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1 National Renewable Energy Laboratory
2 Veer Renewables

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Strategic Partnership Project Report
NREL/TP-5000-90770
OCS Study BOEM 2024-038
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List of Acronyms

BOEM	Bureau of Ocean Energy Management
CapEx	capital expenditures
CETA	Clean Energy Transformation Act
COD	commercial operation date
FCR	fixed charge rate
FLORIS	FLOw Redirection and Induction in Steady State
FORCE	Forecasting Offshore wind Reductions in Cost of Energy
GCF	gross capacity factor
GW	gigawatt
IEA Wind	International Energy Agency Wind Technology Collaboration Programme
km	kilometer
kV	kilovolt
kW	kilowatt
LCOE	levelized cost of energy
m	meter
MW	megawatt
MWh	megawatt-hour
MYNN	Mellor-Yamada-Nakanishi-Niino
NDBC	National Data Buoy Center
NCF	net capacity factor
NOAA	National Oceanic and Atmospheric Administration
NOW-23	2023 National Offshore Wind dataset
NREL	National Renewable Energy Laboratory
NRWAL	NREL Wind Analysis Library
O&M	operations and maintenance
OpEx	operational expenditures
ORBIT	Offshore Renewables Balance-of-system and Installation Tool
PBL	planetary boundary layer
PNUCC	Pacific Northwest Utilities Conference Committee
POI	point of interconnection
RFP	request for proposals
S&I	staging and integration
WCMAC	Washington Coastal Marine Advisory Council
WOMBAT	Windfarm Operations and Maintenance cost-Benefit Analysis Tool
YSU	Yonsei University

Executive Summary

The state of Washington must double its clean electricity supply by 2050 to meet its clean energy goals and comply with the Clean Energy Transformation Act (Carlyle et al. 2019; Washington State Department of Commerce 2020; Furze et al. 2023). Although hydroelectric generation capacity is likely to remain a part of Washington's renewable energy mix, it is unlikely to keep pace with the state's increasing energy demand (and future hydroelectric capacity may decrease from dam removal or drought). The expansion of the state's non-hydropower renewables, such as land-based wind and photovoltaic solar will likely play a major role in filling the clean electricity gap. However, the demand requirements are immense and additional renewable energy resources may still be needed. With more than 6.6 gigawatts of technical[1] resource potential in federal waters where the Bureau of Ocean Energy Management has leasing authority, offshore wind energy could play an important role in diversifying Washington State's clean energy mix, reducing dependence on out-of-state energy sources, and helping meet state decarbonization goals (National Renewable Energy Laboratory [NREL] 2023; Zuckerman et al. 2023).

Decision makers need technology-specific information to assist with long-term energy system planning, so the Bureau of Ocean Energy Management requested that the National Renewable Energy Laboratory provide an overview of several drivers of offshore wind energy feasibility and cost in Washington. This study summarizes some of the existing engagement efforts and perspectives on offshore wind energy in the region and quantifies the offshore wind resources in Washington as well as technology costs and performance of potential projects. Furthermore, this report reviews existing grid and port infrastructure and discusses infrastructure needs along with information gaps. This study also explores opportunities and barriers to Washington entities supporting the broader floating offshore wind energy supply chain along the U.S. West Coast. Note that this study is not part of a formal project planning process or official engagement effort; it also does not assess environmental or economic impacts from potential offshore wind energy development.

Being in the early stages of exploring potential offshore wind energy deployment in Washington means there is an opportunity to design decision-making and development processes that are suited for the state, including meeting the needs and protecting the interests of key parties like Tribes and fishers. However, the experiences of those in other West Coast states and uncertainty about what is being planned for Washington are shaping perspectives about offshore wind energy and may present roadblocks to future actions. Any potential wind energy development in federal waters offshore Washington would require broad and effective coordination between federal and state agencies, Tribal governments, ocean industries, environmental groups, coastal communities, and others.

Independent of in-state offshore wind energy development, Washington is well-positioned to participate in the emerging floating offshore wind energy supply chain and support early projects in other West Coast states. Limited portside infrastructure on the West Coast means Washington ports will likely be needed for domestic production of floating offshore wind energy components

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[1] Lopez et al. (2012) define technical resource potential as "the achievable energy generation of a particular technology given system performance, topographic limitations, environmental, and land-use constraints."

and project-related infrastructure (Shields et al. 2023a). Although Washington has many assets, including workforce, existing industries, and portside infrastructure, that can be part of the floating offshore wind supply chain, there are several knowledge gaps that could impact the timing of deployment and overall contribution needed. Continued in-state and regional coordination and collaboration are needed to maximize Washington's potential to contribute to the buildout of a sustainable and cost-competitive floating offshore wind energy supply chain on the West Coast and attract a larger share of global floating offshore wind energy supply chain investments. Doing so could help drive cost reductions for potential future in-state offshore wind energy projects.

While Washington was included in a recent nationwide offshore wind energy cost assessment (Fuchs et al. 2024), there has never been an analysis of how unique regional drivers may impact offshore wind energy cost and performance. This study enhances cost and performance data by validating wind resource models with measurements and applying a correction factor to account for a bias due to planetary boundary layer choice on net capacity factor estimates. For most of the offshore region of interest, the correction factor is on the order of 3% and is treated as a loss in the performance estimates. Furthermore, this analysis more closely examines infrastructure assumptions, which serve as inputs to the cost models. These include both potential points of interconnection and ports used for staging, integration, and maintenance activities.

The consideration of site-specific metocean conditions, grid and port infrastructure, and capacity factor corrections results in the best understanding of floating offshore wind energy levelized cost of energy (LCOE) and net capacity factors in Washington to date. The study presents several scenarios for how costs may evolve between 2035 and 2045 using bottom-up modeling and learning curve projections. These scenarios (conservative, mid, and advanced) are intended to reflect how costs may evolve over time with different levels of global floating offshore wind energy deployment, technology innovation, and supply chain investment. Resulting mean, minimum, and maximum unsubsidized LCOE values and mean net capacity factors for the mid scenario are summarized in Table ES-1. Under the 2035 mid scenario, we find floating offshore wind energy LCOE in Washington ranges from \$175/megawatt-hour (MWh) to \$235/MWh, with a mean value of \$206/MWh, using the International Energy Agency Wind Technology Collaboration Programme 15-megawatt reference turbine (Gaetner et al. 2020). Table ES-1 indicates that we expect mean floating offshore wind energy LCOE to decrease 21% between 2035 and 2045 in Washington from \$206/MWh to \$162/MWh as the industry matures.

Table ES-1. Summary of LCOE and Net Capacity Factor Results Across All Sites Under the Mid Scenario

Year	Mean LCOE (\$/MWh)	Minimum LCOE (\$/MWh)	Maximum LCOE (\$/MWh)	Mean Net Capacity Factor (%)
2035	206	175	235	36
2040	174	148	198	36
2045	162	138	184	37

The cost estimates presented in Table ES-1 are higher than in much of Oregon and California, where the wind resources are stronger. Based on the 2023 National Offshore Wind dataset (NOW-23) (Bodini et al. 2023), mean wind speeds at 160 meters (m) above sea level in Washington are similar to resource estimates for the Gulf of Mexico and South Atlantic regions, ranging from 7 meters per second (m/s) to just under 9 m/s.

Figure ES-1 shows the spatial distribution of 2045 LCOE under the mid scenario. The locations with the lowest cost of energy are offshore Grays Harbor in the central portion of the analysis domain (confined to waters where the Bureau of Ocean Energy Management has leasing jurisdiction with depths between 60 m and 1,300 m—this does not include the Olympic Coast National Marine Sanctuary). The spatial LCOE variations are primarily driven by differences in net capacity factors (Figure ES-2), water depths, and distances to installation, maintenance, and grid infrastructure.

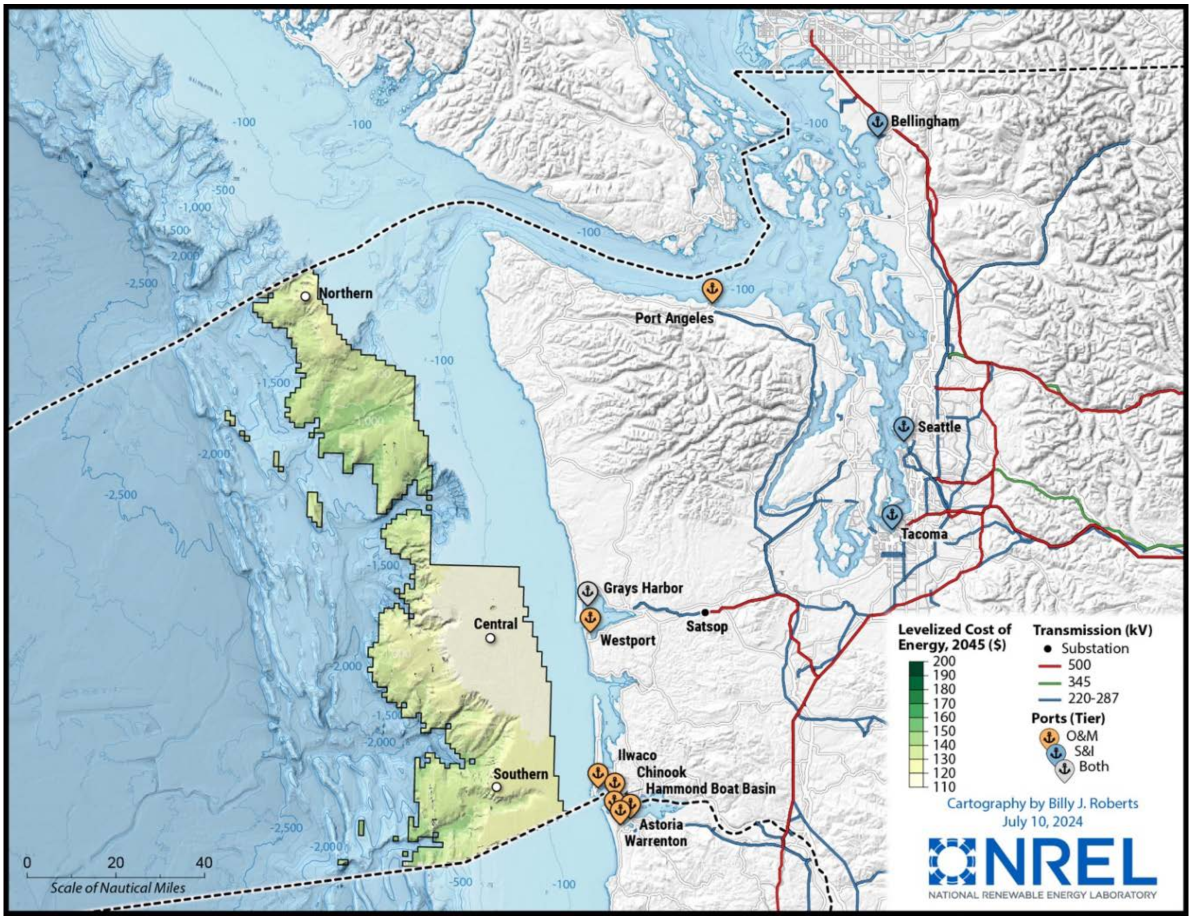

Figure ES-1. Map of LCOE for offshore wind energy projects with a commercial operation date of 2045 under the mid scenario.

Figure by Billy Roberts, NREL

Figure ES-2 presents the spatial variation of 2045 net capacity factors under the mid scenario, which is most strongly correlated to the underlying strength of the wind resource.

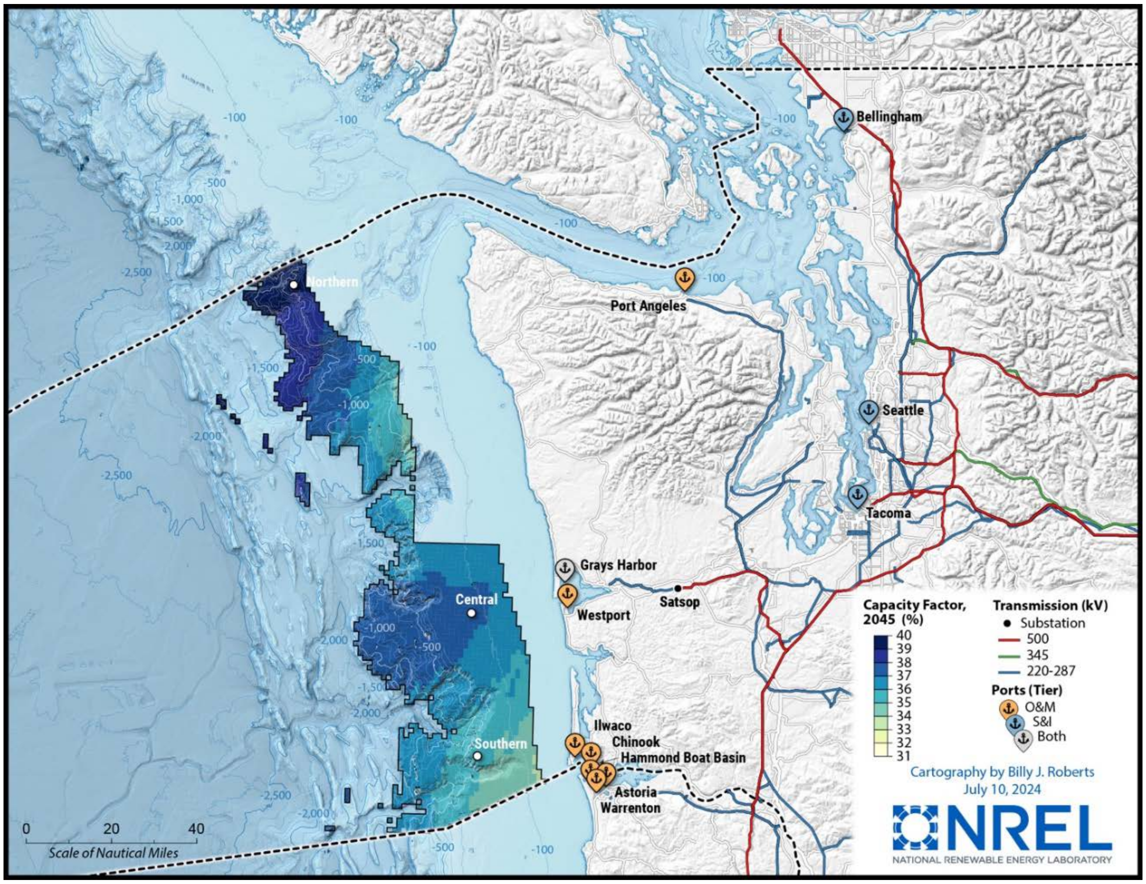

Figure ES-2. Map of average annual offshore wind plant net capacity factors for a commercial operation date of 2045 under the mid scenario.

Figure by Billy Roberts, NREL

The cost projections we present rely on learning curves that describe anticipated cost reductions as floating offshore wind technology matures and the global industry gets better at building and operating commercial-scale floating offshore wind energy projects (refer to Shields et al. [2022a]). While lower net capacity factor projections result in higher LCOE estimates in Washington than in other West Coast states, Washington's existing marine workforce, industries, and portside infrastructure could drive further cost reductions for potential projects in the region. Leveraging these advantages requires coordinating with other states, agencies, and supply chain stakeholders to attract the greatest share of global floating offshore wind energy supply chain investments, and to build manufacturing and installation infrastructure.

While LCOE can be a helpful starting point for comparing the competitiveness of potential electricity generation technologies, it fails to account for numerous factors important for energy system planning. These factors include pollution and environmental impacts, grid value of the resource, reliability and resilience, domestic production of critical energy infrastructure, and energy security. More work needs to be done to quantify these factors for offshore wind energy and for other clean energy resources. As Washington weighs potential clean energy resources, offshore wind energy may prove critical in helping meet state goals set out in law, diversifying the clean electricity generation mix, and bolstering energy security.

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1 Introduction and Study Scope

Ratepayers in the state of Washington benefit from some of the lowest-cost electricity in the country, due in part to the state's large hydropower resources, which accounted for 60% of Washington's net electricity generation in 2023 (U.S. Energy Information Administration 2024). The remaining shares came from natural gas (18%), non-hydropower renewables (10%), nuclear (8%), and coal (4%). Electricity demand is expected to increase in Washington over the next two decades as a result of population growth, decarbonization of other fossil-fuel-dependent sectors, climate change driving greater cooling demand, and expansion of the U.S. Department of Energy's clean hydrogen hub in the Pacific Northwest (Pacific Northwest Utilities Conference Committee [PNUCC] 2023; Northwest Power and Conservation Council 2022; Washington State Department of Commerce 2020; U.S. Department of Energy [DOE] 2023).

In 2019, Washington adopted the Clean Energy Transformation Act (Senate Bill 5116) into law, committing the state to eliminating coal-fired electricity by 2025 and developing a 100% carbon-neutral electricity supply by 2030 and a 100% carbon-free electricity supply by 2045 (Carlyle et al. 2019). Meeting these goals will require improving energy efficiency, modernizing aging grid infrastructure, investing in new transmission across the Pacific Northwest, coordinating with other governments in the region, and developing new clean electricity generation resources at a wider scale. The *2021 State Energy Strategy* indicates that the clean electricity supply will need to double by 2050 (Washington State Department of Commerce 2020; Furze et al. 2023). While hydroelectric generation capacity is likely to remain a key part of Washington's renewable energy mix, it is unlikely to keep pace with the state's increasing energy demand (and future hydroelectric capacity may decrease from dam removal or drought). The expansion of the state's non-hydropower renewables, such as land-based wind and solar photovoltaics will probably play a major role in filling the clean electricity gap, especially east of the Cascade Mountains. However, the demand requirements are immense and additional renewable energy resources may still be needed.

In early 2022, the U.S. Department of the Interior's Bureau of Ocean Energy Management (BOEM) received two unsolicited lease requests to develop utility-scale wind energy projects offshore Washington (Turner 2022), indicating commercial interest in offshore wind development that warranted a closer investigation. Wind resources off the coast of Washington have the potential to meet a significant portion of the state's future electricity demand and help diversify its clean energy mix. Estimates for the wind energy technical[2] resource in federal waters in this region where BOEM has leasing authority exceed 6.6 gigawatts (GW) (National Renewable Energy Laboratory [NREL] 2023; Zuckerman et al. 2023). As such, BOEM requested NREL's support to assess costs and opportunities for wind energy offshore Washington to support long-term energy planning in the region.

1.1 Study Scope and Objectives

The primary goal of this study is to review several feasibility and cost drivers for offshore wind energy in Washington and provide data on technology costs and performance to inform long-

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[2] Lopez et al. (2012) define technical resource potential as "the achievable energy generation of a particular technology given system performance, topographic limitations, environmental, and land-use constraints."

term energy planning in the state and the wider Pacific Northwest region. It is not part of a formal commercial offshore wind project planning process, marine spatial planning process, or official stakeholder engagement effort. Objectives for the analysis include:

- Summarizing some of the existing engagement efforts and perspectives on offshore wind energy in the region
- Identifying potential barriers and opportunities for Washington businesses participating in the supply chain for floating offshore wind energy projects along the U.S. West Coast
- Quantifying the wind resource and assessing the performance of floating wind energy technology offshore Washington
- Discussing infrastructure considerations for potential offshore wind energy development in the region
- Incorporating resource and infrastructure information to improve offshore wind energy cost and performance information to support discussions about the clean energy transition in Washington.

1.2 Analysis Domain and Project Cost Boundaries

This analysis focuses on reviewing factors impacting the feasibility, cost, and performance of offshore wind energy costs and performance in federal waters offshore Washington. Because approximately 92% of the wind resource lies above waters that likely require floating offshore wind energy technologies, the authors focused on areas with depths between 60 and 1,300 meters (m) where BOEM has leasing jurisdiction (Zuckerman et al. 2023).[3] Note that this does not include the Olympic Coast National Marine Sanctuary. NREL considers 1,300 m the maximum depth limit for cost-effective floating offshore wind energy systems based on existing technologies, though these technologies are rapidly maturing.[4] Figure 1 shows the analysis zone (purple area) used in the cost analysis along with bathymetric contours indicating lines of constant water depth for reference. Note that most of the analysis zone falls outside the 10-nautical-mile distance from the shore reference line.

Figure 1 also shows critical transmission infrastructure, which may be relevant for integrating offshore wind with the electricity grid and port infrastructure that could support offshore wind energy projects (discussed in Section 7). In the cost analysis (Section 3), we use identified ports according to their assumed roles: operations and maintenance (O&M), staging and installation (S&I), or both.

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[3] The remaining 8% of the resource in shallower waters was considered too close to shore and would likely be unsuitable for development because of potential conflicts.

[4] In parallel with this study, the National Renewable Energy Laboratory is developing a technical analysis of mooring technologies in waters up to 3,000 m (Cooperman et al. forthcoming).

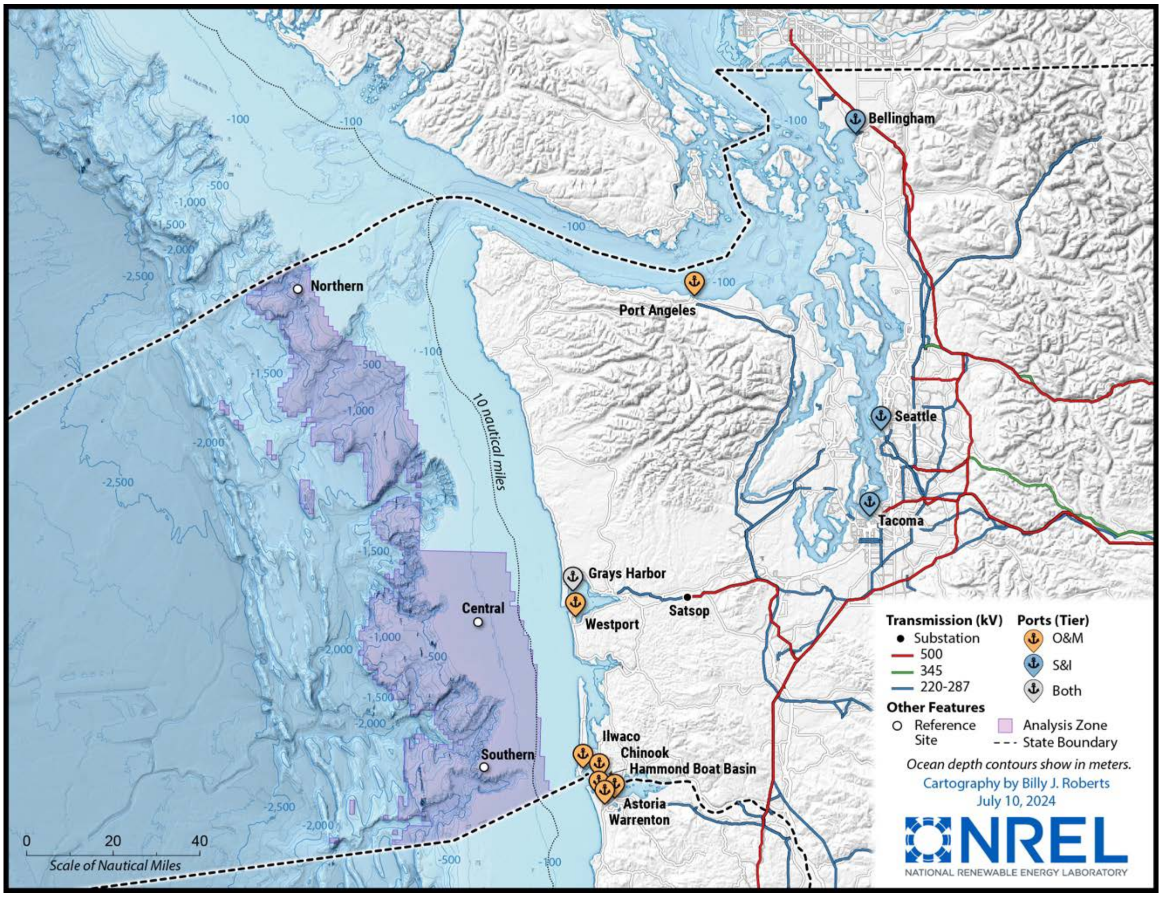

Figure 1. Topographic and bathymetric map of Washington with the spatial extent of cost analysis in U.S. federal waters highlighted in purple.

Figure by Billy Roberts, NREL

Note: The 60-m depth contour bounds the analysis zone to the southeast and the Olympic Coast National Marine Sanctuary to the northeast; the 1,300-m depth contour bounds the analysis zone to the west. Three locations—Northern, Central, and Southern—were arbitrarily selected to explore cost and performance results in Section 8. Ports included in the cost analysis are identified by their assumed roles: O&M, S&I, and both.

The estimates detailed in this report include the costs associated with installing, operating, and decommissioning offshore wind energy projects over a 30-year project life. The project costs include the wind turbines, substructures, mooring systems and anchors, electric collection system, floating offshore substation, export cable, and onshore substation, as well as a short spur line to the point of interconnection (POI). We do not model costs associated with grid upgrades, which may be required to integrate offshore wind power into the existing power system. Figure 2 emphasizes this by showing a box around the system costs included in this analysis (or the scope of costs considered in levelized cost of energy [LCOE] estimates presented).

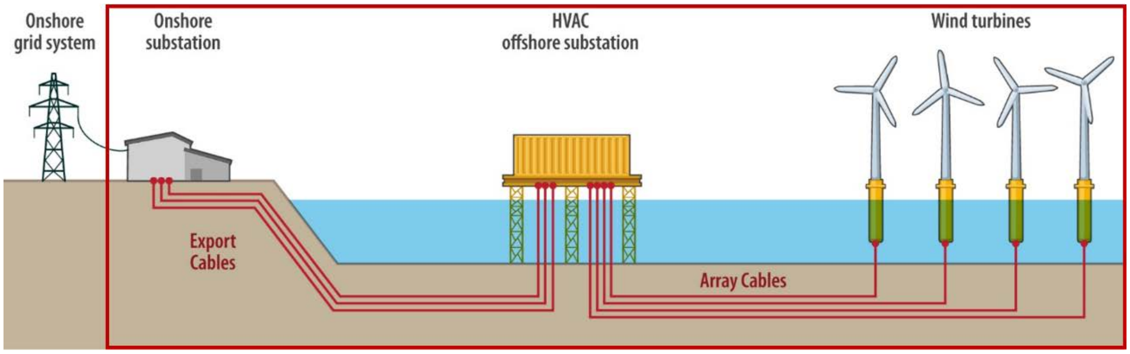

Figure 2. Diagram presenting the scope of offshore wind project costs modeled in this study.

Figure by Al Hicks, NREL

All costs presented in this study are unsubsidized (reported in 2022 U.S. dollars), unless otherwise indicated. Note that tax incentives such as those available through the Inflation Reduction Act[5] can have a significant impact on project economics, depending on which bonus credits projects qualify for (Zoellick et al. 2023).

Note that this study is not part of a formal project or marine spatial planning process or official stakeholder engagement effort. Further, it does not:

- Replace a formal stakeholder engagement effort or planning process for a wind energy project
- Conduct detailed environmental, social, cultural, or workforce development studies
- Recommend specific companies for supplying technology, equipment, project development services, or labor for potential projects
- Calculate the direct impacts to ratepayers of offshore wind energy deployment in Washington.

1.3 Report Structure

This report is structured as follows. First, we provide an overview of offshore wind energy engagement efforts different entities are conducting in Washington and summarize some of the perspectives about offshore wind energy development that are present among different groups (Section 2). Next, we outline opportunities and barriers facing Washington businesses interested in supplying components for the emerging floating offshore wind market along the U.S. West Coast, as well as Washington’s strengths (Section 3). Then, we describe the modeling approach used to estimate costs for hypothetical projects offshore Washington (Section 0). This process involves quantifying the wind resource (Section 0), specifying appropriate wind energy technologies for the region (Section 6), and identifying critical electric grid transmission and port infrastructure (Section 7). Finally, we present the results of the cost analysis (Section 8), discuss key findings and recommend future work (Section 0).

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[5] The Inflation Reduction Act extended the period in which offshore wind energy projects may qualify for tax incentives like the investment tax credit and included provisions for bonus credits which increase the among of the tax credit.

2 Offshore Wind Energy Engagement and Perspectives in Washington

Offshore wind energy development has the potential to affect a wide range of groups and individuals—from Tribes and those working in ocean-based industries to ratepayers and coastal residents—and it is critical to understand and consider these positions and perspectives when making decisions about offshore wind energy. Such impacts and perspectives can vary greatly between and within regions, so it is important to become familiar with the unique perspectives in each place. Early engagement and inclusion of these diverse groups in the offshore wind energy decision-making process can help support procedural equity (i.e., fairness of processes) and increase the likelihood that they will have a meaningful impact on the decisions that are made.

Thus, it is important to consider many different perspectives on offshore wind energy and to describe ongoing and future engagement opportunities in Washington as part of this study. Given that this is an early-stage exploratory study, it is an opportunity to lay the groundwork for incorporating these perspectives early in the process and to give Washington residents dedicated attention that they may not receive in a national or regional (i.e., West Coast) offshore wind energy study. Additionally, describing the engagement processes already underway or planned in Washington, as well as providing recommendations for future engagement, can help support a more coordinated, equitable, and effective offshore wind energy engagement landscape in the state.

2.1 Methodology

This exploratory study is not part of the offshore wind regulatory process, which comes with its own formalized engagement and consultation processes. When designing the methodology for engagement in this study, it was important to be aware of the sensitivities surrounding offshore wind energy in the region and to avoid conflicting with and/or duplicating existing engagement efforts in Washington. Our approach to engagement in this study was to meet with some of the key entities in Washington and the larger West Coast region that are already convening and/or participating in discussions or forums related to offshore wind energy. These conversations were focused on ongoing or planned engagement activities, insights gleaned from those activities, and recommendations for future engagement around offshore wind energy in Washington. We identified the organizations and individuals involved in public engagement and coordination on various topics related to offshore wind energy and conducted informal interviews with 13 individuals from the following organizations and agencies:[6]

- Pacific Fisheries Management Council
- Washington Sea Grant
- Maritime Blue
- Washington State Department of Ecology
- Washington State Department of Commerce
- Pacific Ocean Energy Trust
- Seattle Jobs Initiative

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[6] This list does not include all organizations invited to participate in interviews, as some chose not to participate.

- Port of Seattle
- Pacific Northwest National Laboratory
- Trident Winds.

We conducted semi-structured, qualitative interviews virtually from January to March 2024. Interviewees were identified through initial research into offshore wind engagement activities in the state, discussion with the BOEM Pacific Regional Office, and network sampling, in which interviewees suggested other potential interviewees. Additionally, we conducted a literature review of news articles, press releases, reports, meeting minutes, public comments, and other public documents to augment the information gained via interviews.

2.2 Summary of Existing Engagement Efforts

There are various avenues and forums through which offshore wind energy conversations, coordination, and engagement are occurring in Washington. As of late 2024, no formal public engagement processes associated with offshore wind energy development and decision-making (e.g., public comment periods within the BOEM leasing process) have occurred in Washington, but a variety of groups within the state have been involved in other forms of engagement led by state agencies, nonprofits, industry groups, ports, and others. This section describes three major engagement and coordination efforts (Figure 3) focused on offshore wind energy that are underway in the state and identifies additional engagement opportunities. The following is not an exhaustive list but rather an introduction to the landscape of existing offshore wind energy engagement efforts in Washington.

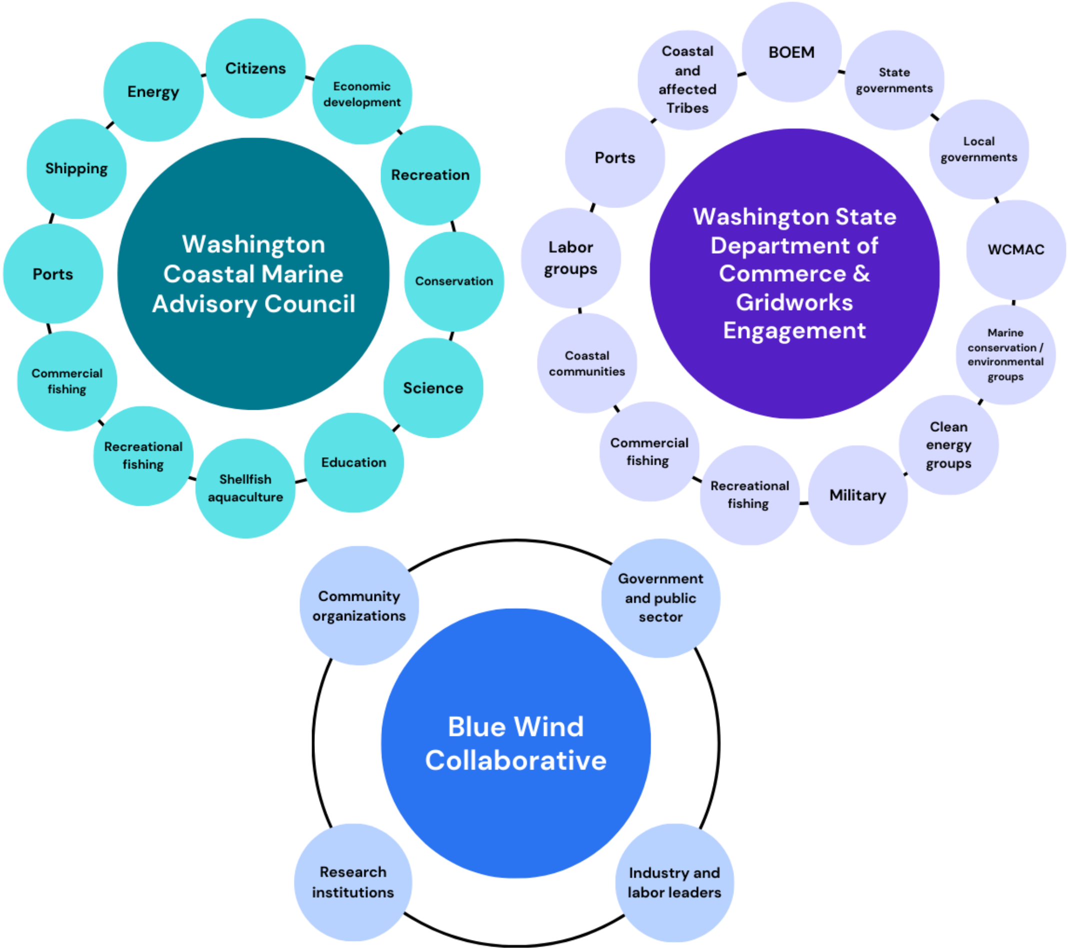

Figure 3. Each convening organization or process described in this section aims to engage a different set of groups or interests.

Figure by Matilda Kreider, NREL

2.2.1 Washington Coastal Marine Advisory Council Offshore Wind Technical Committee

The Washington Coastal Marine Advisory Council (WCMAC)[7] was established by the Governor's Office in 2013 and is administered by the Washington State Department of Ecology. The governor appoints 26 members representing coastal interests such as commercial and recreational fishing, coastal residents, conservation, ports, shipping, energy, science, education, and recreation.[8] The council advises the governor, state legislature, and state and local agencies

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[7] For more information on the Washington Coastal Marine Advisory Council (WCMAC): https://ecology.wa.gov/about-us/accountability-transparency/partnerships-committees/boards-councils/washington-coastal-marine-advisory-council.

[8] Coastal treaty Tribes are not formal members of the WCMAC but may designate individuals to participate; this is because Tribes are not stakeholders and have different pathways to consult with the state about coastal and marine issues (e.g., government-to-government consultation). There has been limited Tribal participation on the council.

on issues related to ocean policy, planning, and management. Meetings of the WCMAC occur four times per year and are open to the public, with meeting minutes shared publicly.

Following several years of discussion about offshore wind energy, the WCMAC formed an offshore wind technical committee in 2022, with representatives from the broader WCMAC members volunteering to participate. At the time of its formation, the committee's primary objectives were to provide recommendations on principles of engagement to the state and BOEM and to review existing data and community research needs considering the unsolicited lease requests submitted by offshore wind energy developers (WCMAC Offshore Wind Technical Committee 2024). The committee submitted its recommended principles of engagement to the governor in 2023, which included transparent and responsive engagement, integration of local knowledge, and impact analysis and information validation (WCMAC 2023). As of mid-2024, the committee is developing an action plan to evaluate existing data and community-focused research needs related to offshore wind energy. This action plan involves learning from processes and experience in other states and reviewing offshore wind energy in the context of the Washington marine spatial plan[9] and other policies.

2.2.2 Washington State Department of Commerce and Gridworks Offshore Wind Engagement

The Washington State Department of Commerce, which oversees the state's energy strategy, released a request for proposals (RFP)[10] in October 2023 for a project intended "to develop recommendations on a Washington-specific consultation and public engagement process to guide the planning and evaluation of potential offshore wind development off Washington's coast" (Washington State Department of Commerce 2023). The state informed BOEM of this RFP and sought their input, as the ultimate purpose of the RFP was to seek input on how the offshore wind energy planning process could be tailored for Washington.

The RFP was awarded to Gridworks,[11] a nonprofit organization that works primarily in the western United States on stakeholder engagement and facilitation related to grid decarbonization. Guided by the state government's expertise, Gridworks carried out an engagement process in winter and spring 2024, with a primary goal of obtaining recommendations for offshore wind energy processes that would meet Washington's unique needs. Gridworks conducted 28 interviews with individuals and small groups (5−15 people) representing coastal and inland Tribes, commercial and recreational fishing groups, coastal communities, ports, clean energy groups, marine conservation and other environmental groups, labor groups, state and local governments, WCMAC, BOEM, and the military. In June 2024, Gridworks published *A Proposed Offshore Wind Engagement Framework for Washington State*,[12] which summarizes findings from this engagement effort.

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[9] The marine spatial plan for Washington: https://msp.wa.gov/wp-content/uploads/2018/06/WA_final_MSP.pdf.

[10] "Recommending a Planning and Evaluation Process for Offshore Wind Projects Request for Proposals": https://www.commerce.wa.gov/contracting-with-commerce/recommending-a-planning-and-evaluation-process-for-offshore-wind-projects-request-for-proposals/.

[11] Gridworks: https://gridworks.org/.

[12] *A Proposed Offshore Wind Engagement Framework for Washington State*: https://gridworks.org/wp-content/uploads/2024/06/Gridworks-WA-OSW-Engagement-Report.pdf.

2.2.3 Washington Maritime Blue Wind Collaborative

The Blue Wind collaborative[13] (often referred to as Blue Wind) is a coalition of community organizations, research institutions, industry/labor leaders, and government/public sector entities working to support Washington's participation in the West Coast offshore wind supply chain through "a collaborative and community benefits approach" (Washington Maritime Blue Wind 2023). Blue Wind is convened by Washington Maritime Blue, a nonprofit organization that supports the larger blue economy, or "the sustainable use of ocean resources for economic growth, improved livelihoods and jobs, and ocean ecosystem health" (Washington Maritime Blue 2019). Launched in 2023, Blue Wind is in the process of establishing working groups focused on economic cost benefit analysis, ports and assembly, vessel needs and construction, West Coast collaboration, supply chain mapping, workforce development, and community benefits and engagement.

2.2.4 Additional Engagement Opportunities

The organizations that we engaged with highlighted other convening organizations offering opportunities for further discussion on offshore wind energy. Some of these are focused on other topics (e.g., coastal and marine management, fisheries, port operations, science and research) that relate to offshore wind energy; others are regional and may not have a Washington focus, but they may still provide a forum for conversations about the future of offshore wind energy in Washington. Formal consultation and engagement processes that are required as part of offshore wind energy development and decision-making, such as government-to-government consultation with Tribes, will also be conducted if development moves forward in Washington. The following are other types of engagement that are available to those looking to become involved:

- The annual Ocean Renewable Energy Conference and Northwest Offshore Wind Conference, with the latter focused on the Pacific Northwest, hosted by Pacific Ocean Energy Trust.[14] These conferences convene members of industry, governments, and communities to align efforts and learn about offshore wind energy and marine energy.
- The West Coast Ocean Tribal Caucus supports inter-Tribal dialogue between sovereign nations on the West Coast. It is convened by the West Coast Ocean Alliance,[15] a Regional Ocean Partnership.
- The Pacific Fishery Management Council,[16] which is one of eight regional fishery management councils established by federal law, has a public comment process through which the public can participate in the council's meetings and activities.
- Washington Sea Grant,[17] a federal-university partnership based at the University of Washington, engages with coastal communities, local governments, Tribes, fishers, and other ocean users through efforts like trainings, K–12 education, and public outreach and events.

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[13] Washington Maritime Blue Wind collaborative: https://maritimeblue.org/joint-innovation-projects/blue-wind/.
[14] Pacific Ocean Energy Trust: https://pacificoceanenergy.org/.
[15] West Coast Ocean Alliance: https://www.westcoastoceanalliance.org/.
[16] Pacific Fishery Management Council: https://www.pcouncil.org/.
[17] Washington Sea Grant: https://wsg.washington.edu/.

- Marine Resource Committees, authorized by state law, have been formed in many of the state's maritime counties. These committees typically provide forums for volunteers representing different interests to discuss local marine resource issues and management.
- The Port of Seattle[18] engages with nearby port communities, Tribes, maritime industries, the public, and other parties through efforts like public events, education and workforce development programs, and participation in local groups and committees.

2.3 Themes in Washington Offshore Wind Energy Perspectives

Though it is not possible to neatly summarize the diverse views on offshore wind energy that exist across groups and individuals in Washington, it can be helpful to consider some of the ideas, concerns, and opinions that have emerged from early discussions of offshore wind energy development. This section includes insights from this study's interviews and a literature review of publications and public statements (e.g., news articles, reports, public comments, opinion articles, press releases). These insights are organized under different themes that emerged during analysis.

2.3.1 Offshore Wind Energy Development vs. Supply Chain Opportunities

Offshore wind energy development is viewed with concern and trepidation by a variety of groups in Washington. A prevailing perspective we encountered is that the state should focus on becoming involved in the West Coast offshore wind energy supply chain in the near term and either avoid offshore wind energy development entirely or forgo any action on development for the next several years or even decades.

Participating in the offshore wind energy supply chain is viewed as an important opportunity by many parties in Washington, especially state agencies, port authorities, and members of the maritime industry. With a strong history of maritime and port industries and workforce development, as well as complementary industries like aerospace, Washington is well-positioned to participate in the West Coast supply chain even if offshore wind energy development is not pursued off the state's coast (Section 3). In fact, Shields et al. (2023a) found that West Coast offshore wind energy deployment goals likely cannot be achieved without using key ports and manufacturing facilities (such as shipbuilding) in Washington. Ports, labor unions, maritime industries, manufacturers, and those seeking employment are some of the key groups likely to realize growth and opportunities from West Coast offshore wind energy development.

However, there are challenges involved in developing a new industry and workforce. For example, local and regional coordination will be necessary between developers, ports, manufacturers, labor unions, and other key actors in the industry. New workforce training programs will need to be established, and programs that already exist for related industries (e.g., electricians, welding) will need to increase their capacity. Developing a local workforce—rather than bringing in workers from other regions—is likely to be a priority in the state, as Washington has already experienced the challenges of workers relocating to the area from other places.

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[18] Port of Seattle: https://www.portseattle.org/.

Notably, with the technology sector boom in the Seattle area, housing costs and general cost of living have increased unsustainably due in part to an influx of highly paid workers (Kim 2020).

Additionally, there may be concerns about impacts to public safety from transitory workers entering the area, as there is a documented relationship between “man camps” (temporary housing areas for workers during the duration of energy projects) and increased violence against Indigenous peoples, especially women, girls, and two-spirit individuals (University of Colorado Boulder First Peoples Worldwide 2020). Though there has not been documentation of a connection between offshore wind energy development and sex trafficking or the Missing and Murdered Indigenous People crisis, concerns about the potential for the industry to have this type of impact have been raised elsewhere on the West Coast. In 2023, the Yurok Tribal Court issued a memo focused on proactive actions to protect Indigenous girls, women, and people during offshore wind energy port development in northern California (Katcher and Abinanti 2023).

2.3.2 Decision-Making, Consultation, and Engagement Processes

Many who are engaging in offshore wind energy conversations in Washington are tracking regulatory and engagement processes in other states—especially California and Oregon—and are keenly aware of negative public opinion surrounding these processes, which has factored into concerns about hypothetical offshore wind energy decision-making and development processes in Washington. If development does advance in Washington, it is likely that some changes will be needed to the federal energy decision-making process used in other states to better integrate Tribal and community views into the process.

The absence of a BOEM intergovernmental task force (a preemptive aspect of BOEM’s leasing process that has been used in many states and regions of the United States) in Washington is evidence of general reluctance to initiate the process of offshore wind energy development. The Washington Department of Commerce’s RFP for engagement to explore alternative forms of a task force in Washington, like including all interested groups rather than just governments, demonstrates that decision-making processes are a key concern within the state and may have significant influence over how offshore wind energy is perceived.

Due to their treaty rights, sovereignty, and government-to-government relationships with the United States, Tribes have a distinct position in questions of land and ocean management in Washington (West Coast Ocean Tribal Caucus 2020). Some Tribes have advocated for Tribe-led decision-making on offshore wind energy given the intersections with coastal resource management and impacts to the environment and Tribal resources. However, concerns were also expressed that past Tribal consultation has not had significant impacts on the offshore wind energy development process in other states and regions, which have led some people to question the viability or purpose of Tribal consultation within the offshore wind energy sector. In 2023, the Affiliated Tribes of Northwest Indians passed a resolution requesting that all scoping and permitting for offshore wind energy projects be halted until the U.S. Department of the Interior and BOEM develop “a comprehensive and transparent procedure that adequately protects tribal environmental and sovereign interests” (Affiliated Tribes of Northwest Indians 2023). The experiences of other Tribes on the West Coast and East Coast are being followed by many in Washington, with concerns that lessons learned from earlier offshore wind energy processes may not be incorporated in a potential process in Washington (Battaglia 2024).

Individuals who are somewhat or fully opposed to offshore wind energy may feel torn between avoiding opportunities to engage in offshore wind energy processes as a way of signaling their opposition and engaging in these processes to try to influence outcomes that would lessen the negative impacts they are concerned about. This challenge suggests that talking about offshore wind energy in any way or in any setting—like a BOEM task force—may be perceived as encouraging its progression.

2.3.3 Evaluating Impacts and Benefits

Perspectives about offshore wind energy vary not only across groups or interests but also within those groups, making it important to engage a diverse set of representatives from different groups. For example, within the fishing community, perceptions of the impacts of offshore wind energy may vary depending on the type of fisher (e.g., recreational, commercial, subsistence), type and location of fishery, and kinds of equipment used. Similarly, the maritime industry is a large, diverse industry in Washington, and individual entities (e.g., ports, labor unions, shipping companies, manufacturing companies) may have differing opinions about the supply chain and workforce opportunities presented by offshore wind energy.

Individual Tribes (as well as individual members of Tribes) also have varying perceptions of offshore wind energy's risks and opportunities. In addition to concerns that decision-making processes do not adequately include Tribes, as discussed earlier, many West Coast Tribes' opposition to offshore wind energy stems from concerns about impacts to the environment, culturally significant fish and wildlife species, and other cultural resources (Cow Creek Band of Umpqua Tribe of Indians n.d.), not only from turbines but also from offshore and onshore transmission infrastructure going through ancestral territory, harming endangered species, and potentially causing fires (Battaglia 2024). Evaluating environmental impacts without working with Tribes to incorporate Indigenous knowledge or traditional ecological knowledge has also been raised as an issue (Battaglia 2024). With development still an uncertain prospect in Washington, the experiences of other West Coast Tribes play a key role in evaluating the impacts and benefits of offshore wind energy in the state.

Some Tribes in Washington have not yet made public statements about offshore wind energy, which could be because no formal actions have been taken to begin development. Other Tribes have expressed concerns about offshore wind energy development elsewhere in the Pacific region. For example, in a 2022 letter to BOEM in response to the Oregon leasing process, the coastal Tribes of Quinault, Quileute, and Hoh discussed impacts to Tribal treaty rights, Tribal fish and marine mammal resources, and fishing (Gridworks 2024). Four coastal Tribes in Washington—Quinault, Quileute, Hoh, and Shoalwater—were involved in the Gridworks engagement process, with a major takeaway for Gridworks from this engagement being that the prospect of offshore wind energy is viewed as a "potential threat to their treaty rights, traditions, and culture, if not carefully evaluated and considered with Tribal rights front and centered in the discussion" (Gridworks 2024). Gridworks' engagement with Tribes identified some of the treaty rights potentially threatened by offshore wind energy development, which include rights to:

- Fish, fishing, and cultural and traditional activities associated with fishing
- Governing and assuring the health, safety, and welfare of Tribal members (in relation to onshore supply chain infrastructure on or near reservations)
- Rights and properties not expressly included in the Treaty of 1855 (Gridworks 2024).

Uncertainty about potential impacts can be difficult to address, given that offshore wind energy has not yet been deployed in this region and the floating turbine technology that will be used has not yet been deployed in the country. Some interviewees suggested large-scale longitudinal analysis of cumulative effects across the West Coast region could help address data gaps and uncertainties, particularly related to:

- Wake effects on upwelling (i.e., cold, nutrient-rich water rising to the surface due to coastal winds) and species that depend on this process
- Impacts on the California Current Large Marine Ecosystem
- Cumulative impacts from multiple offshore wind energy projects
- Impacts over a project's lifetime
- How fishing might be done in and around the project area
- Different species' avoidance of or attraction to offshore wind energy infrastructure.

Legislation has been put forth to this end; for example, a bill introduced in the state legislature in 2023 would have directed the University of Washington to study the cumulative effects of offshore wind energy development in the Pacific Ocean (Stang 2024). In 2024, a U.S. congressional representative from Washington introduced federal legislation (the Protecting Coastal Communities Act) that, if passed, would prohibit any offshore wind energy leasing near southern Washington and northern Oregon until it is proven that development would not negatively impact Tribal resources, marine species and ecosystems, air quality, aquaculture, fishing, or tourism and recreation in the area (KXRO 2024).

Awareness of the potential risks and negative impacts of offshore wind energy development, such as environmental impacts and lost fishing revenues, is high among many groups; however, awareness of and/or belief in potential benefits may be lower. Some interviewees suggested that communication and knowledge sharing (e.g., peer exchange) between individuals in Washington and in areas with more offshore wind energy experience, like Europe and the Northeast, would lead to greater awareness about benefits like workforce and economic development, community benefit agreements, and clean power generation. However, interviewees also expressed that concerns some people have about the process and technology and a general reluctance to engage in the possibility of offshore wind, may inhibit their openness to learning about potential benefits.

Although many concerns are rooted in issues specific to offshore wind energy, the history of hydropower generation in the state and region is also important context for how people are considering offshore wind energy. In some cases, hydroelectric dams have disturbed ecosystems and decimated populations of key species like salmon that hold great cultural significance for many Tribes in the region, as well as flooding Tribal lands and infringing on Tribal fishing practices (U.S. Department of the Interior 2024). After long-term advocacy by Tribes and environmental groups, some of those dams are being removed or considered for removal in places like the Klamath River and Snake River (Daly 2024). Promises of renewable energy generation that will benefit—and not harm—the environment and residents of the region may ring hollow in this context, making it difficult for some to trust the prospect of offshore wind energy. At the same time, reduced hydropower generation could put pressure on energy supply for the state and region, with some looking to offshore wind energy to fill this gap.

2.3.4 Need for State and Regional Leadership and Coordination

An influential factor in some of the offshore wind energy activities currently underway in Washington, such as supply chain decisions and the Gridworks engagement effort, may be that an impending administration change at the state level is creating uncertainty about future support for offshore wind energy. For those supportive of offshore wind energy (whether deployment or supply chain development), this impending change has created some pressure and a sense of urgency to advance certain offshore wind energy actions under the current administration.

Coordination and communication within the state and the West Coast region are needed, particularly for supply chain development. Some interviewees suggested that a regional collaboration between California, Oregon, and Washington could provide consistency and stability during political leadership changes and help clarify and organize decision-making and accelerate the supply chain development needed to support planned offshore wind energy development off the coasts of those states, even if offshore wind energy is not developed offshore Washington. This regional approach would also make it easier to address issues that extend beyond one state, such as potential impacts to migratory species from offshore wind energy development in California. The coordination of engagement efforts is also needed to avoid duplicating efforts and overburdening those being engaged.

2.4 Compiled Recommendations for Future Engagement

Given that concerns and opinions about decision-making, consultation, and engagement processes were ubiquitous in this study's interviews and literature review, creating equitable and effective engagement processes should be a key priority if offshore wind energy development is going to be pursued in Washington. Designing engagement processes that meet the needs and wants of diverse parties in the state is likely to be challenging, especially within the constraints of preestablished state and federal regulatory processes, but some insights about engagement emerged from this study that are worth considering. Interviewees provided the following recommendations for engagement practices related to offshore wind energy in Washington:

- **Modify the BOEM task force model** to fit Washington, including allowing nongovernmental entities to join and addressing problematic power dynamics that give federal and state governments more decision-making influence than other governments.
- **Pursue proactive communication between BOEM and Tribes**, in addition to the formal government-to-government consultation process; for example, make direct inquiries to individual Tribes about the design of a potential task force, even if such an action would not statutorily require consultation.
- **Encourage communication and knowledge exchange between individuals in Washington and regions/countries with more offshore wind energy experience** (e.g., the Northeast, Europe) to support more trusted dialogue about impacts and opportunities. For example, Washington communities interested in establishing a community benefit agreement[19] could meet with communities that have already established an agreement.

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[19] A community benefit agreement is a formal agreement between a developer and local government(s) or community organization(s) that describes the benefits that will be given in relation to a project.

- **Deliver monthly email updates to the public from BOEM** and other decision makers that report on all offshore-wind-energy-related activities performed in the past month, rather than only announcing major actions or decisions.
- **Create opportunities for members and leaders of Tribes, port communities, and underrepresented communities to learn about offshore wind energy** and provide the tools they need to plan and participate in decision-making processes. Building capacity for people to engage in processes can take a variety of forms, such as technical assistance from government and research institutions, knowledge exchange with peers, and training.
- **Foster multidirectional conversation before, during, and after public engagement activities**. Key actions include responding to and acknowledging participants' ideas and concerns as opposed to merely collecting them and following through on engagement by addressing concerns and answering unresolved questions through research.
- **Ensure transparent and consistent communication between BOEM, developers, and interested parties about environmental assessment and possible environmental impacts**, beginning in the early surveying and site assessment stages. This step would include engaging fishers, Tribes, environmental groups, state and federal agencies, and research institutions as sources of information and expertise.
- **Establish the groundwork for workforce development and early engagement from employers** (e.g., manufacturers, port operators, vessel operators) to ensure education and training are in place and make connections between the labor pool and job opportunities.
- **Conduct educational outreach about the opportunities and risks presented by offshore wind energy**, with an emphasis on information coming from longitudinal research in other regions and with targeted outreach to K–12 educators and students.
- **Develop an early engagement and scoping phase related to offshore wind energy impacts to different state resources and groups**. This effort would occur at the same time as other preemptive activities conducted before a leasing process begins (e.g., technical and economic analysis) and led by trusted, neutral entities on the local level.

2.5 Relationship to Cost Modeling

Though findings from this section were qualitative and thus not directly incorporated into the techno-economic analysis in this study, it is worth noting that engaging impacted/interested groups and addressing their concerns (e.g., making changes to wind turbine siting plans or technology choices) involve costs that can impact overall costs for project development. Opposition to offshore wind energy development can be expensive, whether because of project delays and cancellations or the costs of alleviating concerns through engagement, mitigating impacts, and sharing benefits. Modeling these costs accurately in advance of project development is not possible, as they vary depending on the context, community, and project, and depending on actions taken by project developers, governments, and other decision makers. However, these are still key factors that affect the costs and feasibility of offshore wind energy development.

3 Supply Chain Opportunities and Barriers

As other West Coast states pursue floating offshore wind development further south, an opportunity emerges to domestically produce the blades, towers, platforms, and other components that are part of a floating offshore wind plant. Because of limited port infrastructure to support offshore wind manufacturing in those states, Washington could play a vital role in the West Coast supply chain. This section describes the potential market opportunity, supply chain barriers and Washington's strengths, which should be considered as the state begins to determine its role in the wider industry.

3.1 Market Opportunity

The pipeline for West Coast floating offshore wind projects presents substantial market opportunities for manufacturers to participate in the supply chain. In alignment with Shields et al. (2023a), this analysis aims to estimate the quantities of required components and total capital expenditures (CapEx) to meet the demand for a conservative pipeline scenario (25 GW deployed through 2030–2045) and an advanced scenario (55 GW deployed through 2030–2045). Additionally, this analysis contextualizes the number of manufacturing facilities that would be needed to support the domestic production of floating offshore wind components for both deployment scenarios.

The conservative scenario assumes that only northern and central California will deploy floating offshore wind projects, whereas the advanced scenario includes deployment in southern and central Oregon along with southern Washington (Shields et al. 2023a). These scenarios were developed using the Concurrent ORBIT for shared Resource Analysis Library model, informed by BOEM's planned leasing schedule along with current and future feasible port infrastructure. The scenarios reflect the total offshore wind capacity that could be installed by 2045 for a scenario in which S&I ports are developed only in California, and a scenario in which S&I ports are developed in Oregon and Washington as well (Shields et al. 2023a). Figure 4 highlights the annual number of gigawatts that would need to be installed to reach deployment goals within each scenario.

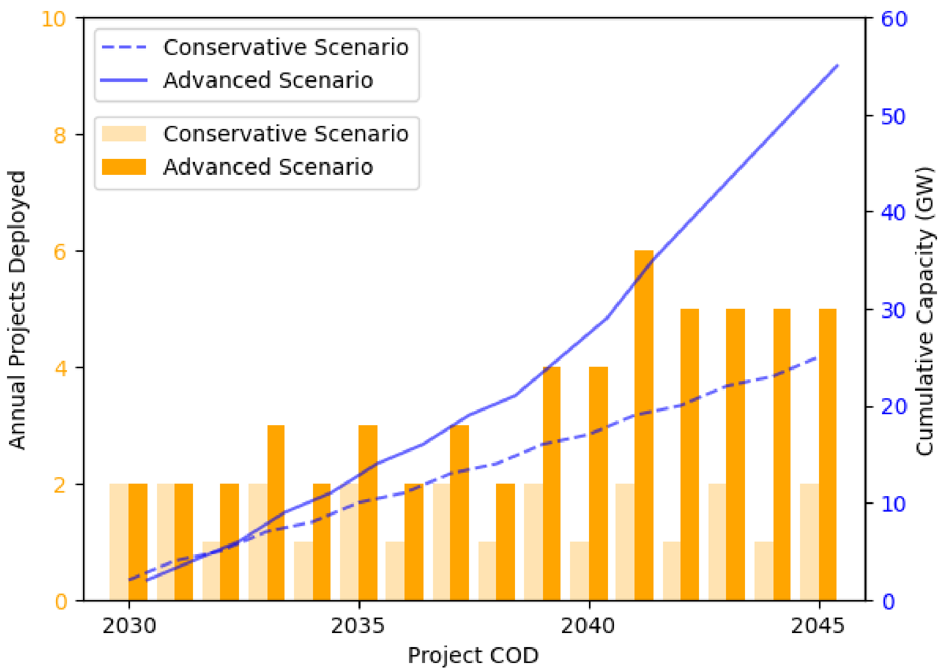

Figure 4. Project commercial operation date (COD) and cumulative capacity for 25-GW (conservative) and 55-GW (advanced) scenarios based on NREL West Coast ports study (Shields et al. 2023a)

NREL conducted additional analysis to better understand total component quantities needed to reach deployment goals for both scenarios. The team assumed 15-megawatt (MW) wind turbines would be used for projects with a commercial operation date (COD) of 2030−2035, whereas projects from 2036 to 2045 would use 20-MW turbines with blades approximately 115 m long and a mass of 50 tonnes (t). All projects are assumed to have a 1-GW capacity, with an average site distance to shore for all projects of 50 kilometers (km). Semisubmersible floating platforms, semitaut mooring systems using three lines per turbine with drag embedment anchors, and 320-kilovolt (kV) high-voltage direct current export cables are assumed to be used in each project (Shields et al. 2023a). Such platforms require a 4,000-t hull with outer columns connected to one central column, and the substations associated with these projects are typically 20-m-tall, 2,000-t structures (Shields et al. 2022b). Additional assumptions include mooring rope lengths of 1,000 m and mooring chain lengths of 600 m, 1.8 km between wind turbines in all projects, and an array cable depth of 300 m.

Table 1 displays these component quantity estimates.

Table 1. Estimated Total Components Required for West Coast Floating Offshore Wind Projects From 2030 to 2045 in 25-GW (Conservative) and 55-GW (Advanced) Scenarios

Component	Conservative	Advanced
Turbines	1,386	2,936
Blades	4,158	8,808
Towers	1,386	2,936
Nacelles	1,386	2,936
Floating platforms	1,386	2,936
Substations	25	55
Mooring rope (km)	4,158	8,808
Mooring chain (km)	2,494.8	5,284.8
Anchors	4,158	8,808
Array cables (km)	3,326.4	7,046.4
Export cables (km)	2,500	5,500

We determined the total CapEx and net present value for the components needed to support the 25-GW and 55-GW scenarios, shown in Table 2, using the per-kilowatt costs of components from NREL's *2022 Cost of Wind Energy Review* (Stehly et al. 2023). These costs are based on industry data for a representative U.S. floating offshore project installed off the Pacific Coast, under the assumption of a mature, global supply chain. To calculate the net present value, costs of components are assigned to the COD year for their corresponding projects. We used a nominal discount rate of 6.23% (Stehly et al. 2023).

Table 2. Estimated Total Component Cost for West Coast Floating Offshore Wind Projects From 2030 to 2045 in 25-GW (Conservative) and 55-GW (Advanced) Scenarios

Cost Metric	Conservative	Advanced
Cumulative CapEx (billion $)	114.13	251.08
Net Present Value of CapEx Spend (billion $)	46.99	92.88

Although these calculations provide general estimates for the total component quantities and costs, they are generated under the assumption that all projects have a uniform design outside of temporally designated 15-MW and 20-MW wind turbine projects. Most notably, different substructure configurations other than the three-line drag embedment anchor mooring system assumed in this analysis may significantly affect the quantities of rope and chain required for each scenario.

Regardless of scenario, the domestic production of floating offshore wind components will require numerous manufacturing facilities along the West Coast. Previous NREL studies estimate that 16 manufacturing facilities would be needed to support the 25-GW deployment scenario, whereas 28 facilities would be needed to support the 55-GW deployment scenario. Table 3 shows the number of facilities by component that will be required for both scenarios.

Table 3. Total Number of Domestic Manufacturing Facilities on the West Coast To Support 25-GW and 55-GW Deployment Scenarios

Component	Number of Facilities (25-GW Scenario)	Number of Facilities (55-GW Scenario)
Blades	2	5
Towers	2	3
Nacelle assembly	2	2
Floating platform	3	5
Floating platform subcomponents[20]	2	4
Substation[21]	2	3
Mooring rope	1	1
Mooring chain	1	1
Anchor[22]	Not applicable	Not applicable
Array cables	1	1
Export cables	1	3
Total	16	28

It is important to understand that manufacturing facilities for blades, towers, and some floating platform designs will likely require 80+ total acres (Lim and Trowbridge 2023; Shields et al. 2023b). Additional large-acreage port space will also be needed to support S&I activities. NREL estimates that four S&I sites will be needed to support a 25-GW deployment scenario, whereas nine S&I sites will be needed to support a 55-GW scenario (Shields et al. 2023a). This means 20 S&I and manufacturing sites could be needed to support a 25-GW deployment scenario, and 37 S&I and manufacturing sites could be needed to support a 55-GW deployment scenario. Though the number of available and suitable sites are still unknown, NREL estimates that there are a total of 19 ports on the entire West Coast that are suitable candidates for S&I and/or manufacturing sites (Shields et al. 2023a). This lack of port infrastructure means Washington ports will be needed to achieve full domestic manufacturing for the 25-GW and 55-GW deployment scenarios.

3.2 Supply Chain Barriers for Washington

Limited port infrastructure throughout the West Coast region increases the likelihood that Washington assets will ultimately be used to support floating offshore wind energy. Still, multiple barriers exist that could impact the timely development and deployment of these

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[20] For this report, we assumed that floating platform subcomponent facility requirements and investments will vary depending on the design of this component. As such, we are not including jobs or facility investments as part of our analysis.

[21] For this report, we assumed that substations are built at existing shipyards with existing jobs.

[22] For this report, we assumed that anchor manufacturing is not done at a portside facility but can be done at an existing facility with existing jobs.

resources. From the pipeline to component design choices, these challenges involve the wind energy industry, decisions in other states within the country and region, and the availability of federal incentives.

The pipeline for floating offshore wind on the West Coast is beginning to take shape, but the timelines for many of these projects are still unknown.

Although there are 14 floating offshore wind energy projects in seven countries with a cumulative capacity of 227 MW, none of these projects are in the United States (Norris 2023). Still, the domestic pipeline for floating offshore wind projects is beginning to take shape with five California lease areas awarded in Humboldt and Morro Bay, and two Oregon wind energy Call Areas identified in Coos Bay and Brookings. Though the projects developed in these areas will help Oregon and California meet their respective offshore wind deployment goals of 3 GW by 2030 (Oregon) and 25 GW by 2045 (California), there are no definitive development timelines for these projects, which is one of the primary uncertainties that limits supply chain decision-making for Washington and the West Coast.

Substructure and wind turbine design choices will impact port, workforce, and component supply chain requirements.

Another barrier for supply chain development in Washington and the West Coast are uncertainties related to platform designs (ABS Group 2021). Different platform designs have varying port, workforce, and component supply chain requirements. For instance, platforms with tubular steel designs could require extensive port space and a significant number of trained welders for final assembly as well as new rolling equipment for subcomponent fabrication. Yet, concrete substructures could require less space for assembly, new equipment for fabrication, and an entirely different workforce. It will be difficult for new and existing manufacturers, ports, and training programs to prepare for regional fabrication of floating offshore wind components without defining the type of substructure that will be used for West Coast projects.

Wind turbine design uncertainty, specifically related to turbine capacity/size, may also be a significant barrier for supply chain development in Washington and the West Coast (Shields et al. 2023a). Project cost and strains to supply chain infrastructure like ports and vessels increase as turbine size increases. For instance, shifts to continuously larger turbines may require new investments for additional portside manufacturing space and specialized manufacturing and lifting equipment.

Increased costs may result in project cancellations or delays that can further complicate market conditions and project timelines.

Increases in commodity prices and supply chain disruptions caused by inflation and global conflicts have created new cost uncertainties that could delay offshore wind deployment in the near term (Durakovic 2022). These unanticipated cost increases have resulted in canceled or delayed projects and manufacturing facilities. Although many of these cancellations and delays have been for fixed-bottom projects on the East Coast, continued increases in commodity prices and supply chain disruptions could create further supply chain and deployment uncertainties that ultimately impact West Coast projects and supply chain development.

A variety of factors could impact Washington's near-term ability to attract Tier I component manufacturers.

Offshore wind supply chain decisions for the manufacturing of Tier I components like nacelles, blades, towers, cables, and foundations are made in a dynamic global context. Factors such as regional/global project pipelines, solicitation and incentive requirements, infrastructure investments, and funding availability, all drive offshore wind supply chain investment decisions. Coordinating at the regional, national, and industry levels can help put Washington in the best position to understand the State's abilities and to attract a share of global offshore wind supply chain investments.

Wind turbine choices, project timelines, procurement choices, and out-of-state port availability will ultimately impact port decisions in Washington.

Port requirements vary depending on component type and wind turbine size. Additionally, port development timelines are directly related to project development timelines and procurement choices. The uncertainties in each of these areas make it difficult for port operators to determine the timing, extent, and number of infrastructure upgrades that will be needed to support offshore wind manufacturing. Furthermore, the West Coast has a limited number of large-acreage sites that are suitable port locations for large component manufacturing, and many of these sites are also ideal for S&I. California and Oregon ports will likely be used for S&I and manufacturing, given their proximity to already-announced lease areas and wind energy Call Areas. The rate at which these out-of-state sites become occupied will further complicate how and when Washington ports could be used for offshore wind energy.

Availability of some incentives may not align with project timelines.

Although the Section 45X advanced manufacturing production credit from the Inflation Reduction Act is currently available, it phases out beginning in 2030 and expires in 2032 for everything except critical minerals (Federal Register 2023). Unless the credit is extended, this incentive may not be available for a majority of West Coast floating offshore wind manufacturers.

3.3 Supply Chain Strengths for Washington

Washington has many assets that can be leveraged to support offshore wind energy supply chain efforts. These assets include multiple existing industries with facilities and equipment that could align with vessel and component fabrication. Additionally, many of these existing industries have workers with unique skill sets that could be recruited to be part of the offshore wind energy workforce. Furthermore, many port communities in the state are located near significant population centers with existing infrastructure to house and support workers and their families.

3.3.1 Existing Industries

Multiple existing industries within Washington, including shipbuilding, aerospace, and composite and metal fabricators, have a history of building complex machinery or fabricating steel components. Some workers in these industries currently have skill sets and experience that apply to various parts of the floating offshore wind energy supply chain. The following is a high-level overview of existing industries that could contribute to Washington's offshore wind supply chain.

Shipbuilding

Washington is home to an $8.2 billion shipbuilding, repair, and maintenance industry that supports 18,500 jobs and is already involved in the fabrication of vessels that will be used for offshore wind energy projects. The state has 61 commercial shipyards and boatyards that can build, repair, and maintain vessels to support a variety of industries including wind. In addition to fabricating vessels, some of these companies have an existing workforce with significant welding and metal fabrication experience that could position their companies for other opportunities like subcomponent fabrication for substructures and/or final assembly of substructures. In fact, there were more than 3,000 welders, cutters, solderers, and brazers working in Washington's maritime industry in 2022 (McKinley Research Group 2023).

Aerospace

Representing nearly 5% of the state's gross regional product, Washington's $29.8 billion aerospace industry supports approximately 105,000 jobs across more than 1,500 businesses. Aircraft manufacturing is the largest contributor to total revenue generated by the aerospace industry, representing nearly 60% of the market (Norton et al. 2023).

Various workers including aerospace engineers, welders, and machinists have many skill sets that are relevant to offshore wind energy manufacturing. Additionally, some of these workers may have experience with carbon-fiber manufacturing and automated manufacturing processes. It is important to note that this industry has reported a reduction in the overall aerospace workforce since the COVID pandemic (down nearly 14.2%), as well as reported difficulties in identifying, recruiting, and retaining trained workers who are interested in welding and machining (Norton et al. 2023).

Steel and Concrete Fabricators

There are numerous existing fabricators in Washington, particularly in the Columbia River Basin area that have previously expressed interest in becoming part of the domestic supply chain for floating offshore wind substructures and secondary steel components. These fabricators have existing facilities and workers whose expertise aligns well with offshore wind, but capabilities, space, and capacity vary for each company.

Additionally, Washington has a rich history in concrete fabrication. Although many of these projects are singular in nature, the state has experience mobilizing the workforce and infrastructure needed to support these efforts. This is especially true for the SR 520 Floating Bridge and Landings Project. This project featured the fabrication of 77 concrete pontoons as well as the construction of portside infrastructure to support the project. Specifically, infrastructure updates included the construction of a portside casting basin facility that featured an on-site concrete batch plant, water treatment facility, and 4-acre casting basin (Washington State Department of Transportation 2017).

Mooring Chain

Existing manufacturers in the state are capable of fabricating large-diameter chains for the U.S. Navy. Equipment and facility upgrades would likely be required to produce chain specifically for floating offshore wind energy, but this industry's existing workforce and skill sets are relevant and could likely be used and expanded upon to support floating offshore.

3.3.2 Workforce Availability

Workforce availability has been identified as a potential barrier particularly for smaller ports that are far from significant population centers. Washington has several port communities (e.g., Seattle, Tacoma, Vancouver) that have significant population centers with existing infrastructure (e.g., housing, schools, and services) and ports that are suitable candidates for offshore wind energy component manufacturing. Additionally, many existing businesses (including those located in smaller port communities) are already staffed. Many of these facilities would likely require expansion of/retraining the workforce instead of establishing (e.g., identifying, recruiting, and training) an entirely new workforce.

4 Cost Modeling Approach

As Washington considers the role it wants to play in the offshore wind energy industry, decision makers need information about costs and performance for potential in-state project development. In this section, we present the modeling approach used to assess floating offshore wind energy LCOE and net capacity factors in Washington for projects with a commercial operation date between 2035 and 2045. LCOE represents the average unit cost of energy generated over an electricity project's lifetime. We calculate LCOE in terms of dollars per megawatt-hour based on the definition from Short, Packey, and Holt (1995):

$$LCOE = \frac{CapEx * FCR + OpEx}{NCF * 8760 * 1000}$$

where CapEx represents the capital expenditures (in terms of dollars per kilowatt [kW]), FCR is the fixed charge rate (%), OpEx is the operational expenditures ($/kW-year), and NCF is the net capacity factor (%). We elaborate on each of these parameters in the following sections.

LCOE provides useful initial insights into the cost competitiveness of electricity generation resources, but different technologies must be compared carefully to account for revenue sources, subsidies, bulk power system upgrade costs, and other benefits (Beiter et al. 2021). LCOE does not account for the grid value of a particular technology's generation profile, ramping capabilities, and other grid services. All costs are presented at the point of electricity grid interconnection and expressed in unsubsidized 2022 U.S. dollars, unless otherwise noted.

While we rely on the methodology outlined in Fuchs et al. (2024) and in NREL's Annual Technology Baseline (NREL 2024), used to estimate offshore wind energy LCOE for the United States, this study improves cost estimates for Washington in several ways. First, we validate the modeled wind resource against available measurements, identify a need for and implement a bias correction factor, and then use this to derive a better understanding of net capacity factors for the region (Section 5). Next, we more closely examine infrastructure assumptions which serve as inputs to the cost model. These include both potential points of interconnection and ports used for staging, integration, and maintenance activities (Section 7).

Sections 4.1 and 4.2 summarize the cost modeling approach from Fuchs et al. (2024) and NREL's Annual Technology Baseline (NREL 2024), which has two primary steps: bottom-up cost modeling and projecting costs into the future under three scenarios to illustrate how costs may evolve with deployment and technology innovation over time.

4.1 Bottom-Up Cost Modeling for Floating Offshore Wind Energy

We derive bottom-up floating offshore wind energy cost estimates using a suite of NREL models presented in

Table 4. These models are periodically updated based on industry and market trends, and they inform the bottom-up estimates of CapEx, OpEx, and NCF. We also rely on market data about financing to inform FCR assumptions (Taylor, Beiter, and Egli 2023).

Table 4. Summary of NREL Modeling Tools Used in the Cost Analysis

Cost Component	Model(s)	Source(s)
CapEx	Offshore Renewables Balance-of-system and Installation Tool (ORBIT),[23] NRWAL[24]	Nunemaker et al. (2020, 2023)
OpEx	Windfarm Operations and Maintenance cost-Benefit Analysis Tool (WOMBAT),[25] NRWAL	Hammond and Cooperman (2022); Nunemaker et al. (2023)
Wake losses and NCF	FLOw Redirection and Induction in Steady State (FLORIS)[26]	NREL (2021)
Other losses	NRWAL	Nunemaker et al. (2023); Beiter et al. (2016)
Future costs	Forecasting Offshore wind Reductions in Cost of Energy (FORCE),[27] NRWAL	Shields, Beiter, and Nunemaker (2022); Wiser et al. (2021)

4.1.1 Capital Expenditures

We utilize the ORBIT model to derive relationships between CapEx costs and spatial parameters like water depth, wave conditions, and distances to infrastructure. NRWAL is a library of these spatial relationships. Note, ORBIT is intended for commercial-scale (>500 MW) project costs reflective of a mature industry. Because the floating offshore wind industry is nascent, we adjust the baseline CapEx estimates 2.5 times to obtain the baseline CapEx (Steps 1 and 2 in Figure 5) (Shields et al. 2022a; Musial et al. 2020, 2019). We do not apply the same multipliers to OpEx; more detail on the derivation of the cost trajectories is provided in Section 4.2. For additional information, refer to Fuchs et al. (2024).

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[23] Access ORBIT on GitHub: https://github.com/WISDEM/ORBIT.
[24] Access NRWAL on GitHub: https://github.com/NREL/NRWAL.
[25] Access WOMBAT on GitHub: https://github.com/WISDEM/WOMBAT.
[26] Access FLORIS on GitHub: https://github.com/NREL/FLORIS.
[27] Access FORCE on GitHub: https://github.com/NREL/FORCE.

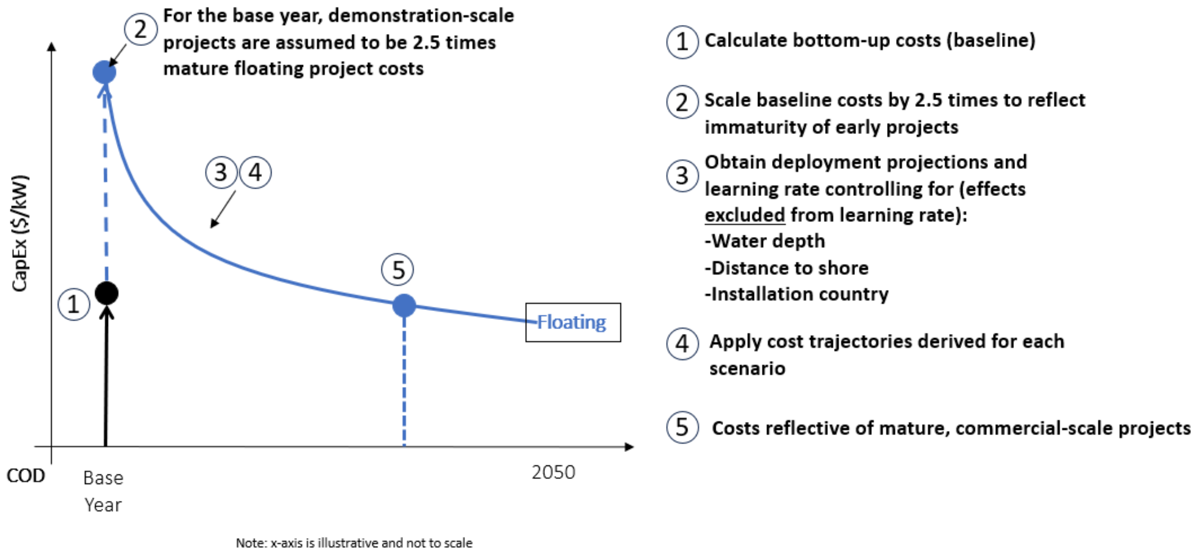

Figure 5. Summary of CapEx modeling approach borrowed from Fuchs et al. (2024) and NREL's Annual Technology Baseline (NREL 2024)

Export System CapEx

For this study, we update the way we calculate export cable distances between potential project sites and the assumed point of grid interconnection onshore. The export system includes the export cables (assumed to be dynamic cables for floating wind plants), offshore substation, and, for high-voltage direct current systems, the onshore power conversion infrastructure. Export cables increase in cost depending on export cable length, which is a function of distance to the POI from the offshore wind plant location. We calculate the distance using a least-cost path algorithm where the cost of transmission over land is weighted significantly more than over water, resulting in cable routes that stay in the water as long as possible. This results in minimal length onshore spur line cabling, which has costs that are calculated separately from the export cables. Export system installation cost increases with distance to port, as costs for specialized vessels (for example, cable-lay vessels) are higher as distances traveled increase.

4.1.2 Operations and Maintenance Expenditures

We model OpEx using the Windfarm Operations and Maintenance cost-Benefit Analysis Tool (WOMBAT) by simulating the wind plant's operational life (Hammond and Cooperman 2022). This accounts for weather windows required to complete maintenance activities using an assumed vessel spread with maximum safe operational limits. In the model, scheduled and unscheduled maintenance occur in response to failures with component-specific failure rates from Schwarzkopf et al. (2021). Major component replacements are assumed to take place at port after a tow-to-shore operation.

4.1.3 Net Capacity Factors

To calculate baseline NCF, we rely on turbine technology assumptions provided in Section 6 and NREL's latest wind resource assessment for the Pacific Northwest. In addition, we included a correction factor to account for known model bias (Section 5.2). We modeled gross capacity factors (without any losses), applied the derived resource correction factor, and then accounted for the loss categories outlined in Table 5 to obtain the NCF.

Table 5. Loss Categories Considered (Aligned With Fuchs et al. [2024])

Type of Loss	Mean Value (% of Gross Energy Production)	Description
Wake (internal effects only)	9% (ranges from 8.4% to 10.2%)	Calculated using the FLORIS model for wind plants with wind turbines spaced 7 rotor diameters apart on a square grid
Environmental	1.59%	Includes hurricane, lightning, and temperature-related shutdowns (Beiter et al. 2016)
Technical	1% for fixed and 1.2% for floating	Power curve hysteresis (shutdown and restart near cut-out wind speed), onboard equipment power usage, rotor misalignment (Beiter et al. 2016)
Electrical	4.2% (ranges from 3.5% to 4.8%)	Export cable system losses to environment, function of distance to point of interconnection (export cable length) (Beiter et al. 2016)
Availability	11% (ranges from 7.4% to 12.3%)	Shutdowns for maintenance and repair, other system shutdowns

We use Version 3.4 of the FLOw Redirection and Induction in Steady State (FLORIS) model to calculate site-specific wake losses for a 1,000-MW offshore wind power plant. Wakes are regions of reduced velocity and increased turbulence that form behind a wind turbine as it extracts momentum from the wind to generate electricity. Wakes lead to lower power production and more wear and tear (mechanical loads). Wake losses depend on the wind resource, turbine technology, and wind plant layout. We did not consider the impact of cluster wake effects from neighboring wind plants (Pryor et al. 2021; Lundquist et al. 2019). Refer to Fleming et al. (2023) and Cooperman et al. (2022) for sensitivity analyses of wake losses to other parameters.

4.1.4 Financing Assumptions

Many offshore wind energy developers rely on debt to finance project development. The FCR annualizes the CapEx in the LCOE calculation and captures the impacts of broader economic conditions on energy project financing. Table 6 summarizes financing terms used in calculating FCR. We assume floating offshore wind projects benefit from the same terms as current fixed-bottom offshore wind projects as the technology matures. Taylor, Beiter, and Egli (2023) indicate this amounts to a cost of equity of 9% and a debt share of 60% for U.S. offshore wind energy projects (as of 2021). We increased the debt interest rate to reflect central bank increases between 2020 and 2023 as governments sought to combat inflation.[28]

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[28] See Bloomberg New Energy Finance (2023b), Lloyd-Williams (2023), Fuchs et al. (2024), and Ury et al. (2024) for analyses and discussion of near-term cost impacts for offshore wind energy.

Table 6. Summary of Financing Assumptions

Parameter	Unit	Value
Capital recovery period	Years	30
Tax rate	%	26
(Long-run) inflation	%	2.5
Share of debt	%	60
Nominal debt interest rate	%	5.9
Nominal return on equity	%	9
Nominal after-tax weighted average cost of capital	%	6.1
Real after-tax weighted average cost of capital	%	3.5
Depreciation basis	%	100
Depreciation schedule	-	5-year Modified Accelerated Cost Recovery System
Present value of depreciation	%	87
Nominal after-tax fixed-charge rate	%	7.7
Real after-tax fixed-charge rate	%	5.7

4.2 Cost Projections

After calculating bottom-up costs, we develop projections of future CapEx based on global industry experience using learning curves. Learning curves can be used to forecast how costs change with growing global floating offshore wind energy deployment. To inform our cost projections, we use the learning curves developed by Fuchs et al. (2024) and provide a brief description of their derivation below. Note that we rely on literature projections for how OpEx and wind plant performance (NCF) may evolve with expected technology innovation (Wiser et al. 2021).

To develop learning curves Fuchs et al. (2024) combine global deployment projections with learning rates calculated from a regression of historical fixed-bottom offshore wind CapEx data with NREL's FORCE model (Shields et al. 2022a). Learning rates describe how quickly costs come down with every doubling of production (higher learning rates and/or faster deployment equate to a greater rate of cost reduction). In the regression model, we do not control for wind turbine rating or project capacity to include turbine and plant upsizing effects in the resulting learning rate. This means that cost reductions from technology maturation, which might include future turbine upsizing and economies of scale, are included in the long-term cost projection. Refer to Fuchs et al. (2024) and Shields et al. (2022a) for additional details on the regression methodology.

The regression process also provides error bounds on the learning rate error bounds, which are combined with a range of global floating offshore wind deployment trajectories to define "conservative" (expensive) and "advanced" (less expensive) cost scenarios. These scenarios are useful for understanding how costs may evolve over time with different rates of technology innovation, deployment, and supply chain maturation. We report the deployment assumptions by scenario in Table 7 and the resulting CapEx learning curves in Figure 6.

Table 7. Summary of CapEx Learning Rates and Assumed Global Deployment by Scenario From Fuchs et al. (2024)

Parameter	Conservative	Mid	Advanced
Learning rate (%)	8.7	11.5	14.2
2022 deployment (GW)	0.123	0.123	0.123
2030 deployment (GW)	1.6	4.0	6.4
2035 deployment (GW)	8.0	20.0	32.0

Floating projections from the 2022 deployment obtained from Musial et al. (2022); other years informed by DNV (2023); 4C Offshore (2024); Bloomberg New Energy Finance (2023a); Jenkinson (2024); Global Wind Energy Council (2023); Wood Mackenzie (2023)).

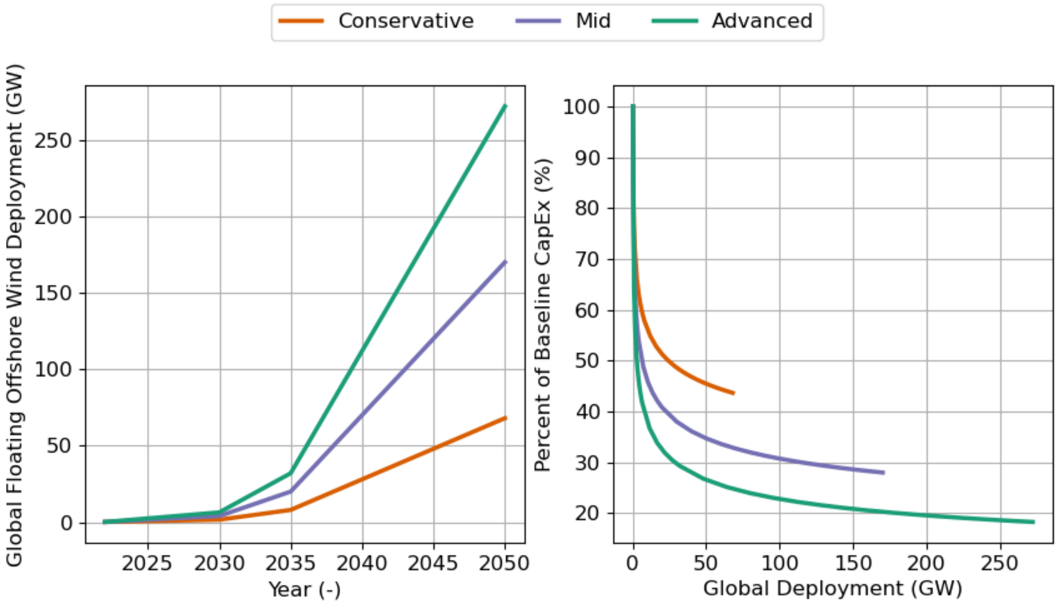

Figure 6. Global floating offshore wind deployment trajectories (left) and project CapEx reduction trajectories from industry learning under different scenarios relative to baseline values (right).

Trajectories from Fuchs et al. (2024)

Figure 7 shows how OpEx evolves over time under three scenarios to the right of the global floating offshore wind deployment assumptions. OpEx trajectories come from fitting a learning curve to match the total cost reductions through 2035 anticipated by experts (Wiser et al. 2021). Fuchs et al. (2024) adjusted the total magnitude cost reduction to account for the fact that respondents' expectations were reported relative to fixed-bottom offshore wind energy in real 2019 terms.

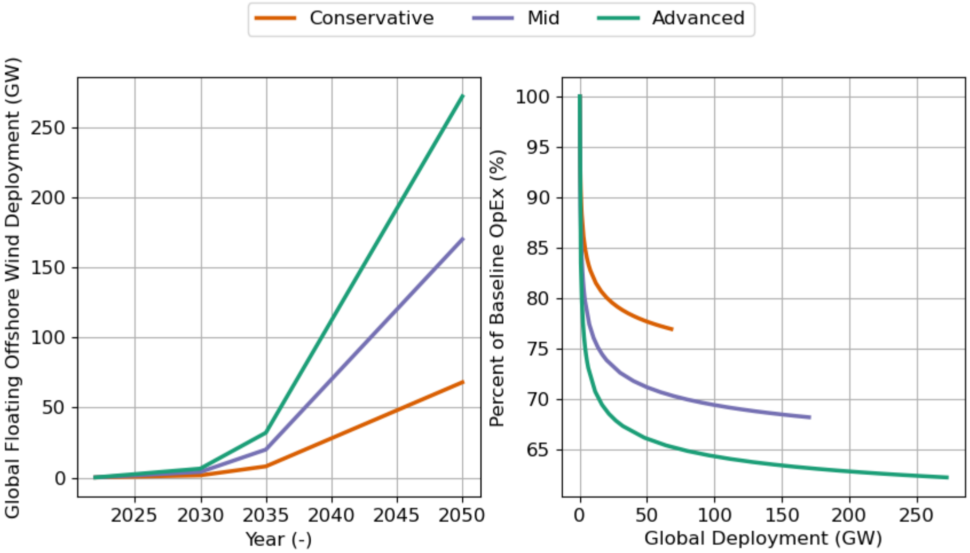

Figure 7. Global floating offshore wind deployment trajectories (left) and derived OpEx trajectories by technology and scenario presented relative to baseline values (right).

Trajectories from Fuchs et al. (2024)

Figure 8 presents net capacity factor trajectories over time under three scenarios. As with OpEx, we also adjusted the total magnitude of annual energy production improvement to account for the fact that respondents' expectations were reported relative to fixed-bottom offshore wind energy in real 2019 terms and assumed the same total percentage improvement for both fixed-bottom and floating offshore wind performance over time.

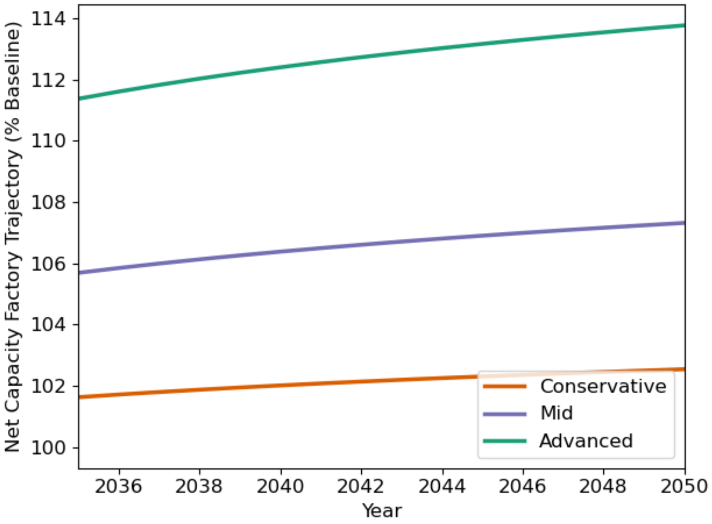

Figure 8. Performance (net capacity factor) improvement trajectories by scenario between 2035 and 2050.

Trajectories from Fuchs et al. (2024)

Note that the values in the plot are presented in terms of the percentage of the baseline performance. The data shown are not capacity factors.

5 Wind Resource in Washington

Understanding offshore wind energy technology costs and performance requires an understanding of the wind resource. This section describes NREL’s wind resource assessment for the Pacific Northwest, summarizes validation against available measurements (detailed validation in Appendix A), and derives a wind resource correction factor to account for potential model bias in performance estimates. We then incorporate these data into the cost results presented in Section 8.

5.1 Background: the NOW-23 Dataset

NREL’s state-of-the-art offshore wind resource dataset is the 2023 National Offshore Wind dataset (NOW-23) (Bodini et al. 2023). In the Pacific Northwest region, NOW-23 has data from 2000 to 2019; Figure 9 shows the mean wind speed at 160 m above sea level. Mean wind speeds range from less than 7 m/s in the Puget Sound and along the coast of the Olympic Peninsula to just under 9 m/s in westernmost portions of the United States Exclusive Economic Zone far offshore. The estimated range of mean wind speeds predicted offshore Washington is similar to estimates for the Gulf of Mexico and South Atlantic regions (Bodini et al. 2023).

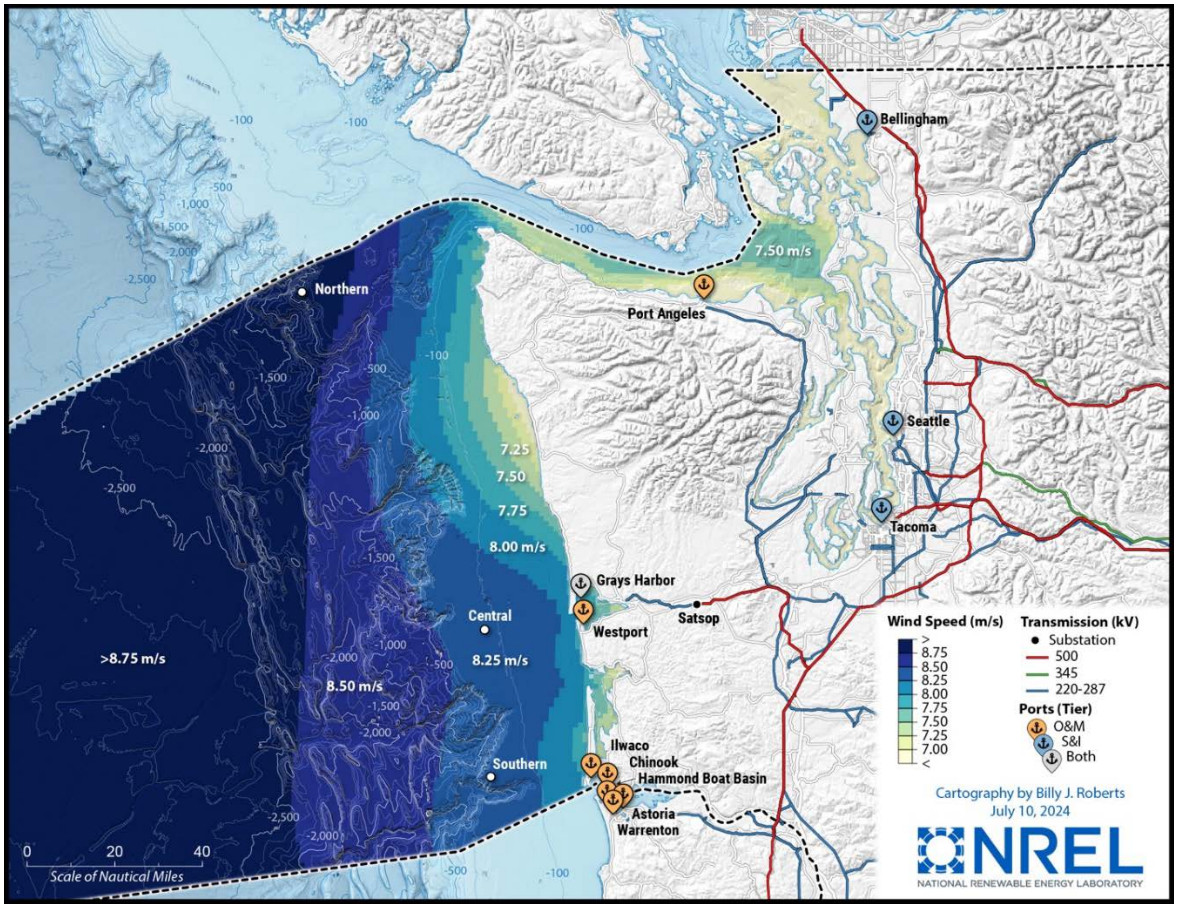

Figure 9. Mean wind speed at 160 m above sea level offshore Washington from the NOW-23 dataset.

Figure by Billy Roberts, NREL

A previous version of the NOW-23 dataset for offshore California (named CA20) showed a significant positive bias in modeled wind speed (Bodini et al. 2022, 2023; Liu et al. 2024) relative to floating lidar observations (Krishnamurthy et al. 2023), with the largest bias off the coast of northern California. Such large wind speed biases were virtually eliminated by changing the planetary boundary layer (PBL) scheme (which controls vertical turbulent mixing in the atmospheric boundary layer) used in the mesoscale numerical model (the Weather Research and Forecasting Model) to create NOW-23 from the Mellor-Yamada-Nakanishi-Niino (MYNN) scheme to the Yonsei University (YSU) scheme. On the other hand, the MYNN scheme provides accurate offshore wind speeds in other U.S. offshore regions, such as the North and mid-Atlantic.

For the Pacific Northwest region, NOW-23 adopts the MYNN scheme. Given the proximity to the northern California region, where we observed the largest biases in the MYNN-based CA20 wind resource assessment, an analysis of potential biases in the NOW-23 offshore wind speed in the region is warranted. This bias assessment allows us to accurately quantify and correct for any potential biases in modeled wind speed in the cost modeling analysis.

To summarize the implications of the detailed bias assessment presented in Appendix A, most of the validation results suggest that, while both the YSU-based and MYNN-based model runs have a positive bias with respect to observations (overpredicting resource), the YSU-based model runs better compare with the available observations as opposed to the MYNN-based runs. While the observations used for model validation are not ideal, they represent the best measurements currently available in the region. While the magnitude of the bias in modeled hub-height wind speed would likely change if floating lidar data were available, all the available information, including results from the adjacent offshore California region, confirms the general conclusion that the YSU model setup will likely perform better than the MYNN one in the region.

5.2 Correction of the NOW-23 Dataset

Given the limited funding available for the project, a complete re-run of the full long-term NOW-23 dataset with the YSU PBL scheme was not possible, despite the conclusion that the setup performs better than the MYNN scheme. Given these project constraints, we developed a simpler correction approach to adopt when using the original NOW-23 dataset for the cost modeling analysis.

The proposed correction approach is as follows:

- For each set of coordinates in the offshore Washington domain, we computed the 5-minute power output from both the MYNN- and YSU-based model runs over the year 2020 using the IEA Wind Technology Collaboration Programme (IEA Wind) 15-MW reference turbine (Gaertner et al. 2020).
- We computed, at each location, the gross capacity factor (GCF) over the simulated 2020 year for both model runs.
- We calculated the relative difference of GCF between YSU and MYNN over the year 2020 (Figure 10):

$$\Delta GCF = \frac{GCF_{MYNN} - GCF_{YSU}}{GCF_{YSU}}$$

- We applied this relative difference as an additional correction (loss) factor when computing the final, long-term GCF values in the cost modeling analysis for the region.

For most of the offshore region of interest, the correction factor is on the order of 3% (Figure 10). Larger deviations occur in bay regions, particularly near the southern coast of the Salish Sea, where there are relative differences higher than 15% between the two model setups.

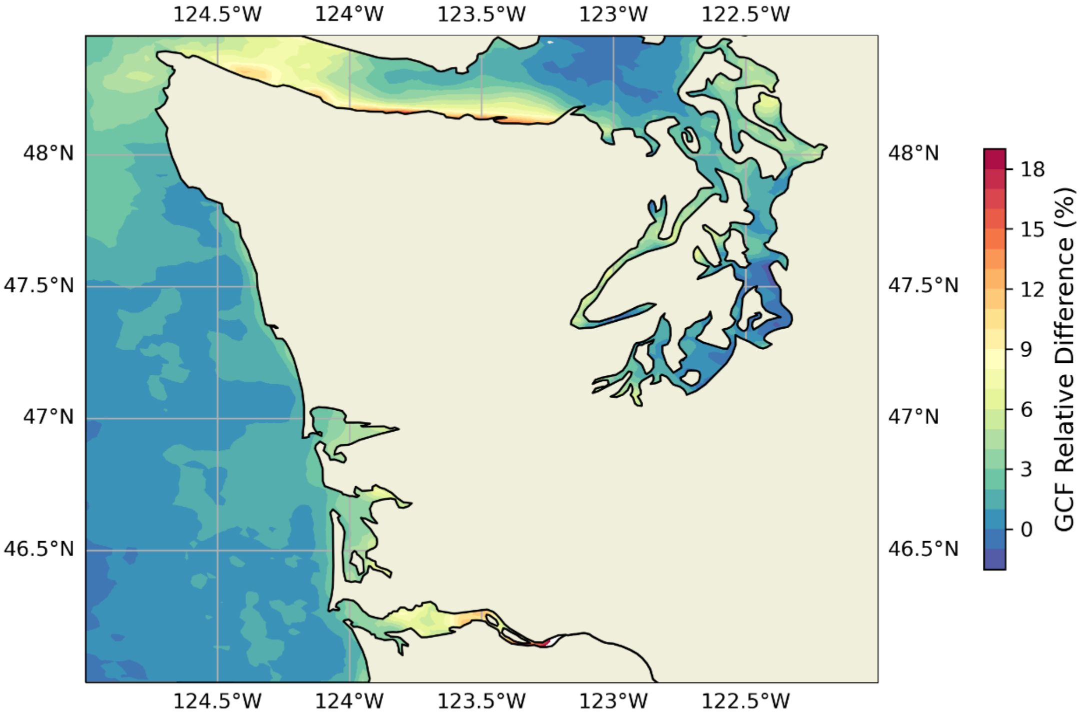

Figure 10. Relative difference in gross capacity factor between the YSU and the MYNN runs for offshore Washington, calculated over the year 2020

We note that this correction approach assumes that the correction factor calculated over the year 2020 successfully represents the long-term conditions in the region of interest.

6 Floating Offshore Wind Energy Technology

This section provides a brief overview of floating offshore wind energy technologies and how we customize the technology assumptions informing the cost modeling analysis. Floating offshore wind technology is in a nascent stage of development, but the pipeline of projects is expanding rapidly as the technology improves (Musial et al. 2023).

6.1 Overview

Floating offshore wind turbines are mounted on floating substructures attached to the seabed via mooring lines and anchors. There are a variety of anchor designs suitable for different soil and load conditions (Sound & Sea Technology Engineering Solutions 2009). Mooring lines are made of chain, steel wire ropes, synthetic ropes, or a combination. Figure 11 shows three common floating substructure topologies: spar, semisubmersible, and tension-leg platform, but there are more than 130 floating substructure design concepts at different stages of development (Wood Mackenzie 2024). Spars and semisubmersibles are advantageous during installation because these designs maintain hydrodynamic stability on their own with the wind turbine installed quayside for tow-out and hook-up; though spars require deep-water ports available in only a few places in the world. Tension-leg-platform designs are challenging to install because they are unstable until the vertical members are tensioned, and they have a smaller anchor footprint, which improves the ability to site wind turbines in deep-water lease areas (Cooperman et al. 2022; Mulas Hernando et al. 2023). The most common substructure choices in announced floating offshore wind projects are semisubmersibles (Musial et al. 2023).

Figure 11. Three floating offshore wind energy substructure designs (left to right): spar, semisubmersible, and tension-leg platform.

Illustration by Josh Bauer, NREL

Offshore wind turbines are among the largest rotating machines, and Figure 12 identifies the major components along with their scale for a 15-MW wind turbine.

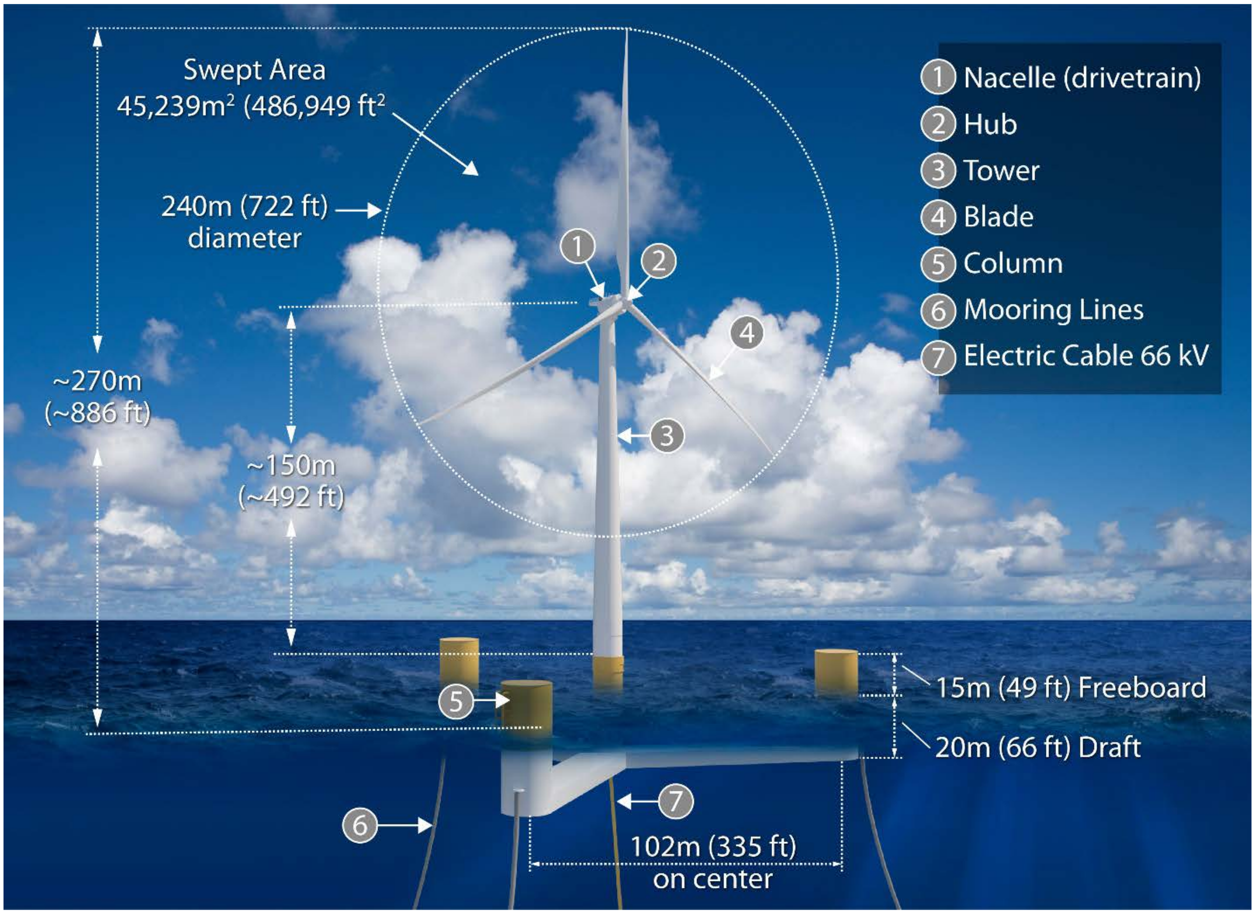

Figure 12. Representative technology based on the IEA Wind 15-MW reference wind turbine (Gaertner et al. 2020).

Illustration by Josh Bauer, NREL

The electricity generated by wind turbines is collected at the offshore substation through the array cables. The voltage is stepped up and power is transmitted to shore through the export cable(s) before entering the onshore substation and being sent to the electricity grid.

6.2 Technology Assumptions for Cost Modeling

We use a 15-MW wind turbine based on the IEA Wind 15-MW reference turbine to obtain the baseline costs and wind plant performance described in Section 4.1 (Gaertner et al. 2020). This turbine is representative of turbine technology likely to be deployed through the mid-2030s, and the cost analysis presents costs in 2035 and beyond.

Table 8. Summary of Representative Technology Assumptions for the BaselineWe do not prescribe specific wind turbine parameters to future years, because the derivation of the learning rate includes turbine scaling effects (refer to Section 4.2).

Table 8 presents key turbine and wind plant technology used in the modeling process.

Table 8. Summary of Representative Technology Assumptions for the Baseline

Parameter	Value
Rated power	15 MW
Rotor diameter	242 m
Specific power	326 W/m^2
Hub height	150 m
Substructure type	Semisubmersible (generic)
Anchor technology	Drag embedment or suction-pile, three anchors per substructure
Mooring configuration	Semitaut, three moorings per substructure

7 Grid and Port Infrastructure

Any offshore wind energy development requires supporting grid infrastructure to deliver power and ports to support component fabrication, installation, and maintenance activities. This section examines existing generation mix and grid infrastructure in Washington, identifies potential POIs to inform the calculation of electrical export system costs, and potential ports to inform installation and OpEx costs for the LCOE data presented in Section 8.

7.1 Summary of Existing Grid Infrastructure

Washington led the United States in renewable energy adoption, generating more hydroelectric power than any other state. Washington has also committed to expanding its other renewable sources with the goal of reaching a 100% renewable or non-emitting retail electricity supply by 2045. Reaching this ambitious goal will require a significant diversification and increase in the renewable electric generation mix and substantial transmission enhancements.

Washington's total electricity generation mix includes 60% hydroelectric power, 18% natural gas, 10% non-hydropower renewables, 8% nuclear, and about 4% coal power (U.S. Energy Information Administration 2024). While Washington has one of the highest shares of renewable energy in the country, the state's load is increasing rapidly, driving the need for additional resources. New hydroelectric generation will likely be limited to current dam infrastructure upgrades, as new dam construction can be environmentally damaging. In fact, the Washington State Department of Commerce announced, "[they] assume there is no opportunity to expand hydroelectricity supply in the future, so wind and solar resources [will] provide the additional energy needed" (Washington State Department of Commerce 2020). Washington has no natural gas production, so it is imported—mostly from Canada—and stored in one storage field in western Washington. Washington currently only has one active coal power plant in the state, Centralia Coal Plant, which is scheduled to retire by 2025 (TransAlta 2024). The non-hydropower renewables are primarily land-based wind resources, with about 1% biomass and minimal solar resources.

The Pacific Northwest Utilities Conference Committee (PNUCC) projects an annual energy deficit of about 8 GW in the next decade. Figure 13 includes existing power production with expected retirements but does not include planned future investments. Washington plans to bridge this gap with new wind, solar, and battery projects.

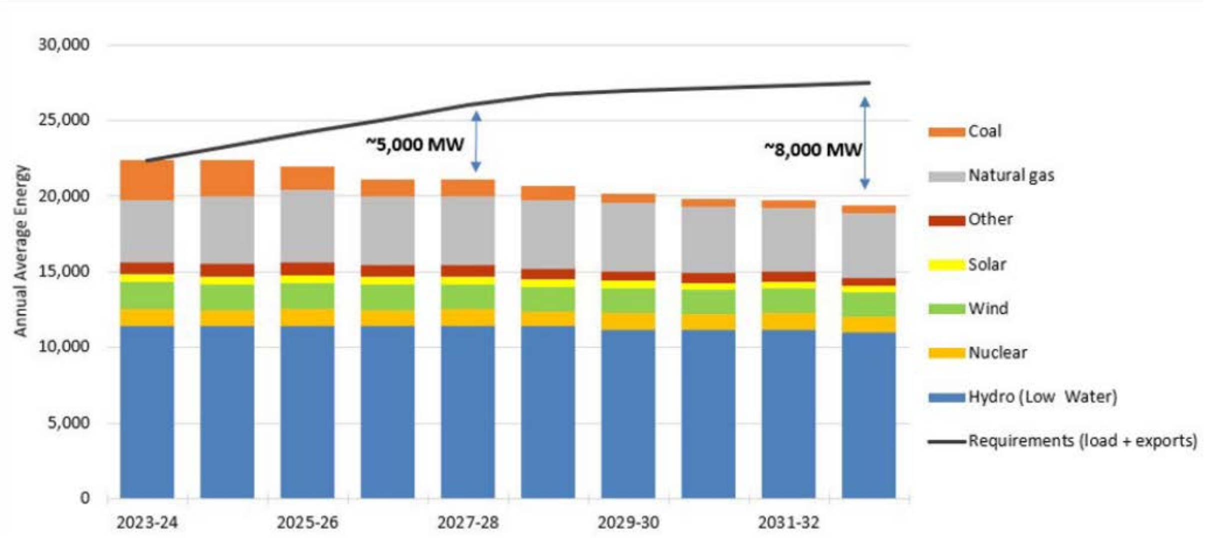

Figure 13. Projected annual energy generation.

Reproduced from the PNUCC Regional Forecast (PNUCC 2023) with permission

The future projections for proposed renewable resources in the region still fall short of load during the summer and winter peak demand periods. Figure 14 provides the planned renewable capacity that Washington's utilities have proposed. While the nameplate capacities appear to meet the deficit discussed earlier, the peak summer generation and load curves for 2027 and 2028 show a 5-GW gap. This gap will continue to grow as electrification causes load increases nationwide. Offshore wind resources could support the generation mix in these situations in the future. Diversifying the generation mix strengthens the power sector, especially in regions with high renewable penetration, such as Washington. Additionally, offshore wind production profiles can complement those of onshore wind and solar (DOE 2023), further increasing its ability to balance the Washington generation mix.

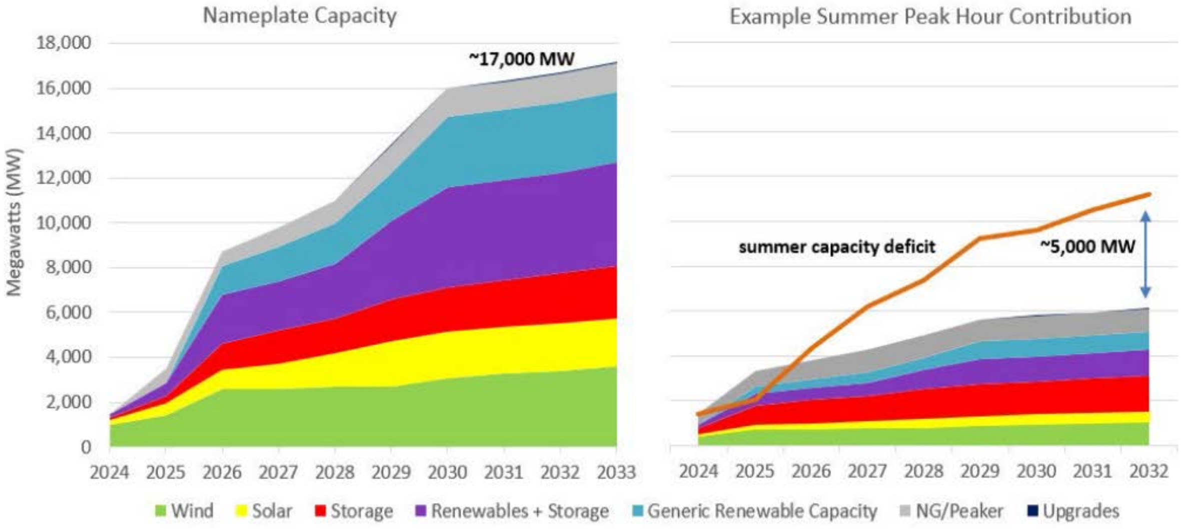

Figure 14. Planned future energy resources.

Reproduced from PNUCC Regional Forecast (PNUCC 2023) with permission

Washington has announced various state climate goals, including the Clean Energy Transformation Act (CETA) (Washington State Department of Commerce 2023). CETA outlines three milestones for Washington in the upcoming energy transition: eliminate coal from retail portfolios by 2050, reach greenhouse gas neutrality by 2030, and reach 100% renewable or non-emitting retail electricity supply by 2045. In a recent interim assessment of the CETA progress, the Washington State Department of Commerce identified the need for "more robust bulk power transmission capacity [and] faster siting and interconnection of renewable generating projects" to meet their targets (Blackmon and Scharff 2023). This assessment aligns with the offshore wind interconnection challenges discussed next.

7.2 Identifying Potential Points of Interconnection

One of the key challenges of offshore wind integration is identifying potential POIs. These points must have the available capacity and supporting infrastructure to handle a large coastal power injection. Securing viable POIs has been difficult for most states as they pursue offshore wind leasing, and Washington will be no exception. Most POIs require transmission upgrades to support the new injections and connect the renewable resource to the load centers.

In Washington, there is one proposed POI for offshore wind energy. Trident Winds submitted an unsolicited lease request for the Olympic Wind floating offshore wind project. In this document, Trident Winds suggests two landing sites that would each feed into Satsop station. Satsop station has a total capacity of about 3,400 MW with 340 MW of excess capacity. The station also connects to multiple transmission lines with voltage ratings at or above 230 kV (HIFLD 2023). BOEM has also identified Satsop station as the primary POI in Washington in their recent study on the benefits of offshore wind on the West Coast (Douville et al. 2023). These characteristics are unique among coastal substations in Washington, and the transmission upgrades required to support other substations would be expensive and difficult to site. Additionally, Satsop station is located inland of Grays Harbor, which is the closest landfall for the optimal wind resources.

In summary, while other substations could theoretically support offshore wind energy, due to the proximity to offshore wind resources and significant upgrades required for these locations, Satsop is the only POI considered in the cost modeling analysis.

7.3 Existing Port Infrastructure

Washington is home to numerous ports that can potentially support supply chain activities for floating offshore wind energy on the West Coast. As shown in Table 9 and

Table 10, 21 total Washington port locations throughout the state were analyzed as part of Shields et al. (2023a). The intent of this analysis was to determine whether ports were suitable candidates for O&M, S&I, or manufacturing of floating offshore wind energy projects. Table 9 shows the ports that were analyzed, their capabilities, and site-specific notes that describe potential limitations.

Additionally, the NREL team used a color-coded system to rate ports as good, likely, or unlikely candidate sites for each capability. Although many ports are potentially suitable for S&I and manufacturing, they have insufficient acreage to meet the infrastructure requirements of both activities. Unless ports have multiple large-acreage sites that can be used for offshore wind energy, it is unlikely that ports would be able to support manufacturing and S&I. As shown in Table 9 and

Table 10, 7 of the 21 ports were identified as good candidates for manufacturing (Shields et al. 2023a).

Table 9. Results From the Columbia River Basin Port Screening for Staging and Integration, Manufacturing/Fabrication, and Operations and Maintenance Activities

Reproduced from Shields et al. (2023a)

Port Location	Capabilities			Notes
	S&I	**M/F**	**O&M**	
Columbia River Basin				
Ilwaco (WA)			Moderate	Not much space available, shallow water depth
Chinook (WA)			Moderate	Not currently fully utilized
Cathlamet (WA)	Unlikely	Unlikely	Unlikely	Not much space available, shallow draft
Port of Longview (WA)		Good		Extensive industrial land, adequate draft
Port of Kalama (WA)		Good		Multiple sites available, adequate water depth
Woodland (WA)		🟨		Zoned for deep-draft vessel terminals, greenfield site
Vancouver (WA)		Good		Extensive industrial land right on the channel
Upriver (east) from I-5 bridge		Moderate		After the bridge, the channel is barge-only. There are ~5–10 barge-only private terminal sites that could be used for M/F. The I-5 bridge is located on the Columbia River spanning Vancouver and Portland.
~10–15 private terminal sites along the Columbia River and Willamette River		Good		This location represents a lot of former industrial sites that are no longer used or are not used to their full potential. Includes sites both west and east of the I-5 bridge. The I-5 bridge is located on the Columbia River spanning Vancouver and Portland.

S&I = staging and integration; M/F = manufacturing/fabrication; O&M = operations and maintenance. Green indicates a good candidate site, yellow indicates a moderate candidate site, and red indicates an unlikely candidate site.

Table 10. Results From Puget Sound and Washington Coast Port Screening for Staging and Integration, Manufacturing/Fabrication, and Operations and Maintenance Activities.

Reproduced from (Shields et al. 2023a)

Port Location	Capabilities			Notes
	S&I	M/F	O&M	
Puget Sound				
Bellingham	Moderate	Moderate		Little available land
Anacortes	Unlikely	Unlikely	Unlikely	Deep channels, little available land
Port Townsend	Unlikely	Unlikely	Unlikely	Little available land, shallow water depth
Everett	Unlikely X	Unlikely X		Land currently in use, but may be available in future
Port of Seattle	Good	Good		One terminal currently not in use
Port of Tacoma	Good	Good		Deep-draft channel, large empty lot near turning basin
Olympia		Moderate		Bridge restriction, currently in use by another industry but may have available land in future
Washington Coast				
Port Angeles		Moderate	Good	Little available land
Neah Bay	Unlikely	Unlikely	Unlikely	Channel is maintained by the Army Corps of Engineers, but not a lot of industrial land available
Grays Harbor	Moderate	Good	Good	Extensive land available, closer to projects than Puget sound/Olympic peninsula; nearby airport will require extensive Federal Aviation Administration coordination for S&I activities
Westport			Moderate	Columbia River has several small harbors that can support O&M
Willapa Bay/Peninsula	Unlikely	Unlikely	Unlikely	U.S. Army Corps of Engineers does not maintain the channel due to rough ocean conditions at entrance, sand bar now formed at entrance

Green indicates a good candidate site, yellow indicates a moderate ("Mod.") candidate site, and red indicates an unlikely candidate site. Red with an "X" indicates an O&M site that could be used for crew transfer vessels only (but not service operation vessels).

Cost modeling efforts for this report focused on 11 ports in Washington and Oregon that were identified in Shields et al. (2023a) as good and/or likely candidates that can support S&I and/or O&M activities for floating offshore wind energy projects in Washington. Eight of these ports are in Washington while three additional ports are in northern Oregon and in proximity to potential Washington offshore wind projects. We used these sites to determine the potential cost impacts transportation could have on the installation and maintenance of floating offshore wind projects in Washington.

Figure 1 identifies the 11 ports assumed available to support potential offshore wind energy projects in the cost analysis as well as their role: S&I activities, O&M activities, or both. Both installation and maintenance costs are parameterized as a function of distance from the nearest S&I or O&M port to the site.

8 Cost Modeling Results

In this section, we present our cost modeling results through the metrics of LCOE, CapEx, OpEx, and NCF. We present maps illustrating the spatial variation in costs as well as cost breakdowns and trajectories over time at three arbitrarily selected sites (refer to Figure 1) to explore results at a greater resolution and explain major cost drivers.

8.1 Capital Expenditures

Spatial CapEx trends are driven by a variety of factors, including water depth, distance to port, and distance to the POI. Therefore, sites closer to the coastline tend to have lower CapEx. Of the CapEx components that vary spatially, export system accounts for the largest proportion of project CapEx (Table 11). Export cable costs are highly dependent on the distance from the modeled wind plant to the landfall location en route to the POI. Both array cabling and foundation procurement, the next largest spatially varying CapEx components, depend on water depth. CapEx components that do not vary in space make up a large proportion of CapEx, namely rotor and nacelle procurement and installation as well as substructure procurement. Although these component costs do not vary in space, they still vary as a percentage of CapEx given that total CapEx varies from site to site.

Table 11. Percentage CapEx Breakdown at Three Representative Sites

Note: Line items with a “Not applicable” entry in the key spatial variable column are not site-specific.

CapEx Component	Northern Site (%)	Central Site (%)	Southern Site (%)	Key Spatial Variables
Development	3.2	3.2	3.2	Not applicable
Lease price	2.5	3.0	2.8	Not applicable
Array cabling	9.0	9.4	9.1	Water depth
Export system	21.2	13.5	16.8	Distance to landfall
Ports, staging, logistics, and management	1.1	1.2	1.1	Water depth
Turbine installation	1.4	1.2	1.2	Distance to port
Land-based spur-line and interconnection	2.6	3.0	2.9	Distance from landfall to POI
Substructure installation	0.5	0.5	0.5	Water depth, distance to port
Substructure procurement	18.0	21.3	20.1	Not applicable
Foundation procurement	3.5	3.0	3.0	Water depth
Balance of system	63	59.3	60.7	Multiple (see above)
Construction financing	4.1	4.1	4.1	Not applicable
Construction insurance	1.8	1.8	1.8	Not applicable
Decommissioning	0.3	0.3	0.3	Not applicable

CapEx Component	Northern Site (%)	Central Site (%)	Southern Site (%)	Key Spatial Variables
Installation contingency	0.7	0.6	0.6	Not applicable
Procurement contingency	4.9	4.9	4.9	Not applicable
Project completion	1.0	1.0	1.0	Not applicable
Project management	1.6	1.6	1.6	Not applicable
Soft costs (financial)	14.4	14.3	14.3	Not applicable
Rotor and nacelle procurement and assembly	19.4	22.9	21.6	Not applicable
Tower procurement	3.2	3.7	3.5	Not applicable
Wind Turbine	22.6	26.6	25.1	Not applicable

CapEx steadily decreases over the course of the study period due to increases in global industry experience, such as technology innovations and supply chain maturation (Fuchs et al. 2024). In 2035, under the mid scenario, nearly all sites have a CapEx less than $7,500/kW (Figure 15), but by 2050, nearly all sites have CapEx values less than $5,000/kW, a reduction of more than 30%. In the conservative scenario, most sites in 2035 have CapEx values less than $10,000/kW, which drops to less than $8,000/kW, resulting in a reduction of nearly 25%. In the advanced scenario, all sites have a CapEx value less than $5,500/kW in 2035, and by 2050, all sites are less than $3,500/kW, with some sites as low as $2,500/kW. The central reference site in the advanced scenarios has a nearly 38% reduction in CapEx from 2035 to 2050. The variation in reductions between scenarios is attributed to uncertainty associated with deployments and subsequent learning.

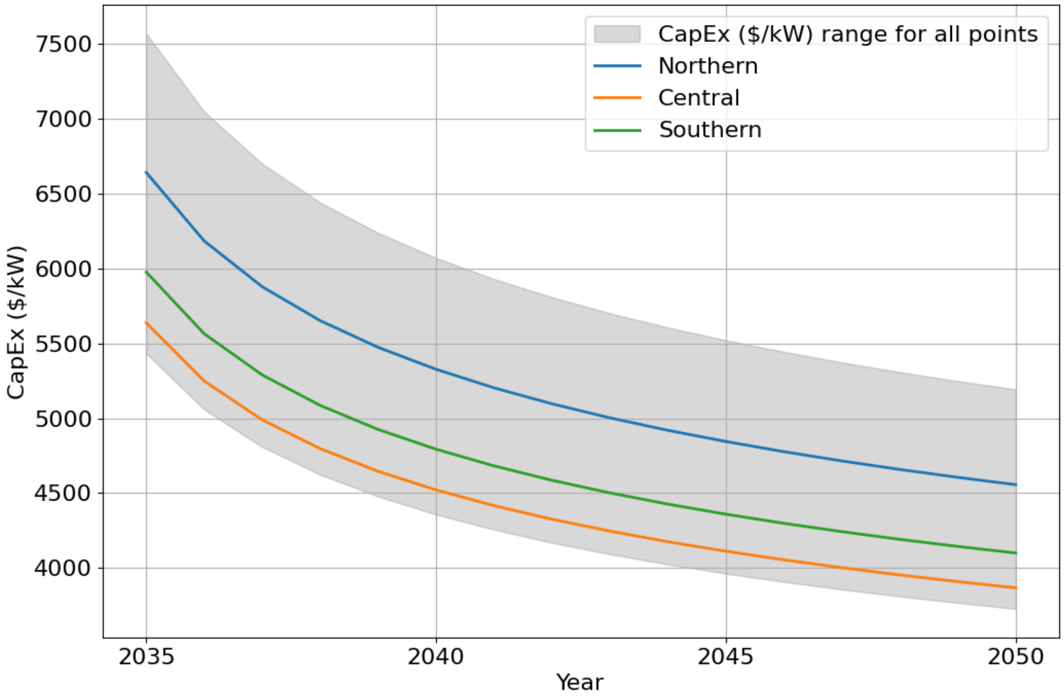

Figure 15. Evolution of floating offshore wind energy project CapEx over time at three representative sites under the mid scenario

In 2035, under the mid scenario, most sites have CapEx values between $5,500/kW and $7,500/kW (

Table 12 and Figure 16). In the conservative scenario, all sites' CapEx range between $8,000/kW and $10,500/kW. Under the advanced scenario, most sites' CapEx values are between $4,000 and $5,500/kW. Across all scenarios and years, sites in waters close to Grays Harbor have the lowest CapEx due to shallower waters and proximity to both an S&I port as well as the Satsop substation.

Table 12. Total CapEx ($/kW) at Reference Sites From 2035 to 2045 in the Conservative (Cons.), Mid, and Advanced (Adv.) Scenarios

Year	Northern			Central			Southern		
	Cons.	Mid	Adv.	Con.	Mid	Adv.	Cons.	Mid	Adv.
2035	9,419	6,643	4,769	7,993	5,638	4,047	8,475	5,977	4,291
2040	7,990	5,327	3,616	6,781	4,521	3,069	7,189	4,793	3,254
2045	7,444	4,844	3,210	6,318	4,111	2,724	6,698	4,359	2,888

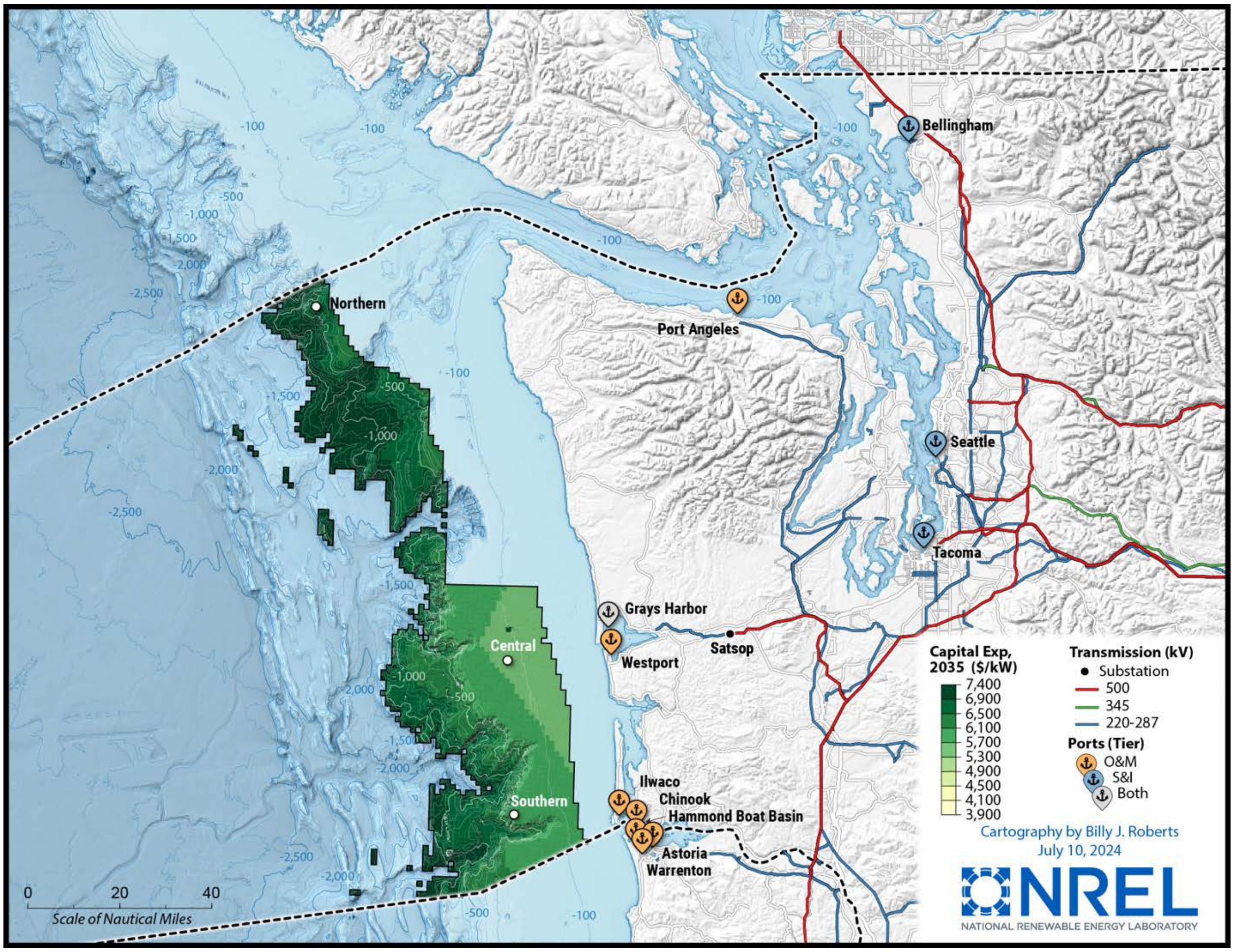

Figure 16. Map of offshore wind energy project CapEx with a 2035 COD under the mid scenario.

Figure by Billy Roberts, NREL

By 2040, CapEx values under the mid scenario are all less than $6,000/kW, with some sites, including the central reference site, around $4,500/kW (Figure 17). Under the conservative scenario, CapEx values range around $6,500−$9,000/kW. Under the advanced scenario, most CapEx values range from $3,000 to $4,000/kW. While absolute values of sites' CapEx have changed since 2035, the relative spatial distribution of CapEx remained the same due to underlying inputs remaining the same.

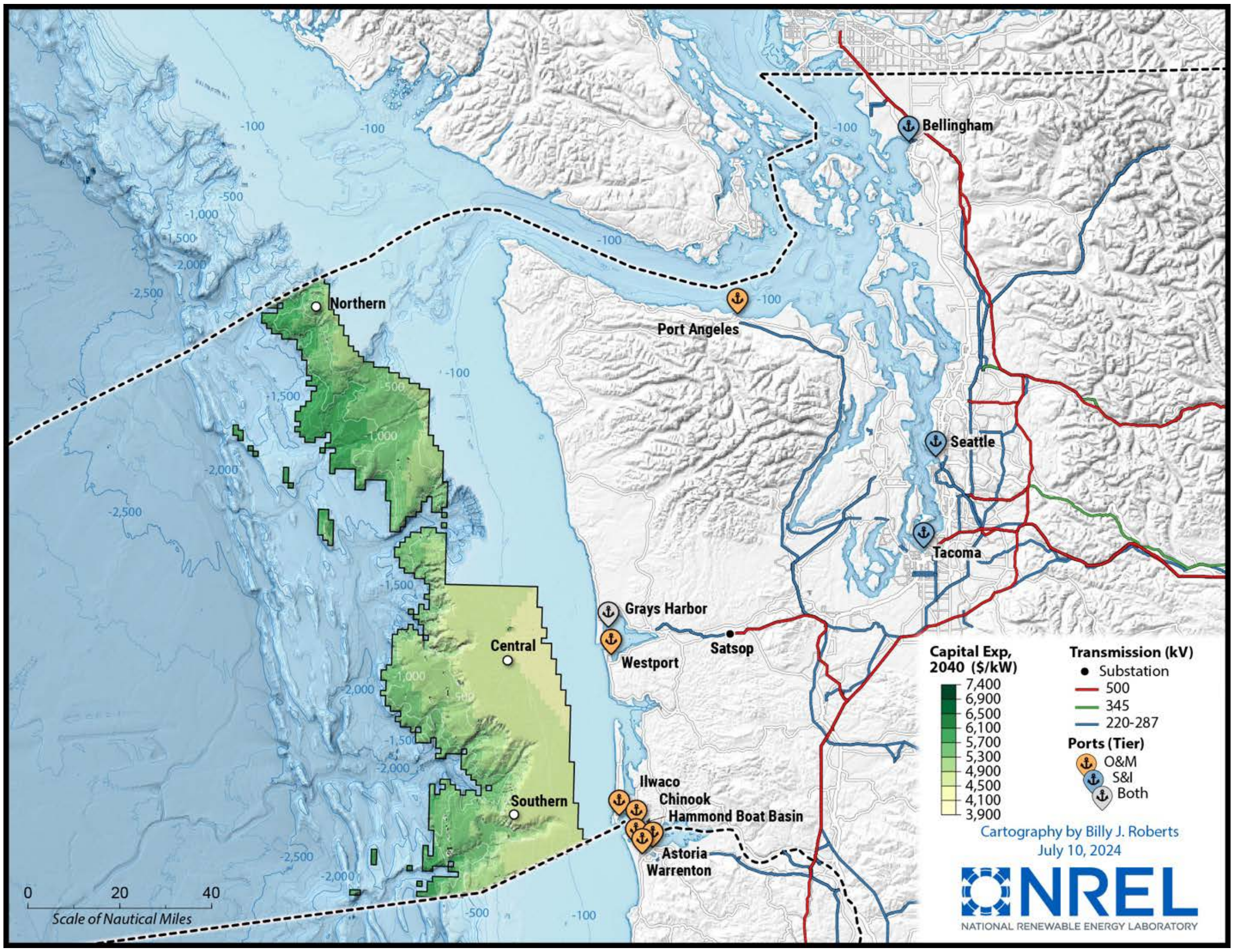

Figure 17. Map of offshore wind energy project CapEx for COD 2040 under the mid scenario.

Figure by Billy Roberts, NREL

In 2045, CapEx values under the mid scenario are nearly all less than $5,500/kW, with some sites, including the Central reference site, closer to $4,000/kW (Figure 18). Under the conservative scenario, CapEx values range from around $6,000–$8,500/kW. Under the advanced scenario, CapEx values range from around $2,600–$3,600/kW.

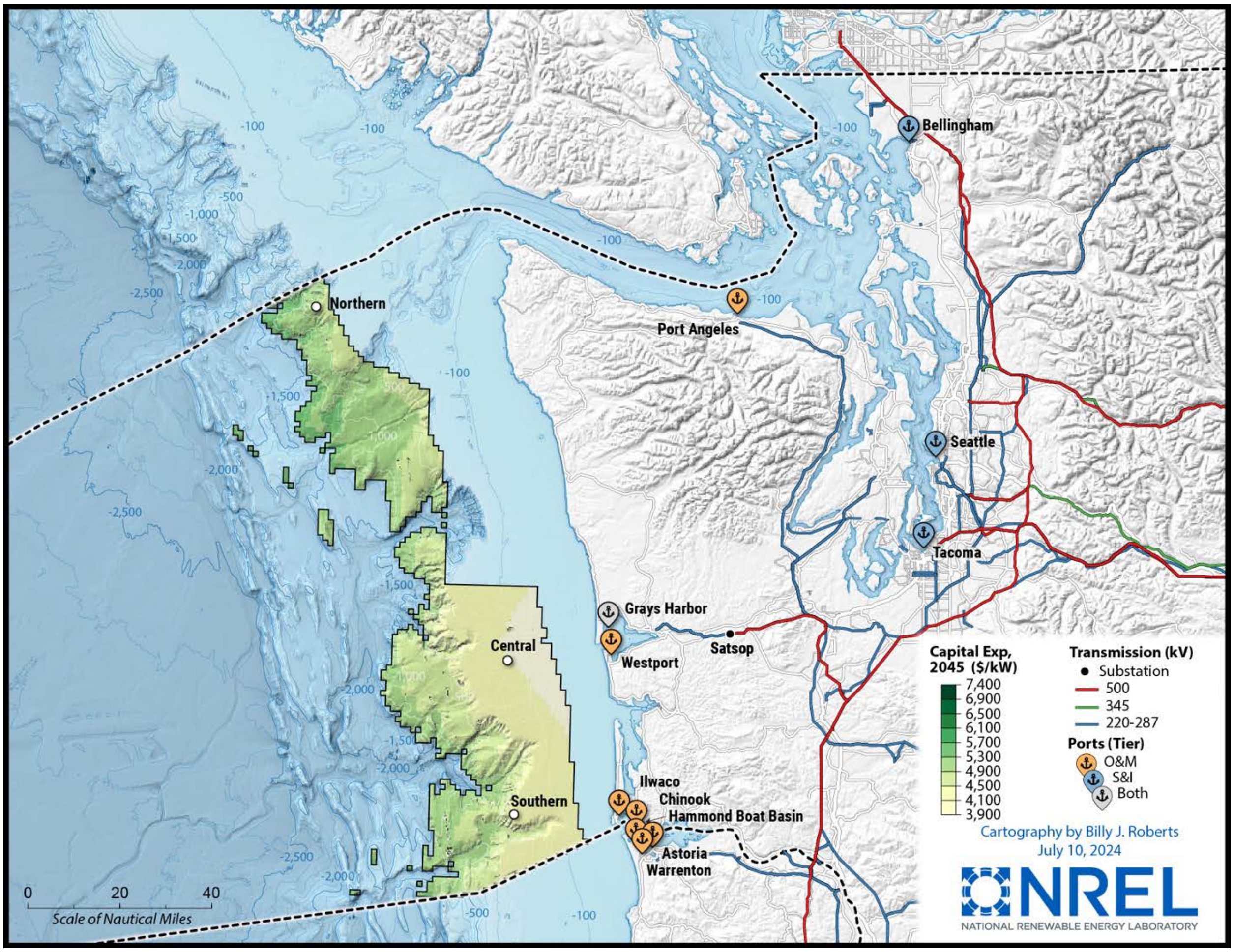

Figure 18. Map of offshore wind energy project CapEx for COD 2045 under the mid scenario.

Figure by Billy Roberts, NREL

8.2 Operational Expenditures

Like CapEx, OpEx values display similar trends, both through time and space. As the industry learns to become more efficient and the supply chain develops, we expect the OpEx values to decrease over time (Figure 19). The conservative, mid, and advanced scenarios all follow similar trends, with the differences meant to capture uncertainty related to speed and impact of learning. When compared to the mid scenario, the conservative scenario shows fewer and slower reductions in OpEx, whereas the advanced scenario reveals faster and greater reductions.

The least expensive OpEx are found in the west and southwestern side of the study area (Figure 20). OpEx is less expensive in this area because of its proximity to potential ports suitable for operations and maintenance. Closer O&M ports mean shorter travel time, resulting in lower overall ship rental time and cost. Similarly, average significant wave heights, our proxy for potential for weather delays, are lower closer to shore.

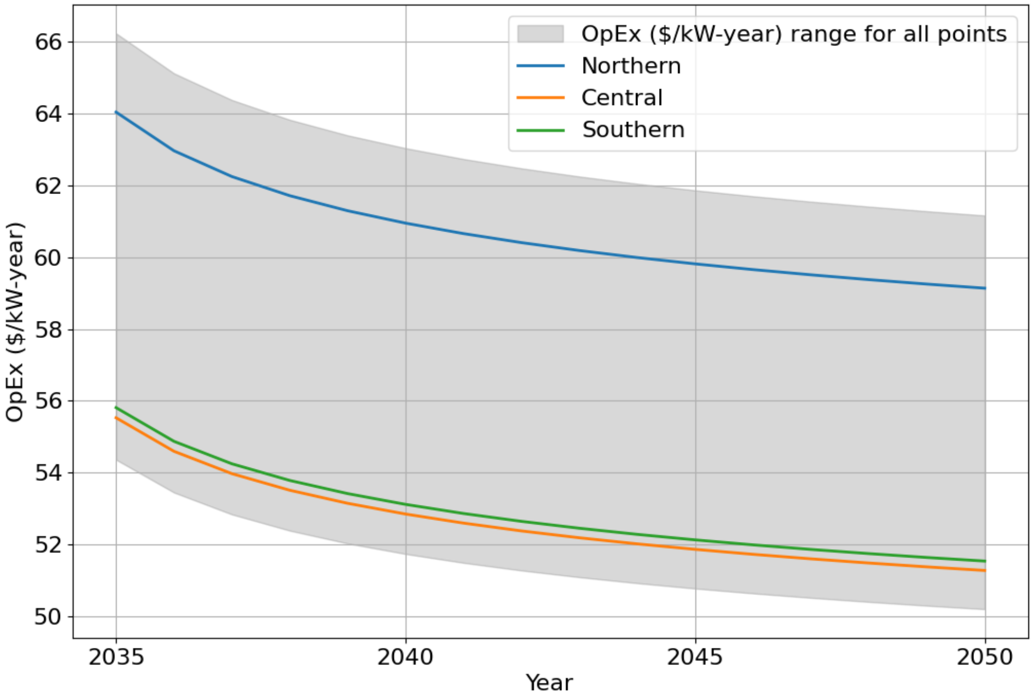

Figure 19. Evolution of floating offshore wind energy project OpEx over time at three representative sites under the mid scenario

In 2035, OpEx values range from approximately $54/kW-year to $66/kW-year under the mid scenario (Figure 20). OpEx values range from $61/kW-year to $74/kW-year under the conservative scenario and from $50/kW-year to $60/kW-year in the advanced scenario. Across all years and scenarios, the central and southern reference sites have OpEx values at the lower end of the range, whereas the northern reference site, with higher distances to O&M ports and higher wave heights, is at the higher end of the range (Table 13).

Table 13. OpEx ($/kW-year) Breakdown at Three Representative Sites From 2035 to 2045 in the Conservative (Cons.), Mid, and Advanced (Adv.) Scenarios

Year	Northern			Central			Southern		
	Cons.	Mid	Adv.	Cons.	Mid	Adv.	Cons.	Mid	Adv.
2035	72	64	58	62	56	51	63	56	51
2040	69	61	56	60	53	48	60	53	48
2045	67	60	55	58	52	47	59	52	48

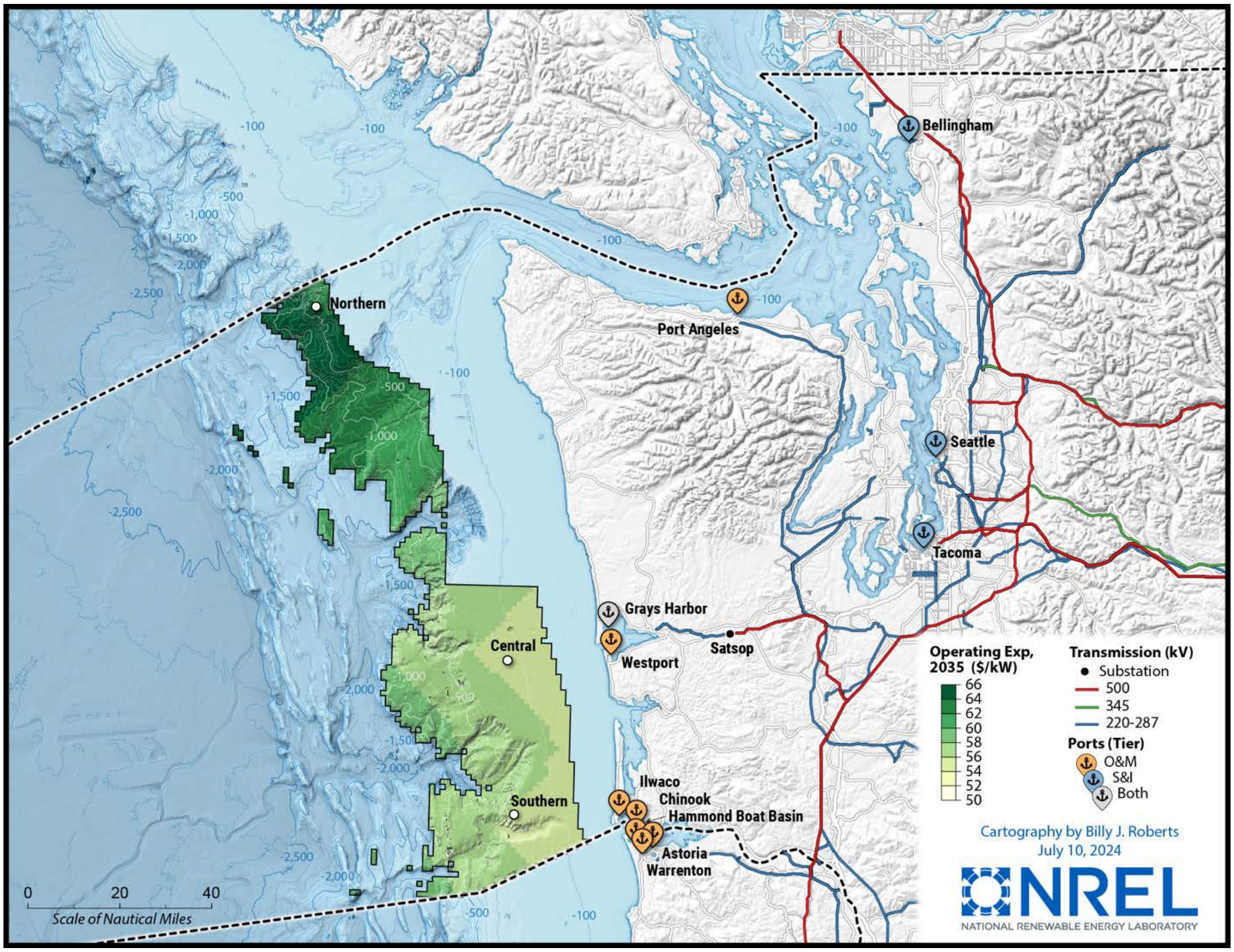

Figure 20. Map of average annual OpEx for offshore wind energy projects with a COD in 2035 under the mid scenario.

Figure by Billy Roberts, NREL

In 2040, OpEx is around 5% lower than 2035 values across all scenarios. In the mid scenario, OpEx ranges from about \$52/kW-year to \$63/kW-year (Figure 21). In the conservative scenario, OpEx values range from \$58/kW-year to \$71/kW-year; whereas in the advanced scenario, OpEx ranges from \$47/kW-year to \$58/kW-year.

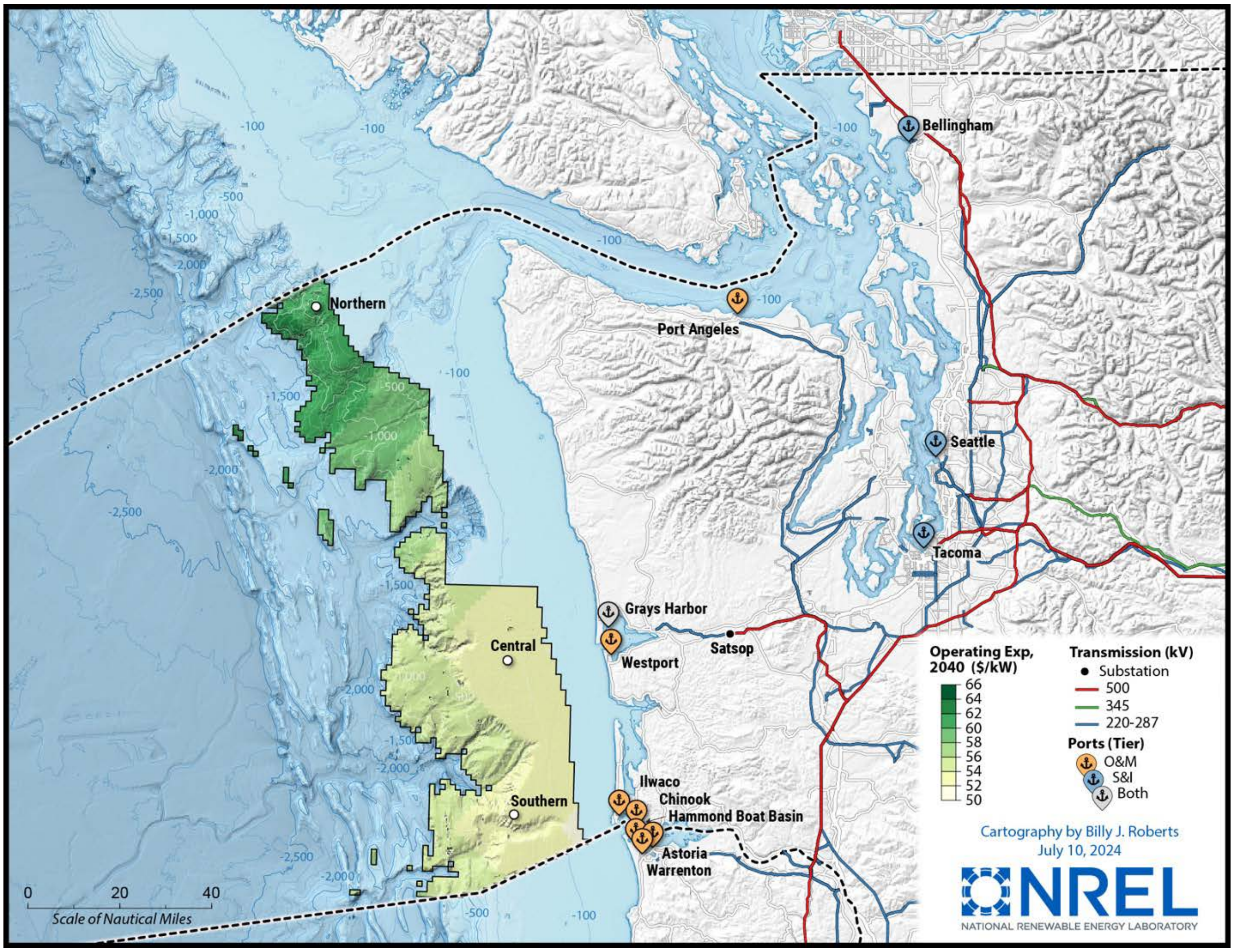

Figure 21. Map of average annual OpEx for offshore wind energy projects with a COD in 2040 under the mid scenario.

Figure by Billy Roberts, NREL

The change in OpEx from 2040 to 2045 is around 2%, which can be observed by comparing Figure 21 with Figure 22. In the mid scenario, OpEx ranges from $51/kW-year to $62/kW-year. OpEx values range from $57/kW-year to $70/kW-year in the conservative scenario and from $46/kW-year to $56/kW-year in the advanced scenario.

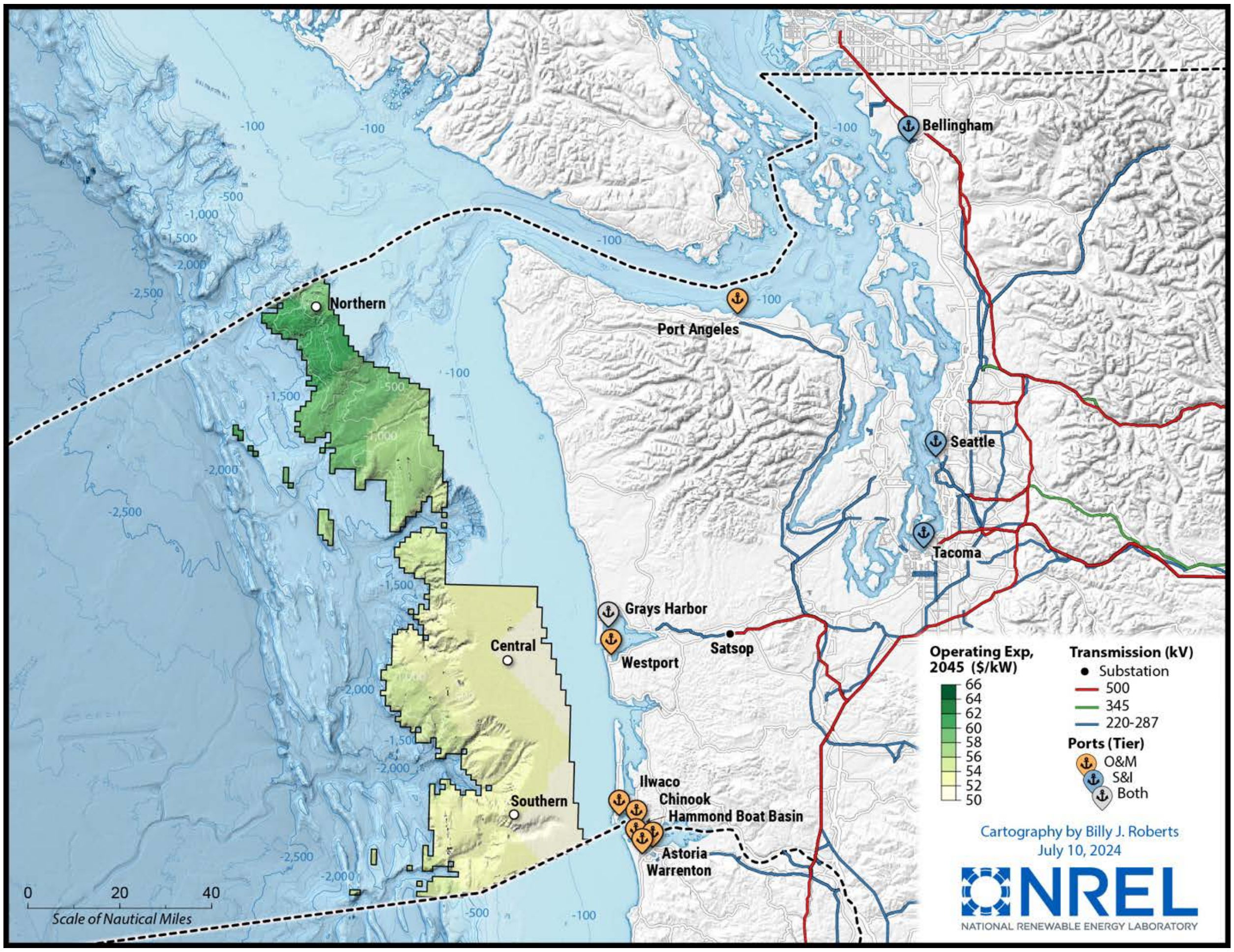

Figure 22. Map of average annual OpEx for offshore wind energy projects with a COD in 2045 under the mid scenario.

Figure by Billy Roberts, NREL

8.3 Annual Energy Production

Annual energy production tends to increase with the strength of the wind resource. The NCF is the fraction of total power output generated by the wind plant divided by its maximum power capability. NCF can be used to compare plant efficiency over a region because it is normalized by wind turbine rating and number of turbines.

In addition to wind resource, NCF also considers losses, including, wake, environmental, technical, availability, and electrical losses. The wind resource ranges across the domain but has an average between 8 and 8.5 m/s, which is comparable to the western Gulf of Mexico, and parts of South and mid-Atlantic waters (Bodini et al. 2023). However, in Washington, there are higher availability losses compared to those same regions, which lowers NCF. The higher availability losses are due to a higher likelihood for inclement weather, indicated by high significant wave heights in our model inputs.

The annual energy production increases over time because we assume wind turbine technology and energy capture efficiency also improve over time (Section 4.2). Like CapEx and OpEx, there are improvements in NCF over the duration of the study period, though at a slower pace (Figure 23 and Table 14). Across all sites, the NCF in the conservative scenario is, on average, around 4% lower than the mid scenario, whereas the advanced scenario is, on average, 5% higher. The range of improvements characterized by the three scenarios represents the uncertainty related to the speed and magnitude of wind turbine technology developments over time.

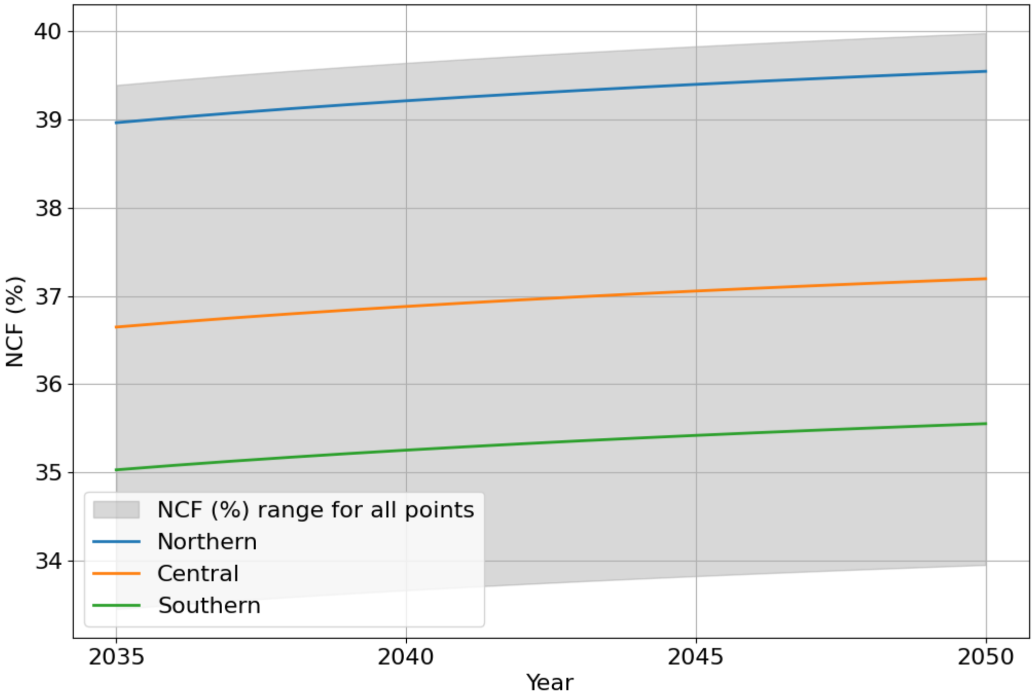

Figure 23. Evolution of floating offshore wind energy project NCF over time at three representative sites under the mid scenario

Table 14. NCF (%) at Three Representative Sites From 2035 to 2045 in the Conservative (Cons.), Mid, and Advanced (Adv.) Scenarios

Year	Northern			Central			Southern		
	Cons.	Mid	Adv.	Cons.	Mid	Adv.	Cons.	Mid	Adv.
2035	37	39	41	35	37	39	34	35	37
2040	38	39	41	35	37	39	34	35	37
2045	38	39	42	35	37	39	34	35	38

In 2035, NCF values are around 31%–33% in the northern regions closer to shore as well as in the south. Higher NCF values (34%–36%) are farther offshore and in the more central and northwest regions (Figure 24).

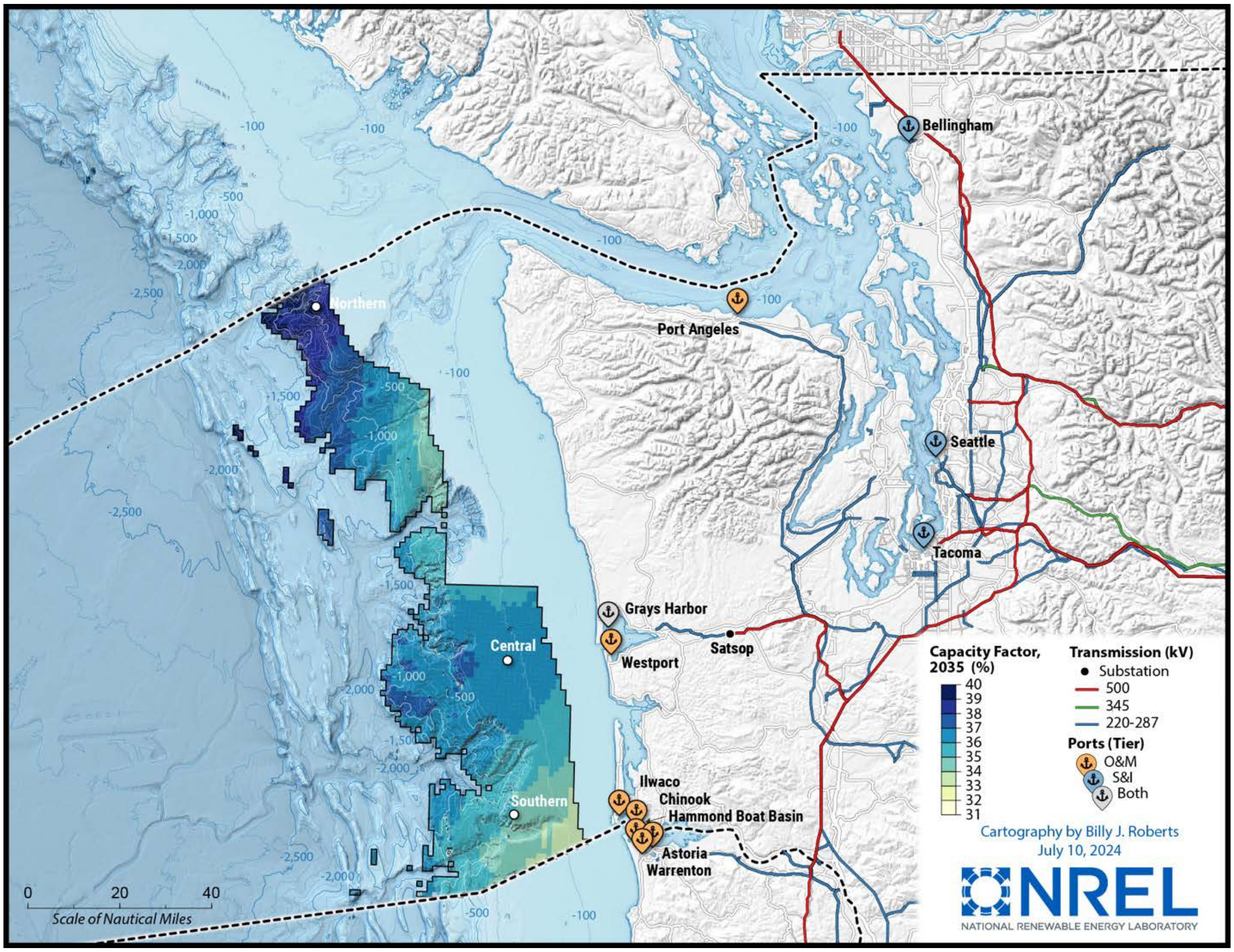

Figure 24. Map of average annual offshore wind plant net capacity factors for COD 2035 under the mid scenario.

Figure by Billy Roberts, NREL

By 2040, the assumed improvement in technology brings up the NCF values closer to 36%–38% offshore Grays Harbor, with lower NCF values (32%–33%) nearer to shore southward (Figure 25).

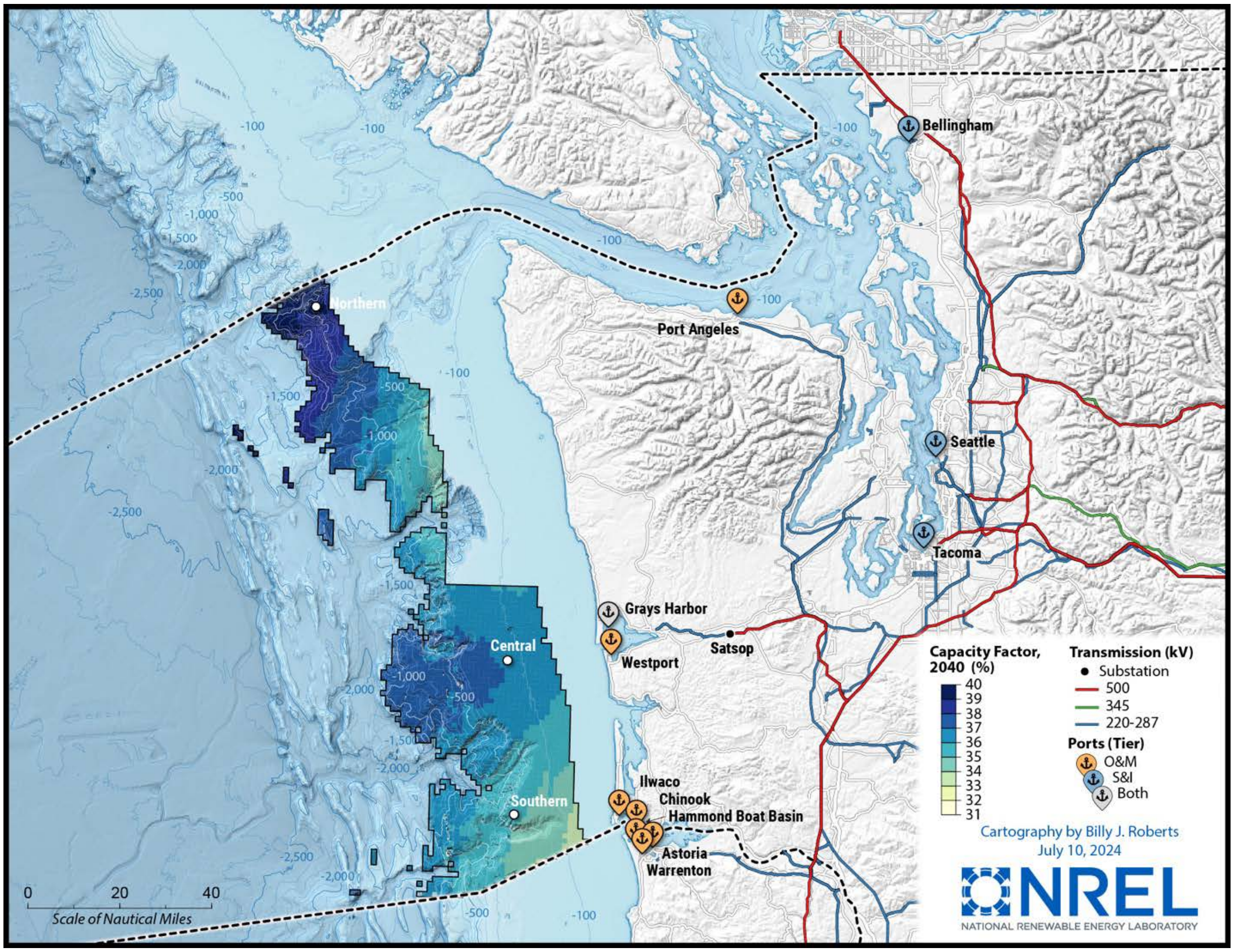

Figure 25. Map of average annual offshore wind plant net capacity factors for COD 2040 under the mid scenario.

Figure by Billy Roberts, NREL

By 2045, NCF values continue to increase slightly, with a broader area above 37% offshore Grays Harbor and Westport (Figure 26). In the northwest corner of the study area, the NCF reaches nearly 40%.

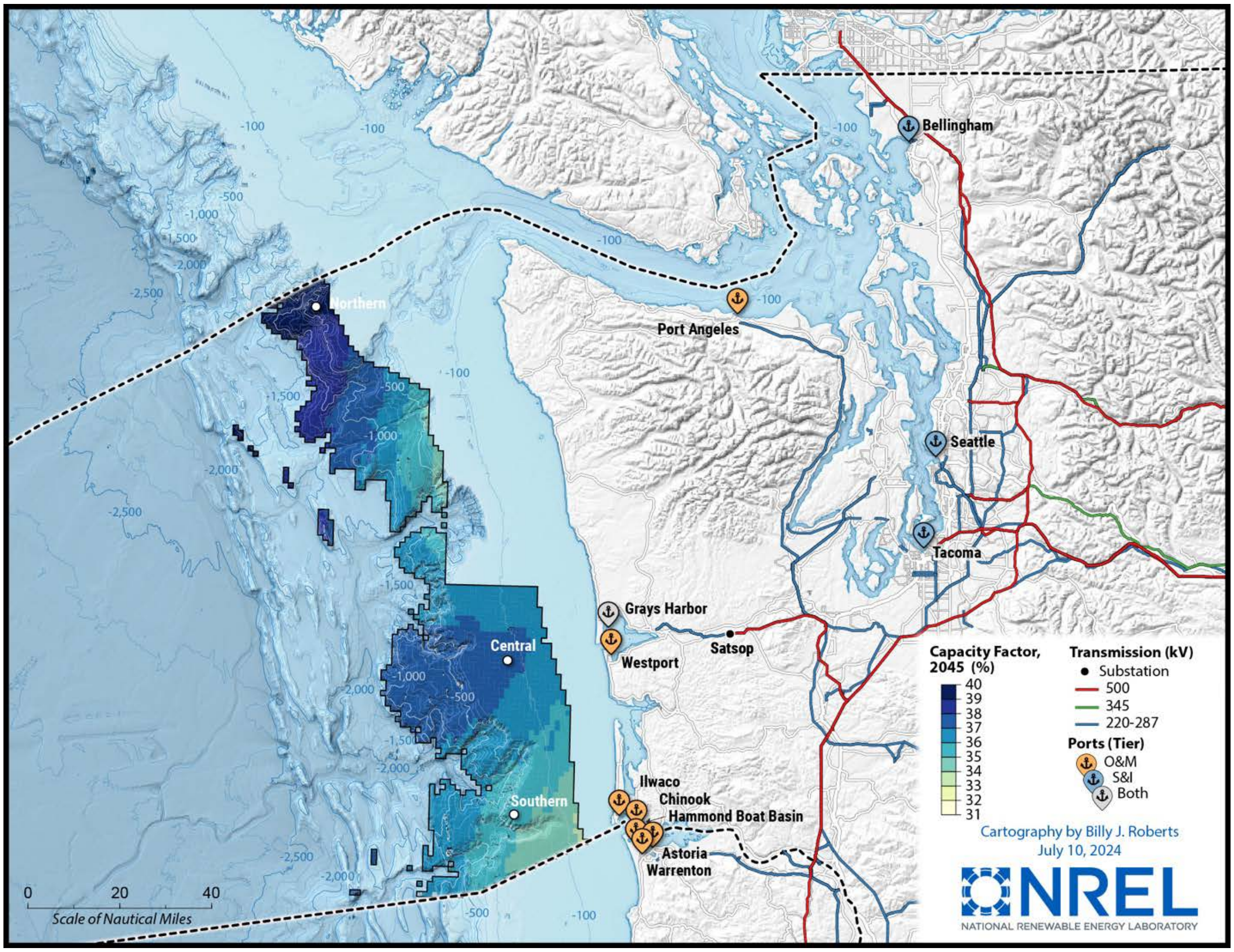

Figure 26. Map of average annual offshore wind plant net capacity factors for a COD in 2045 under the mid scenario.

Figure by Billy Roberts, NREL

8.4 Levelized Cost of Energy

The LCOE is a metric that encapsulates the various components of a wind plant’s costs and financing (e.g., CapEx, OpEx, FCR, NCF) and can therefore be used to compare sites and regions. LCOE tends to scale most with FCR, CapEx, and NCF values, but it is also impacted by OpEx and thus decreases over time like the other metrics. In 2035, all LCOE values are below $285/MWh, $200/MWh, and $140/MWh under the conservative, mid, and advanced scenarios, respectively (Figure 27). By 2050, all LCOE values fall below $220/MWh, $140/MWh, and $90/MWh under the conservative, mid, and advanced scenarios, respectively. The LCOE reductions can be attributed to reduced CapEx and OpEx, which in turn are due to predicted increases in global industry experience, supply chain maturation, and technology innovations. Additional turbine technology improves NCF, which also contributes to LCOE reductions. Given the magnitude of change in these three metrics over the study period, the reductions of CapEx play the largest role in bringing down LCOE values.

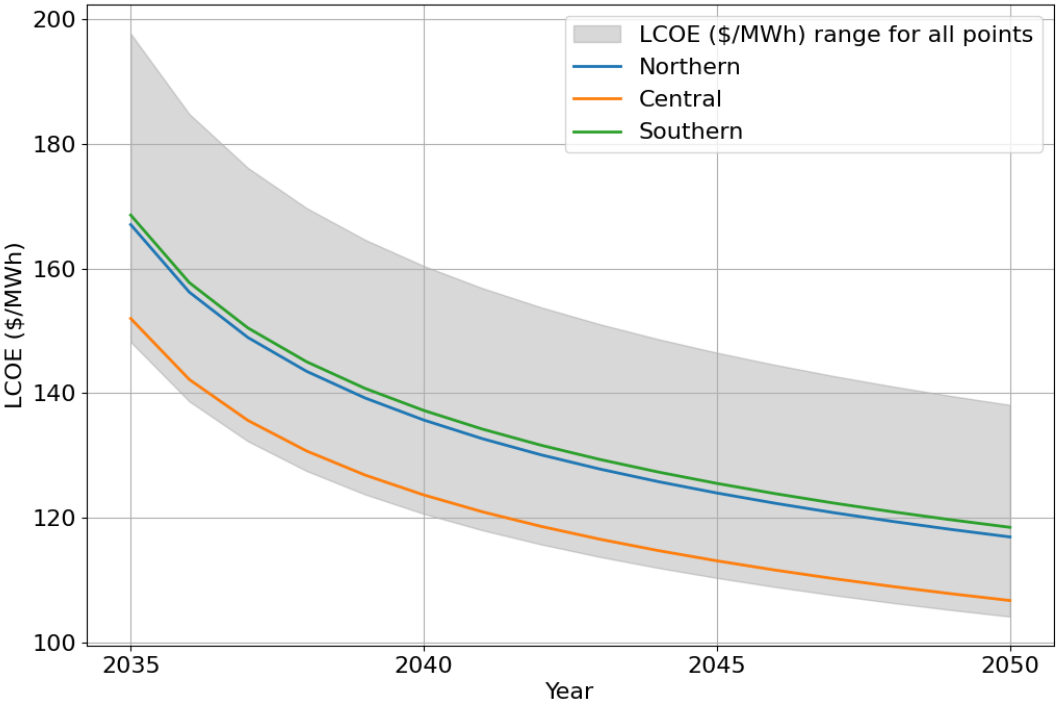

Figure 27. Evolution of floating offshore wind energy project LCOE over time at three representative sites under the mid scenario

Given that LCOE tends to scale most with CapEx and NCF values, we found the lowest LCOE values in areas with low CapEx and high NCF. In waters offshore Washington, the lowest LCOE values occur near Grays Harbor (refer to the central reference site in Table 15 and Figure 28). In 2035, the values offshore Grays Harbor are around $150/MWh, with higher values northward and southward at roughly $170/MWh (Figure 28). LCOE is lower nearer to Grays Harbor because of the lower CapEx, OpEx, and better wind resource in that area. In the southern part of the study region, the CapEx and OpEx are also low because of the proximity to potential ports, but the wind resource is not as high. In the conservative scenario, LCOE values off Grays Harbor are greater than $240/MWh, whereas in the advanced scenario they are closer to $100–$110/MWh.

Table 15. LCOE ($/MWh) Breakdown at Three Representative Sites From 2035 to 2045 in the Conservative (Cons.), Mid, and Advanced (Adv.) Scenarios

Year	Northern			Central			Southern		
	Cons.	Mid	Adv.	Cons.	Mid	Adv.	Cons.	Mid	Adv.
2035	242	168	118	219	152	107	241	168	118
2040	207	137	92	187	124	83	206	136	91
2045	193	125	82	175	113	75	193	125	82

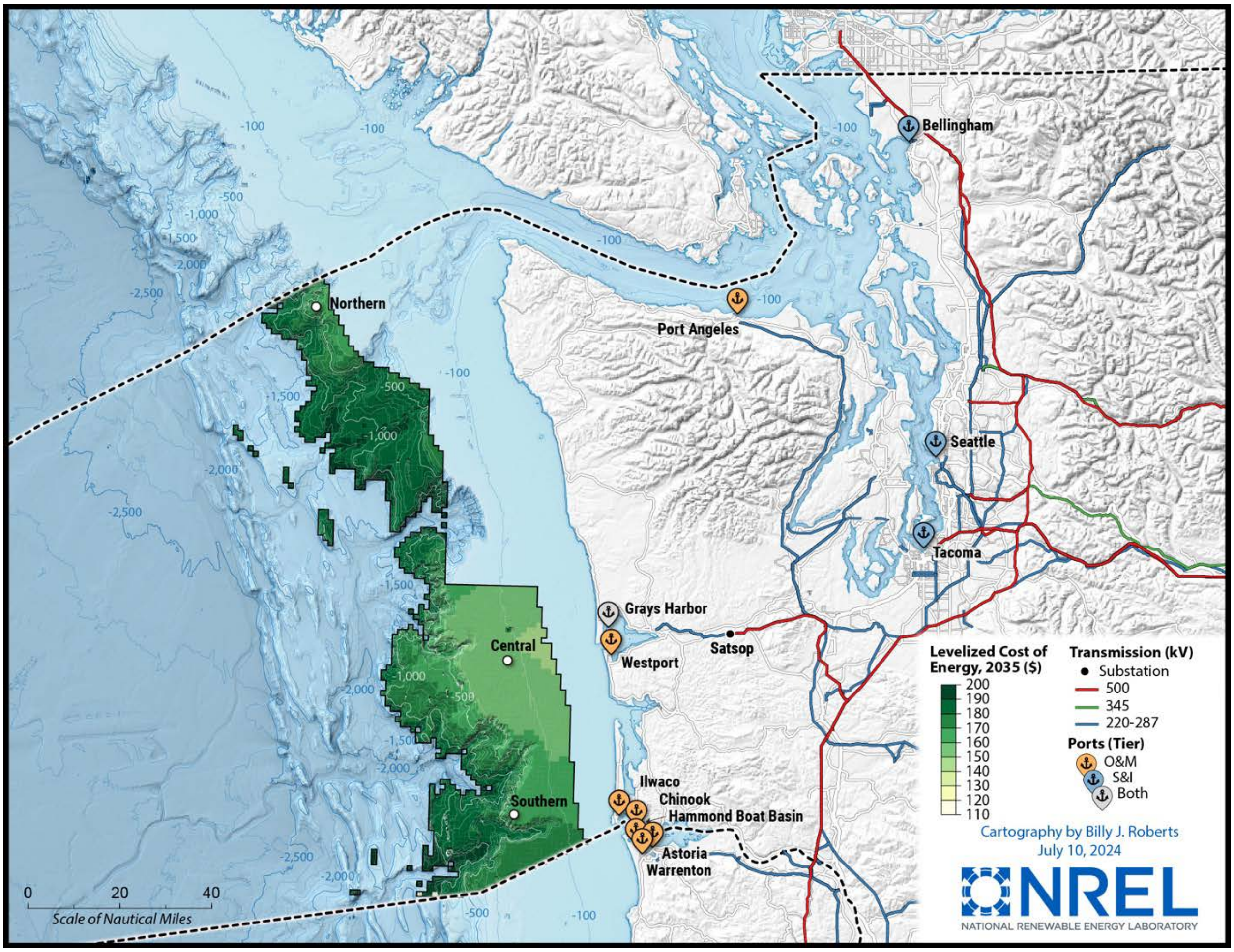

Figure 28. Map of LCOE for offshore wind energy projects with a COD in 2035 under the mid scenario.

Figure by Billy Roberts, NREL

By 2040, the LCOE off Grays Harbor remains the lowest in the region, with values around \$120/MWh, and \$130–\$140/MWh just north and south of that area (Figure 29). The highest values (>\$150/MWh) are found farther from the infrastructure, in areas with deep water or a low wind resource. In the conservative scenario, LCOE values off Grays Harbor are around \$180–\$190/MWh, whereas in the advanced scenario they drop to around \$80–\$90/MWh. Attaining different cost trajectories (advancing from the conservative scenario to the mid scenario, or from the mid scenario to the advanced scenario) requires global commitments to larger, highly certain pipelines of projects to enable greater levels of infrastructure investment, accelerating deployment to enable industry learning, and greater levels of research and development to spur technology innovation.

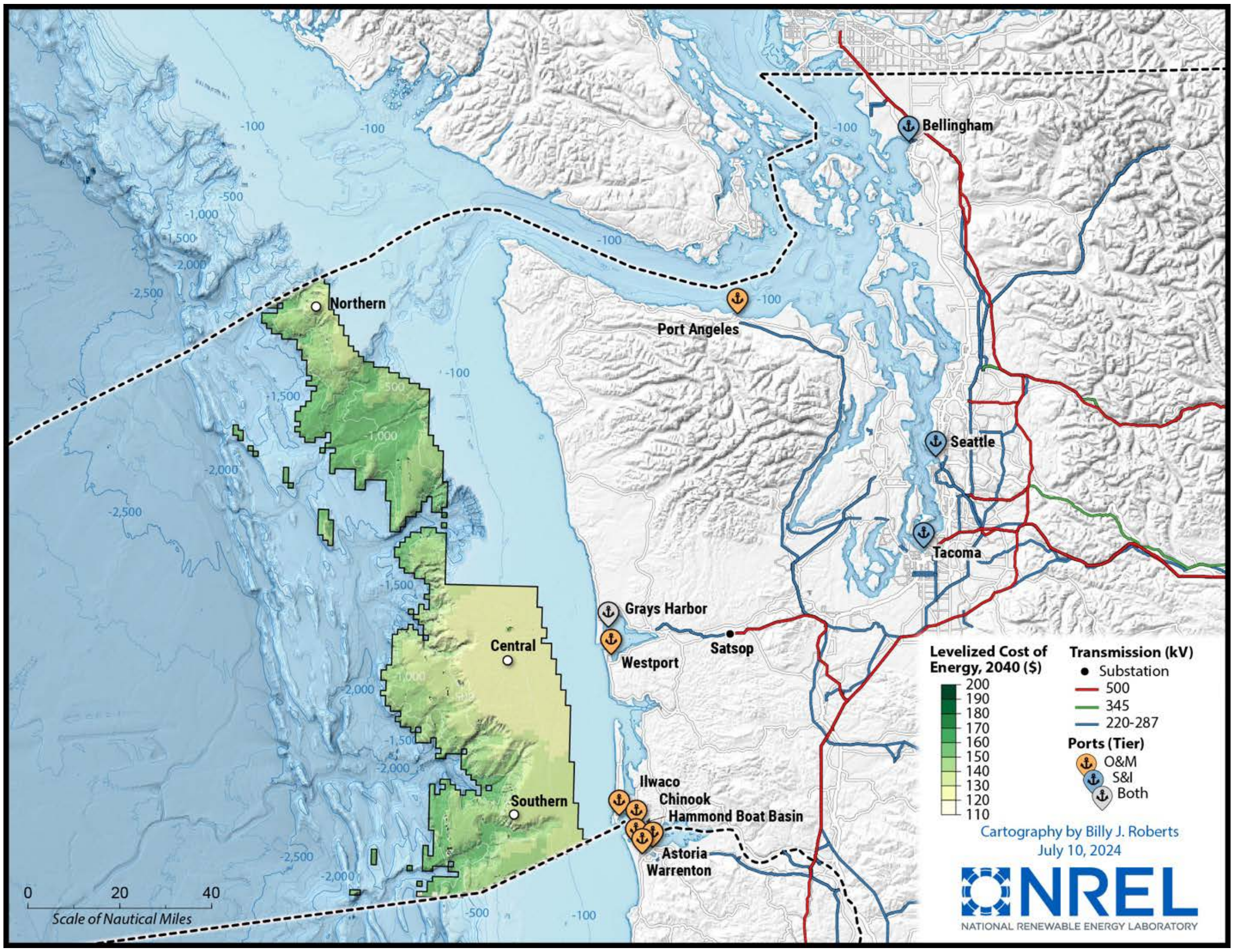

Figure 29. Map of LCOE for offshore wind energy projects with a COD in 2040 under the mid scenario.

Figure by Billy Roberts, NREL

In 2045, costs further decline so that the area offshore Grays Harbor is roughly $110/MWh (Figure 30). In the conservative scenario, this value is closer to $175/MWh, whereas in the advanced scenario it is around $75/MWh.

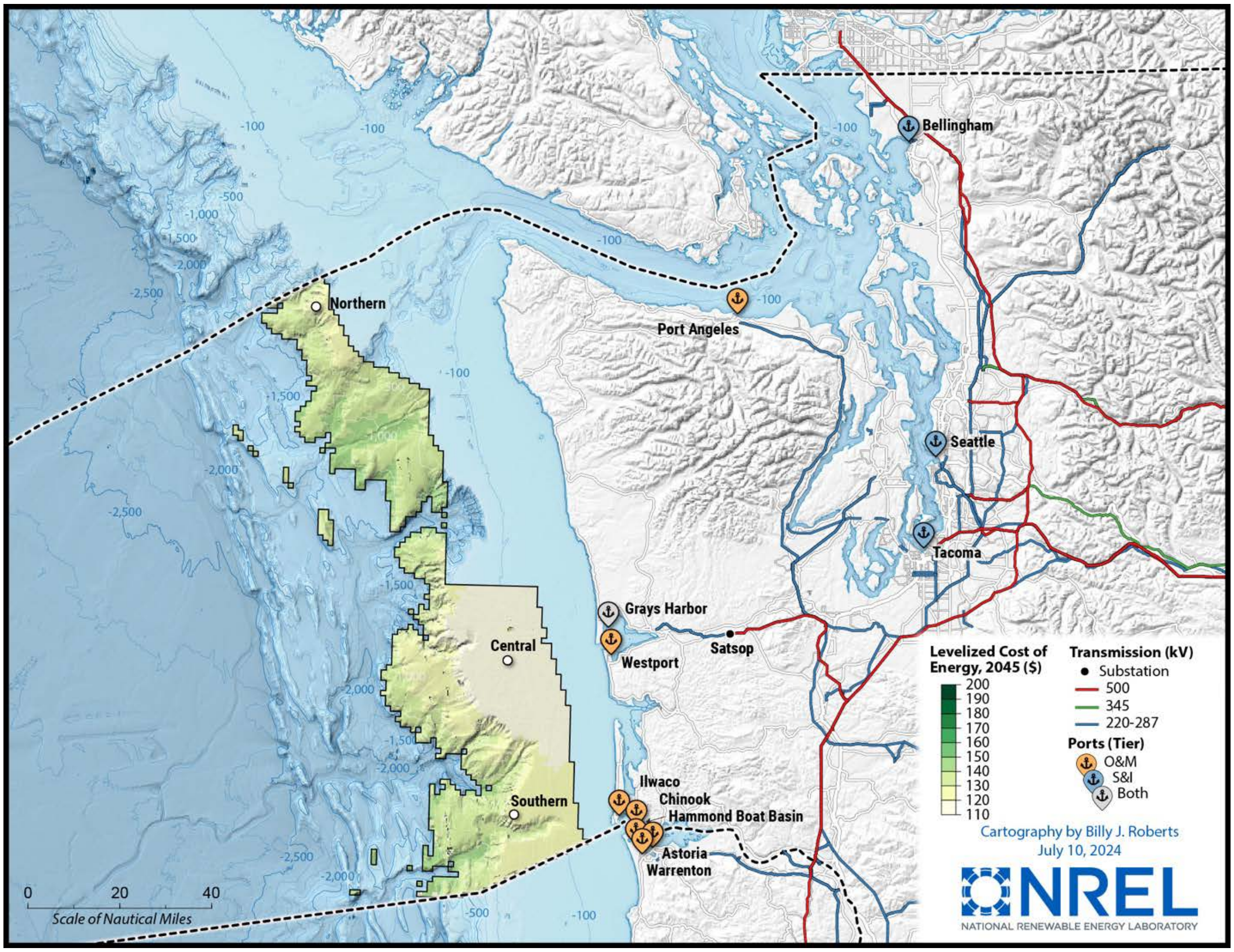

Figure 30. Map of LCOE for offshore wind energy projects with a COD in 2045 under the mid scenario.

Figure by Billy Roberts, NREL

Error! Reference source not found. summarizes mean, minimum, and maximum LCOE values across the analysis domain in 2035, 2040, and 2045 for the mid scenario, along with the mean NCF value for each year.

Table 16. Summary of LCOE and NCF Results Across All Sites Under the Mid Scenario

Year	Mean LCOE ($/MWh)	Min. LCOE ($/MWh)	Max. LCOE ($/MWh)	Mean NCF (%)
2035	206	175	235	36
2040	174	148	198	36
2045	162	138	184	37

8.5 Sensitivities

Figure 31 explores the sensitivity of LCOE to changes in intermediate cost parameters that represent a significant portion of the total cost or have greater underlying uncertainty. These parameters include wind turbine CapEx, substructure CapEx, export cable CapEx, and grid connection CapEx. We calculated the resulting 2035 LCOE at the central reference site as a function of changes in these parameters (±25% in increments of 1%). We also included the FCR and NCF to determine impacts from the debt interest rate (Section 4.1.4) and plant performance. For a 2% change in the debt rate, the nominal FCR changes more than 8%.

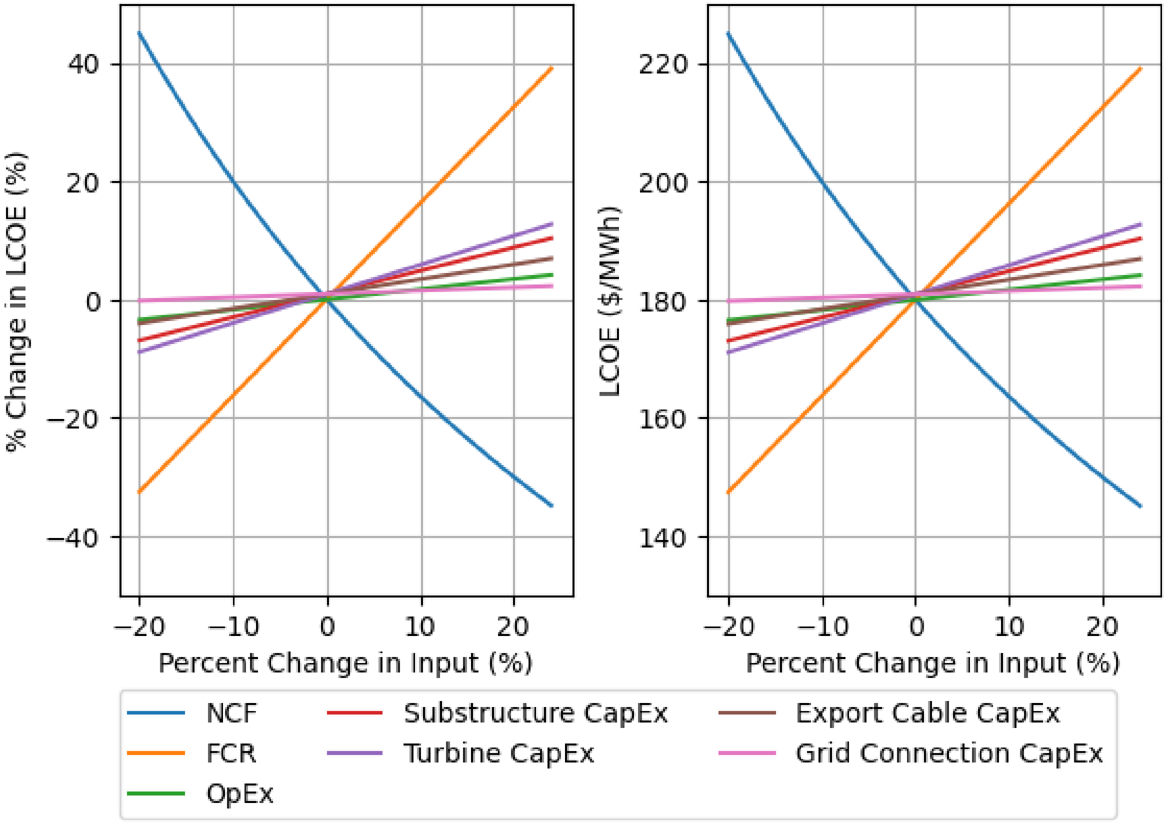

Figure 31. Sensitivity of 2035 LCOE at the central reference site to major input parameters

Figure 31 demonstrates that LCOE at this site is most sensitive to NCF, then FCR (or the debt interest rate). The most impactful CapEx line items are wind turbine CapEx and substructure CapEx.

We conducted an additional analysis of sensitivity to LCOE based on availability loss, which is summarized in Table 17. In the results presented above, we model availability loss as a function of mean significant wave heights and distances to O&M ports. Availability loss is, on average, higher in Washington than other regions due to more extreme wave conditions and greater assumed port distances (Fuchs et al. 2024). While availability losses derived in this study are within the range of historical fixed-bottom values (SPARTA 2022), a prior NREL study assumed future availability losses of 5% are achievable (Beiter et al. 2020). Adopting this more aggressive availability loss value of 5% at the central reference site shown in Figure 1 increases the 2040 mid scenario. This results in an LCOE of $109/MWh (compared to $124/MWh). This analysis combined with the sensitivity in Figure 31 demonstrate that small improvements in net capacity factor can have a large impact on LCOE in regions with lower wind speed. There could be opportunities for future technology innovations and research and development activities, which would improve floating offshore wind energy project availability. Fuchs et al. (2023) explore how turbines designed for lower-wind climates (like the Gulf of Mexico) could improve capacity factors.

Table 17. Availability Loss Sensitivity at the Central Reference Site

	Availability Loss	2040 Mean NCF (mid scenario)	2040 Mean LCOE (mid scenario)
Default availability loss calculation	11%	37%	$124/MWh
Low availability loss assumption	5%	41%	$109/MWh

9 Discussion and Conclusions

Meeting the clean energy goals in Washington included in the Clean Energy Transformation Act requires improving energy efficiency, modernizing grid infrastructure, and deploying clean electricity resources at a wide scale. To achieve these goals, non-hydropower renewables must play a major role in meeting the state's future electricity demand. Washington's offshore wind technical resource potential exceeds 6.6 GW in federal waters where BOEM has leasing authority. To help better understand this potential and support long-term energy system planning, we reviewed several key drivers for floating offshore wind energy costs and performance. In this section, we summarize key findings and caveats of this analysis and provide recommendations for future work to advance understanding of offshore wind energy resources in the region.

9.1 Key Findings

We identify the following key findings of this study:

- Being in the early stages of exploring potential offshore wind energy deployment in Washington provides an opportunity to influence decision-making and development processes that are suited to the state of Washington, including meeting the needs and preferences of key parties like Tribes and fishers. However, the experiences of those in other West Coast states and uncertainty about what is being planned for Washington are shaping perspectives about offshore wind energy and may present roadblocks to future actions.
- Limited portside infrastructure on the West Coast means that Washington ports will likely be needed to support domestic production of offshore wind turbine components and project-related infrastructure.
- While Washington has many advantages, including workforce, existing industries, and portside infrastructure that can be part of the offshore wind supply chain, there are several knowledge gaps that could impact the timing of deployment and overall contribution needed from the state.
- A validation of a recent offshore wind resource assessment (NOW-23 dataset) suggests the presence of a wind speed bias (overestimate) in data for Washington. This study developed a gross capacity factor correction to address this bias in the modeled data. For most of the offshore region of interest, the correction factor is on the order of 3% and is treated as a loss in the performance estimates.
- Resulting unsubsidized LCOE and NCF values for the mid scenario ranged from \$175/MWh to \$235/MWh in 2035 (mean of \$206/MWh), and this decreases to \$138–\$184/MWh (mean of \$162/MWh) by 2045 (Table 16). The least-cost locations in the domain are offshore Grays Harbor near the central representative site depicted in Figure 1.
- While our estimated costs are higher and net capacity factors are lower in Washington than in other West Coast states, Washington has several potential supply chain advantages that could drive further cost reductions for potential projects in the region. Advancing technologies which improve floating offshore wind turbine availability and increase AEP could significantly reduce offshore wind energy LCOE in Washington.
- Continued in-state and regional coordination and collaboration are needed to maximize Washington's potential to capture global floating offshore wind energy supply chain

investments and contribute to the buildout of a sustainable and cost-competitive floating offshore wind energy supply chain on the West Coast.
- Importing electricity generated from other sources in neighboring states or countries presents challenges related to permitting and securing rights-of-way for long-distance transmission infrastructure.
- As Washington weighs potential clean energy resources, offshore wind energy resources may prove critical in helping meet state goals set out in law, diversifying the clean electricity generation mix, improving reliability and resilience, and bolstering energy security.

9.2 Caveats

As part of this analysis, we must include the following caveats:

- This work sought to summarize ongoing engagement efforts but is not part of any official engagement or marine spatial planning processes. We do not show impacts from siting constraints, which may be significant.
- LCOE estimates provided do not include the bulk power system or additional infrastructure (port) upgrade costs.
- Offshore water depth limits the potential capacity based on the current understanding of cost-effective mooring designs for floating wind systems. As mooring technology improves, the buildable area offshore will likely increase, as will the potential for floating offshore wind energy.

9.3 Future Work

Considering the work presented in this study, we outline several priorities for further exploration related to supply chain, wind resource assessment, and grid integration.

9.3.1 Supply Chain

Robust participation in the West Coast supply chain will require ongoing analysis and resource development efforts at the state and regional level. These efforts should assess, align, and advance Washington's infrastructure and workforce capabilities along with the evolving landscape of the larger regional supply chain. As such, these efforts will require coordination and collaboration between states, agencies, and other offshore wind energy supply chain stakeholders, and are specified as follows.

Develop a supply chain roadmap that focuses on regional- and state-level capabilities and needs. This effort will help stakeholders better understand how each state's existing capabilities align with regional needs while identifying supply chain investments that could most effectively leverage these resources and provide the greatest benefits to the state while furthering the responsible development of offshore wind energy. This document could be similar to the nationally focused *Supply Chain Road Map for Offshore Wind Energy in the United States*

(Shields et al. 2023b) and the regionally focused SMART-POWER Workforce and Supply Chain Analysis[29] that is being developed for the mid-Atlantic region.

Conduct a supply chain analysis that focuses on assessing workforce capabilities at a community level in alignment with Inflation Reduction Act incentives. The Inflation Reduction Act renewed and expanded the 48C advanced energy project credit, which provides an investment tax credit of up to 30% to qualifying advanced energy projects, including many offshore wind component manufacturing facilities. To qualify for this program, advanced energy projects must meet prevailing wage and apprenticeship requirements. Assessing statewide prevailing wages and availability of apprenticeship programs is an essential part of supply chain planning, as these dynamics differ for each community.

Prioritize strategic collaboration between West Coast states to create a coordinated supply chain approach that supports domestic fabrication of cost-competitive floating offshore wind energy components. Domestically produced floating offshore wind components for West Coast projects will be competing against an already established Southeast Asian supply chain that has low labor costs. Still, current incentives and transportation costs create a scenario where components produced on the West Coast could be cost competitive. This effort would focus on developing a supply chain approach that aligns each state's goals, capabilities, and policies in a way that supports the development of a cost-effective West Coast supply chain but can also include best practices from supply chain development on the East Coast.

9.3.2 Wind Resource Assessment

Given the results of this analysis, recommended future work regarding the offshore wind resource in the region includes:

Conduct a proper validation of the NOW-23 dataset against offshore lidars, once any lidar with publicly available data in the region becomes available. While this analysis used the best available measurements for the validation exercise presented in Appendix A, a lack of hub-height measurements limits the accuracy of the validation and the derivation of the bias correction factor.

Performing a complete, long-term re-run of the NOW-23 dataset using the YSU setup, which would provide a more accurate dataset (with a full set of meteorological variables) to interested stakeholders. The gross capacity factor adjustment helps mitigate bias effects in the net capacity factor estimates but is no replacement for a long-term dataset based on a properly validated model setup. Adding a temporal extension of the NOW-23 dataset in the region up to the present would further improve the value of this resource assessment. In fact, it is necessary that the modeled results overlap with short-term lidar observations that may become available. This will help create long-term corrected time series that are critical to perform energy production analysis for the region.

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[29] For more information about the SMART-POWER Workforce and Supply Chain Analysis, visit https://www.commerce.nc.gov/news/press-releases/2023/10/03/north-carolina-partners-mid-atlantic-states-and-national-renewable-energy-laboratory-assess-offshore.

9.3.3 Grid Integration

To fully understand the grid impacts of offshore wind and quantify the transmission upgrades required to support coastal power injections, further modeling is necessary. There have been multiple studies conducted by NREL addressing these questions for different regions in the United States.

Further the relationship between LCOE and distance to assumed electricity grid point of interconnection. In 2021, a cost and feasibility study conducted on the Hawaiian island of O'ahu quantified the sensitivity of LCOE to the number and location of available POIs (Shields et al. 2021). Given the limited POI availability in Washington, this type of analysis could provide motivation for coastal transmission infrastructure investments.

Quantify grid impacts and value from potential offshore wind energy integration in Washington. Another NREL study focused on grid impacts of offshore wind energy in Oregon used capacity expansion modeling to explore the least-cost method of connecting offshore wind to the onshore grid (Novacheck and Schwarz 2021). The authors found that offshore wind injections were proportional to the transmission line ratings associated with coastal substations and that coastal transmission congestion is the main driver for offshore wind curtailment in Oregon. Both findings support the need for coastal transmission upgrades to maximize the benefits of offshore wind. Additionally, the authors found that offshore wind is capable of relieving onshore transmission congestion in Oregon, especially along the east/west corridor. Considering the higher proportion of renewable resources in eastern Washington, this could likely apply in Washington as well. A study like this in Washington would be valuable for understanding the impacts of coastal transmission availability on offshore wind performance and the value of offshore wind energy to the Washington grid.

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Appendix A. Validation of the NOW-23 Dataset in the Pacific Northwest

To validate NOW-23 in the Pacific Northwest region, we ran two additional simulations for year 2020:

- The first simulation mimics the NOW-23 setup with the MYNN PBL scheme.
- The second simulation uses the YSU PBL scheme while keeping all the other setup choices the same as in NOW-23.

We chose the year 2020 because it offers good coverage of observations in the region, and the 2020 mean wind speeds over the region align with their long-term mean.

Offshore wind speed observations in the region are scarce, which limits the extent of the validation that can be completed. The ideal measurements for this application would be coming from floating lidars, which provide full wind profiles at offshore locations. Notably, no floating lidar with public data is available in the region. Instead, we considered all the publicly available observations in the region and compared the two 1-year model runs against observations from:

- Near-surface (between 3.8 and 4.5 m above sea level) wind measurements from eight National Oceanic and Atmospheric Administration (NOAA) National Data Buoy Center (NDBC) buoys.
- Full wind speed profiles from two NOAA coastal (both less 5 km from the Pacific Ocean) radar profilers in northern and southern Oregon.

We noted that both observational datasets have inherent limitations: near-surface buoys do not provide observations at heights relevant for wind energy; coastal radars only provide information for near-coastal regions. These coastal regions present significant challenges for validating the modeled wind speeds from the Weather Research and Forecasting Model. This difficulty stems from the relatively coarse resolution of the mesoscale model (2 km in this case) and the strong wind speed gradients often encountered near coastlines. Nonetheless, in the absence of offshore lidar data for the region, datasets from NDBC surface buoys and NOAA coastal radar remain the most reliable sources available for validating NOW-23. The locations of the instruments used for this validation are shown in Figure A-1.

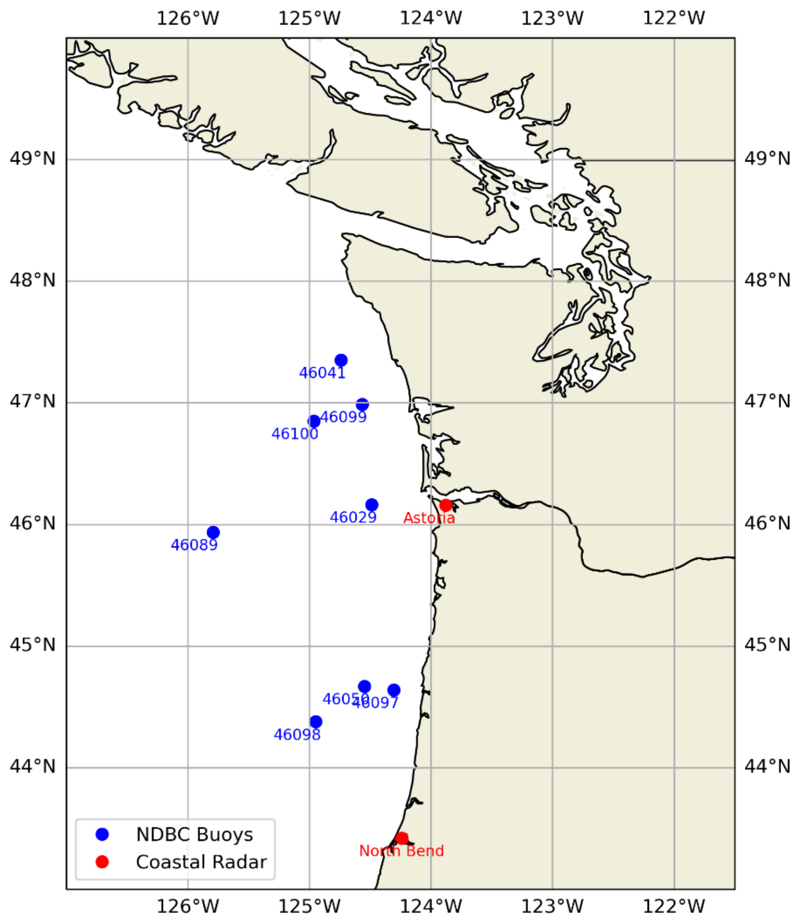

Figure A-1. Map of the instruments used for model validation

The Astoria and North Bend coastal radar profilers provide wind speed measurements between 200 and 500 m above the ground. As mentioned earlier, being located on the coast, they represent a less-than-ideal source of validation data given the 2-km horizontal resolution used in the numerical model, which cannot fully capture the strong gradients in wind speed at the land-sea interface. When comparing the mean wind speed profiles from the two Weather Research and Forecasting Model runs against the coastal wind profiler observations over year 2020, we find that both model setups overestimate wind speeds at all heights and at both locations, with MYNN showing a more severe bias at both sites (Figure A-2).

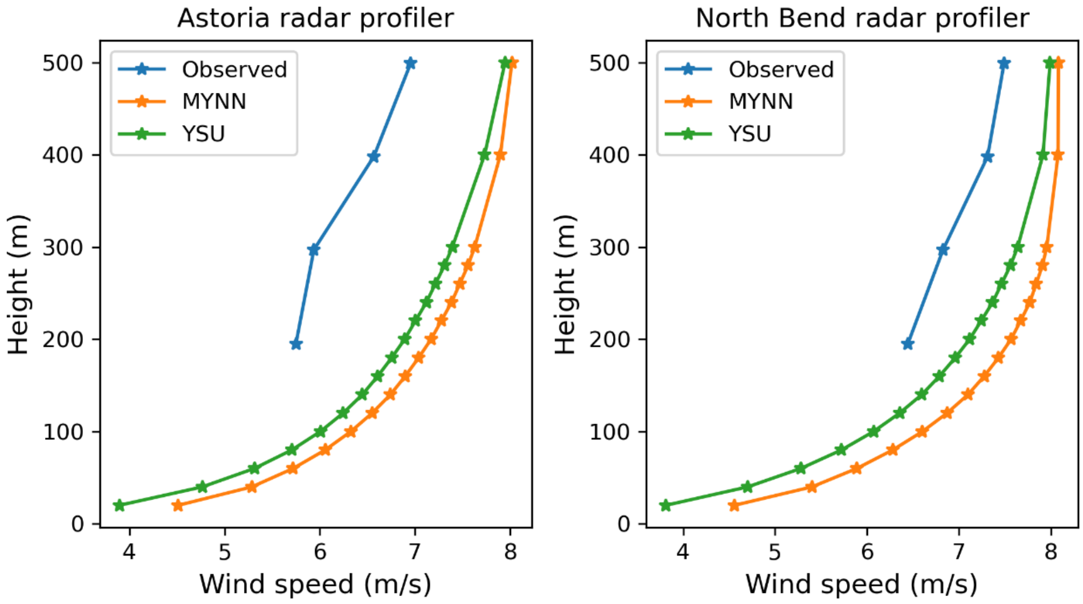

Figure A-2. Mean modeled and observed wind profiles over year 2020 at the (left) Astoria and (right) North Bend coastal wind profilers

Next, we considered the validation of our model runs against near-surface buoy measurements. The lowest Weather Research and Forecasting Model output is 20 m above sea level. To compare simulated and observed winds, we extrapolated modeled winds from 20 m to the buoy height using the standard Monin-Obukhov similarity theory (Monin and Obukhov 1954), with representative correction functions for unstable and stable conditions (Beljaars and Holtslag 1991). Results for such validation are shown in Figure A-3 for the eight buoys considered in the analysis. As shown for the coastal wind profilers, we find that both model setups overestimate wind speed, with MYNN once again having a more severe bias at seven of the eight considered locations.

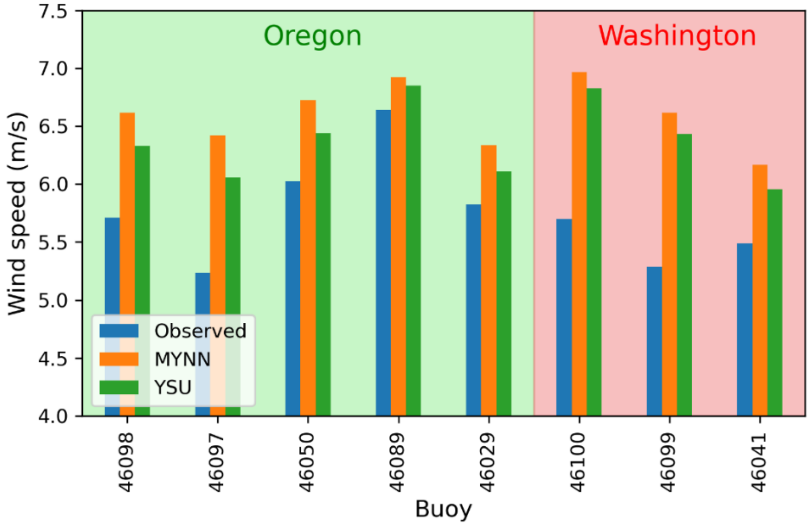

Figure A-3. Observed and modeled mean near-surface wind speed over year 2020 at the locations of eight buoys

To fully understand the impact of the observed biases on offshore wind power production, additional considerations are needed. In fact, a given bias in wind speed has a different impact on wind power production depending on where (i.e., for which wind speeds) on a wind turbine power curve the bias occurs. In fact, should a bias be confined to high winds, its impact on produced energy would be smaller or even negligible (if a turbine is between its rated and cut-out wind speed values). To assess this, we evaluated the bias at Buoy 46041 off the coast of Washington as a function of wind speed bins (Figure A-4). As observed in the NOW-23 bias analysis for offshore California (Bodini et al. 2022), we find that the largest biases for both the MYNN- and YSU-based model runs occur for high wind speed values—those above typical rated wind speed values for modern commercial turbines, where the impact of such bias on wind energy production is limited. Also, we find that the difference between MYNN- and YSU-modeled wind speed is smaller at relatively low wind speeds (above cut-in, in Region 2 of the power curve), when the impact of power would be largest.

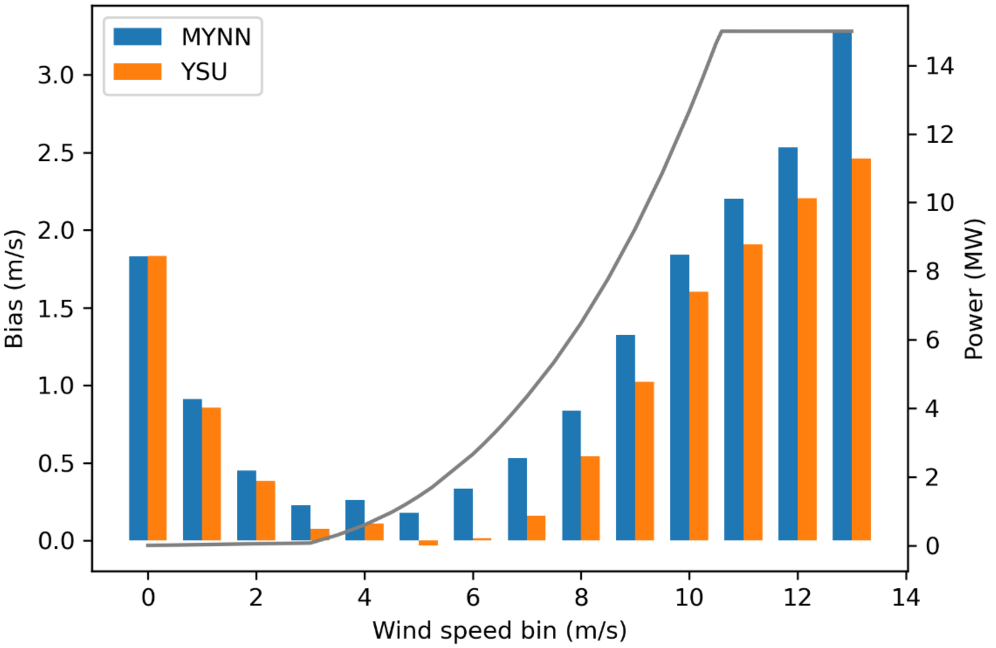

Figure A-4. Wind speed bias for various wind speed bins over year 2020 at the location of Buoy 46041, with the power curve of the IEA Wind 15-MW reference wind turbine overlaid

To further assess the impact this uneven distribution of wind speed bias has on offshore wind power production, we consider the IEA Wind 15-MW reference offshore wind turbine (Gaertner et al. 2020) and calculate the GCFs at the location of the eight NDBC buoys. GCFs represent initial estimates of wind plant performance without losses such as wake losses (refer to Section 4.1.3 for incorporation of losses into the NCF). Figure A-5 shows that YSU has slightly lower GCF values (and closer to what observed values would be) than MYNN across seven of the eight offshore locations, with relative differences ranging from −4 to +0.2%.

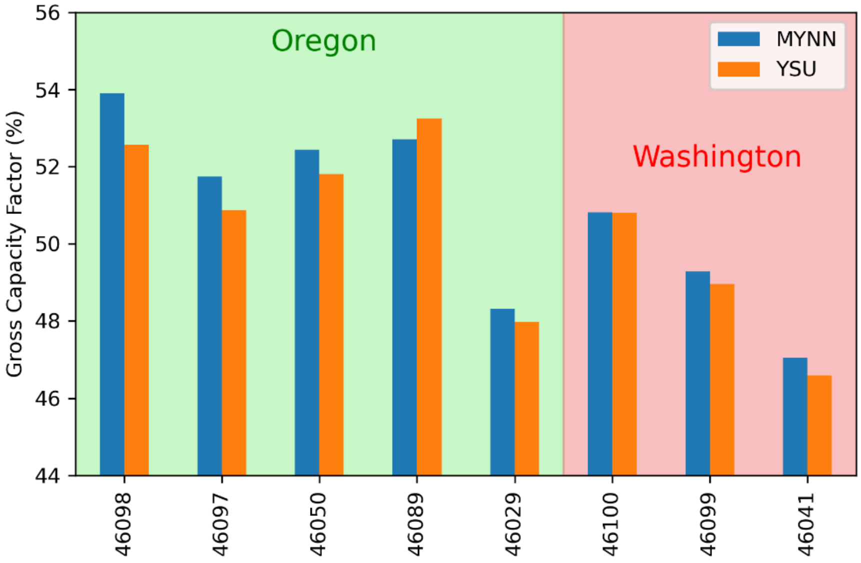

Figure A-5. Gross capacity factors for the MYNN and YSU simulations at the location of the eight NDBC buoys used for model validation

Finally, the analysis of the offshore wind resource for California revealed that the model's ability to represent atmospheric stability was one of the key factors to explain the bias in modeled wind speed. Here, we assessed the ability of the YSU- and MYNN-based model runs to capture atmospheric stability at the considered NDBC buoy validation sites. We used as proxy for atmospheric stability the difference between 4-m air temperature and sea-surface temperature, wherein a positive difference indicates stable conditions, and plotted observed and modeled distributions at the locations of the four buoys in Washington (Figure A-6). We find that MYNN shows a positive bias in temperature across the four Washington buoys, as already observed in northern California, which leads to more frequent stable stratification than what is observed. On the other hand, the YSU-based runs are capable of better capturing the observed atmospheric stability, which therefore can explain its better agreement with the observed wind resource data in the region.

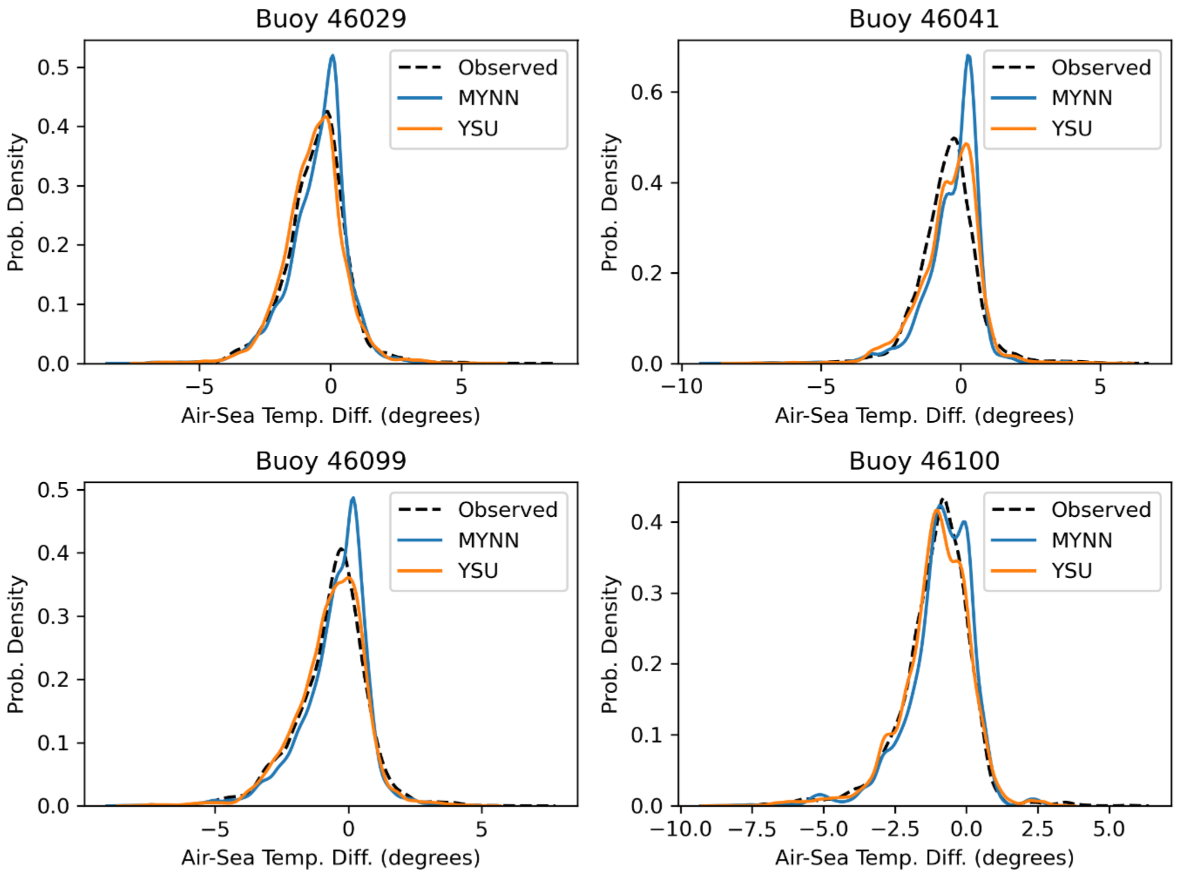

Figure A-6. Observed and modeled distributions of the difference between air temperature and sea-surface temperature at the location of the four buoys used for model validation

To summarize, most of the validation results suggest that, while both the YSU-based and MYNN-based model runs have a positive bias with respect to observations, the YSU-based model runs better compare with the available observations as opposed to the MYNN-based runs. While the observations used for model validation are not ideal, they represent the best measurements currently available in the region. While the magnitude of the bias in modeled hub-height wind speed would likely change if floating lidar data were available, all the available information, including results from the adjacent offshore California region, confirms the general conclusion that the YSU model setup will likely perform better than the MYNN one in the region.

We note that the bias correction approach derived in Section 5.2 assumes that the correction factor calculated over the year 2020 successfully represents the long-term conditions in the region of interest. To test this assumption, we compare the annual wind speeds at Buoy 46021 modeled by the ERA-5 reanalysis product[30] and find that the year 2020 is well representative of the long-term conditions in the region (i.e., close to the value of 1 in Figure A-7).

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[30] ERA-5 stands for European Centre for Medium Range Weather Forecasts Reanalysis v5.

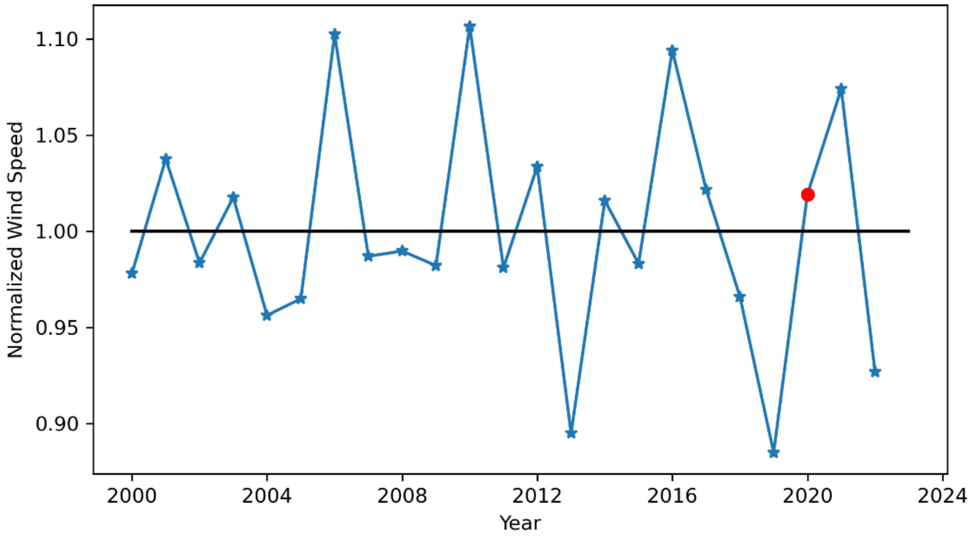

Figure A-7. Normalized annual averaged wind speeds from the ERA-5 product extracted at the grid point closest to Buoy 46041. The model validation year of 2020 is shown as a red dot.

Appendix B. Note From the U.S. Department of Defense

The U.S. Department of Defense (DOD) is committed to support energy development in a manner that is compatible with military activities. DOD collaborates with stakeholders to identify and avoid conflicts between proposed energy projects and current and anticipated future military requirements.

Washington is home to a number of military installations, including homeports for a large number of naval forces supporting national defense interests in the Pacific. At-sea training, testing, and routine operations rely on the availability of adequate air, sea, and undersea space to safely and effectively execute their missions.

DOD coordinated with the study team to support mapping analysis for the siting of offshore wind transmission infrastructure. Analysis of the potential for impacts to at-sea readiness activities conducted offshore Washington is ongoing within DOD. Offshore wind has the potential to impact at-sea military operations, largely through the introduction of obstructions to air and sea space, and interference with radar, telemetry, and other range systems.

Early and ongoing coordination with the DOD to address any potential impacts is critical to achieve sustainable energy solutions and ensure viability of critical military training and testing activities and operating areas.