



Capacity contributions of Southern Oregon offshore wind to the Pacific Northwest and California

Travis C. Douville^{a,1,*}, Steven Zhou^{b,2}, Jinxiang Zhu^{b,3}, Mark Severy^{c,4}

^a Pacific Northwest National Laboratory, 620 SW Fifth Ave., Suite 810, Portland, OR 97204, USA

^b Hitachi Energy, 901 Main Campus Dr., Raleigh, NC 27606, USA

^c Pacific Northwest National Laboratory, 1100 Dexter Ave. N, Suite 500, Seattle, WA 98109, USA

ARTICLE INFO

Keywords:

Associated System Capacity Contribution
Resource adequacy
West Coast offshore wind

ABSTRACT

Variable renewable energy generation poses unique capacity challenges, which increasingly depend on weather events at varying timescales. Facilitated by transmission planning, geographic and technological diversity of the generation fleet may provide a mitigation to capacity shortfalls. In this work, offshore wind (OSW) energy is sited in the areas off the West Coast between Coos Bay, Oregon, and Crescent City, California. Three generation and transmission scenarios are modeled within the Western Interconnection: (i) 3.4 gigawatts (GW) of installed OSW capacity connected to Southern Oregon through a High Voltage Alternating Current (HVAC) Radial Topology in 2030; (ii) 12.9 GW of installed OSW capacity connected to Washington, Oregon, and California through a High Voltage Direct Current (HVDC) Radial Topology post-2030, and (iii) the same 12.9 GW connected to the same locations through a Multi-terminal DC (MTDC) Backbone Topology post-2030. Zonal dispatch simulations assuming coincident wind, solar, and hydropower production and loads over 18 meteorological years, accounting for temperature-dependent equipment derating and forced outages, serve as inputs to the Associated System Capacity Contribution (ASCC) methodology. The capacity credit is 33%, 25% and 34% for the 2030 HVAC Radial Topology, 2030 + HVDC Radial Topology, and 2030 + MTDC Backbone Topology, respectively. Transmission design is shown to mitigate the typical erosion of marginal capacity contribution as more OSW is developed, underscoring the opportunity for grid modernization while decarbonizing the generation mix.

1. Introduction

Offshore wind (OSW) energy on the U.S. West Coast is a resource that poses system value today through diversification of renewable energy resource portfolios, rather than on a leading cost of energy basis (Younes et al., 2020; Musial et al., 2023). Inherent timing and consistency of power supply from OSW underlie this value, resulting from sea surface boundary conditions and, at times, differing regional weather systems from loads or other generation sources. Interconnection and transmission designs are fundamental to the capture, potential enhancement, and delivery of this system value (Brinkman et al., 2024).

A critical value of resources in future generation mixes in the Pacific Northwest (NW), California (CA), and across the Western Intercon-

tion (WI), which may be less dispatchable than those today, may be found in capacity contributions accrued through bulk transmission systems. Several recent studies have explored capacity contribution potential of offshore wind on the West Coast. Jorgenson et al. (2021) quantified Equivalent Firm Capacity of wind energy across the Western Interconnection and found that OSW offered more than double the capacity of land-based wind. Douville and Bhatnagar (2021) concluded complementarity of Oregon (OR) OSW with NW loads and with other variable renewable energy (VRE) resources in the winter, spring, and summer seasons. Novacheck and Schwartz (2021) quantified OR OSW production during the top 100 load hours across seven meteorological years and concluded capacity credit, or capacity contributions as a fraction of

* Corresponding author.

E-mail addresses: travis.douville@pnnl.gov (T.C. Douville), steven.zhou@hitachienergy.com (S. Zhou), jinxiang.zhu@hitachienergy.com (J. Zhu), mark.severy@pnnl.gov (M. Severy).

¹ 0000-0001-7738-6552

² 0000-0002-1374-2682

³ 0009-0008-8909-4336

⁴ 0009-0004-8125-0083

<https://doi.org/10.1016/j.tej.2024.107407>

Received 6 February 2024; Received in revised form 3 May 2024; Accepted 7 May 2024

1040-6190/© 20XX

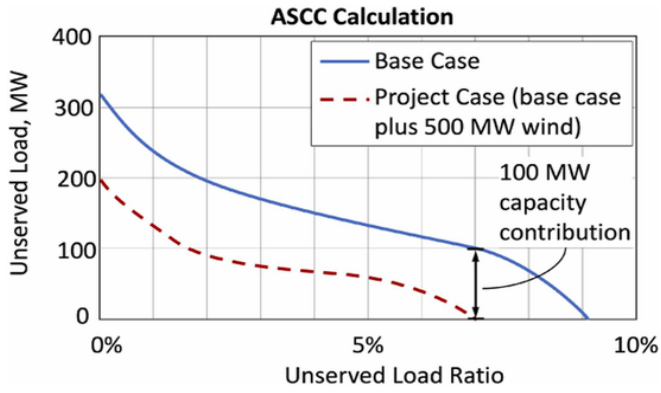


Fig. 1. ASCC example calculation shows top hourly unserved load organized in descending order for an example base case and project case. Figure adapted from NWPCC (2016).

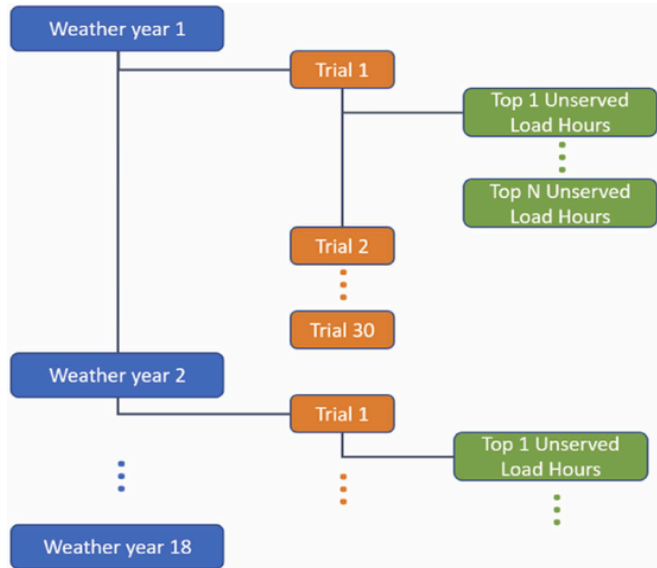


Fig. 2. The relationship between weather years, trials, and unserved load hours which were queried to resolve ASCC.

Table 1
Load scaling for the 2030 HVAC Radial case and the 2030+ HVDC Radial and MTDC Backbone cases.

Topology	Load Scaling	
	CA (%)	NW (%)
2030 HVAC Radial	100	120
2030+ HVDC/MTDC	104	126

nameplate power ratings, averaging 33–62% and increasing from the northern to the southern OR coast.

Despite these investigations of capacity contribution, questions remain around the effects of temperature-dependent technology de-rating factors, forced outages of equipment, coincident supply and demand profiles, and the impact of transmission design on capacity contribution. In this work, siting optimization, intentional transmission design, and novel tool development and deployment in the context of an OSW transmission planning effort were undertaken to further understand the potential OSW capacity contribution on the U.S. West Coast.

Conventional planning practices to ensure sufficient power generation and transmission assets, referred to as resource adequacy (RA), rely upon simulations of hourly power system operation under many different futures, with each future comprised of a set of unknown variables such as temperature, thermal generator performance (including probability of failure), water, wind, and solar power resources, and demand profiles. Typically, these simulations are run stochastically to capture many potential combinations of these variables, and shortfalls in resources to meet loads are tracked within an established reliability criterion, such as a Loss of Load Probability (LOLP) of 0.1 days per year (NERC, 2011). No single definition of capacity has been universally adopted by utilities or regulators (Stencik et al., 2021; Schlag et al., 2020). The most common RA metric, Effective Load Carrying Capacity (ELCC) (Garver, 1966), compares the marginal load that can be supported by a resource to that of a resource that is always available to serve load without transmission limitations. Other approaches include Equivalent Firm Capacity (EFC) (Söder and Amelin, 2008) and the average power production over top net load (load less wind and solar) hours as a proxy for capacity valuation.

However, conventional applications of these RA methods are inadequate for assessing energy supply sufficiency because they (i) do not accurately model supply and demand variability with weather, (ii) do not model all hours of the year, (iii) do not model annual variability, (iv) oversimplify transmission constraints, and (v) do not account for compounding shortfalls of generation due to equipment reliability, fuel supply, and weather.

2. Methodology

In this work, we employ the Associated System Capacity Contribution (ASCC) metric to account for weather variability on equipment de-rates and forced outage rates, regional transmission limitations, and realistic system dispatch conditions of three different representations of OSW in the WI.

2.1. Zonal dispatch model

GridView simulations of dispatch across the WI were utilized in this study at a zonal resolution to allow the faster solution times necessary to achieve adequate sampling across weather years. The regional breakdown of the WI into zones matched the California Public Utility Commission Unified Resource Adequacy and Integrated Resource Plan inputs and assumptions (CPUC, 2019). Across the WI, 24 regions were represented, with eight inside CA.

2.2. Temperature-dependent power production

As power generation fleets shift from dispatchable plants to variable renewable energy assets, resource adequacy becomes more reliant upon weather. Models to estimate the performance of any generator need to incorporate ambient weather conditions that affect the forced outage rate and thermal derating factors of the plants. There are three major effects which must be captured in generator adequacy assessments of emerging systems.

First, forced outage rates of generators of all types vary by weather conditions. Hotter conditions result in greater rates of component failure due to component overheating and resulting material stresses. Extreme cold weather may also drive increased failures by freezing cooling or hydraulic lines.

Secondly, and particularly acute for renewable energy generators and battery assets, equipment must de-rate under weather conditions outside of designed operating profiles. Technology options may expand these operating profiles somewhat, but extreme events such as Winter Storm Uri or Polar Vortex conditions in 2019 have been shown to drive equipment de-rates and even equipment shutoff. Across Balancing Ar-

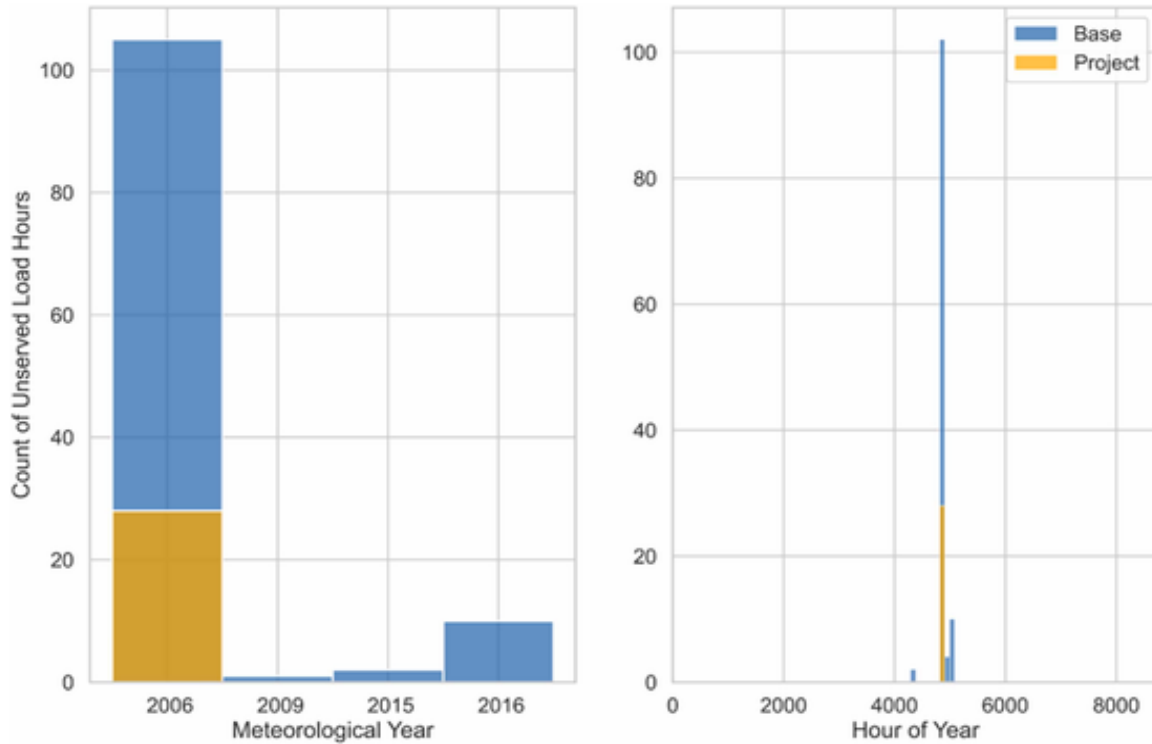


Fig. 3. Weather year and hours resulting in unserved load in California with load scaling of 96% and 111% in California and the Northwest, respectively. Hours per year are sorted chronologically.

eas, even partial equipment de-rates may force widespread adequacy shortfalls. For example in the 2019 Polar Vortex, wind generation fell below expected levels and the Mid-Atlantic Independent System Operator (MISO) declared an emergency load reduction request because the wind power forecast did not account for equipment derating in cold conditions (MISO, 2019). Third, renewable energy generation introduces a direct dependence on natural resources, such as solar irradiance and wind speed, and their variations in time. Demand will also become more weather dependent as heating, cooling, and transportation loads are electrified. The natural variability of resource must be inspected across transmission systems and compared with load patterns. Adequacy reviews should incorporate as many coincident wind, solar, and hydropower energy supply and load profiles as possible to consider the impacts of supply and demand side variability.

These three factors were applied to the production cost model with the following methods:

- Forced outage rate
 - Hydropower - 2.5% outage rate between 0 and 30°C and increasing outside that range, using data from Murphy et al. (2019)
 - Wind - Same values as hydropower from Murphy et al. (2019)
 - Solar - 0% forced outage rate across all temperatures
- Thermal derating
 - Hydropower - No thermal derating
 - Wind - Can operate at full capacity from -20°C to 30°C; derates by 1%/°C from 30°C to 40°C; operates at 0% capacity below -20°C or above 40 °C, based on industry experience.
 - Solar - Solar output decreases linearly with module temperature as

$$P_{output} = P_{rated} * (1 + T_{coeff}(T_{module} - 25^{\circ}C))$$

Using an assumption of

$$T_{coeff} = -0.4\%/^{\circ}C$$

and estimating the module temperature as 28°C higher than ambient temperature in normal operating conditions (1 m/s wind and 800 W/s² solar irradiance) (Ross and Smokler, 1986), the resulting function is

$$P_{output} = P_{rated} * (1 - 0.004^{\circ}C(T_{ambient} + 3^{\circ}C))$$

- Battery storage - Lithium-ion batteries are derated for charging and discharging in low and high temperatures using de-rating strategy described by Sowe et al. (2022).
- Supply and demand-side variability
 - Eighteen coincident hydropower, wind (onshore and offshore), solar, and load profiles of resources across the Western Interconnection spanning all hours from 2000 to 2017, at zonal resolution (CPUC, 2021).

2.3. Associated System Capacity Contribution

The ASCC metric was employed to evaluate the capacity contributions from a resource portfolio at a system level. First described by Northwest Power and Conservation Council (NWPPCC), ASCC measures the change in the peak hourly load curtailment between a base portfolio and a project scenario to determine how a resource portfolio may improve system reliability (NWPPCC, 2016). ASCC allows efficient comparison of multiple scenarios because it evaluates the system-wide change to loss of load probability using one additional series of dispatch simulations instead of the several iterative simulation series required to calculate ELCC.

To calculate the ASCC, the top hourly unserved load hours are extracted from an annual production cost model run for the base case and a project case. This model may be run numerous times with variable,

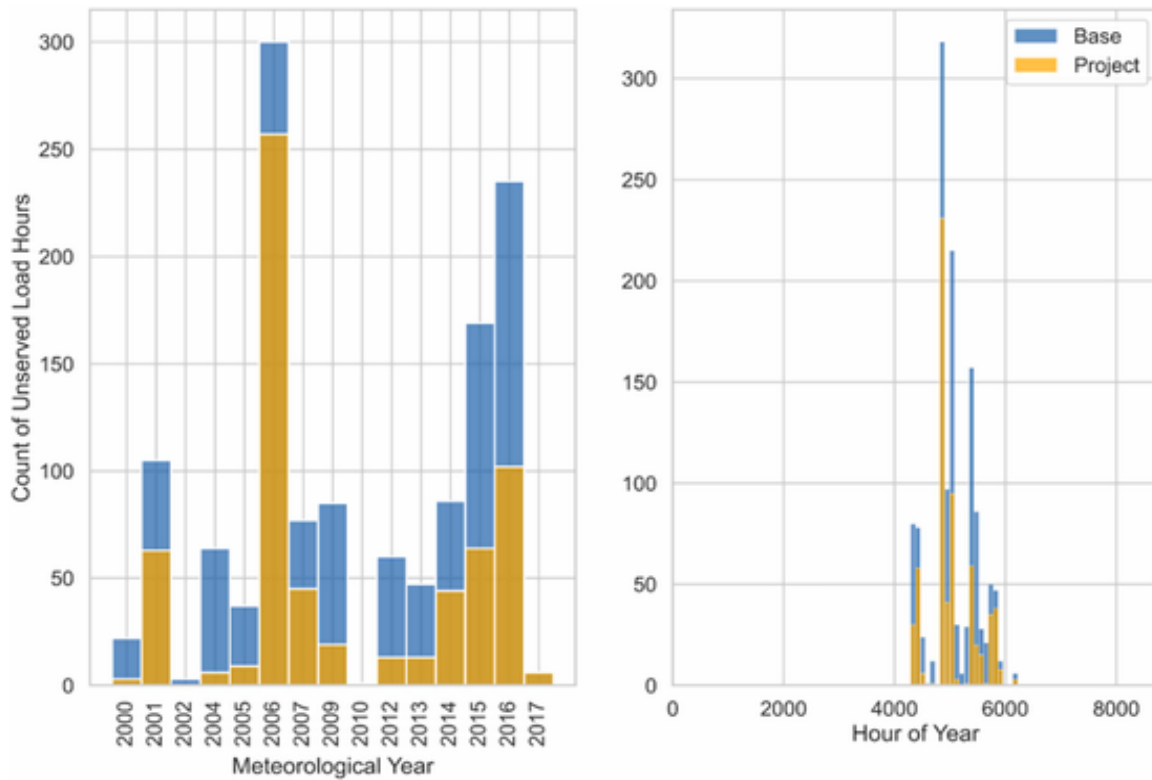


Fig. 4. Weather year and hours resulting in unserved load in California with load scaling of 100% and 120% in California and the Northwest, respectively. Hours per year are sorted chronologically.

Offshore Wind Capacity Contributions to the Pacific Northwest and California

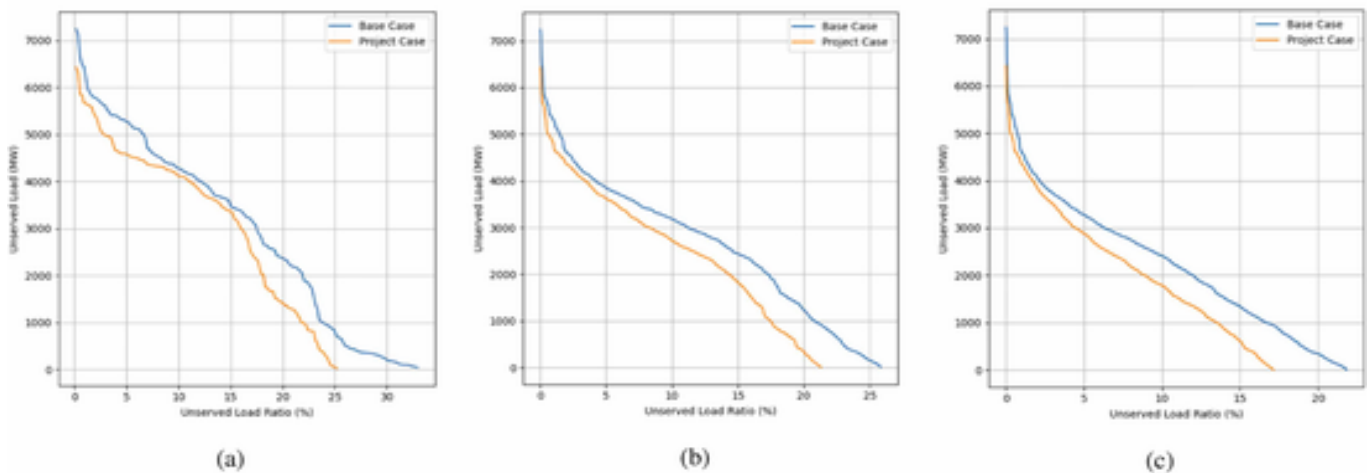


Fig. 5. Sample load curtailment curves for the base case (in blue) and project case (with the OSW increment, in orange) constructed from $N = 1$ (a), $N = 5$ (b), and $N = 10$ (c) top unserved load hours from each trial.

random forced outage rates of generation and transmission assets. From all simulations, the hourly unserved load is then sorted in descending order on a load curtailment duration curve (Fig. 1). One load curtailment curve is generated for each of two cases, the base case and the project case, and the curves are compared. ASCC is found as the difference in lost load between the first point where the project case has zero unserved load and the equivalent location on the base case duration curve. This difference indicates the reduction in unserved load after imple-

menting the changes represented in the project case. In the example shown in Fig. 1, adding 500 megawatts (MW) of wind in the project case drops peak hour curtailment by 100 MW, relative to the base case, for a capacity contribution of 100 MW and capacity credit of 20%.

Several important changes were made in the application of ASCC. First, 18 coincident weather years of wind, solar, hydropower, and load profiles were provided to the zonal dispatch model at hourly resolution. To introduce supply variability and maintain efficient computational

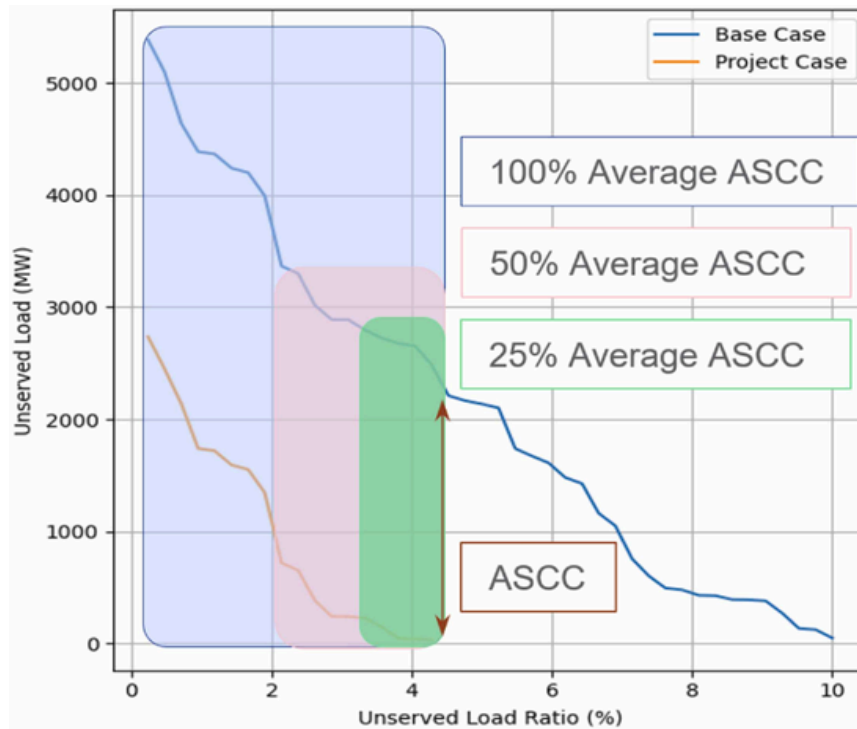


Fig. 6. Various ASCC reduction metrics as a function of overlap interval between the load curtailment curves.

performance, 30 trials, each an 8760-hour annual dispatch simulation with random generator forced outage rates, were executed (Fig. 2). Weather variability across all 18 years drove impactful changes in wind, solar, and hydro supply, including equipment de-rates for wind, solar and energy storage assets.

Second, loads were scaled to generate sufficient unreserved load in the base case as indicated in Table 1. Load scale factors and hydropower dispatch were retained from these base cases when the OSW project cases were assembled. Care was taken to ensure even sampling of weather years and hours of the year to compose the load curtailment curve, and iteration between scale factors and the resulting weather sampling was undertaken. Without proper scaling, disproportionate samples are taken from a subset of weather years and hours, as shown in Fig. 3. Alternatively, once scaled, a more robust sampling is observed (Fig. 4).

Third, and in coordination with load scaling, to leverage the power of multiple years and multiple weather conditions, convergence was explored by considering the top N unreserved load hours from each trial (Fig. 2). The net effect was a smoothing and paralleling of the load curtailment curves, as shown in Fig. 5.

Lastly, averages of the differences at each hour between the two curves were computed for different sets—namely the last 25%, 50%, and 100% of the overlapping hours of unreserved load from both cases—and compared with the single hour ASCC metric, as depicted in Fig. 6. The goal of averaging differences between the curves over multiple hours was to avoid spurious conclusions driven by a localized difference between the two curves arising from only two operating states or weather conditions.

2.4. OSW topologies

2.4.1. Optimized power production footprint

The OSW generation footprint was identified by co-optimizing the energy generation and approximate capacity contribution within geographic boundaries of Florence, OR, to the north, Eureka, CA, to the

south, the state seaward boundary to the east, and the 1300 m bathymetric depth contour to the west. Power generation profiles for these offshore locations on a 2 km x 2 km grid were calculated using hourly modeled wind speed profiles between 2000 and 2019 at 140 m height from Optis et al. (2020) passed through a 15 MW wind turbine power curve with 22% loss factors applied, based on experience with industry resource assessments. Approximate capacity contribution for each location was estimated by finding the unreserved load during the top 175 h of peak net load throughout the year for the balancing authorities on the West Coast in the 2030 Western Electricity Coordination Council (WECC) Anchor Data Set (ADS). The optimal footprint was then found by co-optimizing for the maximum annual energy production and the minimum unreserved load during peak hours. The optimal footprint, named *Opt20* for this analysis, was then split between eight points of interconnection (POIs), by minimizing distance to the POI and constraining power output to POI interconnection capacity (Fig. 7). The optimum footprint was located in federal waters adjacent to OR.

2.4.2. Deployment Scenarios

In this work, OSW energy is primarily sited in the areas off the West Coast between Coos Bay, OR and Eureka, CA. Three generation and transmission scenarios across two future representations of the WI are modeled, including 3.4 gigawatts (GW) of installed OSW capacity connected through a 2030 high voltage alternating current (HVAC) Radial Topology, 12.9 GW of installed OSW capacity connected through a 2030+ high voltage direct current (HVDC) Radial Topology, and 12.9 GW of installed OSW capacity connected through a 2030+ multi-terminal high voltage direct current (MTDC) Radial Topology (Fig. 8).

A base case for comparison is developed for each topology, as summarized in Table 2. The base case for the 2030 HVAC scenario is built from WECC's 2030 Anchor Data Set (ADS), which constitutes utility projections of generation and transmission fleets by the year 2030. For the 2030+ topologies, the base case was updated to account for an additional 15 GW of land-based wind, 20 GW of solar energy, and 3.8 GW of offshore wind interconnected through Diablo Canyon. These incre-

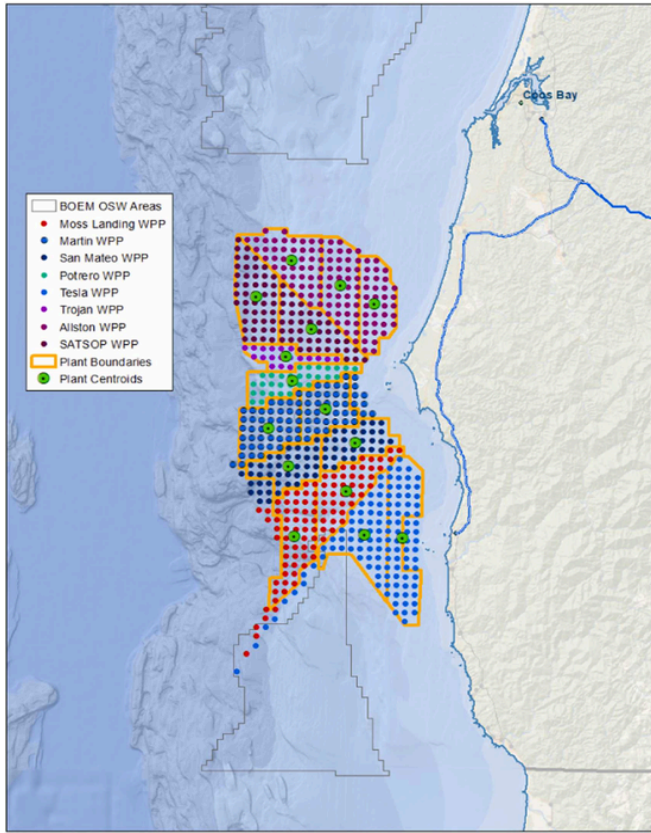


Fig. 7. Opt20 footprint split among eight wind power plants (WPPs) associated with specific onshore POIs to minimize transmission cost.

ments are realistic changes to the generation portfolio in WECC beyond 2030 that are likely to emerge simultaneously with further OSW plant development in Northern CA and Southern OR. Generator capacity growth was limited to the bounds of existing transmission networks,

such that individual plants did not surpass an uneconomic curtailment threshold, which was assumed at 15%. In addition, the base case was modified to add a new Collinsville substation in accordance with California Independent System Operator (CAISO) studies (CAISO, 2022). Lastly, OSW generation from the 2030 HVAC Radial Topology scenario was included in the 2030+ base case. Total WECC generator capacity additions in the 2030+ base case are 38.4 GW, 7.2 GW of which correspond to OSW generation. Including the base cases, the 2030+ topologies include a total of 20.1 GW of West Coast OSW. These scenarios were constructed as reasonable representation of OSW generation and transmission designs for the West Coast from 2030 and beyond. Though the marginal capacity contribution of each scenario can be compared as the base case changes, only the two 2030+ scenarios, with the same base case, can be directly compared. After constructing the nodal models, a zonal aggregation was completed. Then, loads, wind, solar, and hydropower profiles were replaced with coincident data from CPUC (2021) to represent many weather years.

3. Results

ASCC trends for the OSW additions in the 2030 HVAC Radial Topology, 2030+ HVDC Radial Topology, and the 2030+ MTDC Backbone Topology are indicated in Tables 3, 4, and 5, respectively. Convergence in ASCC was found when using the top 10 unserved load hours from the 30 trials to generate the load curtailment curves. Load curtailment curves for $N = 10$ with ASCC25% statistics are provided in Fig. 9.

After reviewing these results along with the load curtailment curves, the Average ASCC of the final 25% of hours (ASCC25%) was chosen to capture a more statistically robust measure of capacity by drawing from many more samples. ASCC taken as the offset of the two load curtailment curves in a single hour was subject to variability due to slope deviation observed in some curves near the zero unserved load crossing. However, proximity of the ASCC25% metric to the zero crossing was also more closely aligned than ASCC50% or ASCC100% with near-zero LOLP planning targets of electricity systems today.

Capacity contributions were tracked separately in CA and the NW regions as capacity plans are currently made separately for these regions. Though the same OSW generation was shown to provide a capacity contribution to CA and the NW (based on transmission capacity and

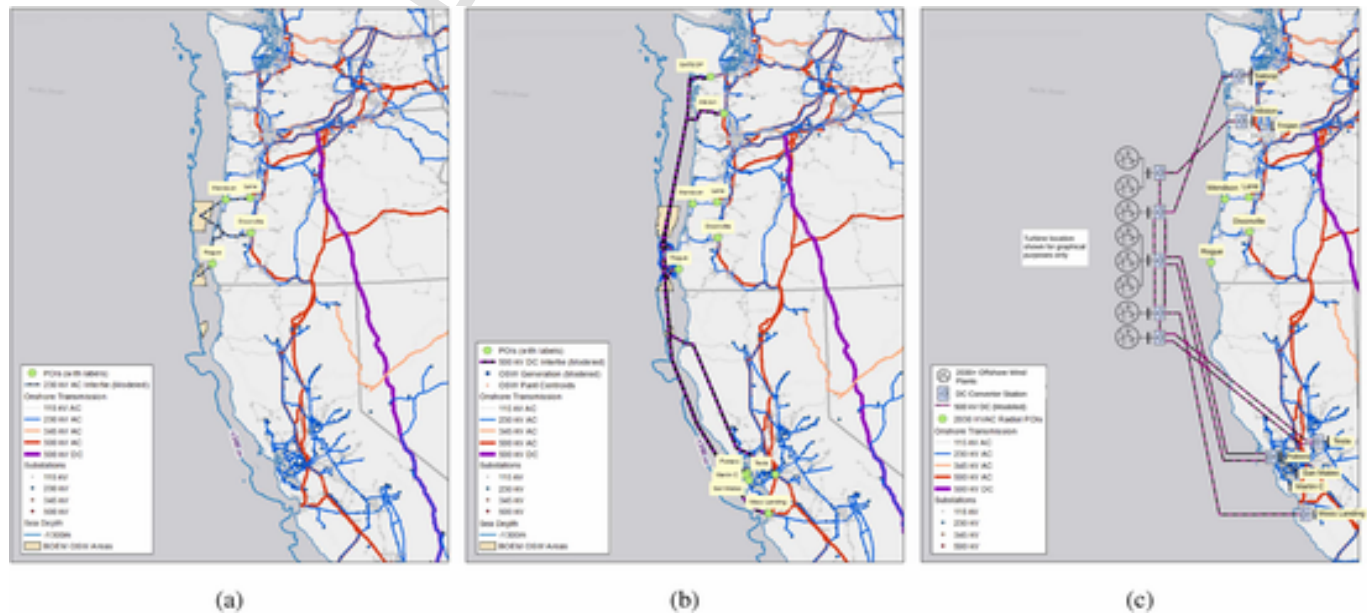


Fig. 8. Generation and transmission topologies. (a) 2030 Radial HVAC Topology, (b) 2030+ Radial HVDC Topology, (c) 2030+ MTDC Backbone.

Table 2
Overview of study topologies.

Topology	Base Case	Base Case OSW (GW)	New OSW (GW)	Total West Coast OSW (GW)
2030 HVAC Radial	2030 ADS	0	3.4	3.4
2030+ HVDC Radial	2030 ADS+	7.2	12.9	20.1
2030+ MTDC Backbone				

Table 3
ASCC Trends 2030 HVAC Radial Topology (+3.4 GW OSW). Bolded values selected as representative.

Top N Unserved Load Hours	ASCC (MW)	Average ASCC 25% (MW)	Average ASCC 50% (MW)	Average ASCC 100% (MW)
CA				
1	1074	1072	1046	1137
3	1054	990	942	1159
5	1062	997	946	1238
10	1152	1119	1132	1391
20	1213	1196	1200	1426
NW				
1	954	850	819	865
3	1061	936	913	865
5	1096	971	924	841
10	1081	964	886	801
20	999	918	844	776

Table 4
ASCC Trends 2030+ HVDC Radial Topology (+12.9 GW OSW). Bolded values selected as representative.

Top N Unserved Load Hours	ASCC (MW)	Average ASCC 25% (MW)	Average ASCC 50% (MW)	Average ASCC 100% (MW)
CA				
1	2251	2169	2153	2711
3	2576	2560	2604	2915
5	3063	3001	3039	3227
10	3180	3162	3171	3303
20	3203	3181	3181	3308
NW				
1	676	856	640	527
3	870	902	733	535
5	915	875	709	525
10	938	751	694	540
20	891	797	768	613

Table 5
ASCC Trends 2030+ MTDC Backbone Topology (+12.9 GW OSW). Bolded values selected as representative.

Top N Unserved Load Hours	ASCC (MW)	Average ASCC 25% (MW)	Average ASCC 50% (MW)	Average ASCC 100% (MW)
CA				
1	2251	2169	2153	2711
3	2576	2560	2604	2915
5	3063	3001	3039	3227
10	3180	3162	3171	3303
20	3203	3181	3181	3308
NW				
1	4190	4238	4385	4469
3	4306	4361	4448	4509
5	4373	4392	4473	4521
10	4373	4393	4474	4521
20	4373	4393	4474	4521

differences in hours of net load peaks between the two regions, CA net load peaks in summer evenings, NW net load peaks in winter mornings and evenings), only the contributions to one region would be available to the system. In an accompanying technoeconomic valuation, which

estimated avoided costs of combustion turbine procurement and operation, assuming such a turbine would be used for capacity only, the maximum contribution between the two regions was utilized (Douville et al., 2023). It was assumed that this capacity resource could serve whichever regional need was higher. Both assumptions differ from how capacity is procured within regions today. However, the assumptions were consistent with the system-wide valuation approach and are not unlike assumptions of perfect capacity resources in other methods.

4. Discussion

As with the addition of any new variable resource to the generation mix with a unique temporal profile, the system capacity contribution of the initial 3.4 GW of OSW associated with the 2030 HVAC Radial Topology is substantial. The capacity credit of 33% or 28% to CA or the NW, respectively, is similar to previous findings in the literature (Jorgenson et al., 2021; Novacheck and Schwartz, 2021).

Typically, an erosion of marginal capacity credit accompanies the growth of the new resource type by technology and location, as every additional MW added to the generation mix reduces the value associated with increased diversity of the resources over all hours of the year. This effect is also seen in the ASCC results as the capacity credit drops in the 2030+ HVDC Radial Topology findings to 25% or 6% to CA or the NW, respectively.

However, the MTDC Backbone acts as a hedge against the capacity credit erosion, without any change to the OSW generation footprint or the Points of Interconnection onshore. Instead, the transmission change from HVDC radial to MTDC backbone enables greater flexibility to deliver OSW and other generation to CA or the NW as needed. In this sense, the recovery of capacity credit is not attributed to OSW alone but to the supporting transmission which further enhances the sharing of all surplus resources during moments of system stress. The production profile of radially-connected 2030+ OSW offers a better match to CA summer net load peaks than NW winter net load peaks. With the addition of the backbone, the NW sees the rise in capacity contributions as non-OSW generation flows north during winter net load peaks.

As a key assumption of this work, the dispatch of west coast hydropower resources from the base cases (with less OSW) was retained in the project cases. This was to avoid the masking of the capacity contribution by hydropower, which was modeled as a zero-cost resource and may be dispatched during time periods associated with potential supply shortfalls. Due to this assumption, capacity contributions to CA with the backbone are likely underestimated. Future work could investigate sensitivity to this assumption by incorporating more detailed economic dispatch linked to the hydropower resource in the base and project cases separately, considering reservoir levels and flood control. The decreasing flexibility of hydropower due to precipitation shifts and operating requirements may be important considerations in this effort.

5. Conclusions

In the near-term, OSW on the West Coast will not be justified in the generation mix based on cost of energy alone, but it offers a compelling capacity contribution in a time of need. In this work, 18 years of coincident wind (onshore and offshore), solar, and hydropower generation and load profiles, including temperature-dependent generator forced outage rates and de-rates, were included in the calculation of ASCC of Southern OR OSW to transmission grids in CA and the NW. Modifications to the ASCC method were proposed and demonstrated, including alternate calculations of offsets between two load curtailment curves, which significantly alter the capacity conclusions. Initial OSW development will capitalize on the uniqueness of the temporal profile and the inherent timing of production and 3.4 GW of radially-connected OSW provides a 1.12 GW capacity contribution, equivalent to a capacity credit of 33%. Eventually, marginal capacity contribution from OSW

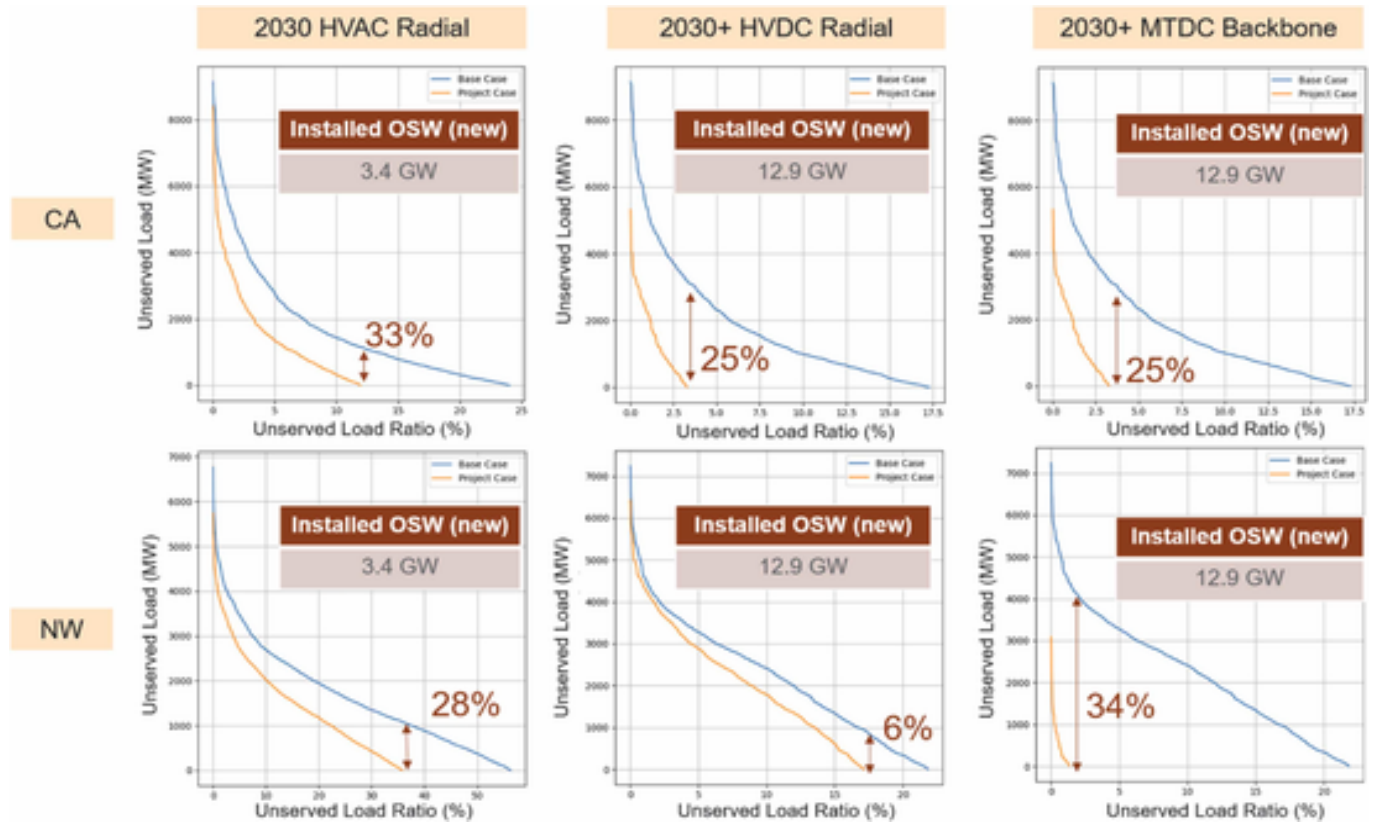


Fig. 9. Load curtailment curves and ASCC25% findings for CA (top row) and the NW (bottom row). Maximum capacity credits are 33%, 25% and 34% for the 2030 HVAC Radial Topology (left column), 2030 + HVDC Radial Topology (middle column), and 2030 + MTDC Backbone Topology (right column), respectively. The base case is shown in blue and project case (with the OSW increment) in orange.

alone will decay as shown in a maximum capacity credit of 25%. However, intentional design of transmission, which enables coordination of OSW delivery to shore and bolsters the connectivity of other resources across the West, is shown to recover the initial capacity credit, providing significant system benefit of an additional 28% capacity credit to the NW over radial interconnections. In this way, OSW generation and transmission is demonstrated to offer a compelling opportunity to both decarbonize and modernize the West Coast grid toward clean and reliable operation.

CRedit authorship contribution statement

Steven Zhou: Visualization, Software, Methodology, Formal analysis, Data curation. **Jinxiang Zhu:** Supervision, Software, Methodology, Formal analysis. **Travis Douville:** Writing – original draft, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Mark Severy:** Writing – review & editing, Methodology, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are grateful to the support extended from the National Offshore Wind Research and Development Consortium and the Bureau of Ocean Energy Management, which funded this work under Contract

Number 108 and Interagency Agreement M22PG00006/P00003, respectively. Discussions with staff at the Northwest Power Conservation Council guided the application of ASCC. WECC's 2030 Anchor Data Set 2030 served as the starting point for all scenarios modeled.

References

- Brinkman, G., Bannister, M., Bredenkamp, S., Carveth, L., Corbus, D., Green, R., Lavin, L., Lopez, A., Marquis, M., Mowers, J., Mowers, M., Rese, L., Roberts, B., Rose, A., Shah, S., Sharma, P., Sun, H., Wang, B., Vyakaranam, B., Huang, Z., Harris, K., Qin, C., Samaan, N., Elizondo, M., Nguyen, T., Nguyen, Q., Guddanti, K., Royer, P., Beretados Reis, F., Siddiqui, S., Nekkhalapu, S., Abdelmalak, M., 2024. Atlantic Offshore Wind Transmission Study. Technical Report.
- CAISO, 2022. 2021-2022 Transmission Plan. Technical Report.
- CPUC, 2019. Unified Resource Adequacy and Integrated Resource Plan Inputs and Assumptions - Guidance for Production Cost Modeling and Network Reliability Studies. Technical Report.
- CPUC, 2021. SERVM Model Input Data for Hybrid Conforming Aggregated LSE Portfolio 2030 Studies. Technical Report.
- Douville, T.C., Bhatnagar, D., 2021. Exploring the grid value of offshore wind energy in Oregon. *Energies* 14, 4435.
- Douville, T.C., Severy, M., Datta, S., Siddiqui, S., He, L., Oikonomou, K., Nekkhalapu, N., Boff, D., Maharjan, M., Nguyen, Q., Harris, K., Zhu, J., Zhou, S., Moore, M., Henry, B., Busch, J., 2023. An Offshore Wind Energy Development Strategy to Maximize Electrical System Benefits in Southern Oregon and Northern California. Technical Report BOEM 2023-067.
- Garver, L., 1966. Effective load carrying capability of generating units. *IEEE Trans. Power Syst.* 85, 910–919.
- Jorgenson, J., Awara, S., Stephen, G., Mai, T., 2021. A systematic evaluation of wind's capacity credit in the western united states. *Wind Energy* 1–15.
- MISO, 2019. Preliminary MISO January 30-31 Maximum Generation Event Overview. Technical Report.
- Murphy, S., Sowell, F., Apt, J., 2019. A time-dependent model of generator failures and recoveries captures correlated events and quantifies temperature dependence. *Appl. Energy* 253, 113513.
- Musial, W., Spitsen, P., Shields, M., Hernando, D., Hammond, R., Marquis, M., King, J., Sathish, S., 2023. Offshore Wind Market Report: 2023 Edition. Technical Report.

- NERC, 2011. Methods and Model to Calculate Capacity Contributions of Variable Generation for Resource Adequacy Planning. Technical Report.
- Novacheck, J., Schwartz, M., 2021. Evaluating the grid impact of Oregon offshore wind. Technical Report NREL/TP-6A40-81244. NREL. Golden, CO.
- NWPCC, 2016. Seventh Northwest Conservation and Electric Power Plan. Technical Report 2016-02. Portland, OR.
- Optis, M., Rybchuk, A., Bodini, N., Rossol, M., Musial, W., 2020. 2020 Offshore Wind Resource Assessment for the California Pacific Outer Continental Shelf. Technical Report NREL/TP-5000-77642. NREL. Golden, CO.
- Ross Jr., R.G., Smokler, M., 1986. Electricity from Photovoltaic Solar Cells: Flat-plate Solar Array Project Final Report. Volume VI: Engineering Sciences and Reliability. Technical Report. NASA.
- Schlag, N., Ming, Z., Olson, A., Alagappan, L., Carron, B., Steinberger, K., Jiang, H., 2020. Capacity and Reliability Planning in the Era of Decarbonization: Practical Application of Effective Load Carrying Capability in Resource Adequacy. Technical Report. E3.
- Söder, L., Amelin, M., 2008. A review of different methodologies used for calculation of wind power capacity credit. In: 2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, IEEE, Pittsburgh, PA.
- Sowe, J., Barreras, J., Schimpe, M., Wu, B., Candelise, C., Nelson, J., Few, S., 2022. Model-informed battery current derating strategies: Simple methods to extend battery lifetime in islanded mini-grids. *Energy Storage* 51, 104524.
- Stenclik, D., Bloom, A., Cole, W., Acevedo, A., Stephen, G., Tuohy, A., 2021. Redefining resource adequacy for modern power systems. Technical Report. ESIG. Reston, VA.
- Younes, A., Severy, M., Chamberlin, C., Guerrero, I., Alstone, P., 2020. California North Coast Offshore Wind Studies: Electricity Market Revenue Study. Technical Report.



Travis Douville leads wind energy grid integration research at Pacific Northwest National Laboratory (PNNL). In May 2023, he planned and launched, with a multi-lab team, the Department of Energy (DOE) West Coast OSW Transmission Study. From 2021–2023, he joined a DOE team to develop the Atlantic OSW Transmission Action Plan and led the development of a strategy to maximize system value of West Coast OSW energy. In 2020, he led the first grid integration study of OSW off the Oregon coast. He joined PNNL in 2019 from the US wind energy industry, where he anchored over 800 megawatts of turbine supply contracts and managed Balance of Plant value engineering.



Dr. Steven Zhou has 10 years of experience in research and consulting relating to power system operation modeling and optimization. His research and consulting experience includes capacity expansion, ASCC/APC calculations, asset extreme weather risk modeling, dynamic ampacity rating, and transient study. He is now working as Senior Engineer in the Power Consulting of Hitachi Energy.



Dr. Jinxiang Zhu has 27 years of experience in energy consulting related to electricity markets, utility economics, power systems operation and planning. His consulting experience includes LMP forecasting, LOLE calculation, CRR evaluation and allocation, transmission and generation planning, renewable integration study, hydro optimal scheduling, economic benefit assessment, and reliability analysis, etc. He is the Consulting Director in the Power Consulting of Hitachi Energy. Dr. Zhu actively worked with WECC and CAISO for Production Cost simulation study.



Mark Severy is a research engineer working within the Coastal Sciences Division at Pacific Northwest National Laboratory. Mark is a licensed mechanical engineer and excels in interdisciplinary projects combining energy, environment, technology, and policy. His work at PNNL focuses on addressing some of the challenges of offshore wind energy development in the United States. In particular, Mark works on projects to understand the environmental effects from offshore wind, develop technologies to monitor marine wildlife, characterize offshore wind speeds with measurements from a buoy, and analyze the electrical transmission system's capability to interconnect large amounts of offshore wind generation. Outside of the ocean environment, Mark has done analysis and design across a range of other renewable energy technologies including, solar, wind, microgrids, and biomass energy.