding of OSW's potential value to the electric grid is important for the consideration of potential OSW development in Oregon. To improve that understanding, this study documents the grid value potential of OSW to Oregon beyond direct energy provision of individual installations.

This study explores and broadly characterizes the Oregon OSW grid value potential that could be spread through electricity transmission systems in the context of regional generation and load compositions. Three types of grid value potential were considered—(i) resource complementarity, or the inherent match of Oregon OSW resources to existing intermittent renewable energy and dispatchable hydropower resources, (ii) load complementarity commensurate with hourly power consumption patterns and the sub-hourly variability of the intermittent resource, and (iii) locational value to support coastal grids and increase regional grid reliability.

Information from existing databases and literature was assimilated and used for grid value analysis and modeling. An overview of the main sources of power in the Pacific Northwest (PNW), namely hydroelectric power along the Columbia River, and the history of their development was gathered. Variable Renewable Energy (VRE) generation from intermittent natural sources of energy—such as wind kinetic energy and solar irradiance—was considered distinctly from the controllable hydroelectric resource, which can be reserved and then dispatched when it is most needed. Recent energy-related legislative and policy activity across the West coast was reviewed. Next, bounded analyses (i.e., exploratory and fairly brief in scope) of the historical OSW resource, other VRE resources, hydroelectric system, and load patterns were undertaken. Power transmission flows in the region under various OSW development scenarios were analyzed. Finally, the grid-supporting power contributions available from modern wind turbines were discussed in the context of locational value.

This study investigates the degree to which resource complementarity, load complementarity, and inherent location of OSW generation may contribute to a stronger, more reliable, and less constrained electrical grid through four major sections. Section 2.0 outlines the opportunities and challenges of Oregon OSW development which directly influence potential grid value contributions from OSW. Section 3.0 is a technical discussion of the complementarity of OSW with (i) other VRE resources such as onshore wind and solar energy and (ii) dispatchable hydropower. Section 4.0 is a similar technical discussion of OSW load complementarity for the Balancing Authorities with territories in Oregon. Finally, Section 5.0 considers the locational value to coastal communities as well as to non-coastal energy consumers and producers throughout the region.

2.0 Background

2.1 The Current Landscape for OSW Energy

Globally, OSW energy reached 22,592 megawatts (MW) of total installed capacity in 2018, including 46 MW of floating OSW capacity across eight projects (Musial et al. 2019b). U.S. OSW resources are abundant, and development has progressed first on the relatively shallow Atlantic continental shelf where foundations can be fixed to the sea floor and sea cables can deliver OSW power to large coastal loads. This is consistent with global trends, where shallow waters and proximity to continental or island loads have been significant factors driving the majority of global OSW to date. Recent development activity in the U.S. may be characterized by an energetic commercial pursuit of 15 commercial wind energy leases on the Atlantic OCS and seven construction and operations plans in processing (BOEM n.d.). Development offshore the Pacific coast has lagged for several reasons, including (i) continental shelf depths in excess of 60 meters, approximately beyond which fixed platforms are no longer cost effective and floating foundations—a relatively new technology—are required, (ii) the PNW's access to substantial amounts of low-cost and clean hydropower, (iii) California's access to plentiful and inexpensive solar power, and (iv) more limited opportunities to deliver power to large coastal loads. However, various floating platform technologies have been commercially deployed in regions outside the U.S. and are poised for significant cost reductions over the next decade (Musial et al. 2016; Myhr et al. 2014).

2.2 Uniqueness of the Oregon OSW Opportunity

2.2.1 Opportunities for Oregon OSW

Wind speeds off the Oregon coast are some of the strongest in the nation and hold a power potential of up to 62 GW (Musial et al. 2016). Several current policies contribute to a favorable policy environment for the development of Oregon's strong OSW resource. The Governor of Oregon issued an Executive Order (State of Oregon 2020) on March 10, 2020 instructing the Oregon Department of Environmental Quality to institute a cap-and-reduce program on fossil-fueled electric generating units currently operating in the state. Oregon has also adopted clean energy policies, such as mandated Renewable Portfolio Standard (RPS) requirements that apply to the state's electric utilities, and policy goals for incremental statewide greenhouse gas reductions, seeking to achieve an 80% reduction below the state's 1990 levels by 2050. Even more aggressive clean energy mandates in the form of RPS laws and others are in place in Washington and California, including California's pricing of carbon through a cap-and-trade program (CA EPA ARB 2015). These policies have combined to create a significant increase interest for renewable power across existing transmission networks up and down the West coast.

Updates to Oregon's RPS or the passage of more stringent clean energy policies, such as a specific OSW mandate for energy portfolios similar to those of several East coast states (AWEA 2018), represent other Oregon policy opportunities that could facilitate floating OSW energy development. Retiring coal plants across the Western Energy Coordinating Council (WECC) over the next 20 years will create a need for more energy resources across the West, including California and the PNW. The time horizons under which any new Oregon clean energy policies and WECC-wide coal retirements may come to fruition are likely to coincide with the projections for significant technical maturations in floating OSW technology. Efforts to refresh prior Oregon legislative efforts on new transmission lines and large, grid-scale storage may also offer increased opportunities to optimize costs of floating OSW and other forms of renewable energy and thus hasten the renewable energy transition (Oregon State Legislature 2015a, 2015b, 2017).

Other sectoral shifts are also relevant. Trends towards increased vehicle and building electrification could also shift the demand for electricity and create opportunities for floating OSW to contribute to increased capacity needs to serve loads. As solar costs continue to fall over the next decade, additional solar is likely to be developed in the PNW region as well as in Arizona, Utah, Nevada, and California where it can be wheeled (i.e., transmitted via power markets and dedicated infrastructure) to Oregon ratepayers. If large amounts of solar energy were ever to be used to serve Oregon's loads, a California-like "duck curve"—where large amounts of solar power are generated during the day and recede rapidly in the evening—could eventually present itself. OSW could contribute to meeting these evening ramps.

Climate change effects on the hydropower system may increase the Oregon OSW opportunity. Currently, much of the integration of variable renewables in the region is facilitated by the flexibility of the northwest hydropower system. That system, however, is expected to be increasingly impacted by climate change in future decades with a reduction of winter snowfall and changes in seasonal precipitation patterns making low flow conditions in summer more likely. Simultaneously, climate change may also bring load changes to the region, including potential reductions and shifts in winter peaks and a growing summer peak driven by cooling loads (Turner et al. 2019). These types of impacts underscore the value of a more diverse portfolio of VRE generation.

Finally, there is also an opportunity for Oregon to benefit from Oregon OSW due to its geographic proximity to California. California, the world's fifth-largest economy, is likely to be the first consumer of any floating OSW that may be developed in the Pacific Ocean due to (i) California's already high solar penetration that results in an extreme need for evening ramping capacity, (ii) California's high cost of power compared to the PNW, (iii) California's aggressive 100% clean energy requirement, and (iv) California's cap-and-trade system that places a price on carbon emissions.

All of these opportunities point to the need for viable energy resources which are complementary to load and also to other sources of hydroelectric and VRE generation to maintain a robust grid with minimal additional transmission and energy storage investment. From this grid perspective and under high-renewable energy futures, LCOE can be a misleading metric in isolation. The temporal and spatial characteristics of a renewable energy resource should also be reviewed in the grid context for implicit value.

2.2.2 Challenges for Oregon OSW

Though floating OSW technology is promising, and the potential wind resource is vast, significant challenges exist that currently hinder the commercial viability of Oregon OSW beyond the costs of floating foundations. Foremost, in stark contrast to the U.S. East coast or California, low-cost and abundant hydropower in the PNW keeps wholesale power prices relatively low throughout the region. Even though some of the region's excess hydropower is wheeled to Southern California at different times of year, its dominance of the PNW's overall electricity resource mix raises the economic hurdle for OSW projects significantly. Further, the Northwest Power and Conservation Council (NWPCC) does not expect an expansion of load in Oregon out through 2028 (net of expected efficiency gains) and in fact expects load to remain relatively stable if not slightly decrease.[2]

To the degree that OSW is inherently complementary with solar resources, it could be used to compensate for receding solar resources in the evenings. Due to relatively low levels of solar energy generation at present, the PNW lacks a large need for evening ramping to meet loads. However, PNW evening ramping needs are likely to increase as new solar is developed in the region, and/or if more solar is imported from other regions. Even load increases and shifts due to factors such as increased electrification of buildings and transportation may exacerbate the ramping need. These future evening ramps would likely be met first by low-cost hydropower3 and potentially through energy storage before OSW would be needed.

Natural gas is another competitor to OSW. Even under aggressive state decarbonization goals (e.g., 80% greenhouse gas reductions by 2050), ample room remains for natural gas-fired generation to serve ramping and seasonal needs. It is likely that the abundance of relatively low-cost domestic natural gas will persist into the future.

Other challenges are geographic in nature. First, unlike the U.S. Eastern seaboard, the Gulf coast, or the southern California coast regions, the Oregon coast is displaced from the primary load centers in the state, which lie in the Willamette Valley from Portland to Eugene and extend southward along the I-5 corridor to smaller load centers in Roseburg, Grants Pass, Medford, and Ashland. Transmission from the southernmost Oregon coast to the I-5 corridor is limited to a few 115kV lines. Even once the power is delivered to the corridor, the amount of OSW development would need to account for in-state demand and potential for export. Secondly, the topography between the optimal locations for OSW development and Oregon's load centers presents a transmission challenge. The Oregon Coast Range rises 1500 feet from the Columbia River to the middle fork of the Coquille River, west of Roseburg, with a breadth of 30-60 miles. Transmission across the Costal Range and along the coastline is limited and requires significant maintenance investments (BPA 2018). Thirdly, coastal electricity generation has not been extensively developed, which limits the availability of robust pre-existing infrastructure that could be reused, with relatively little additional financial investment, to interconnect OSW.[4]

Due to these challenges, moving power to coastal loads as well as from coastal generation to the larger load centers incurs significant costs, and broader grid dynamics throughout the region must be carefully considered alongside the potential values to coastal and non-coastal stakeholders of Oregon OSW energy.

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[2] Despite some load growth, the Northwest Power and Conservation Council's expectation of significant energy efficiency and demand response growth results in a reduction in expected demand for Oregon through 2028 in its Seventh Power Plan. A load forecast for the 2021 Northwest Power Plan has not yet been released but includes even more aggressive energy efficiency and demand response projections. See https://www.nwcouncil.org/energy/7th-northwest-power-plan/about-seventh-power-plan.

[3] The Federal Columbia River Power System's ability to provide balancing reserves is limited to 1,000 MW of increments and 1,000 MW of decrements. See Schaad J. 2011. *Integrating Renewables Ocean Renewable Energy: Why Would Anyone Buy It?* Washington State Ocean Energy Conference. Bremerton, WA.

[4] In contrast to the infrastructure associated with thousands of megawatts of Once-Through-Cooling power plants in California (CEC 2019).

2.3 Contributions to a De-Carbonizing Grid

The regional grid is undergoing dynamic transition. Recent legislation portends an acceleration of renewable power interconnections. VRE contributions to the Oregon power supply are on the rise due to adoption of a 50% RPS and due to the continued reduction in cost for VRE technologies (State of Oregon 2016). State neighbors to the north and south have passed 100% clean energy bills, which will accelerate early thermal retirements (Fazio 2019). And efforts to establish a cap-and-trade system in the last two Oregon legislative sessions underscore the urgency with which some Oregon policymakers seek to decarbonize electricity. Executive Order 20-04 directs state agencies to address greenhouse gas emissions (State of Oregon 2020). Also, the proliferation of more distributed energy resources (DERs) is altering consumption and generation patterns in significant ways.

Grid integration of wind power plants in the future VRE-dominated grid has been highlighted as one of wind energy's three "grand challenges" (Veers et al. 2019.) Market operations and the impacts on unit commitment and economic dispatch must be reconsidered (Simao et al. 2015). Improved resource forecasting and control strategies are also needed to optimize grid-forming capabilities through entire farms of power converters. However, these challenges also provide opportunities to develop a grid that is more robust, cleaner, and cheaper for a wide range of power consumers.

Related to these challenges, several state legislative actions have sought to facilitate grid integration of OSW energy. Introduced in the 2017 Oregon legislative session, HB 2502 sought to give a local or county government the option for a bond initiative to finance installation of ocean renewable energy transmission infrastructure (Oregon State Legislature 2017). In 2015, HB 2187 called for the consideration of ocean renewable energy in any local or regional transmission planning process (Oregon State Legislature 2015a). Also, HB 2193 (2015) required Oregon's two largest investor-owned utilities to develop grid-connected battery storage projects by 2020 (Oregon State Legislature 2015b). These discussions could be relevant to the potential to share large storage systems, costly interconnection, or transmission projects, which might help optimize OSW benefits and costs to Oregonians. These grid integration efforts necessitate considerations of system capacity.

2.4 Definitions of Capacity Value

Under Oregon Public Utility Commission (OPUC) Docket No. UM 2011 (OPUC 2020), a discussion is underway to improve understanding of grid capacity value. Currently, there is inconsistency regarding how capacity services from different resources should be valued, a problem which has become more prevalent as the energy market has faced ongoing transformation and new types of resources have been integrated. Utilities must examine system capacity needs in different ways than they have needed to historically.

One conventional metric is the Effective Load Carrying Capability (ELCC) (Milligan and Porter 2008). The ELCC of a given generator is a measure of the additional load which can be supported across a transmission system with the addition of that generator and without incurring a net change in system reliability. The ELCC values timing of power supply when it aligns with high-risk periods such as in periods of peak loads or peak net-loads that result in needs for fast-ramping capacity.[5] For VRE generators in the PNW, ELCC is first a function of the correlation of natural resource with load but it is also impacted strongly by operations of the hydropower supply. For example, if a hydropower resource was exhausted during peak hours, higher Loss of Load Probability (LOLP) values would be seen off-peak and the ELCC would be impacted by the ability of the VRE to produce power during these off-peak hours. The NWPCC seeks to model this interaction of the hydroelectric system with non-hydro resources through the Associated System Capacity Contribution (ASCC), a ratio of the system capacity effect to the installed nameplate capacity (NWPCC 2016). This ratio can be greater than one, in the case of gas-fired generation dispatched in the place of hydroelectric output, which can then be shifted to peak hours with greater capacity need. The ASCC can also be much lower than one if significant hydropower reserves are required to level variable generation off-peak. In this sense, generation complementarity among VRE generators, resulting in a more even production of power, provides relief on the hydroelectric system with synergistic capacity benefits through hydropower storage.

Given the emergence of more VRE generators and capacity decrements due to coal retirements, OPUC Docket UM2011 highlights the need for new methods of determining a resource's capacity values. Capacity service, given its central role with regards to resource value in a continuously changing grid, needs to be fairly compensated in a clear and consistent manner.

Though there is no single definition of capacity across utilities, participants have described the most important types of capacity value in the following terms (OPUC 2020):

- A resource which provides long-duration power generation at a low fixed cost
- A resource with high "locational value," which aligns load and supply or addresses location-specific needs.
- A capacity "portfolio" which maximizes the benefits of resource diversity
- A resource that is always available / dispatchable
- Capacity that facilitates the integration of (other) intermittent resources
- Responsive resources that can balance variable renewable generation on a real-time basis
- Resources that can meet peak load - especially on an uninterrupted basis and particularly without the legacy thermal generation that is likely to be retired.
- Resources that satisfy week-ahead and day-ahead bulk system reliability needs

Grid integration and valuation of OSW energy along the Oregon OCS was considered in light of these capacity considerations, though in broad terms consistent with the OPUC themes above rather than specifics of ELCC, ASCC or other industry-standard metrics. Three specific vectors, (i) resource complementarity, (ii) load complementarity, and (iii) locational value, were pursued within the context of an evolving grid.

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[5] Hours of the highest loss of load probability (LOLP), a measure of the probability in any hour that overall (including imported) supply cannot meet load, are multiplied over the year to produce a Loss of Load Expectancy (LOLE) probability. An LOLE of 1 day in 10 years is a common benchmark of system adequacy. ELCC is calculated by adding a new generator, recalculating the LOLE and quantifying the additional load which can be supported at the same LOLE probability. Power plants which are able to provide power when the system is under strain thus are often quantified with a higher ELCC. However, higher LOLP hours can occur off-peak due to maintenance schedules or scheduled hydro production.

3.0 Resource Complementarity under Resource Adequacy and Climate Change Pressures

3.1 Background

3.1.1 Hydroelectric Power Development in the PNW

With development of the Federal Columbia River Power System (FCRPS) starting in the 1930s (NWPCC 2020a), and preceded by smaller dams developed by a substantial fleet of additional hydropower facilities mostly owned and operated by northwest utilities on local rivers, renewable carbon-free electricity energy has dominated energy supply in the PNW. In the decades since, hydropower became the foundation of electrical supply. Today, there are 300 hydroelectric projects providing two-thirds of the region's energy (NWPCC 2016). The majority of this energy originates in projects operated by the Bonneville Power Administration (BPA). Development of the BPA federal hydropower system led to 31 dams, owned and operated by the U.S. Bureau of Reclamation and the U.S. Army Corps of Engineers, with power marketed by the BPA. Federal hydropower facilities currently provide approximately 65 percent of the generating capacity and half of the firm energy (i.e., energy that is available whenever needed) produced in the Northwest (NWPCC 2020b). However, recent shifts in the generation mix pose challenges to the ways in which power has historically been supplied.

Development of the FCRPS by the federal government in the 1930s through the 1960s resulted in a system which was tailored to meet the electrical loads at the time. Given large differences in wet and dry years, it was economically viable to install turbines capable of generating, in a wet year, three times the dry year average energy production. The Columbia River Treaty between the U.S. and Canada resulted in a surplus of generation in the mid-1960s, which spurred the construction of the Pacific Northwest-Pacific Southwest Intertie transmission. Thus, the federal fleet is oversized in power capability with a focus on generating as much low-cost power as possible and moving it to wherever it was needed. The FCRPS has very little storage compared to the volume of the Columbia River; the system can store only approximately one-third of the annual runoff.

Satisfying winter peaks in the PNW, barring drought conditions, was historically straightforward with such an overbuilt system, and further aided by seasonal exchanges through the Pacific Northwest-Pacific Southwest Intertie. The Hydro-Thermal Power Program, developed in the 1960s during a growth of electrical loads, planned for capacity supplementation through thermal generators (Hardy 2019). Later, the departure of aluminum smelting industrial loads and energy efficiency campaigns provided an additional capacity cushion.

3.1.2 Trends in VRE Development

As can be observed at national scale, the contribution of renewable energy to the PNW energy mix is increasing. In 2017, hydropower, wind, solar, and geothermal energy combined to serve 80%, 33%, 57%, and 88% of load within the four WECC balancing authorities in Oregon,[6] respectively (WECC 2019). Across the PNW, 69% of generation was attributed to hydro, but also 7% through wind and 1% through solar and geothermal energy. Further, a clear trend is

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[6] BPA Transmission Services (BPAT), Portland General Electric (PGE), PacifiCorp West (PACW), and Idaho Power Treasure Valley (IPTV)

emerging of utility-scale solar development in Oregon since 2015 (ODOE 2020) as can be seen in Figure 1.

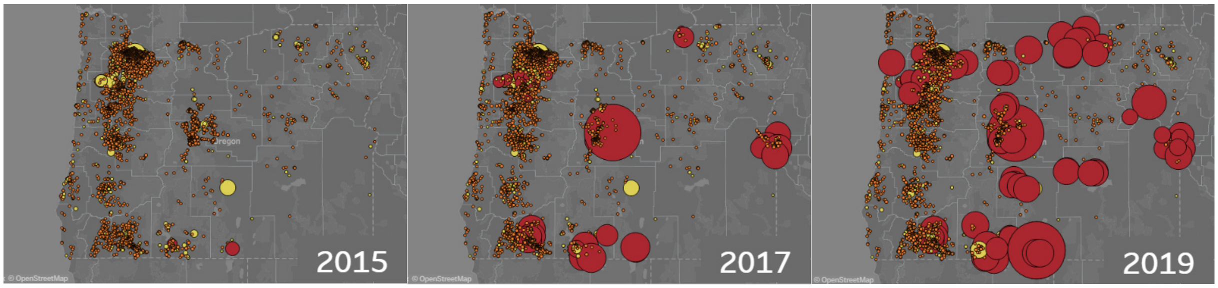

Figure 1. Growth of residential (orange), commercial (yellow), and utility-scale (red) solar energy development from 2015-2019 as indicated on the Oregon Solar Dashboard (ODOE 2020). Circle area size denotes annual energy production.

Clean energy legislative measures recently passed in Washington and California are forcing the early retirements of 8 GW of coal plants in the early 2020s. New gas plants (both combustion turbines and combined cycle turbines) are politically challenging. Finally, the current hydro resource, which traditionally has more than satisfied regional capacity needs, has little room for capacity growth due to limitations with regards to how much runoff can be stored, as discussed in Section 3.1.1. However, intermittency of significant penetrations of renewable generators poses a significant problem.

On 1 March 2019, after a few days of cold weather in the Northwest, which exhausted gas and the limited hydro storage reserves, and during gas transmission constraints from Los Angeles and Canada, the Mid-Columbia index price shot above $900/MWh for energy and $160/MMBtu for gas (Hardy 2019). This happened with coal plants operating at full capacity. The event raised questions, such as why the region would build more gas capacity which would only increase the risk exposure to a similar event. It also highlighted the need for VRE capacity contributions.

With the larger share of VRE generators interconnected today than in previous years, hydropower has been implemented to balance solar generation and 5,100 MW of wind generation, and is expected to balance another 3,000 to 4,000 MW of wind power across the BPA service area by 2025 (BPA 2020a). Precipitous drops in wind speed at individual plants or wind turbines can induce drastic shortfalls in power supply from these units. At these scales, if many megawatts are affected in a given region, and without thermal resources and sufficient hydro to balance the shortfalls, supply will be unable to meet the full load under normal operations. Energy storage technologies may offer some assistance, but at significant cost and on limited time durations only. In future VRE buildouts, these capacity shortfalls correspond to reduced tolerance for long-duration system failures. Resource adequacy studies indicate significant increases in LOLP (Fazio 2019; E3 2019).

The Western Energy Imbalance Market, which provides sub-hourly economic dispatch to balance supply and demand every five minutes, offers one mitigation of system capacity erosion due to renewable energy generation intermittency. Another effective integration technique may be spatial diversity and resource diversity of VREs, which ideally combine to create a flatter, firmer generation curve in aggregate (Western Governor's Association 2012). This VRE firm aggregate, where it can be found and the degree to which it can be attained, will ease the supply burden while maintaining grid reliability and operability as the system continues to decarbonize.

3.2 Methods

As a first-order proxy for wind power timing,[7] historical wind characteristics were used to investigate the degree to which OSW naturally complements PNW hydropower and other VRE resources. Wind speeds at 100 meters above the surface were sourced from the techno-economic database of the WIND Toolkit, a compilation of seven years of wind data at 5-minute resolution and 120,000 locations across the nation (Draxl et al. 2015).[8] The hub height was deemed representative of larger OSW turbines, which are characterized by rotor diameters in excess of 160 meters. These hub heights are also technically attainable of onshore wind turbines. Federal Aviation Administration permitting, which can pose challenges above tip heights of 499 feet/152 meters, was neglected. Power generation was not modeled. Wind direction, air density, temperature, humidity, and wind speed variation through the rotor plane were all neglected.

Figure 2 provides an example of the resolution available from the database, which is summed to match intervals of other data sources. A head and tail of the 5-minute data are shown without the time summations to indicate the richness of these data. Comparing hourly and half-hourly trends, smoothing of the variability is clear, as expected. However, this excerpt qualitatively indicates that 15-minute summations may capture variability of the OSW resource.

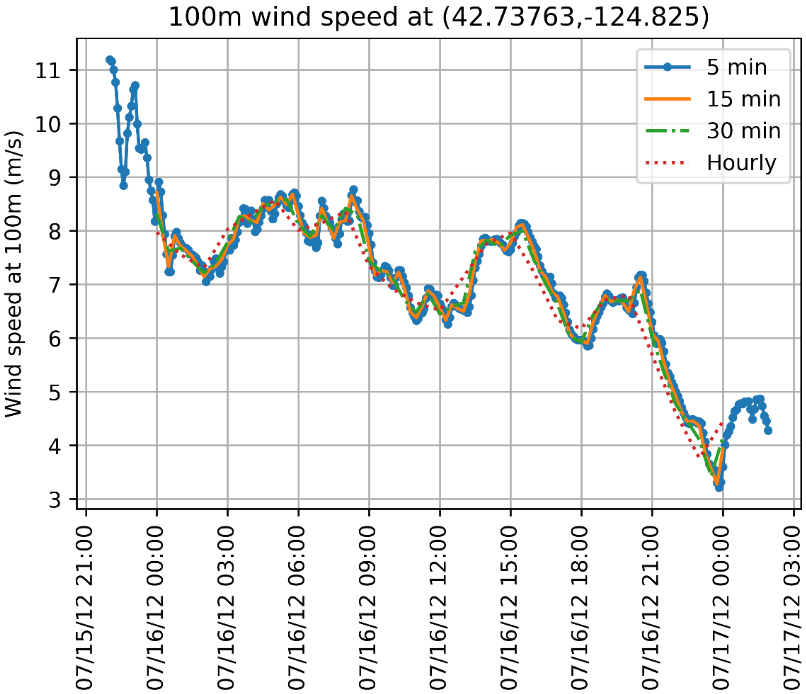

Figure 2. Data extract from the WIND Toolkit, summed at 15-, 30-, and 60-minute intervals, and at a location corresponding to approximately 30 km west of Port Orford.

The WIND Toolkit provides unique insights into OSW patterns, and it has been validated at the ocean surface (Wang et al. 2019). However, validation at hub heights of interest over the ocean surface is needed.

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[7] Available wind power is a function of the cube of wind speed. Wind turbines capture some of this power.
[8] Only six years of data, 2007-2012, could be located through the WIND Toolkit for this study.

Using the WIND Toolkit, data from 2007-2012 at the OSW locations shown in Table 1 were analyzed and averaged on a monthly basis. These location along the Oregon OCS were chosen to capture the variation in the OSW resource as well as to consider impacts to the transmission system.

Table 1. Approximate OSW locations chosen for complementarity study

Location	Distance Offshore (km)	Latitude, Longitude (NAD83)
Astoria	42	(46.13978, -124.5193)
Newport	33	(44.63749, -124.4879)
Reedsport	30	(43.76358, -124.5609)
Port Orford	27	(42.73763, -124.8250)

3.2.1 Hydroelectric Complementarity

Complementarity for dispatchable hydropower resources should be considered in a different manner than complementarity for other VRE generators which lack as much control over their fuel source. As opposed to VRE hourly production in the next section, hydropower was viewed on seasonal and interannual scales. Hydroelectric complementarity was considered by identifying the dominant shapes in annual production profiles and evaluating to what degree OSW evidences complementary seasonal aspects. Primarily, availability of the OSW resource was targeted during the seasonal pinch point of late summer and early fall months, when river flows are their weakest.

The dominant seasonal hydrologic regime in the Northwest is the result of snowpack. This means that hydropower generation tends to be very strong for a few weeks in spring, and relatively weak in late winter and late summer. Climate change is anticipated to adjust the traditional hydrologic cycle by reducing interannual snowpack accumulation, with more precipitation occurring as rain rather than snow, and increase the criticality of instream flow and water temperature to meet other, particularly ecological objectives. This shift will cause hydropower limitation to be increasingly acute in late summer, at the same time that electric loads are growing. Limitations on hydropower production create system-wide resource adequacy challenges, shortages in available power supply. The character of these shortages is likely to be multi-day.

3.2.2 VRE Complementarity

To investigate the potential of resource complementarity, additional renewable resources representative of significant present and emerging contributions to supply within Balancing Authority regions in Oregon were compared with Oregon OSW resources. Though only the resource was targeted for this brief study, resource complementarity is expected to offer a reasonable proxy for generation complementarity for the conceptual locations and hub heights chosen.

Onshore renewable resources were selected based on their scale to date or clear growth trends. Where significant development activity has been geographically concentrated, several locations were sampled. The Columbia River Gorge has seen significant wind energy development for more than 10 years and is home to more than 750 MW of rated capacity today.

Similarly, southeastern Washington represents a significant wind resource, with more than 1.5 GW of nameplate capacity. Importantly, though benefitting from a similar wind resource, this cluster of locations is separated by approximately 150 miles from the Columbia River Gorge locations selected. Wind from Wyoming was also considered. Abundant wind speeds and higher Weibull wind distribution shape factors position wind farms in central and southern Wyoming with some of the lowest cost of wind energy in the nation. Furthermore, PacifiCorp wheels this power westward to PNW load. This is a key ingredient—strong wind potential in Montana lacks the transmission infrastructure to bring it to substantial loads in the PNW (NWPCC 2016).

Finally, utility-scale solar development in Oregon is on the rise (ODOE 2020). Two locations with the largest utility-scale solar farms in Oregon, one in Central Oregon and the other in Southern Oregon, were chosen to investigate complementarity. The OSW and onshore renewable resource locations are shown in Figure 3.

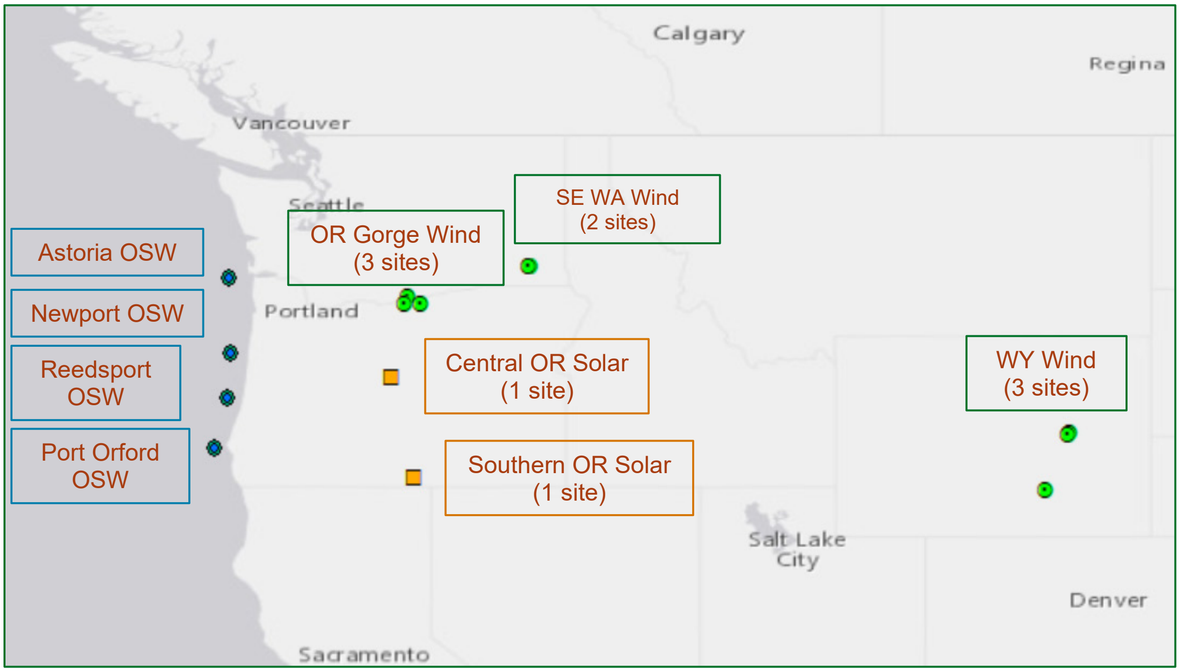


Figure 3. Renewable energy resource locations for resource complementarity study.

Solar irradiance is quantified at hourly intervals in terms of direct normal irradiance (DNI) and global horizontal irradiance (GHI) in the National Solar Radiation Database (NSRDB) (NSRDB 2020). As with wind, because it is the nature of the resource that drives complementarity, the conversion to units of power was not pursued in this study. However, depending on the orientation of panels and/or tracking systems, both the DNI and GHI could be important. To account for both factors, a simple magnitude of the irradiance resource was calculated through the square root of the sum of the squared DNI with the squared GHI at every hour. Figure 4 presents the hourly resource data for all six years from OSW, terrestrial wind (TW), and solar locations under consideration.

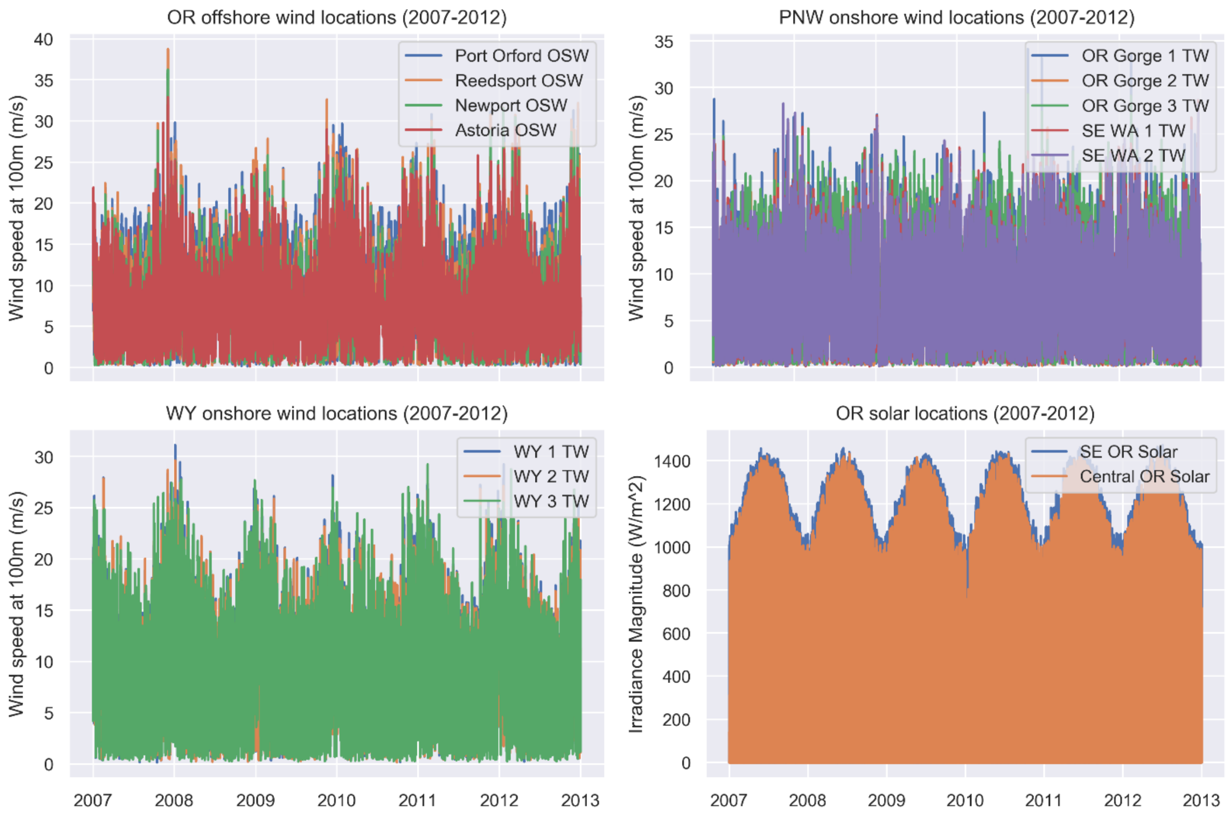


Figure 4. Time series resource availability, 2007-2012.

Quantification of complementarity on various time horizons offers a means to understand the degree of the capacity value which may be available when combining these resources across the transmission system. Numerous studies have quantified complementarity of renewable energy generation on various time horizons through the Pearson's correlation coefficient, *r* (Jurasz et al. 2020; Silva et al. 2016; Yi et al. 2013; Monforti et al. 2014; Slusarewicz and Cohen 2018; Katzenstein et al. 2010). The correlation coefficient quantifies correlation as:

$$r_{x,y} = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}}$$

where *X* and *Y* correspond to the time series data of two signals, with means $\bar{X}$ and $\bar{Y}$ of the number of samples, *n*, in each series.

To demonstrate how correlation coefficients correspond to time series data, consider successive 90 degree phase shifts of 1-Hz sinusoidal output in time, as shown in Figure 5.

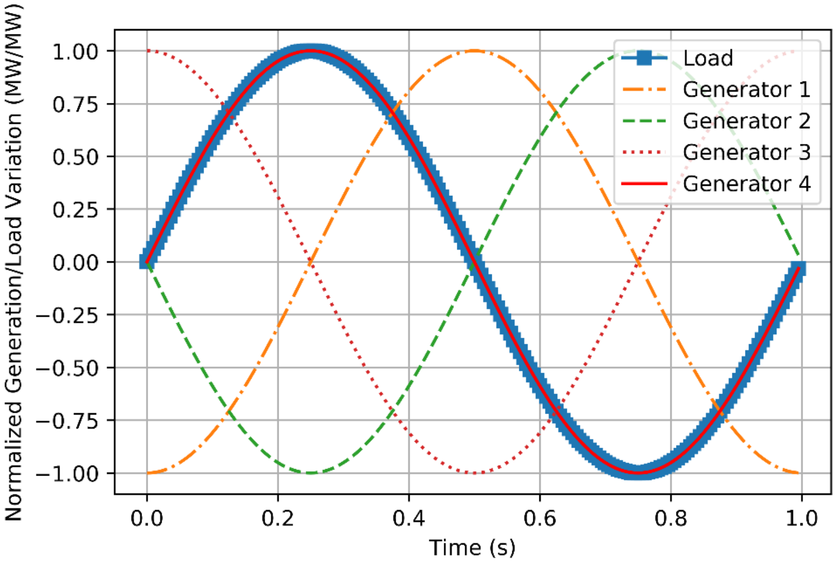


Figure 5. Sine waves representing variations from average load or generation for example correlation calculations.

These waves can be interpreted as fluctuations about a mean. We can consider the unshifted sine wave to be a trend in load consumption, increasing and then decreasing about some mean value. Generators one through four then correspond to waves which have been shifted successively by 90 degrees in phase. After two shifts, the total phase shift is 180 degrees, or that of a cosine or Generator 3. After four shifts, Generator 4 becomes perfectly in phase with the load signal. A generator with this behavior would offer a perfect positive correlation with load, with an *r* value of 1.0. This would also be the correlation coefficient of any signal with itself. In practice, such high *r* values are not attainable, even for dispatchable, peaking resources, and certainly not in any repeatable way for a VRE. Nevertheless, summed over various time scales, these coefficients indicate the tendency of certain resource to complement load or other generation.

Capacity value is found in a more level generation profile. In this way, VRE generation complementarity requires negative correlation. If one considers generator 1 paired with generator 3, a perfectly negative correlation is seen, with a *r* value of -1.0. This could be interpreted as analogous to solar generation fading at the end of day while wind generation starts to climb, maintains production through the night, and then ramps down just as the solar resource reestablishes. An snapshot of excellent correlation over an eight-hour time excerpt is shown in Figure 6 as an indicative example. While perfect or near-perfect negative correlation among generators is not a realistic expectation over a significant time horizon, the resource complementarity indicated by more negative *r* values indicate greater capacity value.

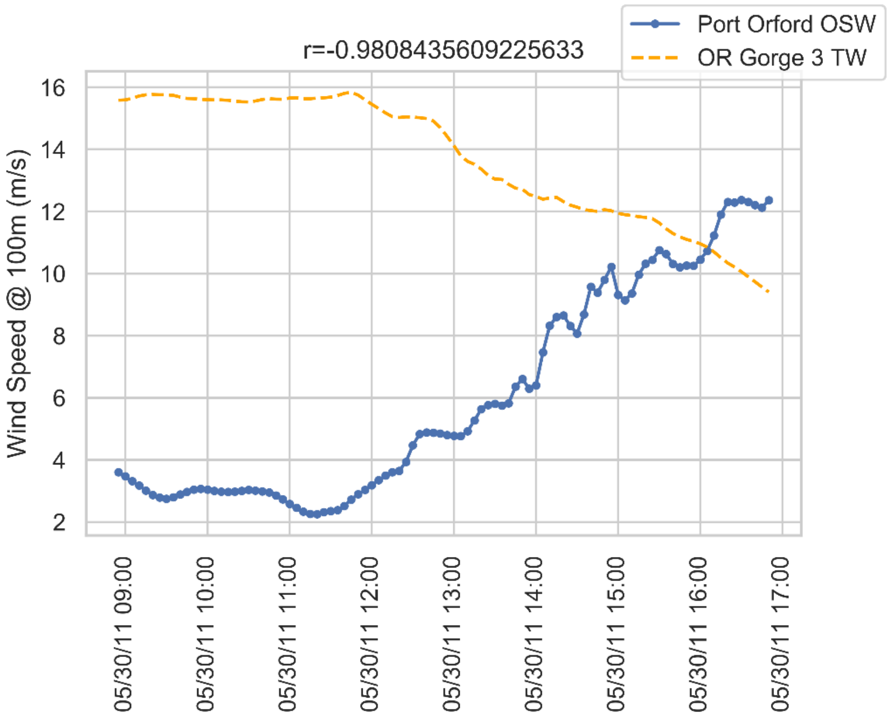


Figure 6. Example of well-correlated generation potential over an eight-hour period.

It is important to note that these types of quantifications, stemming from resource data only and not considering any congestion or efficiency loads with regards to power transmission, are highly idealized. The goal here is only to indicate the potential value of OSW and identify future investigations into value inclusive of barriers to its achievement.

3.3 Results and Discussion

3.3.1 Complementarity of Hydroelectric Production over Seasonal Scales

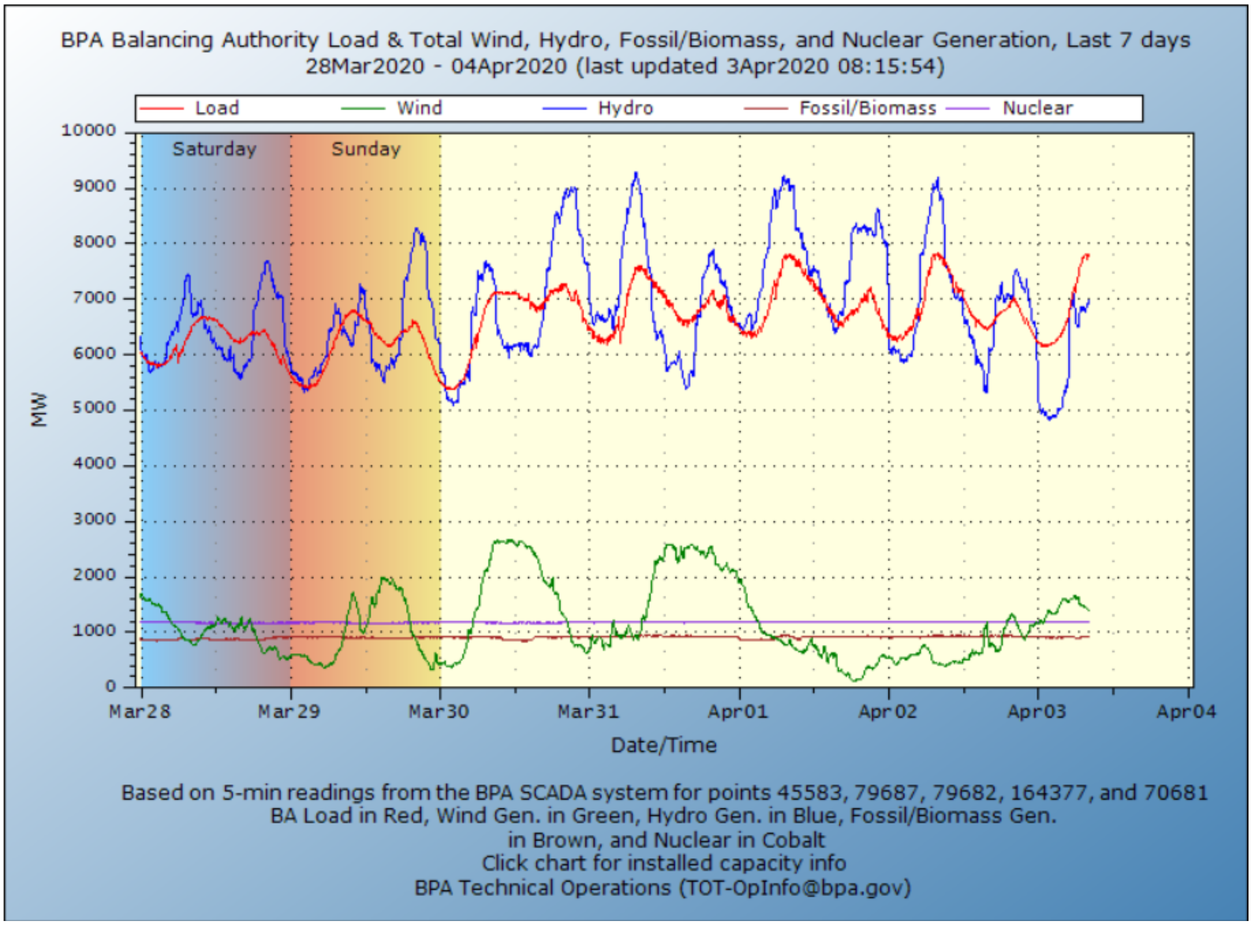
To complement regional hydropower production, OSW resources would need to demonstrate both consistency and presence during the seasonally evident periods of known regional hydropower limitation in late summer and late winter; as well as anti-correlation with spring high flows. In our review, the OSW resource held promise of complementarity in critical periods. Of particular note, Oregon OSW resources appear relatively strong in mid-summer bridging to fall, in contrast to terrestrial wind generation on the PNW grid.

Beyond a seasonal correlation, a detailed study that evaluates grid-scale shifts and multi-objective river management would be needed to analyze the potential benefits of OSW production on the complex hydropower system. This possibility is described in Section 6.2.

3.3.1.1 Hydropower is a Flexible, Dispatchable Resource

Utility-scale hydropower facilities regulate energy generation through reservoirs, spill, and hydraulic management of multiple generating units. Hydroelectric facilities are typically divided into “run-of-river” facilities, where storage is limited and inflow is roughly equivalent to outflow, and storage hydropower, where an impounded reservoir is capable of holding substantial capacity in the form of water storage (DOE 2016). While industrial scale hydropower facilities may not all be capable of significant storage, output generation is still controlled and dispatched. Hydropower (including pumped storage) is typically cited as one of the top two most flexible generation technologies. Many large hydropower facilities in the Northwest are effectively load-following, following the daily curve of electricity demand. Others may be simple baseload resources, without significant flexibility. The most flexible hydropower resources may be used to handle peak load conditions (DOE 2018a). Many PNW hydropower resources are already dispatched to support integration of wind generation.

Because hydropower can operate in the full range within a generating stack (i.e., it can fulfill various roles in the combination of generation resources used to meet electric demand at a given time), the concept of short-term complementarity, as it is applied here for uncontrolled generating resources which have no significant storage element, does not suit hydropower resources. Figure 7 shows the capabilities of federal hydropower to perform local load following as it parallels daily load shapes, in particular morning and evening ramps (shown in red); non-local load following, due to the volume of generation exceeding that of load; and balancing of regional onshore wind, as hydropower generation drops down to accommodate wind production. Given hydropower's flexible capabilities over short timeframes, in place of hourly complementarity, complementarity of the OSW resource to hydroelectric production is considered on a seasonal basis, where there are substantial changes as inflows for hydropower generators vary significantly over the course of a year.



Based on 5-min readings from the BPA SCADA system for points 45583, 79687, 79682, 164377, and 70681
BA Load in Red, Wind Gen. in Green, Hydro Gen. in Blue, Fossil/Biomass Gen.
in Brown, and Nuclear in Cobalt
Click chart for installed capacity info
BPA Technical Operations (TOT-OpInfo@bpa.gov)

Figure 7. Federal hydroelectric production follows load, inter- and intra-regionally (BPA 2020b).

3.3.1.2 Hydropower Production Profiles Vary over Seasons and Years

Hydroelectric production is typically high in the spring, as most upper watersheds in the PNW that drive hydroelectric facilities are fed by snowpack. As the temperature warms and rains fall, snow melts and there is a rush of mainstem inflow called the spring freshet in April and May. Though certain rivers are glacially fed, which has a later, summer peak once temperatures are sufficiently warm, or spring-fed, which provides year-round flows, most hydroelectric facilities experience a spring high that drops precipitously over the summer. Hydropower capacity is limited at the end of summer, when instream flows diminish until the fall rains replenish them. Figure 8 provides a glimpse of this seasonal variation for combined hydropower in the Chelan, Washington PUD study, which is representative of resource variation at other hydropower facilities in the region.

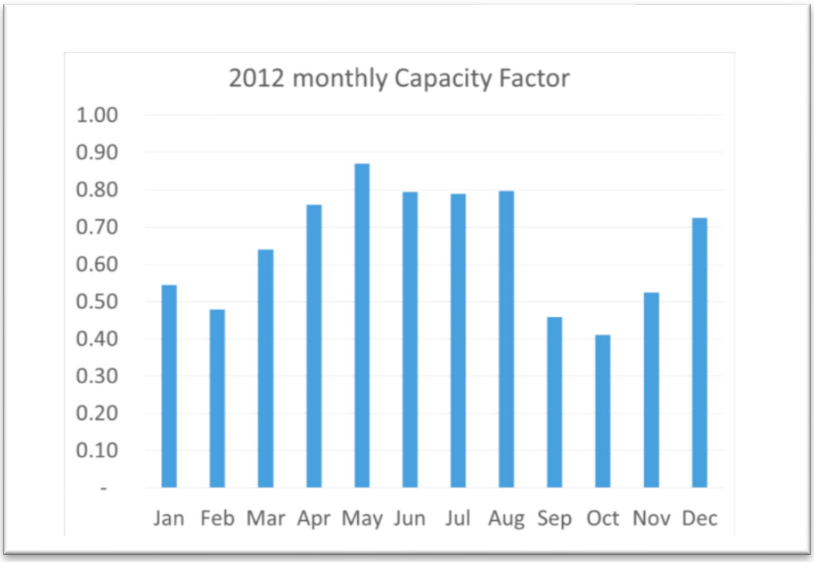


Figure 8. 2012 monthly capacity factors of the Chelan PUD combined projects (Voisin et al. 2019).

3.3.1.3 Climate Effects on the Hydrologic Cycle in the Columbia River Basin

Climate change will adjust this hydrologic cycle, volumetrically and in timing, due to changes in both precipitation and temperature. As temperatures warm season over season, the residual snowpack that is available to support hydropower production dissipates and melts more quickly, causing the spring freshet to spike earlier and higher as well as late summer flows to be very low.[9]

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[9] See, for example: River Management Joint Operating Committee (RMJOC): Bonneville Power Administration, U.S. Army Corps of Engineers, U.S. Bureau of Reclamation. *Climate and Hydrology Datasets for RMJOC Long-Term Planning Studies: Second Edition (RMJOC-II). Part I: Hydroclimate Projections and Analyses.* June 2018. https://www.bpa.gov/p/Generation/Hydro/hydro/cc/RMJOC-II-Report-Part-I.pdf. U.S. Army Corps of Engineers, Bonneville Power Administration, U.S. Bureau of Reclamation. *Columbia River System Operations Draft Environmental Impact Statement.* February 2020. https://www.nwd.usace.army.mil/CRSO/

Exacerbating this challenge of managing low late-summer flows for energy is the need to keep water flowing in-river to support aquatic life, especially endangered salmon runs which rely on cool water.

The late summer energy availability pinch will be compounded as warming temperatures drive higher electric loads, such as for space cooling and irrigation pump loads. The effects of climate change on hydropower resources and on electric loads in isolation masks this compounding effect (Turner et al. 2019). As a result, in a memo regarding the NWPCC's 2021 Power Plan, the quantitative impacts of climate change will be integrated in their framework. Specifically, they aim to address the effect of precipitation and temperatures on regional hydropower generation timing as well as water runoff impacts (Kujala 2019). In their review of various IRPs from Northwest utilities, NWPCC additionally notes that some utilities are exploring the shift in seasonal snowmelt over time and the streamflow reduction in summer months in how they will develop their integrated resource plans moving forward (Charles 2019). Shifting streamflows are illustrated in Figure 9. If the shift in hydropower production exposes a multi-day resource adequacy problem, new generating resources will be required; today's battery energy storage technology is limited to 4-hour durations and is unlikely to solve this issue.

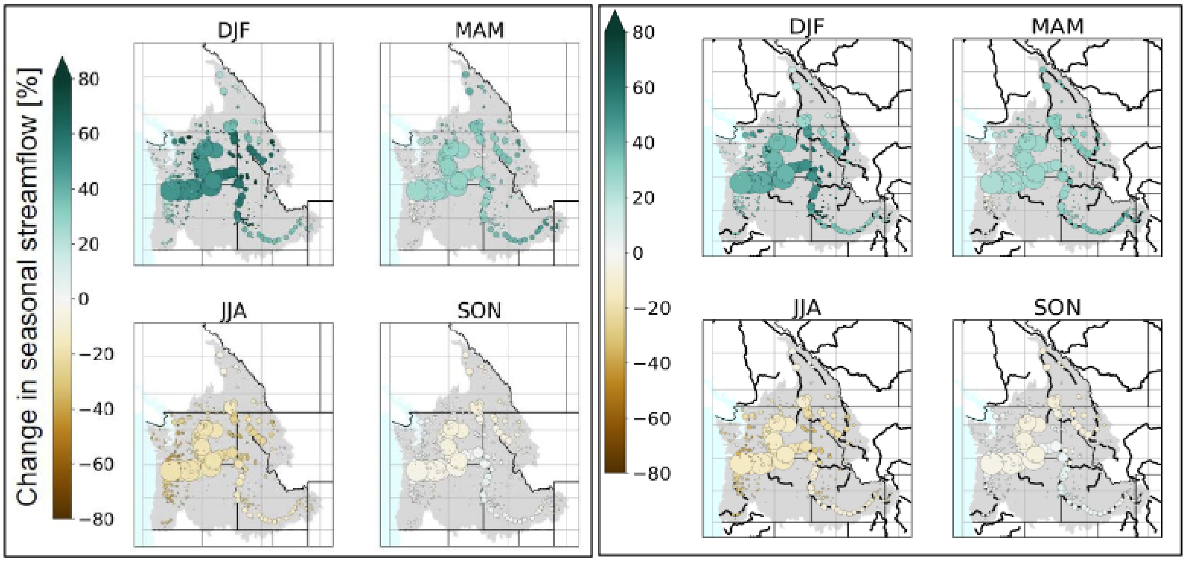

Figure 9. Anticipated shift from historical streamflow (1976-2005) to streamflow futures (2020-2049), by seasons, showing modeled increase in winter flows and decrease in summer flows. The left and right chart represent Representative Concentration Pathways (RCP) 8.5 (watts/square meter) and RCP 4.5 warming scenarios, respectively. Circle size is correlated to volume. FCRPS DEIS, citing University of Washington as the source.[10]

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[10] As discussed in Columbia River System Operations Draft Environmental Impact Statement, Chapter 4, Climate, Subsection 4.1.2.4. Streamflow. March 2020. "https://cdm16021.contentdm.oclc.org/utils/getfile/collection/p16021coll7/id/13754"https://cdm16021.contentdm.oclc.org/utils/getfile/collection/p16021coll7/id/13754

3.3.1.4 OSW Suitability for Complementarity

OSW has promise to complement Northwest hydropower resources during periods of anticipated deficit. As described above, complementarity would be most clearly evidenced by the potential for OSW to supply consistent winter and late summer generation over multiple days. Figure 10 demonstrates the average monthly wind speeds from 2007-2012 for several of the wind resources under consideration in this study. On these monthly time scales, as shown by the Port Orford resource—which is representative of all OSW resources considered in this study—OSW indicates more consistent power potential than other TW sites, particularly in the June through September months when the hydropower resource is increasingly constrained and energy demand is anticipated to increase.

OSW may benefit hydropower resources by relaxing requirements on facilities to generate power during time periods when water is less available or units are less flexible; when other water management objectives such as flood control, navigation, or irrigation are also in high demand; or by allowing hydropower to operate more flexibly by supplying resources on the shoulders of resource insufficiency periods or shaving off a portion of baseload obligation.

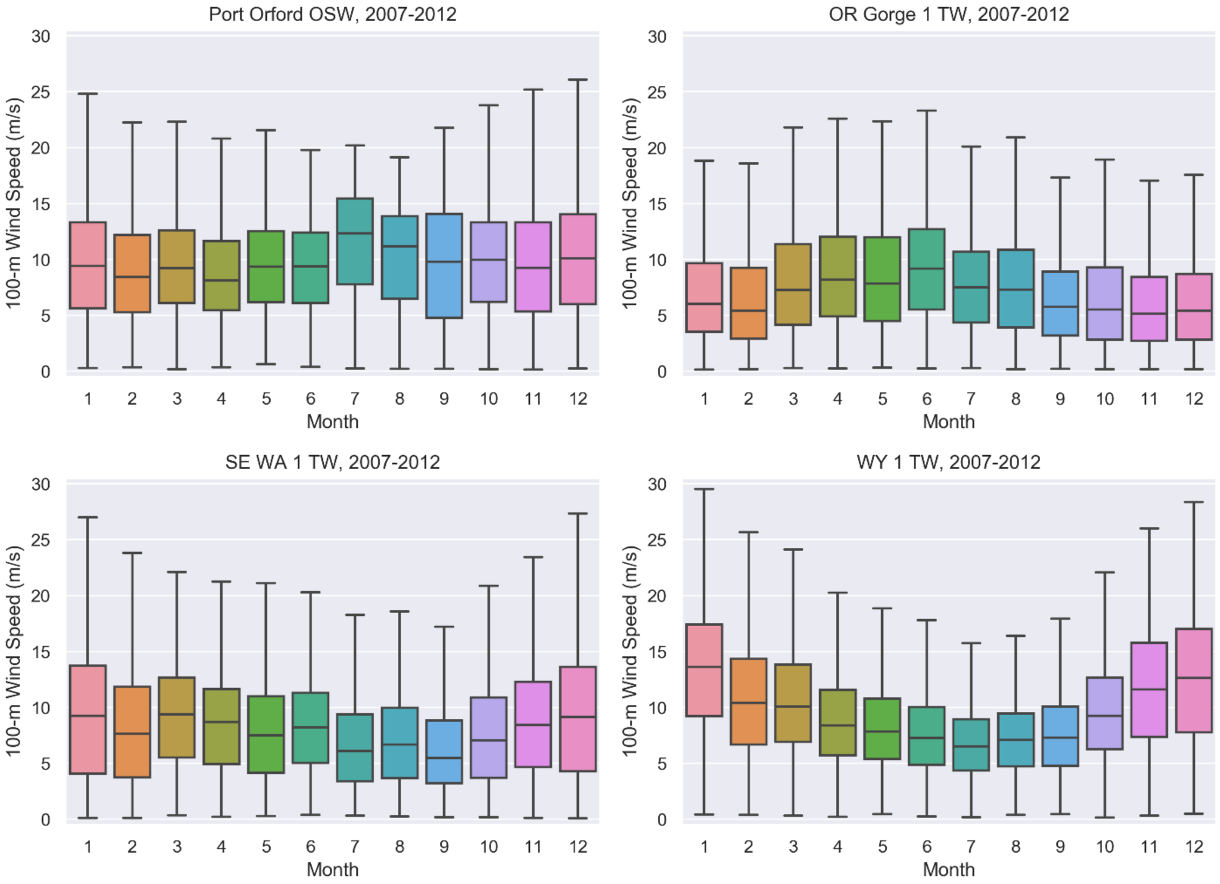


Figure 10. Monthly wind speed distributions for (clockwise from upper left) Port Orford OSW, Columbia Gorge, Southeastern Washington, and Wyoming terrestrial wind. Box plots denote the minimum (lower error bound), 25th percentile (lower box bound), median (middle box bound), 75th percentile (upper box bound), and maximum (upper error bound) values of the wind speed by month.

3.3.2 Hourly Complementarity with VRE Resources

In Figure 11, the calculated resource complementarity coefficients are summarized by season for the year 2012, which was scrutinized in this study because necessary load data were readily available. Seasonal perspectives are important due to the significant changes in solar and wind resources between the winter, spring, summer, and fall. Seasonal dynamics drive important changes in load patterns as well, and generation capacity is planned around these trends. On a grid with significant penetration of VRE resources, this same level of scrutiny must be applied to resource and generation characteristics.

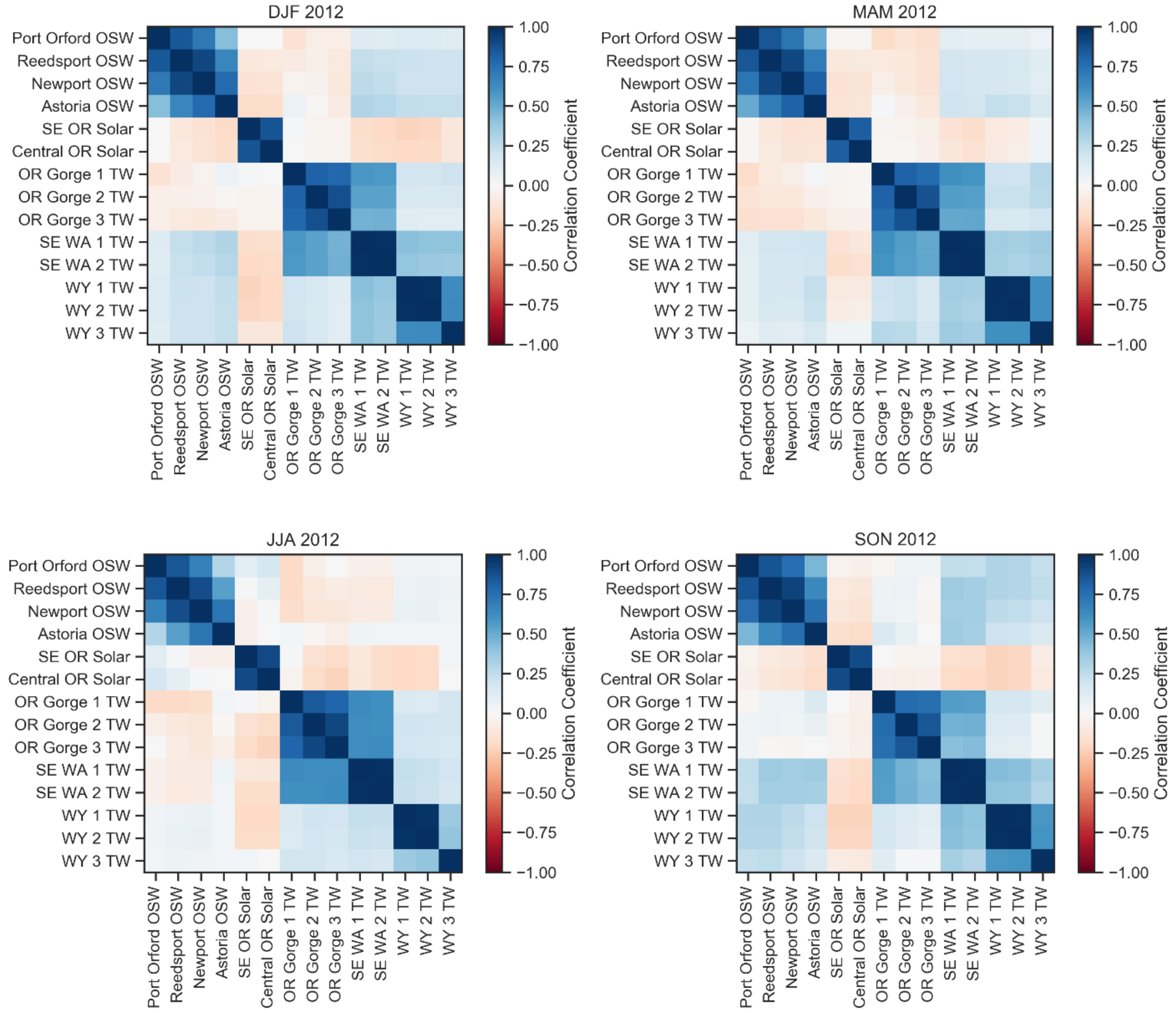


Figure 11. Seasonal resource complementarity in 2012: December, January, February (DJF); March, April, May (MAM); June, July, August (JJA); and September, October, November (SON). Red colors indicate resource complementarity.

Several themes emerge from the 2012 seasonal correlations. First, OSW complementarity with Columbia Gorge wind is shown in the spring ($r \approx -0.15$) and summer ($r \approx -0.19$). Secondly, there is some potential for solar balancing (i.e., providing power when solar irradiance is low) primarily in the winter ($r \approx -0.18$) and to lesser extent in the spring ($r \approx -0.13$) and fall ($r \approx -0.15$). Interestingly, Columbia Gorge, SE Washington, and Wyoming wind show the highest complementarity with the solar resources in summer (*r* ≈ -0.20). As expected, positive correlation among the four OSW sites is high (0.29 < *r* < 0.85) and *r* diminishes with geographic distance between the OSW sites. This effect holds for all seasons.

Just as there are clear seasonal trends, inter-annual variability in wind and solar resources can be significant. Seasonal correlations for all six years are summarized in Figure 12. Generally, trends are the same as those seen in 2012, though there are several exceptions. Complementarity of the southern Oregon OSW resource with the Gorge is stronger in the fall (*r* ≈ -0.08), which coincides with lower hydro resources. Complementarity is stronger between OSW and Columbia Gorge and Southeast Washington terrestrial wind in the summer (*r* ≈ -0.20). In general, OSW is largely uncorrelated or slightly positively correlated with Wyoming terrestrial wind.

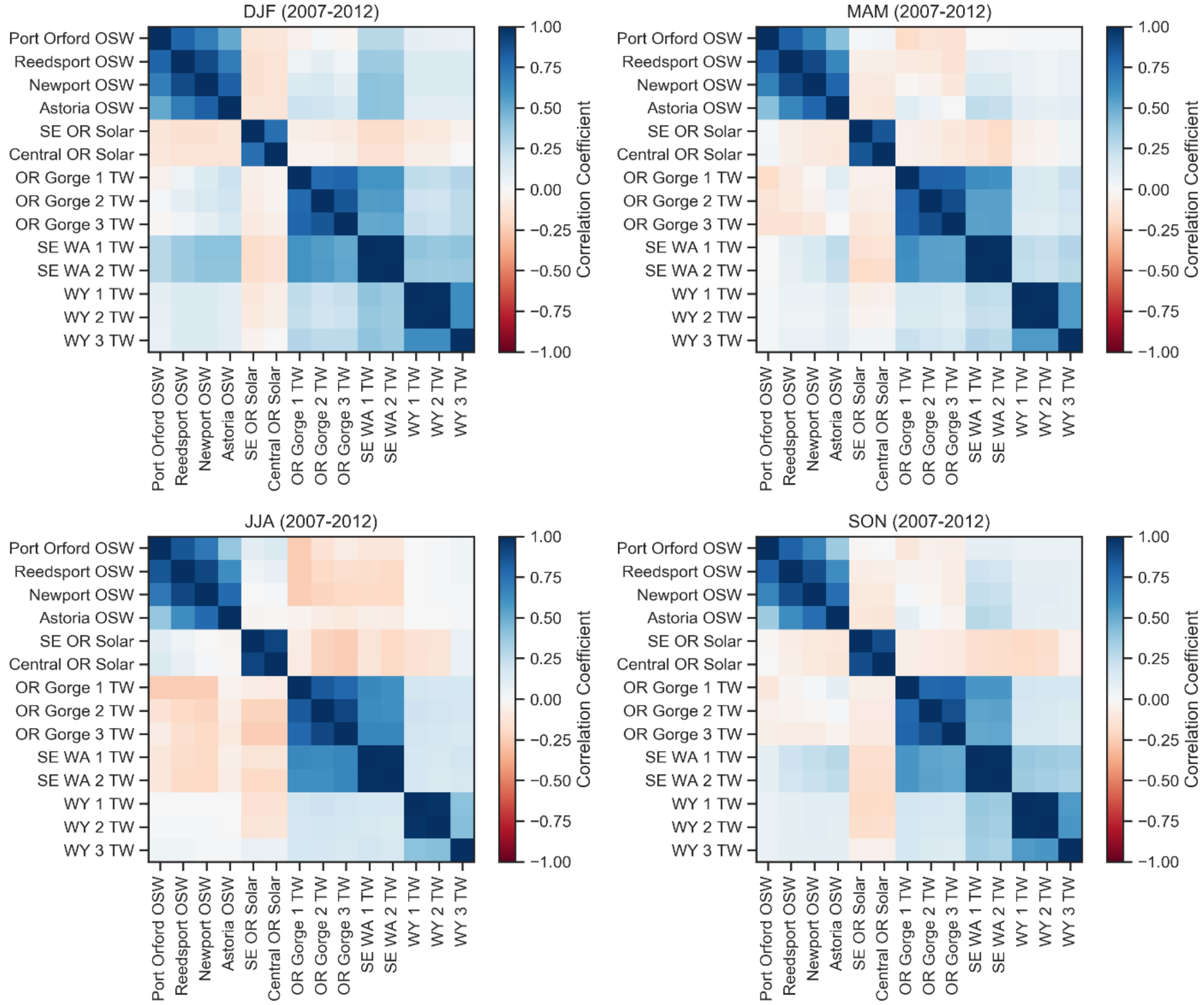


Figure 12. Seasonal resource complementarity, 2007-2012: December, January, February (DJF); March, April, May (MAM); June, July, August (JJA); and September, October, November (SON).

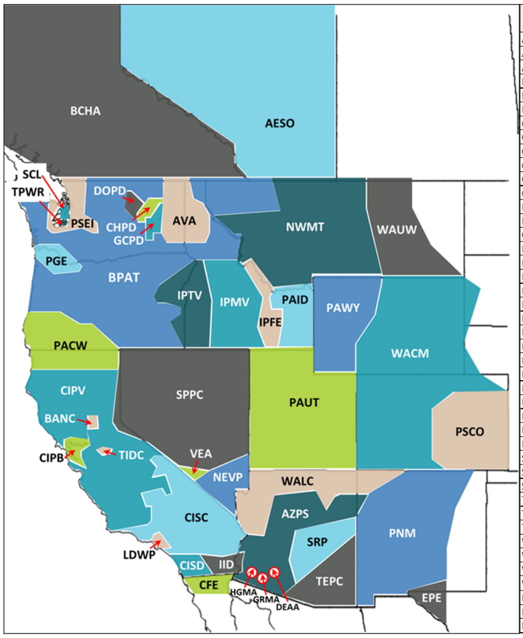
4.0 Load Complementarity on Various Time Horizons

The complementarity of the OSW resource to load can be considered through several different lenses. One is the evaluation of statistical complementarity. This approach identifies how the OSW resource may naturally align with the regional load pattern, highlighting the value of the resource in meeting load. A second approach is to consider OSW resource capacity factors during hours in which the grid is stressed, that is peak hours. A third approach is the statistical evaluation of OSW resource volatility, which may indicate a better match to load patterns that are inherently more consistent than some terrestrial wind resources on the PNW grid. A final lens is to use a software modelling tool, known as a production cost model (PCM), in which the OSW resource is added to the system as it exists and the resulting impacts considered relative to the base model without the OSW.

Each of these lenses characterizes the value that OSW represents to the surrounding region, the State of Oregon, in this case. The next few sections evaluate load complementarity through these lenses and discuss the results, in the order that they are listed above.

4.1 Complementarity to Load: Benefits to Oregon Energy Users

As with resource complementarity, an examination of how the wind and solar resources align with the need for power is insightful. Load time histories from 2012 in units of megawatts were sourced for the BPAT, PGE, PACW, and IPTV balancing authorities (WECC Stakeholder Services, personal communication, August 16, 2019). Territories for these balancing authorities are shown in Figure 13.



TEPPC Area	Area Description
AESO	Alberta Electric System Operator
AVA	Avista
AZPS	Arizona Public Service
BANC	Sacramento Municipal District
BCHA	British Columbia Hydro
BPAT	Bonneville Power Administration
CFE	Comision Federal de Electricidad
CHPD	Chelan Co PUD
CIPB	Pacific Gas & Electric Bay Area
CIPV	Pacific Gas & Electric Valley Area
CISC	Southern California Edison
CISD	San Diego Gas & Electric
DOPD	Douglas Co PUD
EPE	El Paso Electric
GCPD	Grant Co PUD
IID	Imperial Irrigation District
IPFE	Far East (Idaho Power)
IPMV	Magic Valley (Idaho Power)
IPTV	Treasure Valley (Idaho Power)
LDWP	Los Angeles Dept of Water & Power
NEVP	Nevada Power
NWMT	Northwestern Montana
PACW	PacifiCorp West
PAID	PacifiCorp East – Idaho
PAUT	PacifiCorp East – Utah
PAWY	PacifiCorp East - Wyoming
PGE	Portland Gen Electric
PNM	Public Service New Mexico
PSCO	Public Service Colorado (Xcel)
PSEI	Puget Sound Energy
SCL	Seattle City Light
SPPC	Sierra Pacific Power
SRP	Salt River Project
TEPC	Tucson Electric Power
TIDC	Turlock Irrigation District
TPWR	Tacoma Power
VEA	Valley Electric Association
WACM	Western Area Power Admin Colorado/Missouri
WALC	Western Area Power Admin Lower Colorado
WAUW	Western Area Power Admin Upper Missouri
N/A	DECA, LLC - Arlington Valley (DEAA)
N/A	Gila River Maricopa Arizona (GRMA)
N/A	Harquahala L.L.C. (HGMA)

Figure 13. Balancing authority territory across the WECC (WECC 2015).

Correlations with these time series were appended to the resource complementarity matrices, as shown in Figure 14.

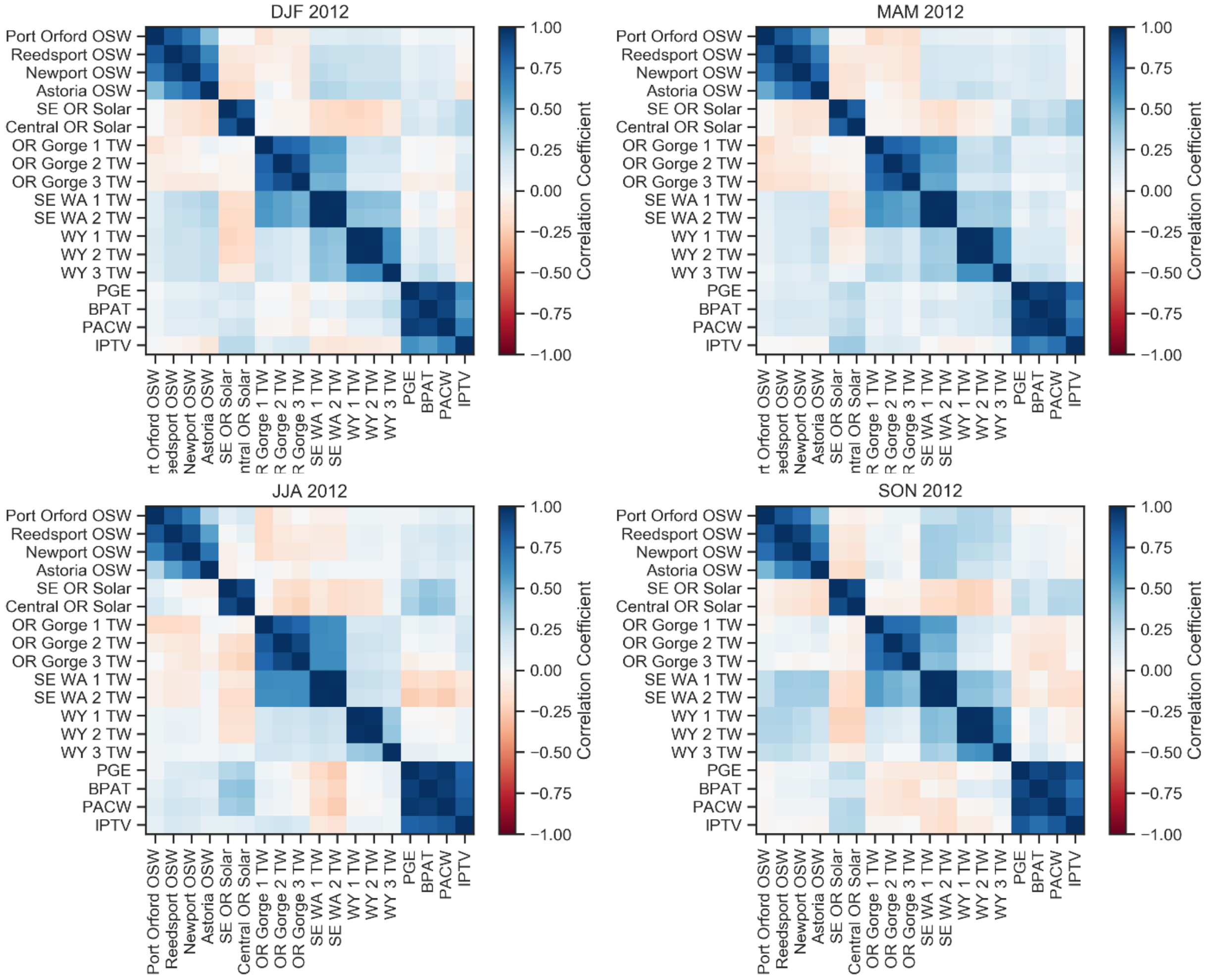


Figure 14. Seasonal load and resource complementarity in 2012: December, January, February (DJF); March, April, May (MAM); June, July, August (JJA); and September, October, November (SON). Blue colors indicate load complementarity.

In contrast to resource complementarity, positive correlation coefficients, *r*, between resource and load indicate complementary power generation when it is needed. Oregon solar clearly shows the highest complementarity of all resources considered, particularly in the summer months ($r \approx 0.40$) in the BPAT, PGE, and PACW territories. However, OSW shows positive correlation with load in the winter ($r \approx 0.15$), spring ($r \approx 0.17$), and summer ($r \approx 0.18$). This complementarity is similar and higher than the Gorge wind and SE Washington wind in the spring, and in the winter and summer, respectively. PNW loads may be characterized by winter peaks due to heating needs, indicating that the winter complementarity is significant. In the fall, OSW is largely uncorrelated with load.

The positive correlation results point to the capacity value that the OSW resource may offer to the Oregon electric system: correlation with load indicates that the resource is available when electric demand is significant, both at a seasonal level as shown by the variability in correlations across seasons in Figure 14, but also at an hourly level, which is the time increment of the resource and load data being analyzed. Overall, the OSW resource has greater complementarity to the load than terrestrial wind resources in the region.

4.2 Capacity Implications of the OSW Resource

Another lens by which to evaluate this complementarity to load is to consider the OSW generator (or gross) capacity factor. Capacity factor is a ratio that measures actual energy delivered relative to the potential energy that would be delivered based on the nameplate capacity of an energy generating resource. For example, both baseload fossil and nuclear units generally have high capacity factors, around 80-95%. That is, they are dispatched at fairly high levels throughout the year. Generally, neither generator type is fuel constrained, and instead constrained by demand, other grid requirements, and maintenance outages. Most renewable generators, on the other hand, are fuel constrained: they can only deliver electricity when the resource is present (e.g., the sun is shining, or the wind is blowing). Typically, onshore wind turbines have capacity factors near 33% and solar photovoltaic (PV) panels have capacity factors around 20% (NWPCC 2016 pp. 13-29, 12-53, and 13-11). Relative to fossil units, these numbers are low, and indicate that to replace a certain level of high capacity factor generating capacity would require a significant overbuild of renewable generators. An important point of note, this analysis considers generator (gross) capacity factor, not including maintenance and other losses. The numbers cited for fossil units above are overall capacity factors, accounting for planned and unplanned downtime due to maintenance and other losses. Nonetheless, in a representative capacity, capacity factor can be considered another value metric.

Beyond an average capacity factor, it is also insightful to consider capacity factors during times when the grid may be stressed, that is, during load peak hours when demand is high and generators are called on to meet these peaks. Within Oregon there are two peaks, a morning peak and an afternoon peak. WECC-wide, that is across the western interconnect, load peaks in the early afternoon. It is important to consider the OSW generation in both frames as although the generation would be delivering electrons into the Oregon grid, Oregon is of course interconnected with the rest of the western interconnect.

4.2.1 Overall OSW Generator Capacity Factor

The average generator (gross) capacity factor for the selected OSW locations was calculated in Table 2 by location and by month across all locations in Figure 15. This capacity factor was calculated using the resource data gathered for each location, as discussed in Section 3.2. This resource data in the form of wind speed was matched to a wind speed to power output matrix for a single theoretical 10 MW OSW turbine to develop an energy output (Musial et al. 2019a). This energy output was then evaluated relative to the turbine capacity to develop the capacity factor for the turbine at a given location and used as input for the production cost model as discussed in Section 4.3.

Table 2. Generator (gross) capacity factor for a theoretical 10 MW OSW turbine by location over the year 2012

OSW Location	Capacity Factor
Port Orford	61%
Reedsport	52%
Newport	50%
Astoria	49%
Average	53%

As Table 2 indicates, generator capacity factors are fairly high across the year, better in southern Oregon (i.e., Port Orford and Reedsport sites), which is expected considering the nature of the wind resource being stronger towards southern Oregon (Musial et al. 2019a). They are higher than onshore wind generator capacity factors, even considering the high quality of Gorge wind. The NWPCC estimates a Columbia Gorge wind capacity factor of 32% and for central Montana at 40% (NWPCC 2016 p. 13-29). They are also far higher than solar generator capacity factors estimated by the NWPCC for distributed photovoltaics at 13% west of the Cascades (i.e., Portland) and 17% east of the Cascades (i.e., Boise), and for utility scale PV located in eastern Washington at 19%.[11] Once again, it is important to note that the capacity factors calculated here and the onshore wind and solar capacity factors cited here are generator gross capacity factors and do not account for downtime due to maintenance and other issues. Musial et al. (2019a) calculate capacity factors accounting for these losses and find them to be on the order of 14-18% for OSW off the Oregon coast. Generally, the generator (gross) capacity factors calculated by Musial et al. (2019a) are similar to the numbers calculated here by geographic region of the waters along the Oregon coast.

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[11] *Ibid at 12-53 and 13-11.*

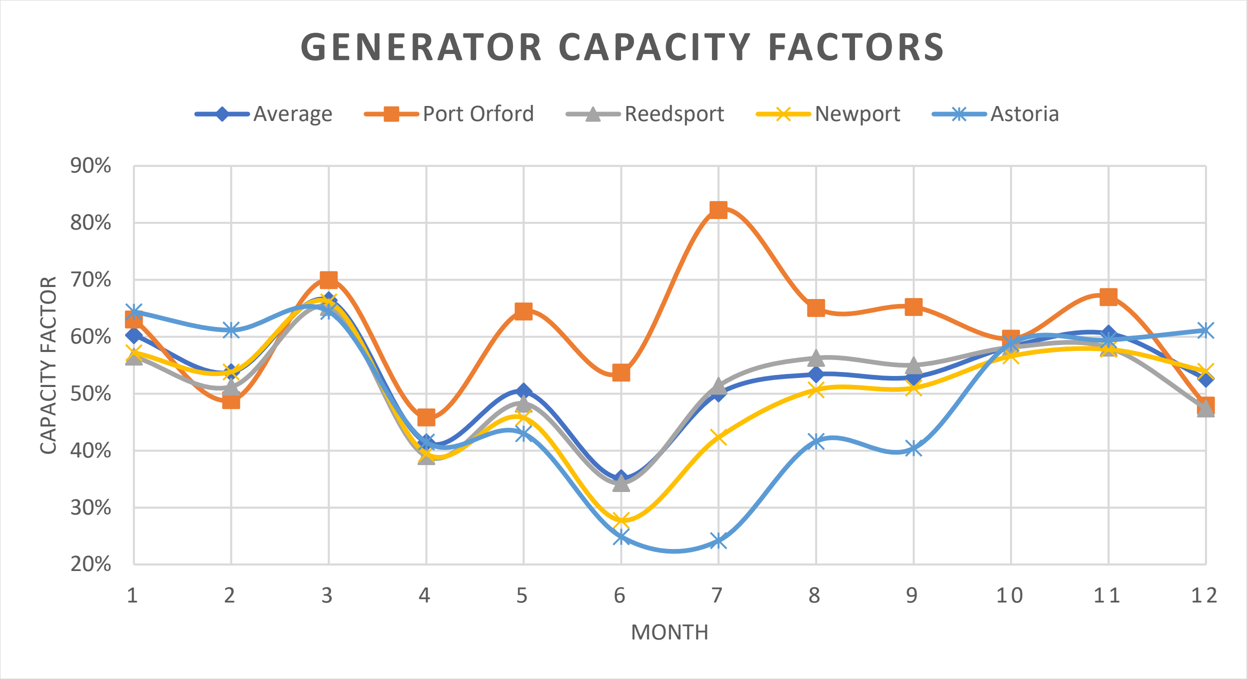


Figure 15. OSW generator capacity factor by month for 2012 for the four sites for a theoretical 10 MW OSW turbine.

As indicated in Figure 15, the sites on average have higher generator capacity factors during late fall through winter to early spring months as compared to late spring, summer and early fall. Port Orford is an exception with a particularly high capacity factor in July. The higher capacity factor during the winter months coincides with peak capacity in Oregon, which occurs during the selected winter months as also identified by NWPCC 2016. In particular, for 2012, across the Oregon balancing authorities, peak demand occurs on January 24th, this coincides with a high OSW capacity factor during the month of January indicated in Figure 15 and accounts for the winter time load complementarity indicated in Figure 14. The WECC-wide peak occurred on July 24th of that year, where OSW capacity factors are lower, however, complementarity to load still higher than spring and fall months. These dates were identified from 2012 load data (WECC Stakeholder Services, personal communication, August 16, 2019).

4.2.2 Peak Hour Capacity Factors

Across Oregon, on average, based on 2012 load for the Oregon balancing authorities, there are two load peaks, one in the early morning from 9 AM to 11 AM and one in the evening from 6 PM to 9 PM. WECC system-wide this becomes one peak in the afternoons from 3 PM to 7 PM (WECC Stakeholder Services, personal communication, August 16, 2019). Musial et al. (2019a) and NWPCC (2016) also identify the same trend. Table 3 identifies the generator (gross) capacity factors associated with these hours across the year.

Table 3. Generator capacity factor across peak hours of the year by OSW generator location and peak period

OSW Location	Morning Peak OR Load (9 to 11 AM)	Evening Peak OR Load (6 to 9 PM)	WECC System-Wide Peak (3 to 7 PM)
Port Orford	62%	61%	50%
Reedsport	49%	55%	39%
Newport	48%	53%	47%
Astoria	46%	51%	42%
Average	51%	55%	44%

Generally, across the morning, evening and afternoon peak periods, OSW generator (gross) capacity factors are higher further south, with an interesting exception at the Reedsport site relative to the WECC system-wide peak period. In terms of the Oregon peak periods, generator (gross) capacity factors are high at 51% and 55% for the morning and evening peaks, respectively. These are in line with the average generator (gross) capacity factor of 53% for the year across all sites, with the evening peak capacity factors being particularly strong. WECC peak period capacity factors are quite a bit lower, at 44% on average, relative to the 53% overall capacity factor.

These numbers speak to the promising value of the OSW generation contributing to the Oregon and northwest regional electric system. These generator capacity factors indicate that the OSW generation has the potential to be relied upon to deliver energy during peak hours relative to other renewables and especially in the context of a changing hydro resource due to climate change and the general trend across the western states to move away from fossil fuel generation.

4.2.3 Resource Consistency

A third lens to evaluate OSW value is resource consistency. The hypothesis of the consistency of OSWs being superior to that of onshore winds remains unproven in most regions with significant OSW resource, including in PNW, even though this consistency is often cited as a benefit of OSW resources. The notion is certainly plausible. Less uneven heating due to solar irradiance on sloping terrain, for example, constitutes a potential mechanism for smoother wind speeds relative to onshore. Further, with fewer topographic obstructions to incite volatility than their onshore counterparts, OSW generators may have comparably improved generating profiles: fewer ramping events, higher resource availability, and natural persistence.

Challenges to these mechanisms are found in the complexity of the ocean. Surface roughness induced through a wave-pumping mechanism is non-negligible in some cases. Ocean depth, large-scale gyres, and upwelling may all impact contributions to thermal mixing. When near surface ocean temperatures are warmer than surface air temperatures, a heating effect promotes a less stable boundary layer, which could contribute to more wind speed variability. Surface winds themselves may induce coastal upwelling and change this boundary condition with seasonal variation (Walter et al. 2018; OrCOOS 2010).

As with many factors related to renewable resources, these considerations warrant regional and even site-specific investigations. In the North Sea and in the U.S. mid-Atlantic waters, atmospheric stability has been shown to vary significantly by region and through time, which results in dynamic and regionally-specific characteristics of vertical wind speed profiles and turbulence (Archer et al. 2019; Kettle 2014). Limited discussion of the time variability of the OSW resource is found in the literature.

The WIND Toolkit offers one lens through which to investigate these effects. It must be noted again that, though validated for onshore wind locations, only limited validation has been seen of the database in the ocean, and nothing at hub heights of interest (Wang et al. 2019).

Resource time variability is an important factor for the power system. Variable resources, whether they are generation or load, by their nature move up and down in output. Particularly quick movement (i.e., a ramp up or down in output over short time durations, quantified as "ramp rates") can lead to a mismatch between generation and load where other generation is not able to keep up with (i.e., ramp its output) the imbalance. This leads to frequency excursions away from normal and could lead to destabilization of the electric grid if not corrected. To address resource and load volatility, traditionally, fast moving natural gas or hydro generators have been used. But as renewable penetration increases on the electric system, the proportion of generation that is volatile and not controlled increases. This has already led to issues where system operators struggle to meet volatility with their ever shrinking dispatchable generation base, whether this is a result of afternoon solar output dropping off in California or volatility in both wind and solar in Hawaii. As renewable penetration increases, the same is expected for other regions. Lacking alternatives, system operators are forced to curtail renewable output and rely on fossil generation. More recently energy storage resources have helped to address these ramping issues.

However, energy storage is costly, and comes with a roundtrip efficiency loss. Further, even with existing generators, there is a cost to ramping their output in the form of wear and tear, fuel, and the lost opportunity cost of not being used to serve load. Accordingly, there is value in renewable resources that do not ramp as much and accordingly require less support from other energy resources. This support is often known as reserves and takes several different forms depending on speed and duration of response.

Ramp rates were examined over the six years of five-minute data, over hourly, 15-minute, and five-minute durations. Ramp rates were generally similar across the northwest, though a trend was spotted through random samples of the five-minute data. Figure 16 provides one such sample, indicating a discrepancy in scale of ramps between Port Orford OSW and the Wyoming 3 TW data.

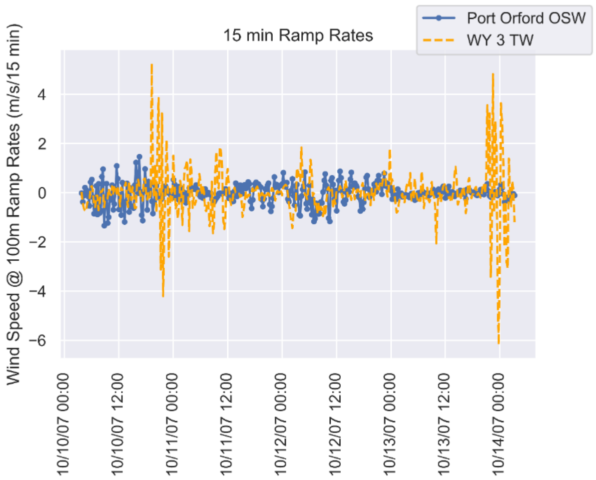


Figure 16. 15-minute ramp rates over a 96-hour excerpt at the Port Orford and Wyoming locations.

Figure 17 indicates that this effect is statistically relevant. First, 1000 random samples of 24-hour periods from 2007-2012 were selected. Next, the absolute value of the maximum and minimum 15-minute ramp rates was computed. Finally, the maximum of these absolute values was extracted. These absolute maximum ramp rates where then plotted on histogram across the 1000 samples for every terrestrial wind location versus Port Orford OSW. As in several instances in the current study, Port Orford was chosen as a single location representative of the OSW resource and is used to indicate a trend.

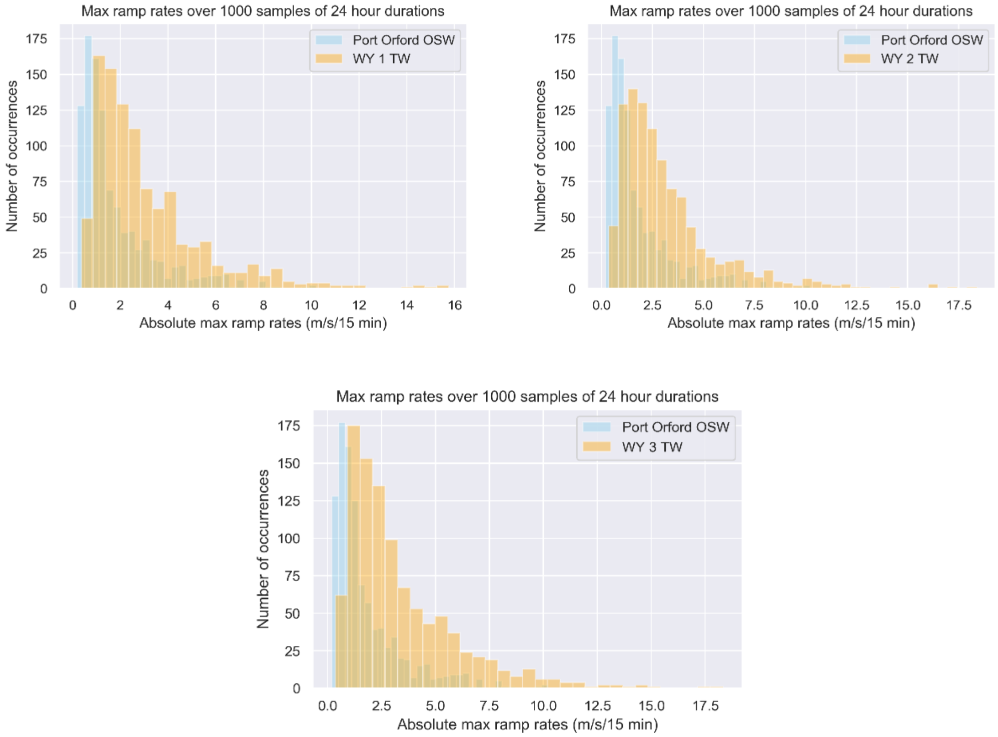
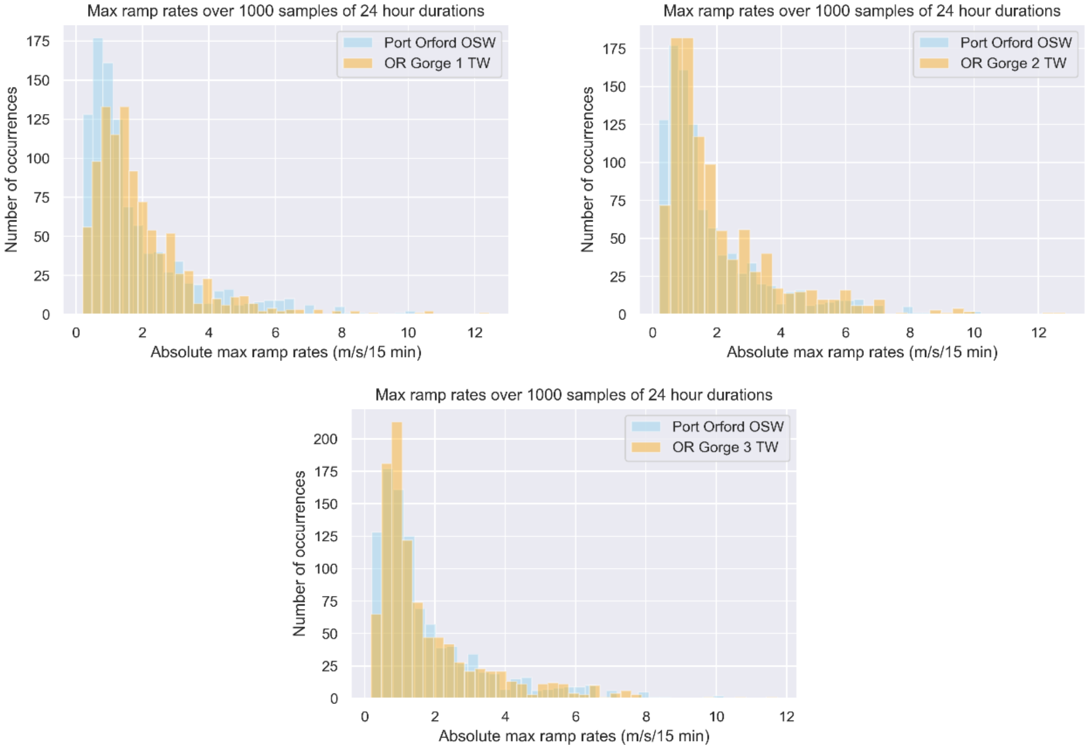


Figure 17. Distributions of absolute, 15-min ramps over 24-hour periods, 2007-2012, Port Orford OSW vs. Wyoming TW locations.

In Figure 17, a clear increase in the average and extreme maximum ramp rates can be observed across all three locations chosen in Wyoming. Of the 1000 samples, significantly more indicate higher absolute maximum ramp rates for the Wyoming onshore wind sites. Where Port Orford shows a peak in the histogram of ramps less than 1 m/s/15 minutes, Wyoming 1, 2, and 3 sites show peaks closer to 2 m/s/15 minutes. The histogram tails also extend farther, to 15 m/s/15 min for Wyoming sites and only 8 m/s/15 min for the OSW site. These effects are muted in Figure 18 which compares the OSW resource to that of the Gorge wind, a similar trend to that which is observed between the various OSW locations also.


Max ramp rates over 1000 samples of 24 hour durations

Max ramp rates over 1000 samples of 24 hour durations

Max ramp rates over 1000 samples of 24 hour durations

Figure 18. Distributions of absolute, 15-min ramps over 24 hour periods, 2007-2012, OSW vs. Gorge TW locations.

Figure 19 indicates a slight improvement over southeastern Washington wind, though not as significant as seen in the comparison with Wyoming wind.

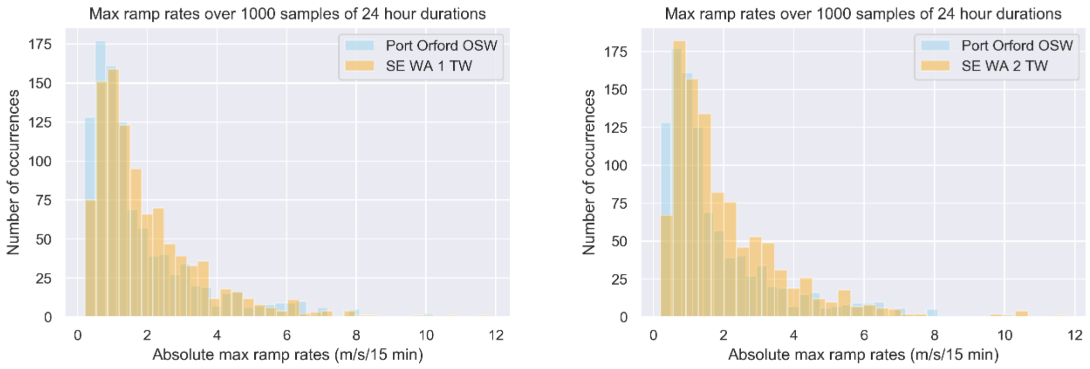


Figure 19. Distributions of absolute, 15-min ramps over 24-hour periods, 2007-2012, OSW vs. SE Washington TW locations.

4.3 WECC Model Integrating OSW

This section considers OSW value from the fourth and final lens of analysis to consider complementarity of OSW to load: production cost modeling. This study used ABB's GridView software to analyze bulk grid impacts of the addition of OSW to the Oregon electric system. 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. It is a tool that is widely used to study the utilization of generators and transmission lines, production cost of generation, locational marginal pricing (LMP), transmission congestion, and more (Anderson et al. 2016).

The WECC currently uses GridView as a tool for production cost modeling efforts in the region. Within WECC's GridView PCM, expected loads, resources, and transmission topology ten years into the future are compiled and maintained. WECC's ADS Data Development and Validation Manual describes in more detail this data collection process and production cost modeling practices.[12] The WECC PCM used in this study 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. Therefore, it was obtained and used for this project to get the most representative results. The study uses this case as-is and did not make any changes to resources, transmission, or topology contained within the case, aside from the addition of OSW resources.

Based on the data within the 2028 ADS V2.0 PCM, significant changes in generation resource mix within WECC are projected. However, the changes to Oregon are limited to a small number of additional PV plants. Otherwise, there is a significant amount of additional capacity in California, Arizona, Colorado, Nevada, and Utah, expected to come online within the next ten years, and reflected in the PCM. This new capacity is predominantly forecasted to be PV and wind. Transmission in the WECC 2028 PCM case provide the best representation of future topology and transmission capacity available. It incorporates the addition of transmission

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[12] 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

projects in the 10-year planning horizon made publicly available to the grid planning community.[13]

In the WECC PCM, loads are modeled as hourly loads for the entire year by balancing authority. The load data within WECC's PCM is based on annual Load & Resource (L&R) data submittals that contain monthly energy and peak forecast for 1-10 years into the future. This data is then broken down from monthly to hourly data by applying the historical FERC Form 714 hourly load shape. The WECC 2028 PCM case currently uses a 2008 historic load shape to create the 2028 hourly load profile by applying the monthly peak load and total energy reported in the L&R. The historic 2008 load shape is an average load year with average weather conditions WECC-wide. For the purposes of this study, no changes were made to the load set by WECC in the model.

Although the model is WECC system-wide, this study focuses on the impacts of OSW resources added off the coast of Oregon, to Oregon. The evaluation of results focused on the BPA, PGE and PACW balancing areas. Unlike in Section 3.0, the IPTV balancing area was not considered here due to a lack of fossil generation within Oregon. The resources were added in increments, scaling the available resource profile, as identified above, for each of the identified resource locations. For each location, the resource was tied to the nearest major (i.e., high voltage above 230 kV) transmission substation on land, and in this case, each substation is a part of the BPA 230kV transmission system. Table 4 identifies the OSW resource locations and substations on the BPA system to which they are tied in the model.

Table 4. OSW resource locations and the BPA 230 kV transmission substations to which the resource is connected

Location	Latitude	Longitude	Substation ID	Sub Name
Astoria	46.13978	-124.519	40243	CLATSOP
Newport	44.63749	-124.488	41083	TOLEDO
Reedsport	43.76358	-124.561	41061	TAHKENITCH
Port Orford	42.73763	-124.825	40895	ROGUE

The model runs of the different OSW deployment scenarios were for a one-year duration, of the model year 2028. These runs were conducted using a nodal model, that is a model with load nodes within each balancing authority (i.e., area, within the model) at an hourly resolution across the entire WECC system. The scenarios evaluated, identified in Table 5, were based on a buildout scenario where all thermal plants are retired and 5 GW of OSW provide 80% of the replacement generation (Musial et al. 2019a). The study used increments of 500 MW initially and then 1 GW to the 5 GW limit to evaluate different levels of integration and leveraged electric vehicle (EV) research at PNNL to consider a scenario with significant EV load.[14]

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[13] Ibid.

[14] EV load here is based on the deployment of 24 million light duty electric vehicles, 200,000 medium duty vehicles and 150,000 heavy duty vehicles across the United States, allocated based on growth projections from the Electric Power Research Institute for light duty vehicles, population for medium duty vehicles, and using a transportation model for heavy duty vehicles. That research uses the same PCM used here to consider generation and transmission impacts associated with a significant increase in load from electric vehicle charging. _See_: Kintner-Meyer M., S. Sridhar, D. Bhatnagar, S.M. Mahserejian, S.H. Davis, and M. Ghosal. *Electric Vehicles at Scale – Phase I Analysis: High EV Adoption Impacts on the U.S. Power Grid.* Pacific Northwest National Laboratory. April 2020. PNNL-29894.

The following sections discuss system impacts resulting from OSW deployment.

4.3.1 System Impacts (Modeled)

Table 5 identifies system impacts associated with each of the OSW deployment scenarios. As is evident from the table, the model results show significant benefits to a deployment of OSW in the form of production cost and emissions savings. The model results indicate significant generation cost savings totaling up to 97 million dollars over a year for an installation of 5 GW of OSW, spread across the four identified resource locations. These cost savings are associated with a reduction in locational marginal prices (LMPs), emissions of carbon dioxide, nitrogen oxides and sulfur dioxide. These savings are associated with a reduction in use of natural gas units in the region. Impacts to natural gas and other resources will be discussed further below.

As discussed previously, Oregon is not in an organized market and does not have pricing nodes in which LMPs would be representative of the localized cost of energy and localized congestion. Nonetheless, the model develops LMPs associated with different node points, which are often transmission substations in the model. As in a market environment, the LMPs represent the localized generation and congestion prices associated with the transmission system within the model. Effectively the prices are a representation of the cost of electricity and costs of congestion to serve load in different nodes within the model. An overall reduction in locational marginal prices, which is fairly significant in some of the scenarios as identified in Table 5, indicates a reduced cost of energy. It may also indicate reduced congestion in the transmission system. Transmission congestion will be analyzed further in the next section.

Table 5. PCM system impacts of OSW

Scenario	Generation Cost ($M)	Average LMP ($/MWh)	CO2 (st)	NOx (st)	SO2 (st)
1 GW OSW	-34.00	-0.92	-704,783	-399	-4.1
2 GW OSW	-67.32	-1.84	-1,332,254	-771	-7.6
3 GW OSW	-85.72	-2.64	-1,667,821	-976	-9.5
4 GW OSW	-92.92	-2.88	-1,793,679	-1,055	-10.2
5 GW OSW	-97.21	-3.04	-1,863,317	-1,116	-10.8
3 GW + EV	-89.68	-3.44	-1,783,355	-1,040	-11.9

It should be noted that for the purposes of this model, OSW is represented as effectively a zero-cost resource with no fuel costs and minimal operational and maintenance costs. The model does not account for any capital costs associated with resources, and for the purposes of this study the cost to deploy these levels of OSW have not been considered. The savings presented here are for the BPA, PGE and PACW balancing authorities and are relative to the base case model for 2028, and for the electric vehicle base model (*forthcoming* PNNL EV study).

Rather than a continuous rate of increase, the generation cost savings associated with an increase in OSW generation exhibit a diminishing rate of returns. This effect is presented in Table 5 and shown in Figure 20, and is the result of several factors. First, considering that the OSW resources were added to the transmission system without any additional transmission upgrades, it is reasonable to expect there is a limit which the existing transmission system can accommodate the increased OSW. The transmission impacts associated with this additional OSW are discussed in the next section. Second, there are other system limitations that might limit this value. There are reserve requirements associated with fossil resources and hydro resources that require them to be online to provide reserve capacity in the case of renewable generation shortfalls. Indeed, while fossil units are used quite a bit less, hydroelectric resources appear to see a very limited change in their output as a result of OSW integration. Section 4.3.2 discusses these resource changes.

These results are important when considering that Oregon has strong goals to develop clean energy and reduce its reliance on fossil fuels (State of Oregon 2016, 2020). The modeling results point to the possibility that OSW may be a suitable replacement to fossil generation for the purposes of delivering energy. It is important to note that the model and this analysis have significant limitations and a detailed analysis of reserve requirements associated with the deployment of OSW has not been conducted. Further analyses may reveal additional reserve and integration costs for OSW that may limit the amount of fossil resources that can be replaced by OSW generation.

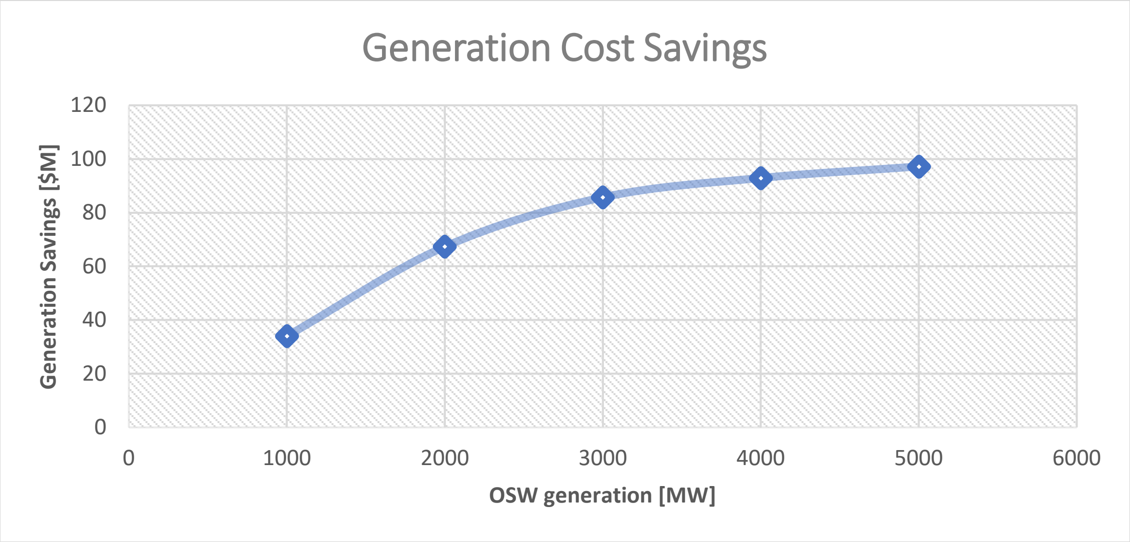

Figure 20. Decreasing generation cost savings associated with increasing OSW deployment.

4.3.2 Generation Resource Impacts (Modeled)

It is important to note that the model dispatches resources according to least cost and does not include contracts that might be in place to deliver specific resources to specific regions. In particular, BPA has contracts to serve Public Utility Districts on the coast of Oregon with its resource base, which is primarily hydroelectric. This also includes any fossil units that have bilateral contracts. If OSW resources serve these coastal loads, the model will not necessarily capture that hydroelectric resources should accordingly be reduced. Instead, the model has minimum run capacity and energy amounts for many of these hydroelectric resources. This captures that they have limited ability to be turned down (i.e., limited water storage). However, it limits the flexibility of the hydroelectric resources to serve load or support renewables on the system. This is of course a limitation of the model and must be considered when evaluating results. That said, there may be, from a resource allocation perspective, some insights to be gained on the impacts of OSW integration on other, non-hydroelectric resources on the system.

Figure 21 and Figure 22 below identify the model results on the impact of the deployment of OSW on other resources within Oregon. Figure 21 represents the change in generation by hour averaged over the year for fossil and hydro resources within the state. Figure 22 represents this same data for the winter months (i.e., DJF) It is evident in this representation that OSW is primarily impacting the use of fossil resources in all months, which is complementary to greenhouse gas reduction goals. Hydro resources are relatively minimally impacted due to their minimum run requirements in the model and their lower costs of generation. Hydro resources along with operating natural gas units are used to balance the added OSW.

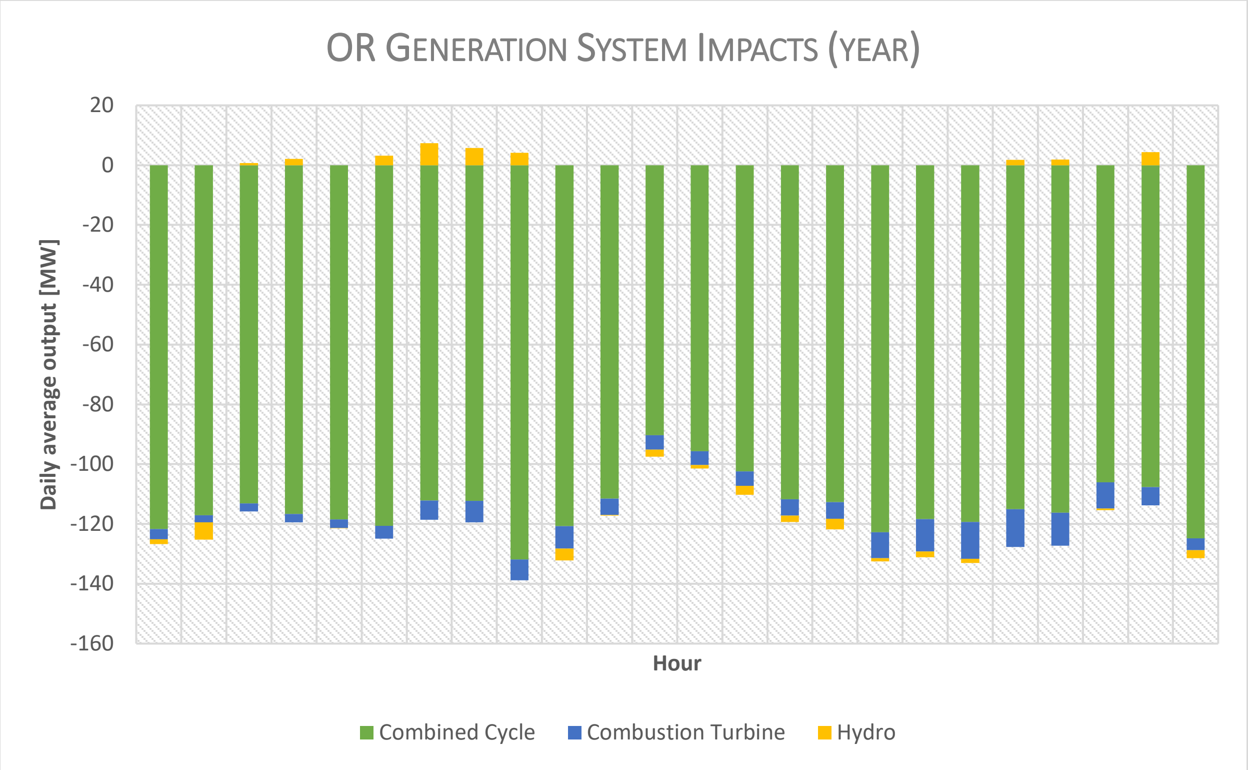

Figure 21. Average change in generation by resource type for each hour during the year.

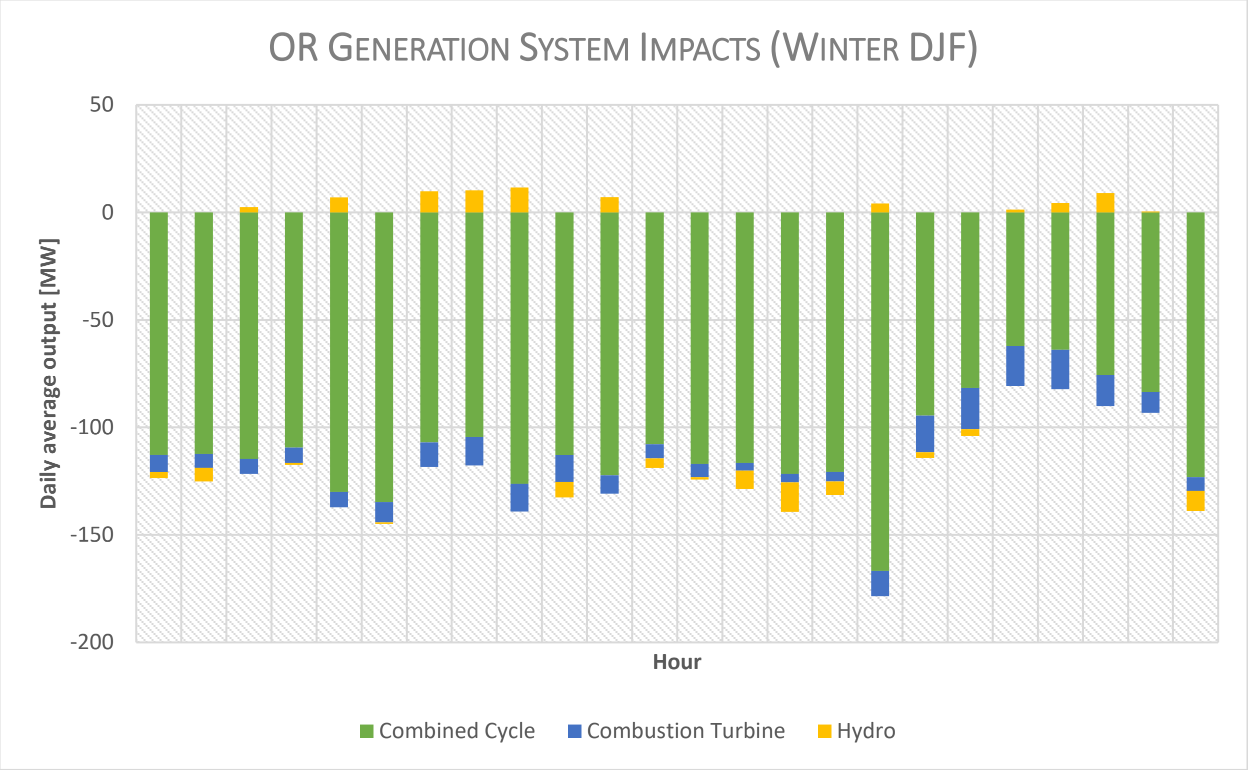

Figure 22. Average change in generation by resource type for each hour during the winter months of December, January and February.

5.0 Locational Value

Except where modeling results are noted in Section 5.8, the following sections are discussions of potential OSW locational value based on existing data and information available from a variety of sources.

5.1 Serving Remote Grids

The Oregon coast includes very few electric generators, as shown in Figure 23. There are only a handful of local generation units that can be called upon such as the Clatskanie gas plant or the Tillamook biodigester. As a result, most of the electricity that serves the Oregon coast – as well as the Willamette Valley – originates east of the Cascades, provided by the Columbia Generating Station nuclear facility, federal and non-federal hydropower system, and coal plants such as Boardman.

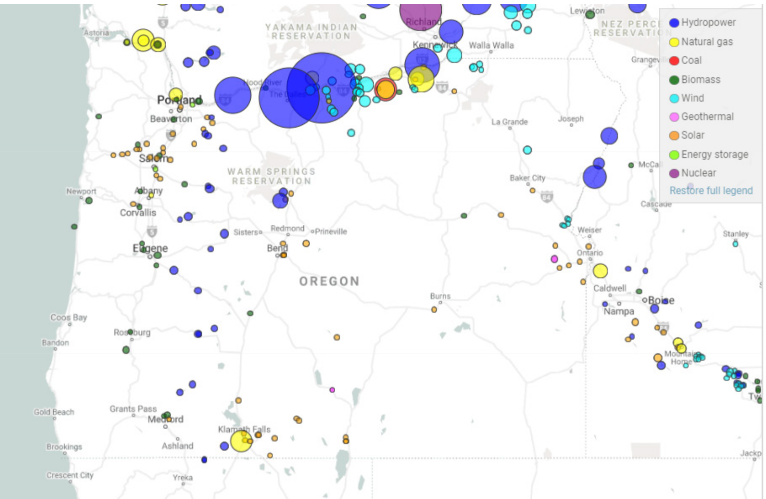

Figure 23. Map of power generation in Oregon (NWPCC 2020C).

The dominant transmission flow is east to west, without reinforcement from other large electric generators. This requires a substantial transmission and distribution infrastructure to ensure power quality to the very end of the line, in places such as Brookings. Figure 24 shows the BPA transmission facilities within western Oregon.

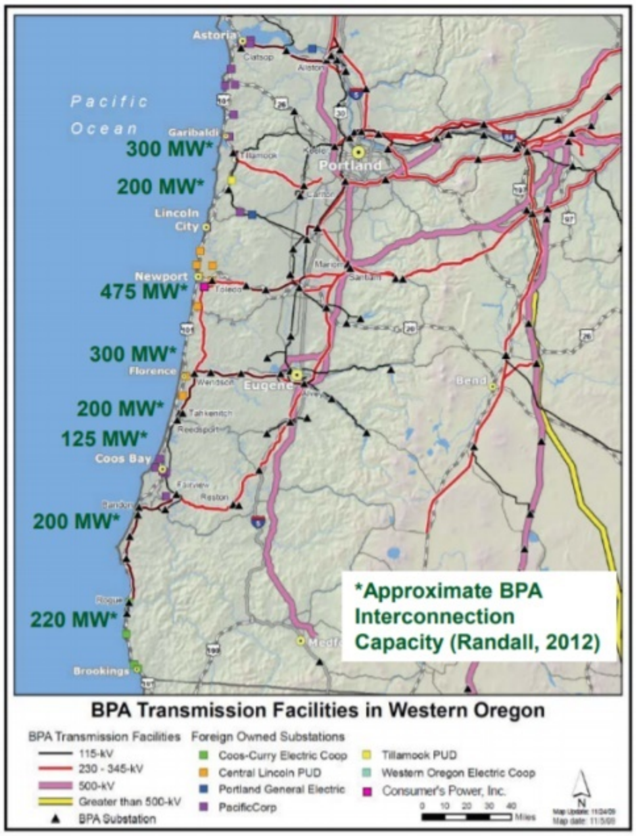

Figure 24. BPA transmission facilities in Western Oregon (Pacific Energy Ventures 2009; Randall 2012).

Most of the lines that cross the Cascade Range are operated by BPA; no expansions of these lines are anticipated in the near-term to extend capacity. For the North Oregon Coast Area there are no transmission reinforcement projects proposed within the next 10 years. In the Southern Oregon Coast Area, the Portland Area, Salem Area, and Eugene Area there are limited service plans in place to maintain acceptable voltage schedules, improve O&M flexibility, and improve reliability of delivering load to customers. Outside of these matters, BPA has stated no other plans regarding transmission investments in these areas (BPA 2019).

Large electric generators on the Oregon coast offer one of many possible solutions to improving grid reliability across many areas, including the coast. Nearby generators minimize *line losses*, or power losses due to transmitting energy over long distances. The practice of accounting for line losses has been active in Oregon for over a decade: Energy Trust of Oregon directly estimates and applies line loss values, as well as avoided transmission and distribution costs, as credits to local energy efficiency measures (Energy Trust of Oregon 2017).

Local generators also support improved performance of the grid by stabilizing power quality and voltage levels. Without these attributes available from electric generators, system operators must install other forms of auxiliary equipment to support the grid. For example, BPA invested over $15 million in a voltage booster system (i.e., static var compensator) near Gold Beach to ensure that high-enough voltage reaches the south coast, all the way to the end of the transmission lines that serve the Brookings-Harbor area (Akhil et al. 2015).[15]

Remote grids with radial (single point contingency) distribution lines and limited grid enhancing components may be referred to as “weak” grids, due to the lack of stabilizing support systems and greater potential for disruption. While small injections of power from residential electric generators, such as from rooftop solar arrays, are acceptable in weak grids, large injections of power from utility-grade developments such as OSW machines will require grid strengthening improvements to onboard and wheel the power for delivery to loads. Due to the possibility that coastal grids may be remote and relatively weak, one strategy is to design and operate the generators themselves to be grid supporting. The ability of OSW machines to support the grid is described in Sections 5.6 and 5.7.

5.2 Economic Limitations of Weak Grids

Industrial enterprises typically have unique characteristics, not just in expanding the basic electric loads required of a utility, but in introducing new short-term peaks in electric loads. Depending on the industry, the introduction of a new electric load can require capacity upgrades to electric delivery systems to accommodate a new peak demand. These costs can be assigned directly to the new industrial facility seeking service, which acts as a financial penalty to siting in a given location. Reliable, cheap, and available electricity can be a strong stimulus to industrial development.[16] The inverse is also true – assigning additional costs to electric system upgrades due to the introduction of an industrial load can be an effective deterrent.[17]

There are strong indications of non-grid economic benefits of coastal industries. For example, the fiber-optic industry has successfully negotiated deployments using agreements with ocean users to mutual economic benefit.[18] The ability of Oregon coastal grids to host large industrial loads could economically benefit the maritime supply chain sector including ports. In this way, grid supporting contributions of OSW could convey non-grid economic benefits also.

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[15] Rogue Substation Static VAR Compensator (SVC) Project. BPA South Oregon Coast Study Summary 7-13-2010. SW Oregon Coast Reinforcement Project_III.ppt. As cited in” Why Wave Energy?” from the Oregon Department of Energy, [2012].

[16] For evidence on the relationship between cheap electricity and electricity intense industries, data centers are a clear indicator as electricity is the primary supply chain dependency. See Washington Department of Commerce, January 2018. ”State of the Data Center Industry,” http://www.commerce.wa.gov/wp-content/uploads/2018/01/Commerce-Data-Center-Study-and-appendices-2017.pdf. or Geekwire, May 2017. “Why the Pacific Northwest will be a data center powerhouse for years to come.” https://www.geekwire.com/2017/pacific-northwest-will-data-center-powerhouse-years-come/

[17] Project Columbus and Project Parkway, through the Oregon Economic and Community Development Department in 2008, explored bringing large new manufacturing facilities to the Gardiner IP Mill Industrial site. As cited in ”Why Wave Energy?” Oregon Department of Energy, [2012].

[18] See Oregon Fishermens Cable Committee (OFCC) on the Oregon Fishermen‘s Agreement. http://www.ofcc.com/about_ofcc.htm

5.3 Alternative Resources

There are very few renewable resources located on the Oregon coast today, with the notable exception of the Tillamook biodigester and other biomass facilities. There is low technical potential for coastal onshore wind or solar development in these areas, as shown in Figure 25, due to the character of the resources: natural volatility of wind speeds as they encounter land masses from ocean surfaces (NREL 1986, 2019) and low insolation levels compounded by common cloud cover (Sengupta et al. 2018; University of Oregon 2004), respectively. The Oregon coast is generally characterized by mountainous terrain rather than the flat terrain that is best suited, though not required, for the spatial demands of large-scale terrestrial renewable energy development. Conditions for onshore wind and solar development in Oregon are significantly more favorable in eastern Oregon. A vast majority of solar production each year takes place in eastern counties with much less being reported for coastal counties (ODOE 2020).

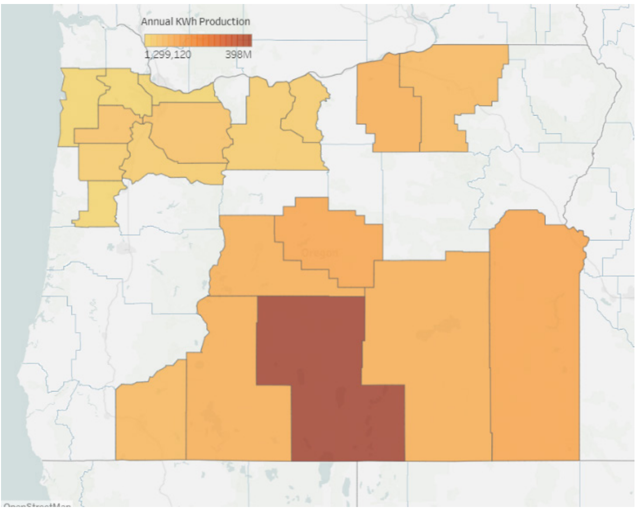

Figure 25. Annual kWh solar production by county (ODOE 2020).

5.4 Land Use under Decarbonization Futures

In addition to the current low-cost economics of commercially available renewable generation technologies, Pacific coast state policymakers are instituting increasingly higher goals for renewable energy and implementing programs for broad decarbonization (Table 6).

Table 6. Renewable standard goals of Pacific States (DSIRE 2019)

State	Clean Energy Targets
Washington	15% by 2020 100% by 2045
Oregon	50% by 2040
California	60% by 2030 100% by 2045

The effects of low-cost renewables and clean energy policies on the electric sector have been dramatic. In 2018 there was an 18% rise of generation capacity growth in a single year for wind in the West alone (DOE 2018b). For solar, the EIA predicts that total generation in the US will double by 2040 (EIA 2019). There is a projected loss of over 15,000 MW of non-economic coal plants in the WECC by 2026 serving electric loads in these states and 1,436 MW in California, Oregon, and Washington, specifically.

Meeting reliability and resource adequacy requirements are currently limiting factors to achieving a very high level of renewable energy on the system, though notably the Midcontinent Independent System Operator (MISO) and the Electricity and Reliability Council of Texas (ERCOT) have achieved very high instantaneous renewable penetrations (Walter 2019; Kleckner 2019) and other countries have achieved persistent 100% renewable energy over months, typically relying on majority support from hydropower resources. Costa Rica, for example, with 75% of their generation portfolio supported by hydropower, has been able to achieve consecutive months of near-100% renewable generation (Davidson 2019). This accomplishment came from increasing wind generation up to 15% of their portfolio and adding geothermal energy. In Oregon, grid-scale renewable energy will almost exclusively consist of hydropower, wind, and solar facilities. Earlier, we discuss the value of complementarity of OSW resources to other renewable resources that are anticipated to dominate the future electric system.

Increasing renewable energy generation in Oregon must be considered in the context of the larger Western Interconnection electric grid (Figure 26). A significant proportion of the renewable energy facilities that serve Oregon's homes and businesses are not located in Oregon. Many of the resources contributing to the Oregon's RPS are from neighboring states including Washington, Idaho, Wyoming, California, Utah, and Colorado (ODOE 2019a). Building new renewable energy facilities to meet state policy objectives may have a significant effect on the transmission system, as facilities are likely to be built where the resource is located.

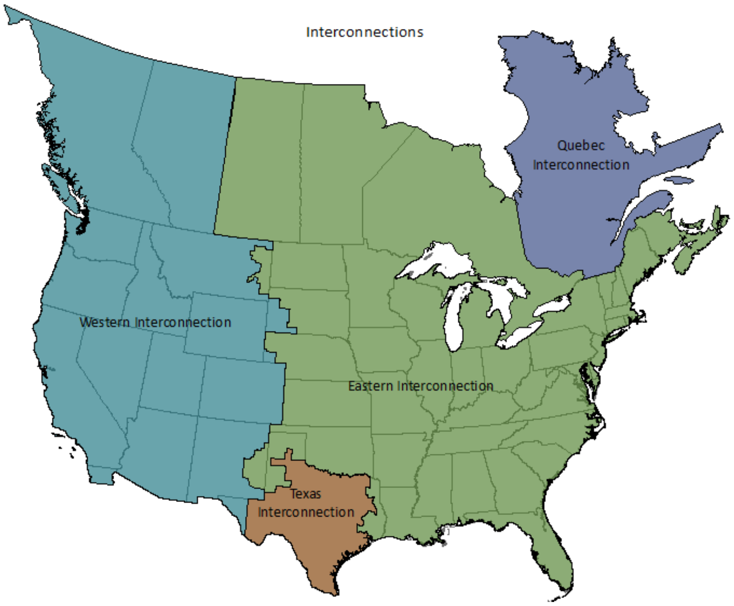

Figure 26. Map of Interconnections of North America (WECC 2020).

The land use implications for new development of large renewable facilities and transmission infrastructure required to deliver that electricity, as well as overbuilding the variable energy capacity in order to ensure adequate supply, could be substantial even if development is distributed across large areas of the grid. Solar energy facilities require 5.5-7.2 acres per MW of nameplate capacity, and wind facilities require approximately 85 acres per MW (Ong et al. 2013, Denholm et al. 2009). As areas with high-quality renewable resource potentials are developed, land can become less available for energy development, offshore development can offer an alternative option for potential renewable development. Offshore spatial footprint favorability is a driver for energy development globally, especially around islands and isolated coastal grids. Even though these communities depend on the ocean for commerce, transport, and local industries, intense land use constraints are primary drivers for recruiting offshore energy solutions such as marine hydrokinetic (UAF 2020), ocean thermal (Whittaker 2018), and floating solar (Osborne 2018; Gazdowicz 2019).

5.5 Coastal Resilience

The use of the term “resilience” in the energy sector is not easily untangled from reliability. Reliability is a well-established concept with supporting planning paradigms, regulatory authorities, and widely accepted and implemented standards. In the electricity generation, transmission, and distribution context, it refers to the consistency of high quality power delivery. Resilience is defined in the U.S. Department of Energy (DOE) Quadrennial Energy Review as “the ability of a system or its components to adapt to changing conditions and withstand and rapidly recover from disruptions” though it is recognized that there are a wide variety of definitions used across the energy industry (DOE 2015). Resilience refers to high impact low frequency disruptions, both man-made such as cybersecurity events and natural such as abnormally large hurricanes, that cause cascading or unpredictable effects (Preston et al. 2016).

Energy resilience is not a new term, and the relationship between resilience and renewable generators has been explored at the state level over the last decade. The Oregon State Energy Assurance Plan (2012), from the Oregon Department of Energy (ODOE) and Oregon Public Utilities Commission, describes the resiliency benefits of renewable generation, energy efficiency, and smart grid capabilities under emergency conditions or grid disruptions (ODOE 2012, Chapter 4). In particular for renewable resources, the Energy Assurance Plan points to the scalability, continued operation under fuel disruptions, and the value of distributed interconnections or proximity of the generator. The Oregon Distributed Energy Resiliency Study, which supported this Plan, also indicates that the strategic location of renewable resources could be a benefit, though it expresses skepticism about capabilities of uncontrolled generation, a reflection of the state of the technology at that time (ODOE 2012, Appendix K).

Back-up generators are a well-established tool to addressing grid outages for a given customer. Typically, a back-up generator is a diesel generator due to the ease of scalable siting, large power output for its size, and ability to rate the output to the need. Behind-the-meter natural gas generators are increasingly common, as events that impair the electric system may not affect a subterranean and reinforced pipeline system. Extreme weather accounts for an estimated 80% of power outages (Walton 2016). Solar and storage projects may be able to supplant diesel generators as a fuel-free option with the potential to provide power beyond the duration of a diesel generator, which would be constrained by the amount of available fuel (CESA 2020). The Army has set a definition of resilience as the ability to supply 14 days of electricity to critical loads on a given installation, and commonly evaluates the combination of diesel, microgrids, solar and battery storage to meet the resilience standard (DoD 2017). It is notable that Camp Rilea, an Army National Guard facility on the Oregon coast near Warrenton, which would be a supply center and shelter for local communities in disaster conditions, has investigated the potential of offshore generators to supply resilient power over the last decade (Shorack 2014).

At the distribution system level, generating resources such as rooftop solar generators are classified as Distributed Energy Resources (DERs). DERs can supply benefits to the electric grid under resilience scenarios, but they need to be sited and sized effectively (NAS 2017). More recently, the Oregon Department of Energy published the Oregon Guidebook for Local Energy Resilience (ODOE 2019b) for consumer-owned utilities, which indicates the potential for DERs to meet resilience objectives. The guidebook offers information regarding using DERs for infrastructure and operational resiliency benefits on a high level and offers resources for further understanding their utilization.

OSW generators will be large and interconnected at a substation, as opposed to nested within communities and distribution systems. For utility-scale generating infrastructure, the resilience benefits are different. One resilience service is the ability to provide "black start," which is an essential service when the grid is rendered completely non-operational, systems are fully de-energized and in a position to be restored. Almost all of the black start generators in the Western Interconnection are hydropower and natural gas, due to their scale, the ability to motivate very large generators without requiring significant electrical input, and their proximity to certain crank paths—transmission pathways that fit protocols to restarting the grid in an orderly fashion (ORNL 2019).

Resilience in the Oregon coastal context is a combination of electric and other critical services, such as transportation, water, and fuel. The DOE's "Powering the Blue Economy" initiative includes local marine energy facilities designed to support desalination for freshwater, embed and reinforce ocean-facing structures such as jetties and breakwaters, and provide microgrid-enabled local power supply for critical emergency services (DOE 2019).

The Oregon Resilience Plan (2013) contemplates widespread disaster-scale events, such as an extremely large earthquake. Stretching 700 miles off the Pacific coast from Cape Mendocino, California to northern Vancouver Island, British Columbia lies the Cascadia Subduction Zone (CSZ) fault. This fault is capable of large-scale and moderate seismic event and associated tsunamis, which could pose devasting effects to the PNW most acutely felt by coastal communities. In deep waters such as the 200 meter-and-greater depths of the Oregon OCS, tsunami waves are characterized by long wavelengths and low amplitudes. The amplitudes may correspond to wave heights on the order of one meter (ITIC 2020). Due to the offshore effects of a large earthquake, in particular the challenges of shoreside connection facilities withstanding tsunami impacts, it is not clear that OSW offers benefits under this specific extreme scenario. However, OSW farms may be capable of continuous power supply during these extreme or more moderate events, provided seismic reinforcement of interconnection equipment, design of mooring lines to accommodate these scales of wave heights, and engineering of subsea high voltage cables to withstand sea floor displacement. Scotland Hywind floating wind farm operated through extreme conditions from November 2018 to January 2019, including a severe winter storm with swells exceeding eight meters (Coren 2019).

Under scenarios where transmission lines that cross the Oregon Coastal Range are disrupted but the offshore facilities are intact and operational, it is possible that offshore energy resources can supply coastal loads, but the specific dynamics between injection points, energy volumes, infrastructure capabilities and load distribution should be studied. Such power supply resilience could prove critical to the coast given a vulnerable transmission network over the coastal mountain range, consistent with a direction from the Oregon Resilience Plan to "evaluate the options for improving power supply to coastal areas located outside the tsunami inundation zone" (OSSPAC 2013).

This resilience benefit would also be seen across the transportation sector statewide after widespread electrification of transportation. Oregon has no fuel refineries. Regional capabilities are located in Washington state and principally delivered by a single pipeline, with a secondary but smaller pipeline in eastern Oregon. In the event of a Cascadia Subduction Zone disruption, Washington refineries will be limited in their distribution, and the main pipeline would likely no longer function (ODOE 2012, p. 13). Coastal availability of electricity supply would be needed to support electrified transportation.

5.6 Reinforcing Isolated Grids Today—Capabilities of Wind Turbines

OSW turbines benefit from the past decade of accelerated technology development and global deployment of their onshore counterparts. Wind energy penetration levels have risen significantly. Denmark, Germany and Ireland, the latter with a particularly challenging weak grid, have operated with annual VRE penetrations (mostly wind) of more than 20% and a penetration record of 56.16% was set on January 19, 2019 in ERCOT (Kroposki et al. 2017, ERCOT 2019). As the VRE-share of the power supply as increased, grid codes have evolved to demand and then call upon their contributions to stabilize the grid. Machines that can interconnect today at utility-scale feature either partial or full-scale converters and control technologies which enable active power control, reactive power control, frequency control, and fault ride through, among other capabilities (Iglesias et al. 2011).

OSW turbines can stabilize weak grids characterized by short circuit ratios lower than 2.0 and can emulate the inertia contributions of large rotating synchronous generators by harnessing kinetic energy of the rotor during sudden frequency events. Damping of sub-60 Hz oscillatory disturbances on transmission networks, which can be amplified and propagated without complex detection and control mechanisms, has also been demonstrated (Zhang et al. 2016). Power plant controllers enable intelligent contributions, spreading the response across entire farms to provide robust control response and also to minimize operational impacts on individual turbines.

Many of these capabilities were demonstrated recently through CAISO tests at the Avangrid Tule Wind Farm in California (CAISO 2020): These tests successfully demonstrated the following capabilities through power plant control of the 130 MW farm:

- Ramp up/down at specified ramp rates
- Response to 4-second control signals from CAISO
- Voltage control
- Frequency regulation similar to conventional resource governor control
- Frequency response deviations for low and high frequency events

Beyond demonstrating capabilities, performance in some of these capabilities exceeded that of other sources of synchronous generation. Regulation accuracy was 25-35 points better than fast gas turbine technologies. Most notably, an individual 2.3MW generator successfully sustained controlled reactive power even when it was not generating active power. Such a contribution, only possible through sophisticated control of power electronics, is not possible through conventional thermal or hydropower generators. Though not demonstrated across the entire farm in this test, continuous voltage regulation in this way will provide value reinforcement to the VRE-dominated grid of the future. With the right market signals, the potential stabilization is akin to dispersing a network of sources or sinks of reactive power (i.e., static synchronous compensators or STATCOMs) across transmission systems. Notable also is that these contributions were made through technology deployed on Type 3 wind turbines, which only feature partial converters. Type 4 machines, with full-scale converters, will be that much more capable of these kinds of services.

5.7 Grid-Following to Grid-Forming Capabilities

As sophisticated as these control strategies of power electronics have become in recent years and the potential they have indicated, the recent demonstrations primarily fall into the category of grid-following capabilities. Grid-following inverters work under the assumption of minimal amplitude and frequency deviations from an AC voltage mean at the turbine low voltage terminals. This implies that other generators and system controllers provide sufficiently stiff frequency and voltage across the grid to the point of interconnection. To enable much higher levels of penetration, converter controls—not the hardware—need to be enhanced to pose grid-forming contributions. These converters must be capable of decentralized control of system voltage. Various control strategies are under development, including droop control, virtual inertia, and dynamics of nonlinear oscillators, and several of these strategies have already been deployed (Kroposki et al. 2017).

In the event of a full system outage, black start capabilities are needed to re-establish the grid, and are the truest to the grid-forming label. Though the capability has not seen utility-scale deployment, black start through wind turbine technology has been shown in laboratory conditions employing permanent magnet generators and full-scale converters (Shan et al. 2019). Importantly, the hardware has already reached the market. The Siemens Gamesa 10MW SG 10.0-193 DD, MHI Vestas V164-10.0MW and GE 12MW Haliade-X, each use permanent magnet generators and full-scale converters (Snieckus 2019). Given what has been demonstrated through Type 3 and Type 4 wind turbines in the field combined with what the research and development arena is indicating, the transition to grid-forming wind turbines is well underway. These capabilities hold benefits to isolated grids as well as larger transmission systems, which become only more important under further VRE penetration. Development of market-based mechanisms to incentivize grid stabilization over active power production, to unlock the potential which technology is indicating today.

5.8 System Transmission Impacts

5.8.1 Wind Curtailment and its Implications (Model)

Table 7 identifies the curtailment associated with the deployment of OSW at different deployment levels (i.e., scenarios) as dispatched within the PCM.[19] Modeling details and scenarios are discussed in Section 4.3. The PCM model results indicate that OSW curtailment increases significantly between 2 GW and 3 GW of deployment. The model output suggests that the system will accept an OSW deployment level of at least 2 GW (likely closer to 2 GW than 3 GW) without additional transmission infrastructure. This 2-3 GW deployment level is only a percentage of the total OSW resource available and harnessing the total resource will require new infrastructure. Further, as is evident by the addition of electric vehicle load in the 3 GW with electric vehicle load scenario, there is some reduction in curtailment to serve additional load, but it is relatively minimal. This provides some further support in indicating a transmission limitation.

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[19] Wind curtailment is defined here as the percent of energy not delivered, or spilled, to the electric grid relative to the possible output of the OSW site.

It is important to note that as part of the forthcoming PNNL EV Study, the expansion of load associated with the electric vehicle scenario is intentionally significantly more than is otherwise planned or expected for Oregon. The study authors used aggressive estimates in the amount of electric vehicle load to stress the system (PNNL EV 2020). Conversely, the NWPCC does not expect an expansion of load in Oregon out through 2028 (i.e., the PCM modeled year) and in fact expects load to remain relatively stable if not slightly decrease.[20]

Table 7. Wind curtailment associated with different penetration levels of OSW.

OSW Penetration	Port Orford	Reedsport	Newport	Astoria
1 GW	0.2%	0.1%	0.0%	0.1%
2 GW	2.0%	7.2%	0.2%	3.1%
3 GW	20.5%	28.1%	10.3%	14.6%
4 GW	36.8%	42.2%	26.1%	30.1%
5 GW	47.3%	51.5%	37.3%	40.9%
3 GW + EV	19.5%	27.6%	9.3%	14.0%

Nonetheless, there is some reduction in curtailment associated with the addition of electric vehicle load, which points to some other factors at play. It's possible that the inability to turn down hydro units due to minimum run requirements may also limit the acceptance of OSW. One important thing to note is this analysis considers deployment of OSW spread across four different major (i.e., 230 kV) substations on the transmission system. The effort did not study in depth different penetrations of OSW at different substation sites and instead assumes that the penetration of OSW is equal across all deployment sites.

As mentioned above, the results indicate that around 2 GW of OSW may be accommodated with the current transmission system. It is important to recognize, however, that the PCM is not a detailed power flow model and does not account for thermal ratings and effects or other localized transmission system impacts that could be associated with the deployment of a significant amount of OSW generation that might limit its development. Further, this model by design is a 50/50 model, that is a 50% chance that loads will exceed this level during the planning horizon. A more detailed analysis would also consider a more extreme load case, that is a 90/10 model in which risk of unmet load is significantly higher. Such a model would be a better representation of the actual amount of OSW that could be accommodated in the Oregon system reliably.

5.8.2 Transmission System Modeling Results

Overall, beyond curtailment, the model does not indicate significant transmission congestion associated with the OSW deployment. There are changes in flows on the coast, particularly reverse in flow direction and increase in magnitude from the I-5 transmission corridor across the coastal range to the coastal transmission network. In addition, OSW interconnection changes

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[20] Despite some load growth, the NWPCC's expectation of significant energy efficiency and demand response growth results in a reduction in expected demand for Oregon through 2028 in its Seventh Power Plan. A load forecast for the 2021 Northwest Power Plan has not yet been released but includes even more aggressive energy efficiency and demand response projections. See https://www.nwcouncil.org/energy/7th-northwest-power-plan/about-seventh-power-plan.

regional path flows. As the western interconnect is an interconnected grid, Oregon cannot be considered alone without considering nearby states. That said, overall, imports and exports do not, on average, appear to be altered significantly, though generally, there does appear to be less reliance on imports.

5.8.2.1 Transmission Modifications in the Production Cost Model

Transmission in the WECC 2028 PCM case provide 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.

5.8.2.2 Coastal Impacts (Modeling)

Considering that all of the OSW integrated in the model is added to the electric system on the Oregon coast, there are transmission impacts that can be observed. These take the form of changes in transmission flows within the model. The transmission system along the coast has limited interconnection to the major transmission lines along the I-5 corridor due to the coastal mountain range in between. There are a few transmission crossings over the mountain range. As described above, the four OSW resource sites are tied in to four separate major 230 kV BPA transmission substations along the coast. These substations are connected to the rest of the state and indeed the region across one of these few transmission crossings. Accordingly, one may expect that these transmission crosses across the coastal range would be bottlenecks to integrate OSW from the coast into the rest of Oregon and the region at large. That said, as discussed in the above sections on curtailments and system impacts, the transmission system appears, based on the model, to integrate at least 2 GW of OSW deployment with minimal curtailment. Per BPA analysis, there is approximately 1 GW of load that can be served locally on the coast, indicating that another 1 GW is transmitted across the coastal range east into Oregon (Randall 2012).

5.8.2.3 Southern Oregon (Port Orford and Reedsport)

In Southern Oregon, the two OSW sites are connected to BPA Rogue and BPA Tahkenitch 230kV substations. Unfortunately, the model is limited in terms of being able to analyze load flows in small regions.[21] Accordingly in order to evaluate localized transmission impacts, the approach taken here is to evaluate load flows across the lines connecting the coast to the I-5 corridor across the coastal range. Figure 27 below identifies the substations of OSW interconnection as well as the lines evaluated for power flow in Table 8 (PacifiCorp 2016).

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[21] A more detailed transmission flow analysis would require power flow modeling.

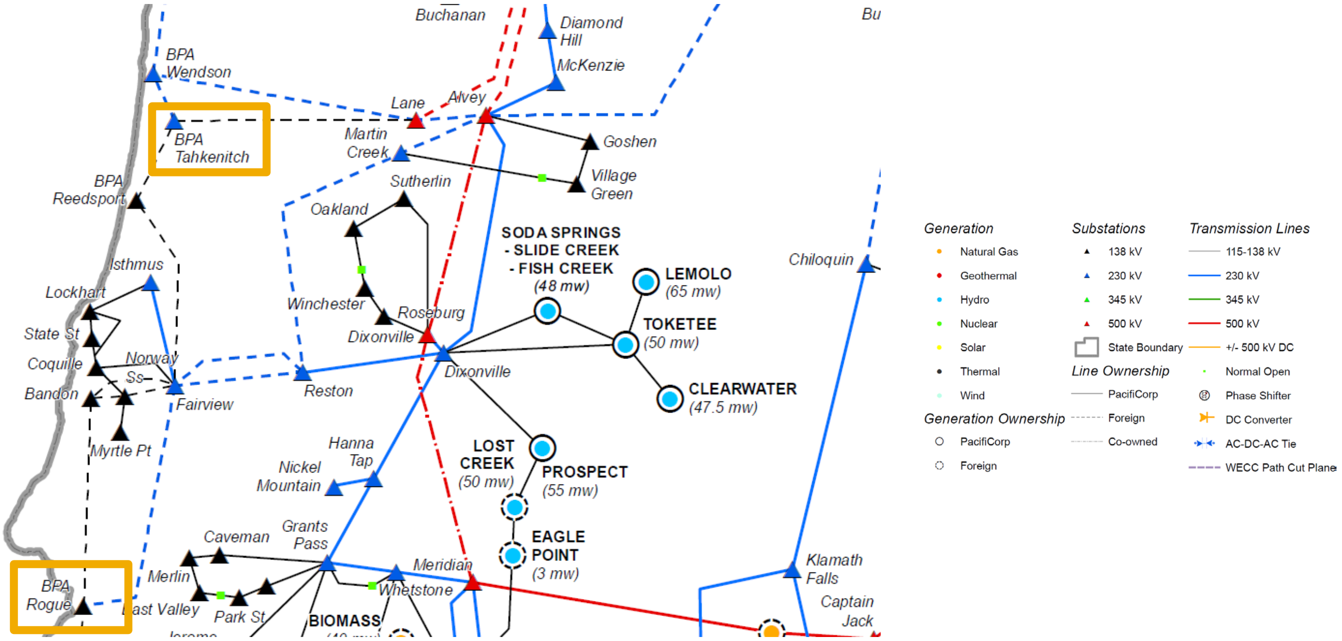

Figure 27. Transmission map for Southern Oregon. OSW interconnection points, Rogue and Tahkenitch substations, highlighted in yellow.

Based on the flows identified in Table 8, the interconnection of 3 GW of OSW creates a significant change in the transmission flows. Loading from the Fairview substation to the Reston substation and along to the Dixonville substation changes direction, both on peak and as a median value. Flow between Reston to Fairview, instead of going west to the coast at a median loading of 79.8 MW, has shifted, going east, away from the coast, at a much higher loading of 370.9 MW as a median value and 636.7 MW as a peak value. Farther north, the transmission flow between the Wendson and Lane substations follows a similar pattern, reversing direction, taking energy east, and at a much higher magnitude. These flow effects also indicate that the OSW generation would serve local loads.

Table 8. Coastal transmission loading for Southern Oregon

	Fairview to Reston	Reston to Dixonville	Lane to Wendson
Normal Loading [MW]			
Median	-79.8	-43.4	46.3
Peak	-199.2	-128.6	90.6
3 GW OSW Loading [MW]			
Median	370.9	253.9	-246.4
Peak	636.7	407.7	-476.8
Positive Direction	east	east	west

Actual loading limits are not public information, and therefore it is difficult to evaluate, based on the flows within the model, exactly how much the transmission system is being congested due to the new generation. However, based on the curtailment analysis from above, the model does seem to allow nearly all of generation to serve load at the 2 GW of OSW level, and most at the 3 GW level.

5.8.2.4 Northern Oregon (Newport and Astoria)

A similar pattern follows for Northern Oregon where OSW is interconnected to the BPA Clatsop and BPA Tillamook 230kV substations. Figure 28 is the transmission map for the area, and Table 9 identifies cross-costal range transmission flows (PacifiCorp 2016).

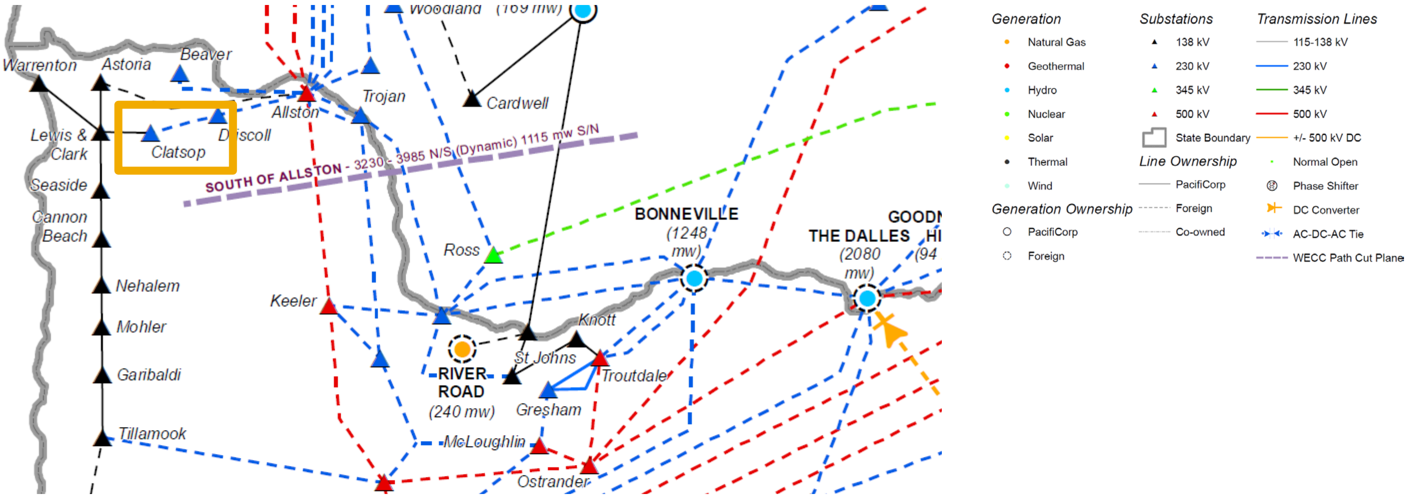

Figure 28. Transmission map for Northern Oregon. OSW interconnection point, Clatsop substation, highlighted in yellow.

Again, as with the southern coast, modeling indicates a significant change in transmission flows going from west to east to deliver the added OSW generation, instead of the typical east to west pattern. The transmission line between Clatsop and Driscoll substations sees a reverse in flow direction and a significant increase in median flow magnitude. As before, these results indicate that the added OSW generation serves local loads. The flow between the Allston substation and the Keeler substation to the south was also considered but does not show much change in north to south flow. This may indicate the added OSW generation is serving local load with some perhaps moving north into Washington.

Table 9. Coastal transmission loading for Northern Oregon[22]

	Clatsop to Driscoll	Allston to Keeler
Normal Loading [MW]		
Median	-41.6	259.3
Peak	-77.4	1121.5
3 GW OSW Loading [MW]		
Median	225.3	220.4
Peak	488.2	1197.1
Positive Direction	east	south

5.8.2.5 BPA Coastal Generation Transmission Analysis

In 2012, BPA conducted a high-level evaluation of the transmission impacts of interconnecting coastal generation resources onto its system at a 69 kV and a 115-kV level (Randall 2012). The modeling here in this study considers interconnection to the BPA system at a 230-kV level, which is potentially capable of significantly higher interconnection capacity. The interconnection analysis found that 2,025 MW of generation could be accommodated along the coast before the system began to overload. This is in line with the curtailment results presented in Table 7. The analysis found that 1,000 MW of the load was absorbed locally on the coast. As it was a high-level analysis, it did not consider several factors a more detailed interconnection study would evaluate including voltage and system stability as well as transmission outside of the area.

5.8.2.6 Regional Impacts (Modeled)

Aside from localized impacts to transmission along the coast and between coastal and inland transmission, the significant deployment of OSW will also have greater regional transmission impacts. Figure 29 below identifies the transmission paths that the WECC considers as the major transmission flow pathways for the region. In particular 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 COI, from Oregon into northern California.

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[22] The default model did not include monitoring for the transmission line between Tillamook and points east.

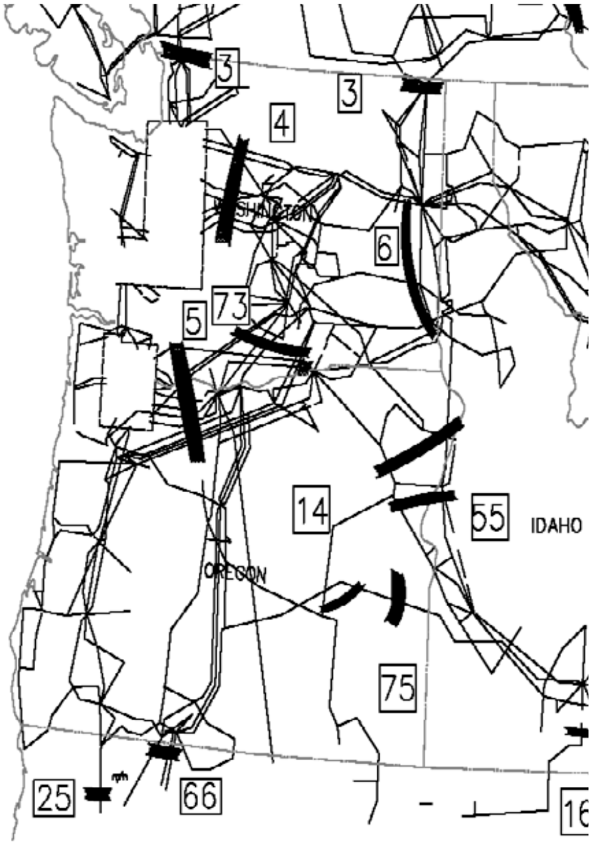

Figure 29. WECC paths for the Northwest. This analysis considers path 5, path 14, path 65 (not indicated on this map) and path 66 (WECC 2013).

Figure 30 below 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 OSW deployment increases, from zero in the base case up to 5 GW, the transmission flows along this path decrease, by about 1 to 1.5 GW for the deployment of 5 GW of OSW depending on the hour of the day. The impacts from 2 GW to 5 GW of OSW deployment are fairly similar in magnitude, with 3 GW, 4 GW and 5 GW being particularly close.

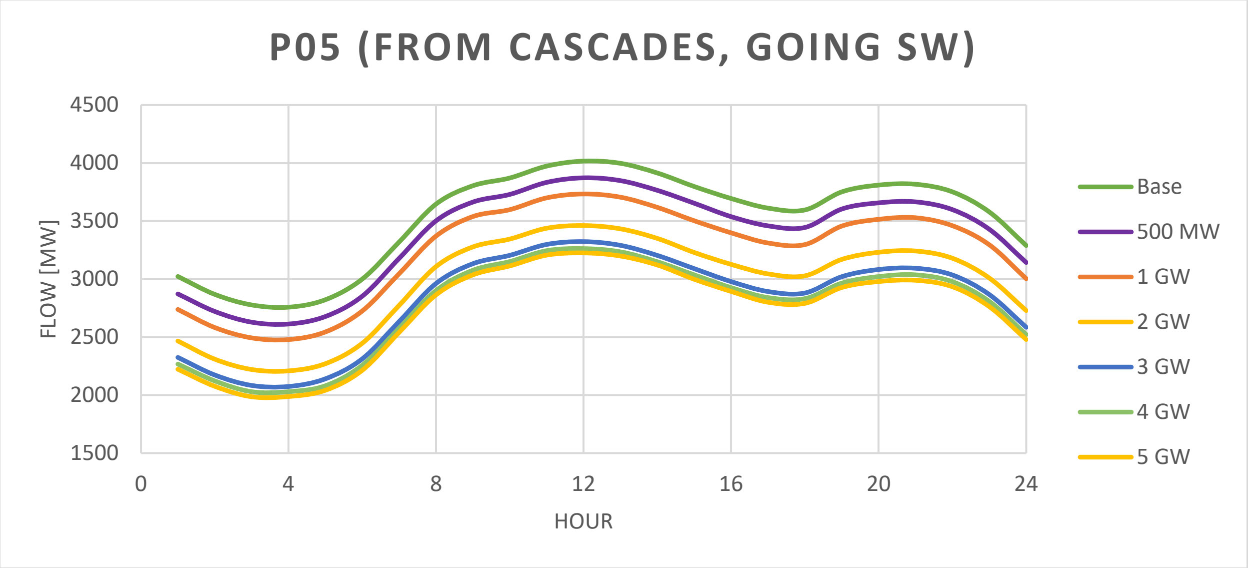

Figure 30. Impacts to daily hourly average flows for each hour of the year from OSW integration on Path 05, the transmission path from the Cascades and the Columbia River Gorge southwest into north/central-west Oregon. Positive direction is flow west.

Figure 31 identifies the daily hourly average flow for every hour of the year 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.

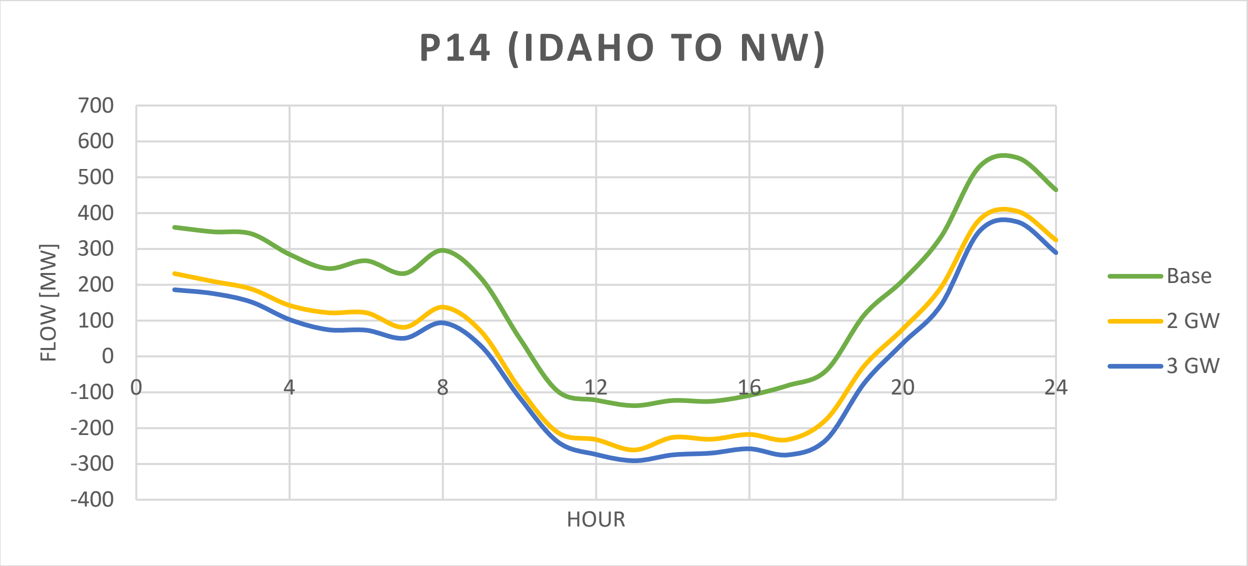

Figure 31. Impacts to daily hourly average flows for each hour of the year from OSW integration on Path 14, the transmission path from Idaho to the northwest into eastern Oregon. Positive direction is flow west into Oregon.

Figure 32 identifies the impact of OSW 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 OSW resource along the coast appears to permit additional flow south to California, on average, from the resources in the area, which are primarily hydroelectric and wind. During mid-day periods, it also appears to reduce imports north from California into Oregon. Both factors indicate that the added OSW resource serves local loads and frees up the system to provide other benefits.

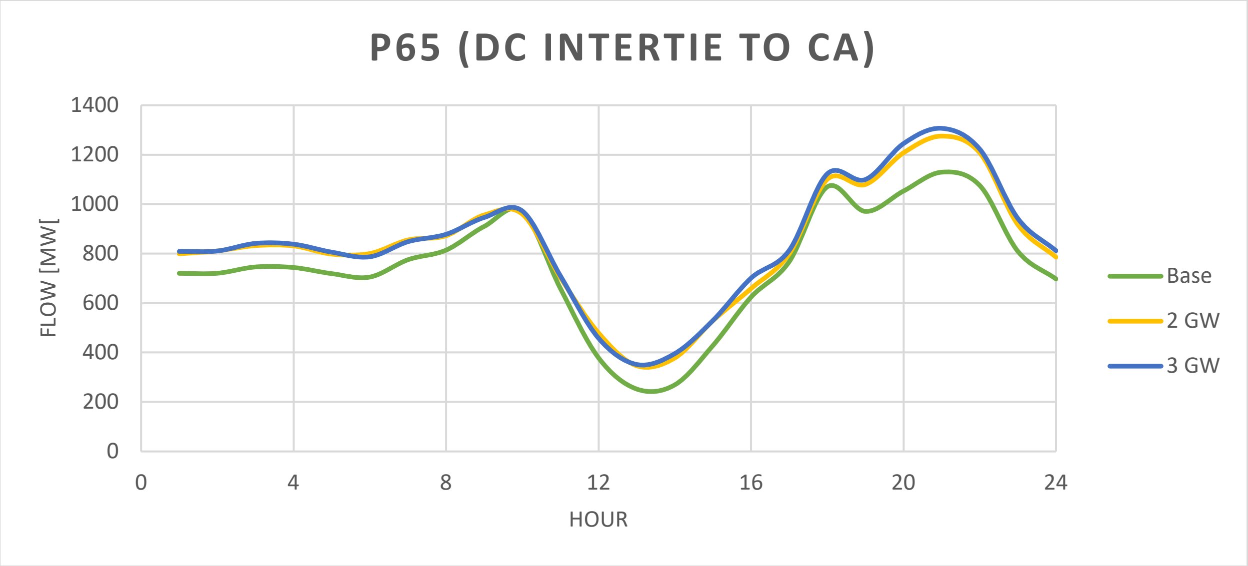

Figure 32. Impacts to daily hourly average flows for each hour of the year from OSW integration on Path 65, the transmission path from the Columbia River Gorge area into Southern California (DC intertie). Positive direction is flow south into California.

Similar to Path 65, Path 66 in Figure 33, is a transmission pathway south into California. However, Path 66, also known as the California Oregon Intertie (COI), consists of 3 500 kV alternating current (AC) lines and enters northern California along the Interstate 5 corridor. Here, the average impacts of the addition of OSW follow a similar pattern, increasing the flow south into California most of the day. Again, as with Path 65, the midday reversal of flow from California into Oregon is reduced. As discussed above, without a detailed power flow analysis, it is difficult to determine where exactly the OSW output goes, but in this instance, as flows along Path 5 have decreased, it appears likely OSW resource power replaces power from the Gorge region and is not only used locally, but also transmitted south.

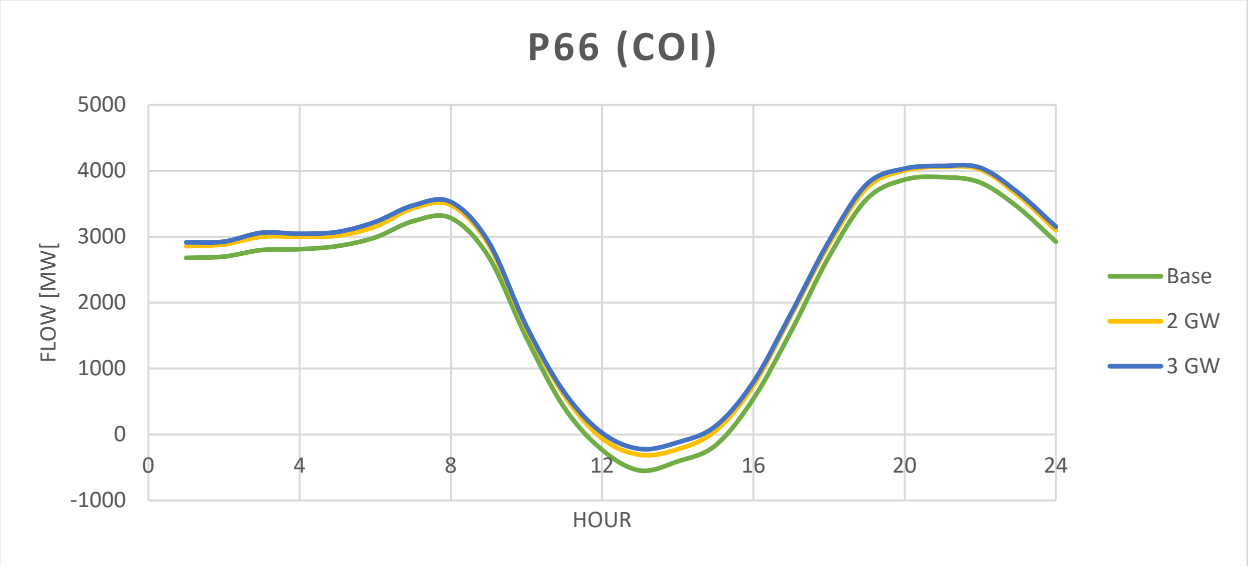

Figure 33. Impacts to daily hourly average flows for each hour of the year from OSW integration on Path 66, the transmission path along the I-5 interstate flowgate path traversing Oregon into northern California. Positive direction is flow south into California.

These results provide some interesting insights. First, the deployment of OSW along the Oregon coast opens up transmission capacity from eastern Oregon and the Gorge into northwest and central Oregon, with an increasing amount of OSW providing increased capacity along the flowgate path (Path 5). This potentially opens up the existing flowgate path to provide additional generation from the Gorge, eastern Oregon and points north and east, such as wind resource-rich Wyoming. This may be a particularly valuable attribute as Oregon and the region shift towards clean energy generation and this additional transmission capacity may permit the delivery of additional renewable energy resources from the east. Second, the flows in Path 5, Path 14, Path 65 and Path 66, across the board, highlight that the added OSW resource is primarily being used within Oregon. Regional flows away from Oregon, that is into California, do not change significantly, and imports from Idaho actually decrease. That said, it does appear that some of the OSW resource is transmitted south into California from Oregon, displacing the resource from the central Gorge region. Third, OSW may serve as an important balance to Columbia Gorge Wind, reducing reliance on Wyoming wind to provide the same balance, which may provide some value in reducing the costs of transmitting that wind from Wyoming into Oregon.

Finally, PacifiCorp serves as the balancing authority and the load serving entity for the PACW area in southwestern Oregon and the PacifiCorp East (PACE) territories in Idaho, Utah and Wyoming, all of which have a considerable resource base. Of course, those regions are relatively remote to southwestern Oregon and accordingly there are transmission limitations between PACW and PACE. OSW 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 up transmission, but also allowing those resources to serve other loads. In addition, as discussed above, OSW opens up the transmission corridor along the Gorge, potentially also permitting PACE energy to be delivered to PACW. Of course, these two benefits may conflict.

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[23] within or between regions, particularly when considering flow from the Gorge to the coast to deliver energy to PUDs and flow south into California. Nonetheless they are insightful in highlighting the potential value to a deployment of OSW on the Oregon coast.

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[23] Several power delivery contracts exist between BPA and PUDs along the coast as well as between other generators and other load serving entities. Neither the impacts nor the implications to these contracts are evaluated.

6.0 Summary

6.1 Grid Value Benefits and Challenges

Based on modeling here and prior efforts from system stakeholders, approximately 2 GW of OSW could be interconnected and transmitted in Oregon's grid today without additional infrastructure investment or significant OSW curtailment, though significant system benefits extend through 3 GW of integration even with some curtailment. The lack of innovative market mechanisms to fully recognize the value that OSW could deliver to Oregon's grid and its coastal communities stands as a barrier to any development. The difficulty in expanding transmission access over the coastal range presents significant challenges to OSW development beyond 3 GW. Without these pieces in place, it is possible that OSW resources off Oregon's coast may be developed for different reasons. For example, OSW development of Oregon's coast could be driven by California which has significantly higher wholesale power prices, larger overall loads, and already has a 100% clean energy standard and cap-and-trade regulation in place.

Based on production cost modeling for the regional power system, there appear to be significant benefits to Oregon from the development of its OSW resource. Though the model does not account for capital or integration costs to deploy the OSW resource, model results indicate yearly generation cost savings total nearly $86 million for 3 GW of OSW deployment resulting from a reduction in fossil fuel plant use. The cost savings are also associated with significant emissions reductions. Further, the deployment of OSW appears to open up transmission capacity from eastern Oregon and the Columbia River Gorge into northwest and central Oregon. This potentially frees the existing transmission corridor to provide additional generation from the Gorge, eastern Oregon and points north and east. This may be a particularly valuable attribute as Oregon and the region shift towards clean energy, as most of the best onshore renewable resources are located east of these transmission constraints. An analysis of coastal transmission flows in addition to regional flows indicates that the OSW energy would serve coastal loads.

Both complementarity with other generation resources, in a general sense, and with load are important facets of capacity value. First, interaction with the hydropower system is qualitatively described. OSW resource consistency was reviewed by month and shown to be more consistent in the late summer and early fall months than terrestrial wind resources. These times of year are those with the lowest availability of hydropower, meaning that OSW could contribute to freeing up that limited hydropower capacity to operate more flexibly to provide a range of services.

Secondly, complementarity with Columbia Gorge wind is demonstrated primarily in the summer but also in the spring. Barring transmission impediments, this relationship indicates that Gorge wind could rely more on OSW resources and less on the hydropower system for balancing. Subsequent reduced reliance on east to west transmission infrastructure frees up transmission for future VRE generation sited in eastern Oregon and Washington. Complementarity of the more southern Oregon OSW resource with the Gorge is a slightly stronger in the fall, timing which coincides with lower hydro resources. This trend should be investigated further at locations south of Port Orford. Complementarity is stronger between OSW and northwest terrestrial wind in the summer. In general, OSW is largely uncorrelated with Wyoming terrestrial wind. Third, OSW shows moderate complementarity with Oregon solar resources in winter, when the region sees most significant loads due to heating, and to lesser extent in the spring and fall. However, in the summer these resources do not align in a statistically significant way and complementarity is better through existing terrestrial resources in the Columbia Gorge, SE Washington, and Wyoming in the summer. Finally, geographic diversity can be seen in differences in correlation between northernmost and southernmost OSW in all seasons.

OSW shows complementarity with load in the winter, spring, and summer. This complementarity is as good as that of Gorge wind and SE Washington wind in these seasons, and even superior in the winter and summer. In the winter, the load complementarity of northern coast OSW with the regional Balancing Authorities BPAT, PGE, and PACW is on par with solar. Solar complementarity with load is superior in the spring, fall, and summer. These naturally occurring complementarities provide important capacity value to the region, which is heightened due to RPS requirements, thermal retirements, and carbon pricing actions.
OSW generation capacity factors are higher than onshore wind and significantly higher than solar. This highlights the value of OSW on a per capacity installed basis. This value is perhaps further enhanced when considering that both onshore wind and solar have significant land use implications that are largely avoided with OSW. Further, during peak hours in the region, these high capacity factors are maintained providing further credence to the value of OSW as a key component of a future resource portfolio.

6.2 Next Steps

The current study, though indicative of the grid values of OSW at a broad scale, has identified the following ways in which additional investigation would further characterize these values:

- **Complementarity of the hydropower system and OSW in the Western Interconnection**. As demonstrated in Section 3.2.1, hydropower complementarity is more appropriate on seasonal and interannual scales, rather than hourly and daily values. The next question is then whether OSW resources may have a negative correlation with hydropower over these longer timeframes and broader geographies, and whether this is a benefit to the regional and western power system, especially in the face of drought or climate change. In Brazil, with very large cascading hydropower systems and extensive coastlines with dominant coastal populations and electric loads, a study analyzed a spatially expansive portfolio of OSW resource regimes for correlation against anticipated river flows in multiple hydrologic regions to find correlations and complementarities between resources (Silva et al. 2016). The Western Interconnection is one interconnected grid with increasing market convergence. A corollary study could investigate complementarity between offshore resources and dominant hydrologic regimes over similarly wide territory rather than in close spatial clusters. In addition, the study should incorporate multi-objective river management and production cost modeling for grid-scale shifts in order to evaluate the potential effects on the complex hydropower system.
- **OSW capacity value through hydropower flexibility for bulk system benefits.** Hydropower can be used for many purposes, including to balance VRE generation and meet peak loads. Capacity of 1 MW of OSW, to the degree it can free hydropower for the most valuable balancing contributions, could enable more than 1 MW of capacity system-wide. A deeper exploration as to the interaction between OSW deployment with the existing hydropower capabilities, independent of further transmission development, would be invaluable. Computation of metrics such as ELCC, ASCC and LOLP may offer insights to various utility planners and transmission operators based on operations today. Evaluation of unit commitment & economic dispatch across the WECC and a consideration of the Energy Imbalance Market may be valuable, particularly for higher penetrations of OSW. Definitions of capacity value out of Docket UM 2011 should also be incorporated.

- **Coastal power flows from interconnection to major transmission corridors**. Power flow modeling. Further analysis of transmission impacts and requirements through power flow modeling would be insightful in understanding the implications of OSW integration on the transmission system and any transmission infrastructure requirements that would be necessary for interconnection. Deeper investigations of coastal power flows from points of interconnection through transmission paths across the Coastal Range should be considered. Review of interconnection alternatives should be considered along the coast.
- **Progression of the resource complementarity study to generation complementarity.** First consider the nuances of power production, including power curves with realistic cut-out wind speeds, air density, and wind direction corrections. In addition to power generation, also include more regional-renewable resources and at different time periods and resolutions. Quantification of impacts on system reserves due to OSW ramping and intermittency characteristics and consideration of the ability of OSW, the existing resource base and new resources to address these reserve requirements. Comparison with solar power and onshore wind ramps and reserve needs.
- **Expansion of the load complementarity study.** Consider sub-hourly load trends, more years of load data, and additional balancing authorities. Incorporate the generation complementarity improvements above to verify trends.

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