The Impacts of Developing a Port Network for Floating Offshore Wind Energy on the West Coast of the United States

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1 National Renewable Energy Laboratory
2 Moffat and Nichol

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List of Acronyms

AEP	annual energy production
BOEM	Bureau of Ocean Energy Management
CapEx	capital expenditure
CEJST	Climate and Economic Justice Screening Tool
GW	gigawatt
CORAL	Concurrent ORBIT for shared Resource Analysis Library
IRA	Inflation Reduction Act
km	kilometer
kWh	kilowatt-hour
LCOE	levelized cost of energy
MF	manufacturing/fabrication
MW	megawatt
N/A	not applicable
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
OpEx	operational expenditure
ORBIT	Offshore Renewables Balance-of-system and Installation Tool
S&I	staging and integration
WOMBAT	Windfarm Operations and Maintenance cost-benefit analysis Tool

Executive Summary

Developing a system of ports that can enable commercial-scale floating offshore wind energy development on the West Coast of the United States will require significant investment and coordination between governments, industry, port authorities, and local communities. A critical first step to strategically planning these resources is understanding the number of ports (and associated investment) that would be required to support different phases of offshore wind energy project development, including manufacturing, installation, and operation. But simply tallying up these costs is not sufficient to understand how a robust network of ports could impact local communities, the environment, workforce development, the offshore wind industry, and the West Coast region as a whole. Decision-makers should consider a broader set of information about these potential effects to understand how strategic investments could enable the most beneficial outcomes of a West Coast floating offshore wind energy port network.

In this report, the authors present analyses and perspectives related to port development in California, Oregon, and Washington. We describe the requirements for ports to support floating offshore wind manufacturing, installation, and/or service activities, and estimate the investment and time frames required to construct these ports at suitable locations in West Coast states. We develop indicators for the vulnerability and workforce accessibility of coastal communities and consider the potential risks and benefits associated with port development in these locations. We model how the proximity of an offshore wind project to installation and operations ports can impact the levelized cost of energy of the project, and then consider how these costs could be affected by local versus foreign supply chains. We build on these analyses by developing scenarios with increasing levels of offshore wind deployment and port assets on the West Coast and show how these ports could help achieve deployment goals. Finally, we draw upon outreach with key floating offshore wind stakeholders to summarize five key challenges that will need to be overcome to develop a comprehensive port network, and present potential approaches that could help address these obstacles. The key findings of this study include the following:

- Developing a port site[1] to support floating offshore wind project installation (referred to as a staging and integration site) could cost around $1 billion and take around 10 years. Government agencies, port authorities, offshore wind energy developers and technology providers, workforce organizations (including organized labor), community representatives, vessel operators, tribes, and other organizations will likely have to collaborate to effectively fund, plan, and develop these port sites in a strategic, equitable, and timely manner.

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[1] A port site is a location within a port that encompasses a wharf (to tie up and load/unload vessels) and upland area (for component storage and manufacturing activities). In this report, we refer to a port as an overarching maritime facility with decision-making authority about the capabilities that are developed at its own site(s). When we estimate the overall infrastructure needs for the West Coast, we discuss the number of required sites for installation, operations and maintenance, and manufacturing activities. A port could have multiple sites dedicated to floating offshore wind energy (as well as additional sites dedicated to nonoffshore wind activities).

- Meeting California's target of 25 gigawatts (GW) of offshore wind energy by 2045 would likely require four staging and integration sites and at least eight operations and maintenance sites within the state. The investment of around $5 billion that would likely be required to develop these sites is significant but could enable the efficient deployment of $125 billion of floating offshore wind projects.

- A more ambitious offshore wind scenario of 55 GW deployed along the entire West Coast by 2045 could require nine staging and integration sites (at 4–5 ports) and 17 operations and maintenance sites in California, Oregon, and Washington, with an associated investment of around $11 billion.

- Offshore wind components must be built at manufacturing sites because they are too large to transport over land. Expanding the port network to create a West Coast supply chain could require 16–28 additional sites to support 25–55 GW of deployment, respectively. These manufacturing sites would likely need an additional $11–$19 billion to construct. A local supply chain could reduce lifetime vessel emissions for the West Coast project pipelines we consider in this report by around 40% by eliminating the need to transport major components across the Pacific Ocean.

- Although labor and raw material costs may be cheaper for overseas manufacturing hubs, a supply chain based on the West Coast could be cost competitive because of reduced transportation costs and tax incentives from the Inflation Reduction Act (including the Domestic Content Bonus and the Advanced Manufacturing Production Tax Credit). Supply chain facilities would have to come online relatively soon to take advantage of these credits, which begin to phase out in the 2030s.

- All West Coast states have several ports with existing sites that are suitable for different aspects of offshore wind project development; however, no single state has enough sites to conduct all the manufacturing needed for even the lower bound of 25 GW of offshore wind deployment. California, Oregon, and Washington could consider collaborating to develop a supply chain that reduces the risk of global supply chain bottlenecks and creates jobs and economic benefits across the region.

- Many of the communities that are likely to be impacted by port development on the West Coast face diverse health, environmental, educational, economic, and accessibility burdens that could impact how much they benefit from new or expanded ports and job opportunities. Ongoing communication and process evaluation between port authorities, local communities, and tribes to understand existing community characteristics, vulnerabilities, and goals could help achieve more equitable outcomes.

- The distance from an offshore wind project to the staging and integration and operations and maintenance ports could have significant impacts on the levelized cost of energy (LCOE) due to the time required for vessel transit. For example, a project with ports 400 kilometers (km) away could have a 15% higher LCOE than a project with ports 50 km away. Strategic planning for floating offshore wind infrastructure should consider many factors, including the LCOE of the projects being developed.

- Developing a West Coast port network will involve overcoming key challenges such as:
    - Existing port infrastructure is inadequate for commercial-scale floating offshore wind build-out
    - Developing an efficient West Coast port network will require effective communication between different stakeholder groups
    - A significant workforce is needed to construct and operate West Coast floating offshore wind ports
    - Permitting and regulatory requirements can be uncertain and/or time-consuming
    - A fleet of vessels dedicated to floating offshore wind installation and operations will need to be developed in parallel with the port network.

  This report presents several recommendations that could help address these challenges.

Although there are challenges to building the port infrastructure that can enable commercial-scale U.S. floating offshore wind deployment, there is currently an opportunity for the West Coast to develop solutions that could set an example for the entire global industry. A coordinated approach to building a comprehensive network of ports that facilitates strategic planning and collaboration between California, Oregon, and Washington could create resilient, cost-effective, equitable, and impactful infrastructure on the West Coast. Further work will be required to develop these approaches, conduct detailed design studies, and convene key stakeholders and decision makers. While there is a clear urgency to implement strategic plans to meet state and federal offshore wind deployment targets, the West Coast floating offshore wind energy sector has the opportunity to set itself up for long-term success by strategically and collaboratively establishing a clear vision for enabling port infrastructure.

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1 Introduction

The waters off the U.S. Pacific Coast are deep because the Outer Continental Shelf drops off rapidly. Shallower sites where fixed-bottom wind energy technology could be successfully deployed tend to be too close to shore to be considered for significant offshore wind energy generation. It is virtually certain that any offshore wind energy projects in these regions will use floating wind technology.

The floating offshore wind energy industry is growing rapidly worldwide because of the vast wind resource and the potential for fewer conflicts with other human uses and the environment. In the United States, about 65% of the total technical offshore wind resource is suited for floating wind technology including the entire Pacific Coast. (Lopez 2022; Musial et al. 2022). At the end of 2022, the global floating wind pipeline was over 100 gigawatts (GW), based on projects that have been announced by developers. According to project announcements, there could be 20–45 GW of floating wind energy worldwide by 2030, as shown in Figure 1 (Musial et al. 2022).

The Biden administration has established a target of 15 GW of floating wind installed by 2035, with California setting a planning target of 25 GW by 2045, and Oregon establishing a goal to plan for the development of up to 3 GW in federal waters by 2030. The West Coast states have also all established 100% clean energy laws that will drive renewable energy development over the next few decades. In addition, the first ocean areas leased for potential West Coast development are in federal waters adjacent to California. These areas were identified by the Bureau of Ocean Energy Management (BOEM) and auctioned in December 2022, with project developers spending over $750 million to gain site control.

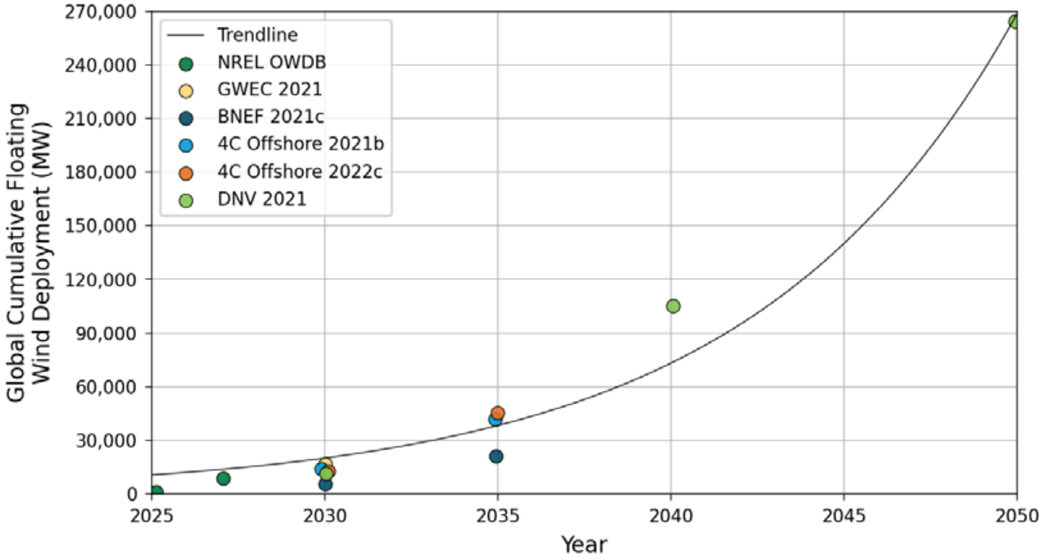

Figure 1. Long-term cumulative floating offshore wind deployment projections. Costs are reported in $2022. *Image from Musial et al (2022)*

MW = megawatts; NREL OWDB = National Renewable Energy Laboratory Offshore Wind Database; GWEC = Global Wind Energy Council; BNEF = Bloomberg New Energy Finance

During the 2020s, floating offshore wind projects are expected to transition from the pilot (10 to 100 megawatts [MW]) to the utility scale (more than 500 MW). With this transition there is also the expectation of significant cost reductions from economies of scale that will make the technology more economical (Musial et al. 2019).

Currently, there are about 123 MW of floating wind capacity installed worldwide. Experience from these pilot-scale projects has been important in de-risking the path to larger commercial-scale floating wind energy development needed to achieve lower and more competitive costs. One of the biggest challenges to project size upscaling will be transitioning from single-turbine or limited series deployment to assembly line production of dozens of substructures and the subsequent installation, assembly, and commissioning of the wind turbine at quayside prior to loadout. To maximize efficiency and cost reductions for commercial-scale deployments, manufacturing and assembly need to take place at a suitable port facility that is designed for safe and efficient storage and movement of heavy and large components.

Conversely, the investments required for efficient port functionality are not economically warranted for pilot-scale projects and the subsequent slow manufacturing times contribute to higher project costs. The port facility in proximity to the lease areas becomes one of the primary enablers for this nascent floating wind industry to reach commercial production and to realize the cost reduction opportunities. The U.S. West Coast has a need for expanded and upgraded facilities because existing infrastructure is inadequate to support the build-out of commercial-scale floating wind energy projects. The investments in this port infrastructure will be substantial, but the potential social benefits and economic return are compelling.

This report contributes to the literature on U.S. floating wind port development by:

- Considering offshore wind deployment and port network scenarios that span the entire West Coast to understand the opportunities and potential benefits of regional collaboration
- Providing expanded modeling and assessment of how port resources impact offshore wind projects, including installation times, weather delays, time-based availability, levelized cost of energy (LCOE), and supply chain decisions
- Introducing and implementing a framework for assessing energy justice considerations as part of preliminary port screening
- Summarizing stakeholder perspectives on key considerations and challenges for developing floating wind ports on the West Coast, including cost to upgrade existing infrastructure; communication between different groups and decision-makers; workforce development; permitting; tribal consultation and potential impacts to tribes; and vessel construction
- Identifying follow-on studies that expand upon the results in this report.

This report is not intended to predict how the West Coast port network will evolve, and we do not provide a decision or recommendation regarding which ports should be developed to support the floating offshore wind energy industry. Instead, the goal of this report is to present information that can help decision-makers understand the impacts of port investment and development. The report complements published and ongoing studies of floating offshore wind port development in California and Oregon. A summary of these complementary studies is provided in Appendix A.

2 Types of Floating Offshore Wind Ports

There are three primary types of sites that will be relevant for floating offshore wind energy activities:

- **Manufacturing/Fabrication (MF) Site.** This port site is located on a navigable waterway that receives raw materials via road, rail, or waterborne transport, creates larger components in the offshore wind supply chain, and loads these components onto vessels to transport them to a staging and integration site. This site typically includes factory and/or warehouse buildings and space for storage of completed components. Major offshore wind components (such as blades, nacelles, towers, and floating platforms) are so large that they need to be fabricated at port sites because they cannot be transported overland.
- **Staging and Integration (S&I) Site.** This site receives, stages, and stores offshore wind components and is where the floating wind turbine system is assembled for towing to the offshore wind area. In addition to turbine integration activities, this site is likely to perform major maintenance on a fully assembled turbine system that cannot otherwise be performed in the offshore wind area, such as replacement of a nacelle or blade.[2] S&I sites could eventually be used for decommissioning of floating wind projects.
- **Operation and Maintenance (O&M) Site.** This site provides a base of wind plant operations with warehouses/offices, spare part storage, and a marine facility to support vessel provisioning and refueling/charging for vessels during the construction and operational period of the offshore wind plant.

Depending on its size, a port could have multiple sites with their own wharves (to tie up and load/unload vessels) and upland area (for component storage and manufacturing activities). We describe ports as the overarching maritime facility and then estimate the number of sites required for offshore wind energy activities on the West Coast.

The high-level design requirements for MF, S&I, and O&M sites are listed in Table 1. We provide a more detailed description of these requirements along with other considerations for floating wind ports in Appendix B.

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[2] It is likely that major replacement activities will be conducted at staging and integration sites because operations and maintenance sites may not invest in the heavy-lift and deep-draft capabilities needed to tow a wind turbine back to the port and conduct major repairs.

Table 1. Port Infrastructure Requirements

	S&I Sites	MF Sites	O&M Sites
Acreage, minimum	30 to 100 acres	30 to 100 acres	5 to 10 acres
Wharf length	1,500 feet (ft)	800 ft	300 ft
Minimum draft at berth	38 ft	38 ft	20 to 30 ft
Draft at sinking basin[3]	40 to 100 ft	Not applicable (N/A)	N/A
Wharf loading	> 6,000 pounds per square foot (psf)	> 6,000 psf	100 to 500 psf
Uplands/yard loading (for wind turbine generator components)	> 2,000 to 3,000 psf	> 2,000 to 3,000 psf	N/A
Air draft	> 1,100 ft	~100 ft	~100 ft
Need for wet storage?	Yes	No	No

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[3] There are several options for transferring a floating foundation from land to water. One option would assemble the platform and wind turbine on a semisubmersible barge that could lower itself into the water and allow the wind turbine system to float away. This float-off operation would take place in a "sinking basin," an area in the harbor where the barge could be submerged to a sufficient depth. Another option is a direct transfer method that would use a crane to lift foundation units from the land into water. Individual ports may select different transfer solutions based on their design choices and/or a project developer's preference.

3 Impacts and Cost/Benefit Trade-Offs of Developing a West Coast Port Network

A network of offshore wind energy ports on the West Coast could require dozens of facilities for MF, S&I, and O&M activities that could have a range of impacts on the offshore wind energy industry, local communities and environments, offshore wind deployment targets, and the opportunity space for domestic manufacturing and economic benefits. We identify five critical areas that could be significantly impacted by varying levels of investment in a system of ports on the West Coast. In the following sections, we describe high-level factors that could influence strategic decision-making for ports in Washington, Oregon, and California. These sections focus on the high-level methodologies, results, and key takeaways, with more detailed information provided in Appendix C–Appendix L.

3.1 Port Infrastructure Investments

Key takeaways:

- Meeting ambitious state and federal floating offshore wind deployment targets will require a dedicated, collaborative effort between industry, governments, workforce, and communities to address the significant investment and lead times (around $1 billion and 10 years for a staging and integration site) required to develop a floating offshore wind port network.

- Although some federal and state funds are available for offshore wind port development, these existing programs will not be sufficient to cover construction costs. Obtaining additional financing (for example, from private equity) is also challenging because of uncertainty surrounding the time frames, locations, and likely technology choices for West Coast floating wind energy projects. These obstacles may delay port infrastructure development on the West Coast.

The different types of port sites described in Table 1 will require varying levels of investment based on the design requirements for each site. Furthermore, the investment costs could vary regionally across the West Coast because of the different existing conditions for each port and different material and labor costs per region. Understanding the required investment in a S&I, MF, or O&M site is an important part of the decision-making process for individual port owners that are considering expanding their own facilities as well as for state or federal agencies that are planning the total level of investment that could be required for the new floating wind industry.

We provide a high-level suitability screening of major ports along the West Coast for S&I, MF, and O&M activities in Appendix C, with the main findings outlined here:

- Several sites in California could serve as S&I/MF sites. The Port of Humboldt has already begun development as a terminal project that could incorporate S&I, and potentially MF and O&M activities. The Port of Los Angeles and the Port of Long Beach in Southern California are additional S&I/MF options, and the Port of Long Beach has announced its intent to develop a 400-acre floating wind installation site on newly built land within the harbor.
- An alternative approach would be to develop a new (or significantly expanded) S&I site on the central coast. Several options have been considered in Porter and Gostic (2022) and

Trowbridge et al. (2023b). These sites would be significantly closer to the Morro Bay offshore wind lease areas; however, they would need a new navigation channel and breakwater. The build-out of these sites could take 20–25 years to go through the design, permitting, and construction process and (possibly) establish a new port authority to manage the port. These alternative port sites may require more investment, pose higher environmental risk to the coastal marine ecosystem, and have longer development schedules than those within existing large ports.

- There are several suitable S&I and MF sites in the Pacific Northwest, including the Port of Seattle, Port of Tacoma, and Grays Harbor (Washington), and Coos Bay (Oregon). Some of these sites would require dredging the navigation channel and sinking basin, which would incur additional costs. Coos Bay faces a challenge due to its proximity to the Southwest Oregon Regional Airport and would require coordination with the Federal Aviation Administration to permit towing operations; however, it may be the only feasible location for S&I operations in Oregon.
- There is a concentration of sites that could be used as MF-only sites in the San Francisco Bay Area of California, including the Port of San Francisco, Port of Stockton, Port of Oakland, and Port of Richmond, and private industrial terminals identified in Antioch and Pittsburg. These sites have adequate channel and berth draft along with sufficient acreage.
- There are several potentially suitable MF sites along the Columbia River (on both the Washington and Oregon sides of the river). Although the Columbia River navigation channels and berth pockets could require dredging, the sites along the Columbia River are well-suited for offshore wind energy component manufacturing because many have existing industrial land. Sites such as the Port of Longview, Port of Kalama, and Port of Vancouver (Washington), and the Port of Portland (Oregon) are well-suited for MF activities due to the existing industrial land available and deep-water draft in some areas, with potential for deep draft by dredging in other areas.
- O&M sites have the simplest requirements out of the different floating wind port types and are most preferable when they are near offshore wind energy projects. Sites such as the Port Angeles (Washington), Port of Astoria (Oregon), Yaquina River/Toledo/Newport (Oregon), Umpqua River/Reedsport (Oregon), and Crescent City, Pillar Point Harbor, Morro Bay Harbor, Ellwood Pier, and Hueneme (California) are well-suited for O&M activities due to their proximity to offshore wind areas, available port space, and navigation channels maintained by the U.S. Army Corps of Engineers.

We developed cost estimates for port infrastructure upgrades in different West Coast regions for S&I, MF, and O&M activities that could support floating wind energy manufacturing, deployment, and operations. The costs are estimated using an American Association for the Advancement of Cost Engineering Class 5 accuracy level (± 50%). These costs focus on improvements to the port infrastructure itself—specifically, dredging of the sinking basin, creation of a suitable heavy-lift wharf, and clearing and preparation of an upland area. Individual ports would have to make additional decisions about specific technologies and equipment that would be needed for floating wind operations. These considerations could include the method for transferring an assembled substructure into wet storage (which could use semisubmersible barges, inclined ramps, lift gates, or other equipment[4]) or the type of crane that can lift and attach the wind turbine onto the assembled platform. We do not consider these cost estimates in this study because they would be specific to individual ports and the preferred technologies (including the platform type and turbine rating).

The cost estimates for S&I and MF sites include:

- Preparation of 80 acres of useable space (including the terminal and upland area)
- Demolition of existing wharf and construction of a new heavy-lift wharf
- Dredging of the harbor area.

Additional dredging of the navigation channel would also be required for most ports, but this work would be conducted by the U.S. Army Corps of Engineers and is not included in our cost estimates (although the permitting time is included in the time frame for port development). Ports, or port tenants, would also need to invest in (or rent) expensive equipment, such as high-capacity cranes, semisubmersible barges, and transport vehicles. We provide further detail about the cost estimation process and port infrastructure improvements in Appendix C.

Table 2 lists average construction costs per West Coast region for S&I, MF, and O&M sites. Where appropriate, we separately list the costs required to dredge a sinking basin that would be required to lower a semisubmersible barge and float off an assembled platform and wind turbine; because this is just one possible transfer option, we do not include it within the average site cost. In any case, the investment in a single S&I site could be approximately $1 billion. Some funding streams have already been provided to prospective offshore wind ports (such as the U.S. Department of Transportation's Port Infrastructure Development Program and state funds from the California Energy Commission) but these awards are not sufficient to cover construction costs and will require port owners to seek additional financing. Although offshore wind ports will require significant investment, it is important to remember that the capital costs of a 1-GW floating offshore wind project could be around $5 billion (Stehly and Duffy 2022). Therefore, California's 25-GW pipeline could represent $125 billion. Developing a port network that can enable this pipeline to be deployed could result in more of these funds being invested locally, returning benefits to states and communities in the form of jobs, economic impacts, tax revenue, and competitive prices for clean energy.

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[4] Although drydocks have been used for early demonstration-scale floating wind energy projects in Europe, they are not likely to be developed for commercial-scale West Coast ports due to prohibitive size and cost.

Table 2. Summary of Port Site Construction Costs for Different Regions on the West Coast. All Costs Are Reported in $2023.

Region	Site Type	Average Site Cost	Sinking Basin Costs		
			18 meters (m)	24 m	30.5 m
Puget Sound and Washington Coast	S&I/MF	$665 million/80 acres	N/A	N/A	N/A
Columbia River Basin	MF[5]	$229 million/40 acres $458 million/80 acres	N/A	N/A	N/A
Oregon Coast	S&I	$713 million/80 acres	$125 million	$250 million	$500 million
Northern California	S&I	$700 million/80 acres	$200 million	$350 million	$600 million
San Francisco Bay	MF	$350 million/40 acres $525 million/80 acres[6]	N/A	N/A	N/A
Central California	S&I	$2,800 million/80 acres	$70 million	$200 million	$400 million
Southern California	S&I	$1,100 million/80 acres	N/A	N/A	$35 million
All	O&M	$25 million	N/A	N/A	N/A

Table 3 lists the approximate planning, permitting, and construction time frames for S&I, MF, and O&M sites on the West Coast. The longest potential time frames would be to develop a S&I port on the central coast of California because of additional permitting and the potential need to create a new port authority.

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[5] Note that MF-only sites include a wharf length of 800 feet (ft), so these costs cannot be directly compared to S&I/MF sites because they include 20 ft of wharf per acre = 20 * 80 acres = 1,600 ft.

[6] Not all sites in the San Francisco Bay have 80 acres available.

Table 3. Estimated Availability Dates for Port Sites on the West Coast

Region	Site Type	Assumed Start Date	Years to Plan, Permit, and Construct	First Site Available for Use
Puget Sound and Washington Coast	S&I	2028	Approximately 8–16 years	2036–2044
Columbia River Basin	MF	2026	Approximately 8–13 years	2034–2039
Oregon Coast	S&I	2028	Approximately 8–16 years	2036–2044
California	S&I	2023	Approximately 8–16 years	2031–2039
	S&I (central coast)[7]	2023	Approximately 20–25 years	2043–2048
	MF	2023	Approximately 8–13 years	2031–2036
All	O&M	2023	Approximately 7–10 years	2030–2033

The long lead times and significant investments identified in Table 3 suggest an urgency for developing ports to establish the infrastructure needed for commercial-scale floating wind energy deployment. Obtaining financing for these projects will require steady revenue streams to justify private investment in the port asset; however, without an established pipeline of leased offshore wind energy projects, the demand for port resources remains uncertain and complicates the ability of the ports to finance upgrades and conduct long-term strategic planning. BOEM's planned offshore wind leasing schedule has helped provide some confidence in the growth of the pipeline (BOEM n.d. [b]), but significant additional leasing will be required to solidify the number, location, and anticipated installation dates of West Coast floating wind energy projects. As this pipeline continues to develop, port authorities will have to operate in an uncertain environment, which may delay development. Conversely, increasing certainty in the offshore wind leasing and permitting process could translate to accelerated port development.

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[7] S&I sites identified in central California in existing ports and brownfield and greenfield sites may require more investment, pose greater environmental impacts, and have longer development schedules than those within existing large ports.

3.2 Environmental and Energy Justice for Port Communities

Key takeaway:

- Many of the communities that are likely to be affected by port development on the West Coast face diverse health, environmental, educational, economic, and workforce-related burdens that could impact how much they benefit from new or expanded ports and job opportunities.

Many port communities experience significant economic and environmental health burdens, and the offshore wind energy industry has the potential to either exacerbate or alleviate those burdens by introducing new industrial activities at ports. Ensuring that port development provides benefits and minimizes harmful impacts to port communities is a way to work toward energy justice, or “the goal of achieving equity in both the social and economic participation in the energy system, while also remediating social, economic, and health burdens on those historically harmed by the energy system” (Initiative for Energy Justice 2019). The impacts of the offshore wind industry will depend on how, when, and to what extent decision makers engage with port communities and prioritize positive outcomes for them. Achieving equitable outcomes will likely require decision makers to continuously evaluate how port development affects local communities and to understand existing community characteristics and vulnerabilities that may shape how communities will be impacted.

As a result, we developed the following two indicators to evaluate energy justice impacts on port communities:

- The **community vulnerability indicator** quantifies the existing burdens faced by port communities. This indicator can be used to understand baseline community context and to anticipate potential health and environmental impacts of port development.
- The **workforce accessibility indicator** examines the ability of port communities to access workforce opportunities offered by port development. This indicator can be used to understand baseline community context as it relates to workforce and education.

We then define a series of underlying metrics that can help evaluate the community vulnerability and workforce accessibility indicators for a specific community. These metrics include exposure to pollution and particulates, travel barriers, linguistic isolation, education levels, and household incomes, all of which are sourced from the (publicly available) U.S. White House Council on Environmental Quality’s Climate and Economic Justice Screening Tool (CEJST) (U.S. White House Council on Environmental Quality 2022). We combine the underlying metrics for each community to provide an overall vulnerability or workforce accessibility score, which we use to make relative comparisons between different port communities. We further aggregate these indicators to understand the overall risk level of different port regions. These indicators and metrics are described in more detail in Appendix E.

We evaluate both indicators for the census tracts within a 5-mile radius of West Coast ports to focus specifically on the communities that will be most impacted by port development. Some of the highest-risk populations tend to live within a 2-mile radius of ports (Greenberg 2021), so we limit our spatial energy justice assessment to understand how these critical communities could potentially be affected by port development.

Figure 2 presents the totaled community vulnerability scores from the West Coast port regions. We specify thresholds in community vulnerability scores to identify relatively higher-risk regions. We find that ports in urban regions, such as the San Francisco Bay Area, southern California, and some Columbia River Basin ports, are often surrounded by the most vulnerable communities with high exposure to emissions, particulates, or Superfund sites.[8] Conversely, ports in more remote areas such as northern California or the Oregon Coast may have relatively lower environmental risk factors but tend to have higher economic barriers. The bottom chart in Figure 2 shows the relative contribution of individual metrics to each region's overall score and demonstrates that each region has a unique set of risk factors that would require custom approaches to develop offshore wind infrastructure in a beneficial and just manner. These unique considerations are likely to be amplified when looking at individual port sites (instead of the aggregated regional results in Figure 1), which further highlights the importance of developing community-specific approaches to ensure equitable port development. The community vulnerability metrics are described in greater detail in Appendix E.

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[8] Superfund sites are locations polluted with hazardous materials that are designated for management and cleanup by the U.S. Environmental Protection Agency as part of the Superfund program.

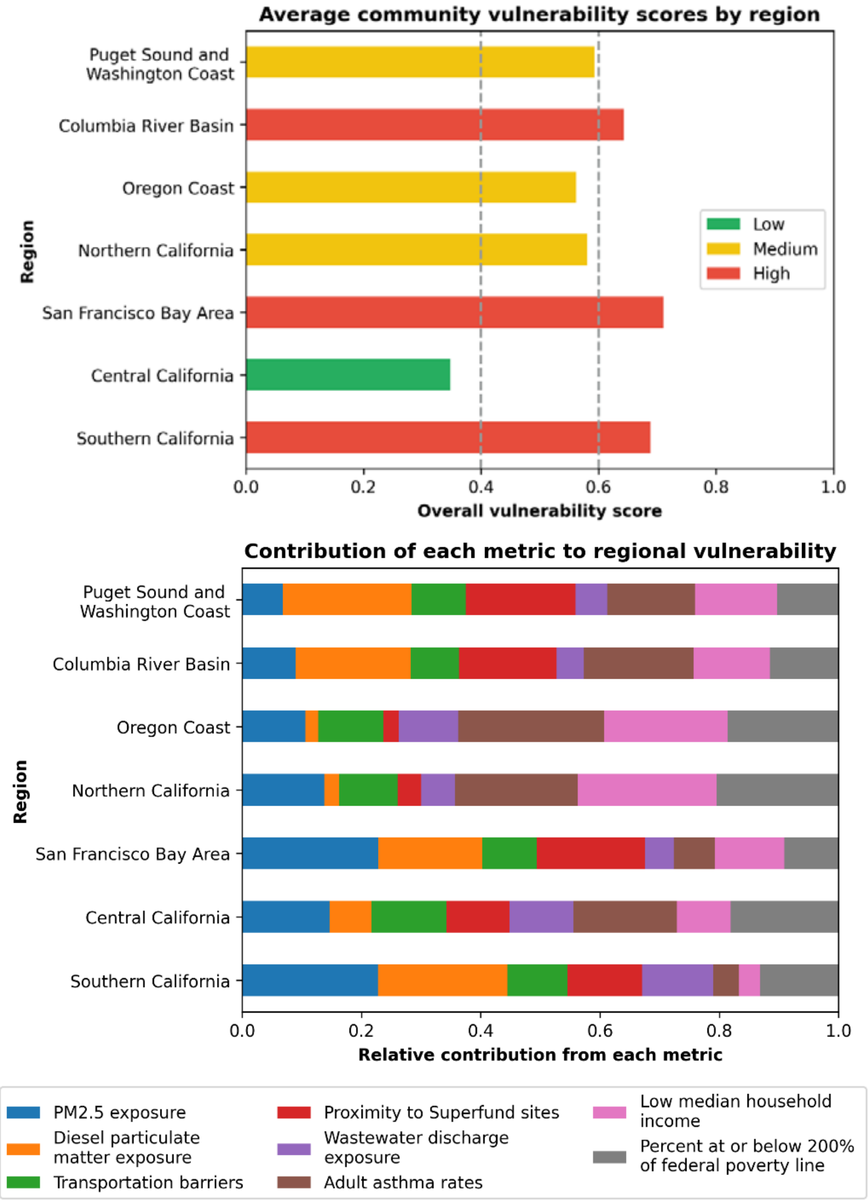

Figure 2. Assessment of community vulnerability (top) and breakdown of underlying metrics (bottom) in West Coast port regions. Vulnerability incorporates metrics for particulate exposure, transportation barriers, proximity to Superfund sites, exposure to wastewater discharge, adult asthma rates, household income, and percent of population below the federal poverty line.

Developing offshore wind ports in a vulnerable community can bring jobs and economic benefits, (Shields et al. 2023); however, it is critical to understand how these opportunities can be made available to the local community. Some community members may face greater challenges in accessing the potential benefits of a local offshore wind port due to factors like linguistic isolation, long-time unemployment, or lower educational attainment which, for example, might make it more difficult to qualify for an available job at the port. Figure 3 identifies the number of ports within each West Coast region that are located in communities with significant barriers to workforce accessibility and shows the contribution of the underlying metrics to the accessibility score. Census tracts near ports in the Columbia River Basin, San Francisco Bay Area, and southern California tend to be designated as “workforce disadvantaged,” and it is worth noting that these regions also have high vulnerability scores (see Figure 2), indicating that port development would be occurring near communities with higher baseline vulnerabilities that may make it more difficult to access potential benefits. The barriers to workforce accessibility also vary by region; for example, more urban port regions tend to experience higher levels of linguistic isolation and rural port regions tend to face lower median incomes. Enabling positive outcomes for these communities likely requires prioritizing their access to workforce opportunities and ensuring they are part of decision-making. Achieving these goals would depend on early, consistent, and transparent communication between decision makers, port authorities or operators, project developers, educational institutions, and community representatives and organizations.

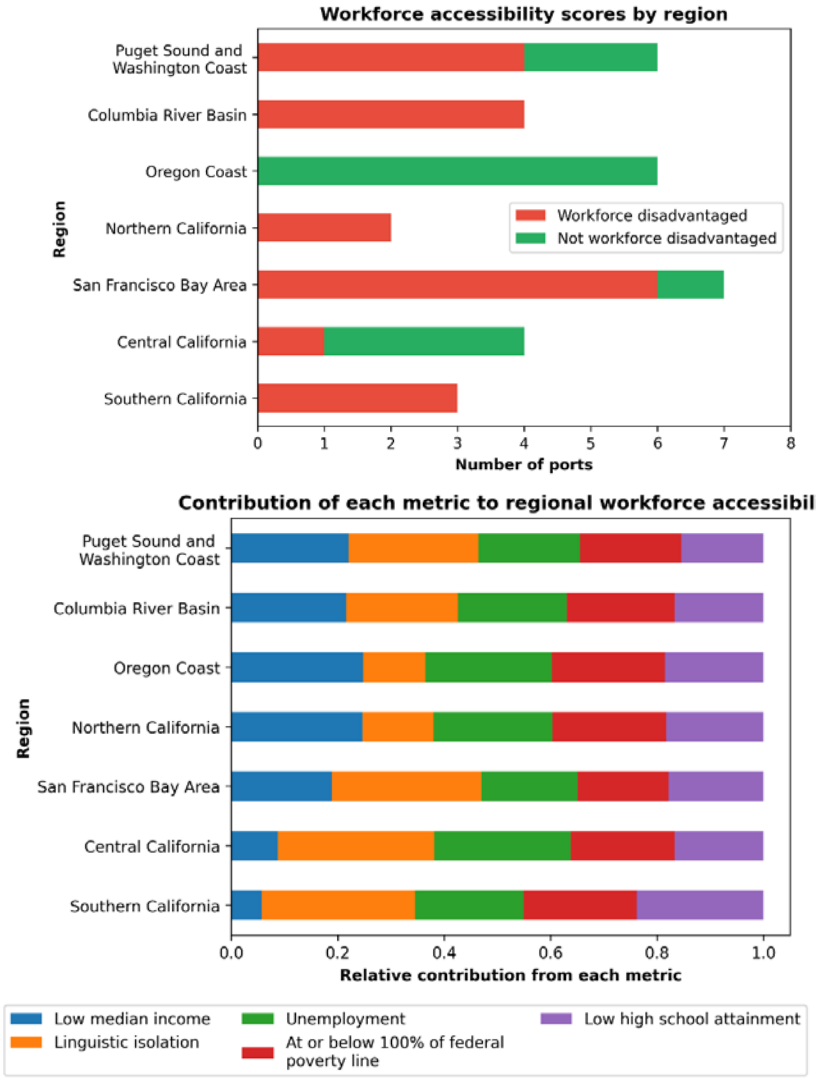

Figure 3. Assessment of workforce accessibility (top) and breakdown of underlying metrics (bottom) in West Coast port regions. Workforce accessibility identifies communities as workforce disadvantaged if they are above the 90th percentile for linguistic isolation, low medium income, poverty, or unemployment, and if more than 10% of the adult population has less than a high school education.

Coordination and engagement with West Coast tribes will be an important consideration for developing a successful and equitable port network. Specifically, the tribes' environmental, historical, economic, and/or cultural resources will likely be affected by port development. Therefore, early, transparent, and meaningful consultation between tribes, port authorities, and decision makers is necessary to create beneficial outcomes and minimize negative impacts for tribes. We discuss some high-level considerations for tribal engagement related to port development in Appendix K.

3.3 Offshore Wind Energy Project Cost and Logistics

Key takeaway:

- The distance from an offshore wind energy project to staging and integration and operations and maintenance port sites could have significant impacts on the levelized cost of energy, which could increase by 15% if this distance increases from 50 to 400 kilometers (km).

Offshore wind project costs are affected by site parameters such as wind speed and water depth, and by access to onshore infrastructure including ports. The proximity of a port to an offshore wind energy project location is a primary cost driver. More granular factors, such as specific port capabilities, facility costs, and availability, will also play a role in port selection for individual projects and will require further study as floating wind technology evolves. In this section, we analyze how the proximity to S&I and O&M sites can affect the cost of a representative offshore wind project.

We model a 1-GW floating offshore wind project comprising 15-MW wind turbines; semisubmersible floating platforms; semitaut mooring systems with drag embedment anchors; dynamic, 132-kilovolt high-voltage alternating current array cables; and 320-kilovolt high-voltage direct current export cables. We use the National Renewable Energy Laboratory's (NREL's) Offshore Renewables Balance-of-system and Installation Tool (ORBIT) (Nunemaker et al. 2020) to estimate capital costs and installation times and NREL's Windfarm Operations and Maintenance cost-Benefit Analysis Tool (WOMBAT) (Hammond and Cooperman 2022) to estimate operational expenditures, time-based availability, and annual energy production (AEP). ORBIT and WOMBAT are process-based models that size components based on turbine rating and site parameters and simulate the installation and operation of the wind power plant at an hourly timescale. We use the results from ORBIT and WOMBAT to estimate the levelized cost of energy, which represents the dollar amount that an offshore wind power plant owner would need to receive for each megawatt-hour of electricity to exactly meet their capital, financing, and operational costs. By varying the distance from the reference offshore wind project to the S&I and O&M port sites, we can understand how port proximity impacts project LCOE. Further details about the modeling approach are provided in Appendix F.

We consider three distances to S&I ports (50, 100, and 400 km) and three distances to O&M ports (50, 100, and 200 km). Assuming that the O&M port distance is less than or equal to the S&I port distance gives us six combinations to model. We consider the installation and operational phases separately, focusing on the S&I port during the installation phase and the O&M port—supported by an S&I port for major component replacements—during the operations phase. The resulting LCOE, capital expenditures (CapEx), and operational expenditures (OpEx) are plotted in Figure 4.

Figure 4 indicates that the LCOE of a floating offshore wind energy project could increase by 5%–15% as the distance to the S&I port site increases from 50 to 400 km. The increase in costs is primarily due to additional vessel costs associated with O&M. The annual tow-to-port cost required to transport wind turbines to the S&I site for major repair increases by a factor of five as the port distance goes from 50 to 400 km. Simulated failures in WOMBAT result in a tow-to-port event approximately once every 10 years for each turbine, or an average of 5−6 turbines being towed to port per year over the lifetime of a 1-GW project. Because the floating wind energy industry is still developing, failure rates remain uncertain. Increasing or decreasing the number of major failures and subsequent tows back to an S&I site would result in a corresponding change in O&M costs. Increasing the distance to the O&M site also results in higher costs for crew transfer vessels or service operation vessels to perform regular maintenance activities, further contributing to higher O&M costs.

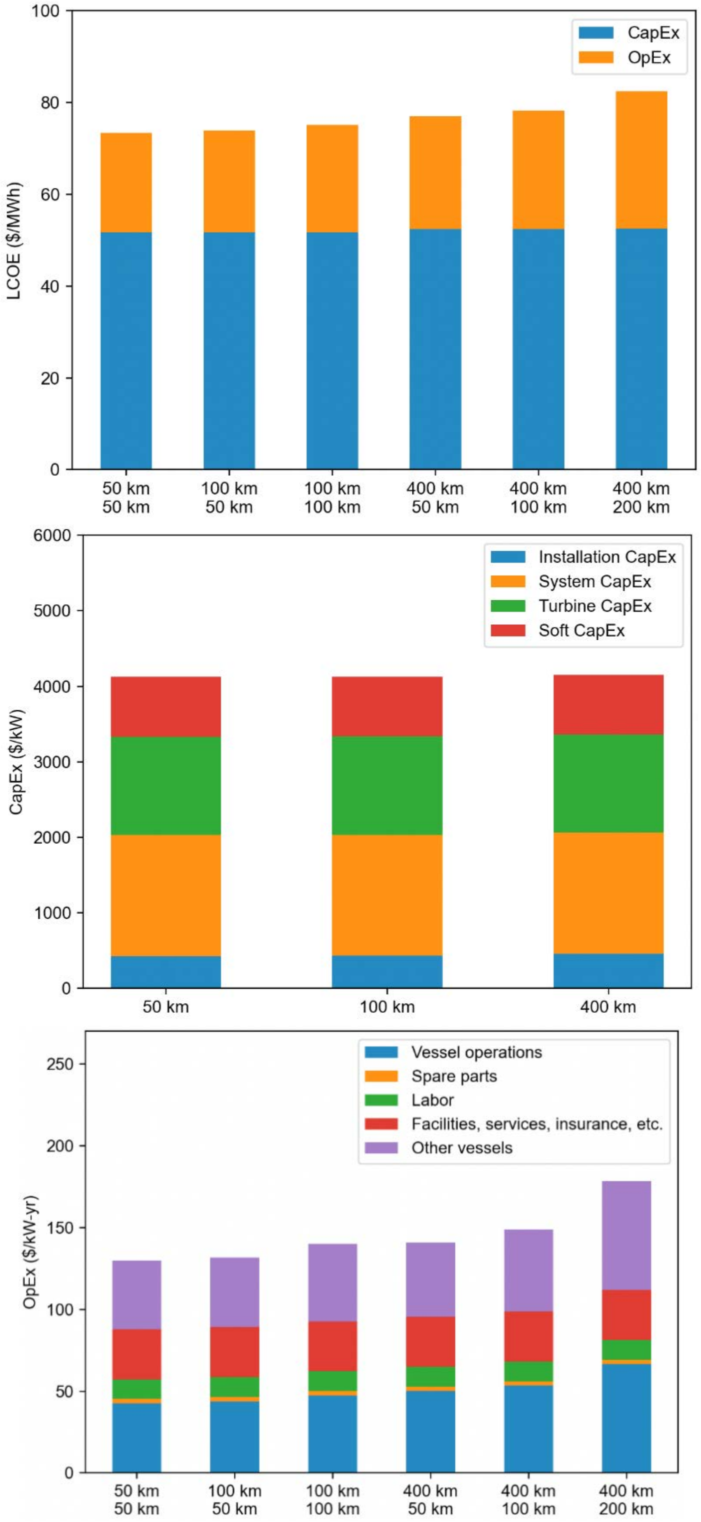

Figure 4. Impact of proximity to staging and integration (S&I) and operations and maintenance (O&M) port sites on floating offshore wind project levelized cost of energy (LCOE), capital expenditures (CapEx), and operational expenditure (OpEx). Costs are reported in $2023.
MWh = megawatt-hour; kW = kilowatt

Wind plant capital costs show a negligible dependency on port proximity. Installation time and costs increase slightly but represent a relatively small fraction of the overall project cost. The insensitivity of wind turbine installation times and costs to port proximity is a counterintuitive result. These costs do not change significantly because the time required to prepare each new floating wind turbine system at the port is greater than the time taken for installation vessels to transit to and from the offshore wind project location (even if this location is 400 km away from the port). As a result, in the scenarios we model the port operations represent the critical schedule bottleneck, not the time required to tow the floating wind turbine. The critical port processes that we use in this analysis (which are listed in Appendix F) include assembling the floating platform, integrating multiple tower sections, the nacelle, and blades; performing cable pull-in and electrical completion; and conducting mechanical completion and precommissioning work. Altogether, this process takes around 2 weeks to complete (roughly 1 week between launches of each newly assembled floating platform[9] and 1 week for wind turbine integration with the floating platform). These time frames already assume a level of industrialization and mass production beyond what the current industry can achieve. If the duration of port operations per turbine could be further reduced—either by further industrializing the production process or by using multiple S&I sites or integration positions at the port—then we would expect to see greater sensitivity of the installation time to port proximity.

It is possible that other factors could affect LCOE as a project gets farther from port; for example, insurance premiums may be higher to account for increased risk of weather delays or damage during a longer tow. However, because floating wind energy is still a new industry, the insurance market for these activities is not well-developed and the magnitude of these premiums is unclear. Because installation represents only on the order of 5% of the overall project capital cost, even if premiums doubled the installation costs, then LCOE would only increase by ~1%. There could be additional costs associated with contingencies, additional support or safety vessels, or other unknown needs that could introduce additional costs to projects. Financing and insurance for floating wind projects will evolve as the industry grows, and it will be important to understand their impact on the viability and insurability of the projects. Even if the cost premiums are relatively small, if projects (or aspects of projects, such as towing a wind turbine) are not insurable, then it would be difficult or impossible for projects to achieve financial close. We discuss insurability for floating offshore wind energy projects in Appendix L.

As the floating wind energy sector begins strategically planning the location of major ports on the West Coast, it will be important to consider both the required infrastructure investment and how the location and capabilities of this enabling infrastructure impact the cost of floating wind projects. Ultimately, higher costs of energy are likely to be passed on to the ratepayer and may make floating wind less competitive in the energy market. We show that these costs could

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[9] A benchmark of assembling one floating platform per week is often used to envision a commercialized floating offshore wind industry. It may be possible to reach this assembly rate, but it is more likely that an industrialized assembly site achieves an average rate of one unit per week by having enough space for multiple build positions with staggered schedules for each substructure. In this scenario, the one-per-week target is effectively the average production rate of the facility (not the average assembly time per unit). In other words, the one-per-week target measures the time between launches of successive floating platforms. In this report, we assume that the floating platform assembly sites have sufficient space for these parallel build positions to achieve an average production rate of one unit per week.

increase as the distance between a project and its supporting ports grows, and these cost differences could be magnified when considering actual port characteristics (e.g., achievable throughput, rental fees at the port, and so on). Decision makers should consider leveraging the results of this report to conduct detailed cost/benefit trade-off studies that investigate port solutions with the highest marginal value to offshore wind energy projects, port owners, and port communities.

3.4 Opportunities for a West Coast Floating Wind Energy Supply Chain

Key takeaways:

- Developing a West Coast floating wind energy supply chain could produce domestically manufactured components with a relatively similar landed cost (which includes manufacturing and transportation costs as well as incentives from the Inflation Reduction Act) as imports from Southeast Asia (unless there is an insufficient U.S. steel supply).

- It is unlikely that any individual West Coast state would have sufficient manufacturing port capacity to fabricate all of the components needed for a 25-GW supply chain, indicating a potential need for regional collaboration to develop the supply chain.

A floating wind energy supply chain does not currently exist in the United States, which has led to some speculation that floating wind projects (especially the first few projects built on the West Coast) will primarily source their components from more established manufacturing facilities in Southeast Asia, Mexico, or other international markets. However, there are many factors that contribute to the landed cost of offshore wind components (which includes the manufacturing and transportation costs to get all components to the S&I port site, but not any additional installation or port operation costs). The potential benefits from international suppliers, such as lower labor rates, cheaper raw materials, and existing shipyards or manufacturing facilities, could be offset by the high transportation costs required to ship the components across the Pacific Ocean. Imported components would also make floating wind energy projects less likely to qualify for tax incentives from the Inflation Reduction Act (IRA), and would significantly increase emissions during the longer transportation time.

We conducted a high-level comparison between hypothetical supply chains centered in Southeast Asia and the U.S. West Coast to evaluate the trade-offs between these options. The supply chains that we consider encompass all major components of an offshore wind energy project, including blades, nacelles, towers, floating platforms and their subassemblies, mooring systems, cables, and offshore substations; we assume that this entire supply chain is either located in Southeast Asia or on the West Coast. We use NREL's ORBIT model to establish a baseline cost for each component needed for a 1-GW floating wind energy project and then adjust these initial costs based on the following cost drivers:

- **Labor and raw materials.** Manufacturing wages in Southeast Asia could be half of those in the United States (The Conference Board 2018) and steel prices can be one-third lower

(Organisation for Economic Co-operation and Development 2022). We develop scaling factors based on relative labor rates and commodity prices between the United States and Southeast Asia and use these factors to adjust the baseline ORBIT components costs depending on the source of the component.

- **Domestic content bonus from the Inflation Reduction Act.** The IRA includes a 10% bonus investment tax credit for offshore wind energy projects that source a prescribed threshold of manufactured products from the United States (known as "domestic content"). The threshold is set at 20% for projects that begin construction before 2025 and scales up to 55% after 2027. We assume that projects using a U.S. supply chain qualify for this credit (10% of the overall capital cost of the project) and those sourcing products from international suppliers do not. The domestic content bonus begins to phase out along with the base investment tax credit in 2032 or when total power sector greenhouse gas emissions decline to at least 75% below 2022 levels (whichever comes later).
- **New factory amortization.** The United States will need to build new factories for floating offshore wind energy components, whereas many components are already built in the Southeast Asia region (such as blades or cables) or can leverage existing shipyards (floating platforms). We assume that the investment cost from a new U.S. facility will be passed on in the form of a premium on the components that it produces. We estimate this premium using the methodology outlined in Shields et al. (2023), which also accounts for the advanced manufacturing production tax credits from the IRA. These tax credits begin to phase out in 2030 and no longer apply to components sold after 2032.
- **Transportation cost.** We estimate the total number of components that can fit on an oceangoing barge and then calculate the number and duration of trips required to transport components from a manufacturing location in Southeast Asia or on the West Coast to a S&I port in northern California.
- **Steel tariffs.** Section 232 tariffs impose a 25% tariff on the price of imported raw steel (but are not applicable to finished components or structures). The demands of the offshore wind energy industry may stress the steel supply both domestically and internationally (Shields et al. 2023); therefore, we consider a case where U.S. manufacturers import raw steel for domestic fabrication of floating platforms, towers, mooring chains, and anchors and have a 25% premium imposed on the base material cost. An additional cost penalty from importing steel would be that it would make a project less likely to qualify for the 10% domestic content bonus from the IRA. The types of steel needed for floating wind platforms are thinner than those needed for the monopiles often used as fixed-bottom offshore wind foundations and are less likely to face supply chain constraints.

Figure 5 compares the total capital cost for a 1-GW project using different component manufacturing locations. This cost comparison assumes that the U.S. supply chain has reached a maturity level commensurate with manufacturing facilities in Southeast Asia and does not account for the costs required to advance along the learning curve. The results indicate that a West Coast supply chain has the potential to be cost-competitive with imported components from Southeast Asia because the significant reduction in transportation costs offsets the lower labor and material costs from international suppliers. Qualifying for the domestic content bonus from the IRA further improves the cost competitiveness of the U.S. supply chain, whereas relying on imported steel (and no longer qualifying for the domestic content bonus) could tilt the cost advantage back to the supply chain in Southeast Asia. The importance of the IRA domestic content bonus imposes some urgency to developing the supply chain because this incentive will begin to phase out either in 2032 or when power sector emissions decline to 25% of 2022 levels (whichever is later). The advanced manufacturing production tax credits, which phase out between 2030 and 2032, have relatively little impact on the cost competitiveness of the floating offshore wind supply chain because West Coast manufacturing facilities likely could not be operational until around 2030 and would only have a short time to claim these benefits.

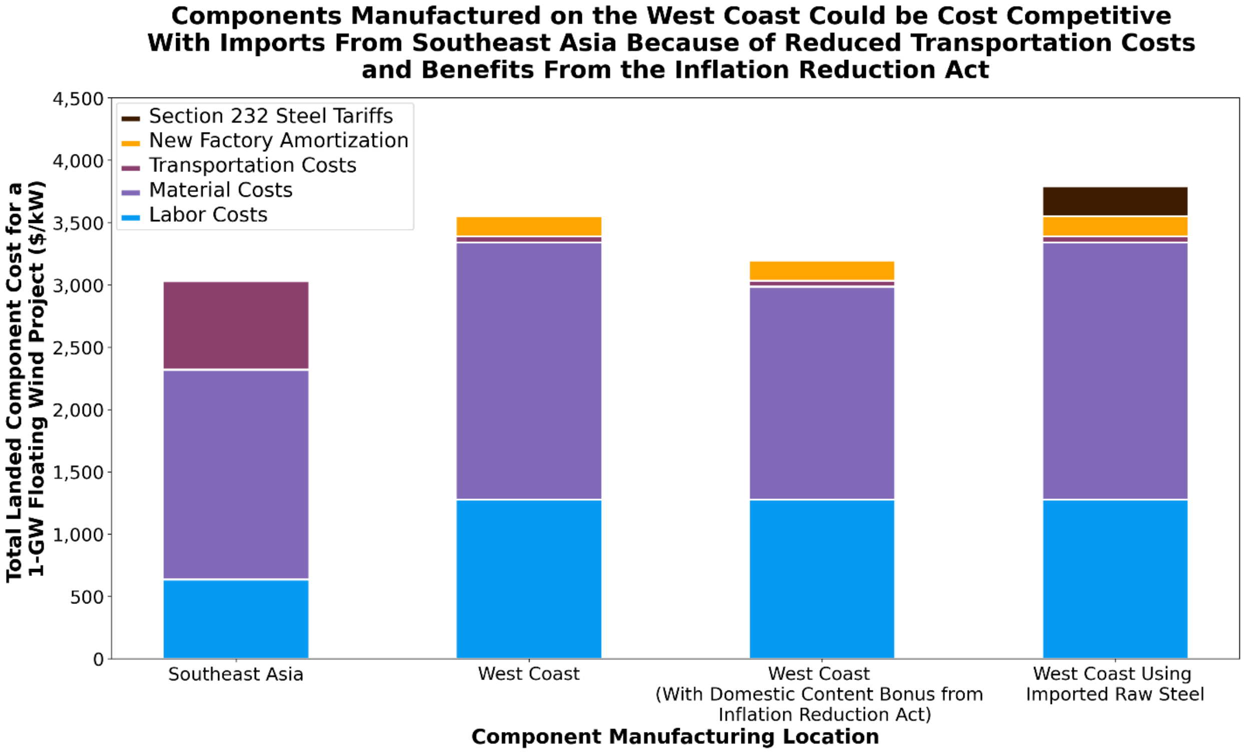


Figure 5. Comparison of the landed cost of components for a 1-GW floating offshore wind power plant that sources components from Southeast Asian or U.S. West Coast supply chains. The U.S. West Coast supply chain case also includes results that demonstrate the additional benefit from the 10% domestic content bonus from the Inflation Reduction Act and the additional costs that would be incurred by sourcing raw steel from international suppliers. Costs are reported in $2023.

Developing a robust floating wind energy supply chain that could serve the U.S. West Coast (and potentially other markets) should not exclusively focus on sourcing the lowest-cost components, and a West Coast-based supply chain could create several additional benefits for the industry and local communities. For example, a supply chain on the West Coast could create a significant number of manufacturing jobs. We estimate that around 4,000–6,500 direct manufacturing jobs would be needed for a West Coast supply chain with sufficient production capacities to support 25 GW and 55 GW of deployment by 2045, respectively. Shields et al (2023) suggest that there could be an opportunity space for up to five times as many jobs in the supporting supply chain beyond these estimates. A significant development effort would likely be required to train a sufficient West Coast manufacturing workforce. Sourcing components from a domestic supply chain could reduce the risk of depending on international manufacturers in countries or regions with their own offshore wind energy targets and (in some cases) geopolitical challenges related to doing business with the United States. We provide further discussion about the manufacturing and geopolitical risks in Appendix G.

A final consideration for developing a manufacturing supply chain on the U.S. West Coast is the number of port sites that would be required to fabricate components. We estimate that a supply chain designed to support California's 25-GW-by-2045 offshore wind energy planning target would require 16 manufacturing facilities that would each require 30–100 acres of space, deep drafts at the berth and navigation channel, and heavy-lift wharves. Our screening of California ports (provided in Appendix D) identified 10 suitable manufacturing locations in the state, indicating that there would be a need for additional manufacturing in the Pacific Northwest just to support California's 25-GW offshore wind target. Additional deployment in Oregon and/or Washington would increase the demand for domestic manufacturing. The potential need for an interstate supply chain, which could provide a stable and resilient supply of components at similar costs to international sourcing, suggests that West Coast states should begin considering how to best collaborate on floating wind supply chain development so that the manufacturing sector can develop in a timely and efficient manner.

3.5 Effects on the Deployment Pipeline

Key takeaways:

- An investment of between $15.3 and $29.8 billion in purpose-built port sites will likely be required to supply, deploy, and maintain 25–50 GW of floating offshore wind energy along the U.S. West Coast by 2045.
- Achieving California's 25-GW-by-2045 planning target would likely require at least four staging and integration sites (located within at least two ports) in the state, and reaching more ambitious deployment levels of at least 50 GW by 2045 would likely require a collaborative network of 9 S&I sites at 4–5 ports along the West Coast.
- Developing a West Coast supply chain could reduce life cycle vessel carbon-dioxide (CO_2) emissions by 40% relative to a scenario where components are imported from Southeast Asia.

Guided by the analysis in the previous sections, we developed scenarios that describe varying levels of planned offshore wind energy deployment and port development through the end of 2045. The goal of this analysis is to estimate how much of the planned pipeline could actually be installed given different levels of investment in S&I port resources. We also include the number of MF and O&M ports to provide an estimate for the overall required investment in a comprehensive port network. The network of offshore wind ports is not intended to be prescriptive, but to represent a reasonable set of scenarios that could be developed to support varying levels of offshore wind energy deployment.

In each scenario, the offshore wind deployment targets range from 25 GW exclusively built in California to 55 GW built in California, Oregon, and Washington. Each scenario has a corresponding number of port sites for each West Coast region. For each level of offshore wind deployment, we consider two types of port investment. In the first case, only S&I and O&M ports are developed on the West Coast (which assumes that the floating wind supply chain will be located elsewhere). In the second case, we include the number of MF sites required to supply all major components to floating wind projects on the West Coast.

The 25-GW scenario includes an additional sensitivity related to the second S&I port in California. The Port of Humboldt on California's north coast has signed an agreement with Crowley Wind Services to develop and operate a floating wind terminal, which is expected to play a critical role in installing and maintaining offshore wind energy projects. Other options in the state include the central coast (with possible S&I port locations at the Port of San Luis, Diablo Canyon, China Harbor, or Gato Canyon) or southern California (with possible S&I ports at the Port of Los Angeles or the Port of Long Beach, which has publicly announced an intention to develop a 400-acre site for S&I and MF activities). We label scenarios with a southern California S&I port or a central California S&I port as (SC) or (CC), respectively.

Instead of identifying specific ports in the scenarios, we outline the number of sites needed in regions along the West Coast to avoid the appearance of endorsing specific locations. Each region could include MF, S&I, and/or O&M ports, and each port could include multiple S&I sites or O&M vessel berths. The results in this report help demonstrate the trade-offs of having port assets in the different regions, but determining which ports are developed to meet demand would be a decision for individual port owners.

We evaluate the achievable level of deployment for each scenario using NREL's Concurrent ORBIT shared Resource Analysis Library (CORAL), which was previously used by Shields et al. (2023) to evaluate port and vessel bottlenecks to achieving the Biden administration's 30-GW-by-2030 deployment target. CORAL allows users to specify a target deployment pipeline where each project is assigned to a specific installation port. The model also has a shared library of port and vessel resources, meaning that individual offshore wind energy projects cannot begin installation until their required ports and vessels are available. If any of these resources are unavailable at the intended installation start date, the project is delayed until all ports and vessels are ready. This approach makes it possible to estimate how much of the planned pipeline is delayed beyond the target date of 2045. The modeling methodology and assumptions are described in further detail in Appendix H.

The different scenarios, including the total investment and achieved deployment, are shown in Figure 6. We observe that higher levels of investment are required to approach the target deployment levels. Several of the conclusions we can draw from these results are:

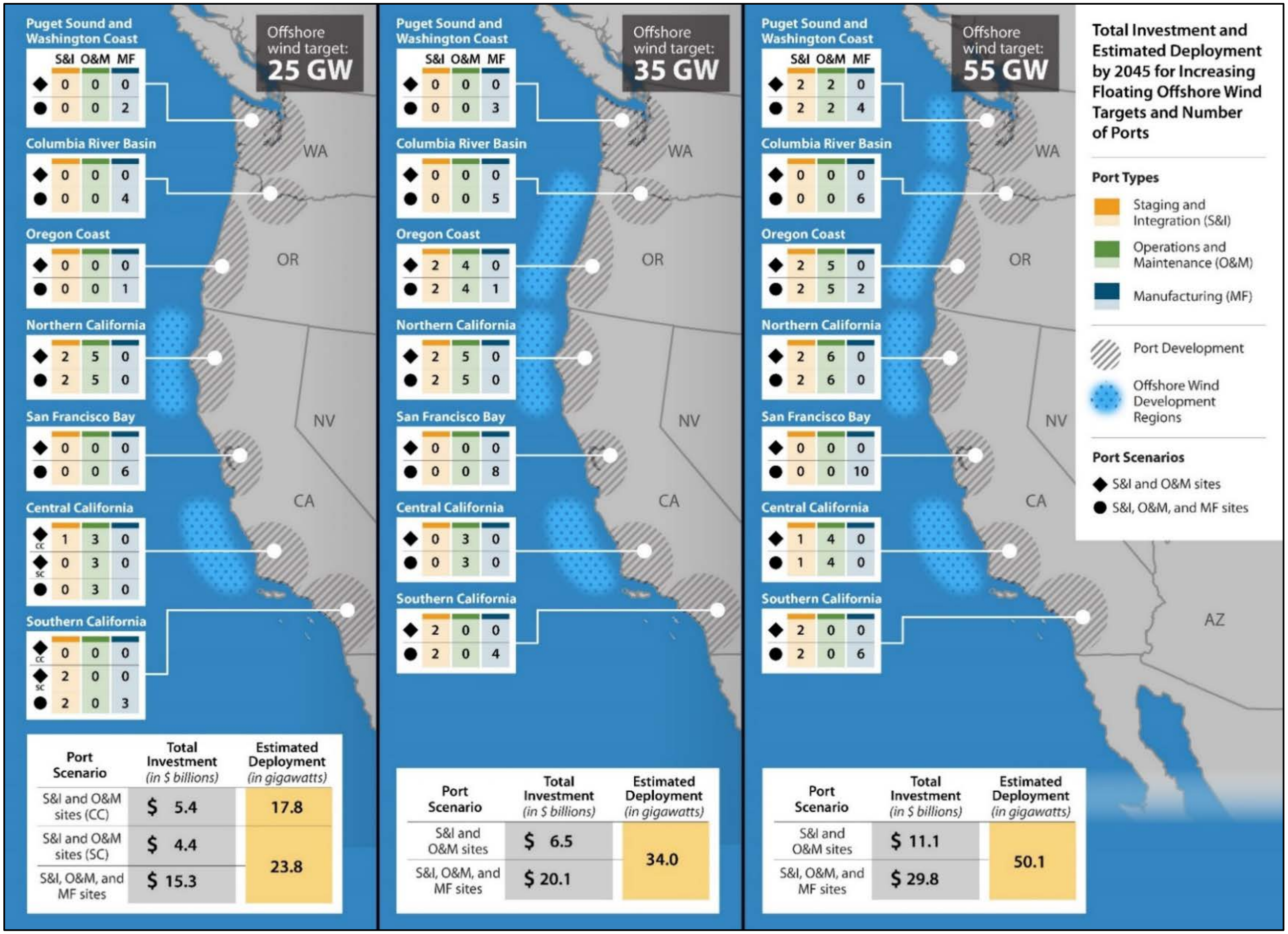
- The 25-GW scenario considers two alternatives for S&I ports. The 25-GW (SC) scenario includes two sites in northern California and two sites in southern California, which could result in over 95% of the target being installed by 2045. The 25-GW (CC) scenario considers the two northern California sites with a third site on the central coast, where there is likely not enough space to build a port with two S&I sites. This scenario deploys only 71% of the pipeline because the central coast region would require longer permitting and construction times than southern California. This result suggests that the most likely way to achieve California's 25-GW offshore wind energy planning target is by developing S&I ports in northern and southern California, although the distance from southern California ports to the existing offshore wind lease areas may result in an increase to project LCOE.
- At least eight O&M sites would be required to support a pipeline of 25 GW built in the central and northern California regions. As shown in Table 2, the investment in O&M sites is small relative to S&I or MF sites; however, having these sites close to project locations can

be critical for providing regular maintenance to achieve offshore wind project performance standards.

- Manufacturing the major components for a 25-GW pipeline could require at least 16 MF sites with a factory at each location. Meeting this demand would need some sites to be in Oregon and Washington in addition to all of the suitable sites in California.
- The 25-GW (SC) and 25-GW (CC) scenarios would likely require investments in S&I sites of $4.2 billion and $5.2 billion, respectively, along with at least an additional $200 million in O&M sites. Developing a West Coast supply chain would potentially need another $10.8 billion to be invested in MF sites.
- Adding a S&I site to the Oregon Coast would enable 34 GW to be deployed in California and Oregon by 2045. Ten GW of this total could be staged out of the Oregon Coast site if it could come online in the early 2030s, with a second site added in the sometime in the latter half of 2030. This scenario would require a total investment of $6.5 billion in S&I and O&M sites. Expanding the supply chain to support the additional 10 GW of deployment would likely increase the level of required investment in MF sites to $13.6 billion.
- Targeting a 55-GW deployment by 2045 would require a significantly higher level of investment in ports in Washington, Oregon, and California. A $10.6-billion investment in nine S&I sites along the West Coast could enable at least 50 GW to be constructed by 2045. An additional $425 million would likely be needed for O&M sites. Developing a West Coast supply chain for 55 GW of deployment could require a further $18.6 billion for a total port network investment of $29.8 billion. Developing these additional MF sites would require ambitious expansion of existing ports to meet space requirements (the 16 MF sites required for the 25-GW scenario could be achieved more easily with existing port sites).

Finally, we estimate the life cycle vessel direct carbon dioxide (CO_2) emissions from the different project phases considered in each scenario (e.g., supply chain transportation, installation, and O&M). We use the simulation results from CORAL and WOMBAT, along with simple estimates of component delivery times and distances, to evaluate the total number of hours the vessels spend at sea and at port. Using emissions factors that estimate the tons of CO_2 produced per hour spent conducting different activities (e.g., idling at port, transit, maneuvering, and idling at sea) we calculate the corresponding amount of CO_2 emitted per phase of each project, and then sum the projects to compare cumulative direct CO_2 emissions for each scenario. Although we only consider direct CO_2 emissions, the combustion of marine diesel fuel also emits nitrogen oxides, sulfur oxides, particulate matters, and additional greenhouse gases. We discuss the modeling and results of life cycle vessel emissions in more detail in Appendix I. The results are shown in Figure 7.

We see that lifetime O&M emissions and transporting components from a supply chain in Southeast Asia provide the majority of direct CO_2 emissions. Removing the trans-Pacific component transport would reduce vessel emissions from the component transportation stage of a project from over 8 grams of CO_2 per kilowatt-hour (kWh) of energy produced to around 0.4 g CO_2/kWh. As a result, over its lifetime a project that sources components from a West Coast supply chain would produce 40% less vessel emissions than a project importing its components from Southeast Asia (although, it is also worth noting that all phases of an offshore wind energy project, including trans-Pacific component transit, would produce on the order of 1% of CO_2 emissions from an equivalently sized coal power plant).



Offshore wind target: 25 GW

Region	Scenario	S&I	O&M	MF
Puget Sound and Washington Coast	◆	0	0	0
	●	0	0	2
Columbia River Basin	◆	0	0	0
	●	0	0	4
Oregon Coast	◆	0	0	0
	●	0	0	1
Northern California	◆	2	5	0
	●	2	5	0
San Francisco Bay	◆	0	0	0
	●	0	0	6
Central California	◆ CC	1	3	0
	◆ SC	0	3	0
	●	0	3	0
Southern California	◆ CC	0	0	0
	◆ SC	2	0	0
	●	2	0	3

Port Scenario	Total Investment (in $ billions)	Estimated Deployment (in gigawatts)
S&I and O&M sites (CC)	$ 5.4	17.8
S&I and O&M sites (SC)	$ 4.4	23.8
S&I, O&M, and MF sites	$ 15.3	

Offshore wind target: 35 GW

Region	Scenario	S&I	O&M	MF
Puget Sound and Washington Coast	◆	0	0	0
	●	0	0	3
Columbia River Basin	◆	0	0	0
	●	0	0	5
Oregon Coast	◆	2	4	0
	●	2	4	1
Northern California	◆	2	5	0
	●	2	5	0
San Francisco Bay	◆	0	0	0
	●	0	0	8
Central California	◆	0	3	0
	●	0	3	0
Southern California	◆	2	0	0
	●	2	0	4

Port Scenario	Total Investment (in $ billions)	Estimated Deployment (in gigawatts)
S&I and O&M sites	$ 6.5	34.0
S&I, O&M, and MF sites	$ 20.1	

Offshore wind target: 55 GW

Region	Scenario	S&I	O&M	MF
Puget Sound and Washington Coast	◆	2	2	0
	●	2	2	4
Columbia River Basin	◆	0	0	0
	●	0	0	6
Oregon Coast	◆	2	5	0
	●	2	5	2
Northern California	◆	2	6	0
	●	2	6	0
San Francisco Bay	◆	0	0	0
	●	0	0	10
Central California	◆	1	4	0
	●	1	4	0
Southern California	◆	2	0	0
	●	2	0	6

Port Scenario	Total Investment (in $ billions)	Estimated Deployment (in gigawatts)
S&I and O&M sites	$ 11.1	50.1
S&I, O&M, and MF sites	$ 29.8	

Figure 6. Scenarios for port development and achievable offshore wind deployment levels. Scenarios are based on target deployments of 25, 35, or 55 GW and include a distribution of staging and integration, operations and maintenance, and manufacturing/fabrication port sites along the West Coast. For each scenario, we report the level of port investment required and the estimated offshore wind capacity that could be deployed by 2045 using the available port resources.

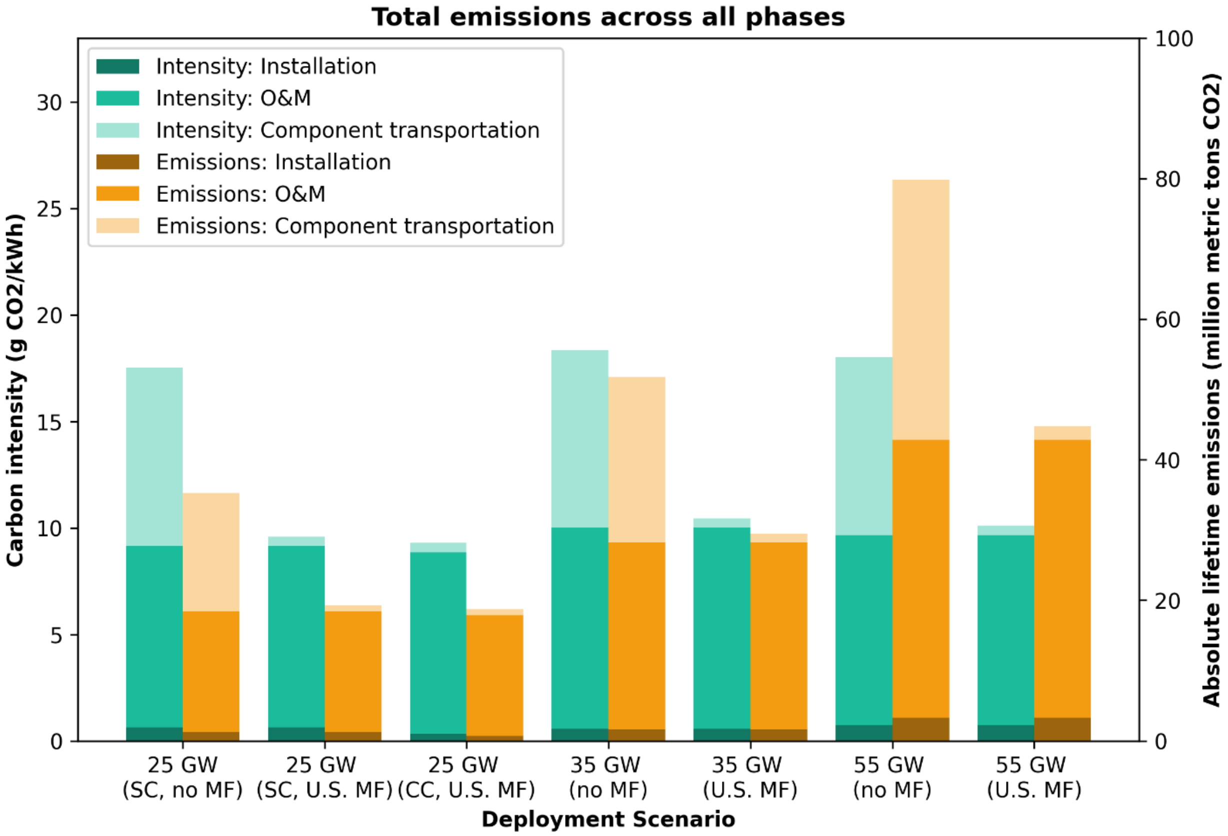


Figure 7. Direct carbon-dioxide emissions results, broken down by wind plant life cycle stage

4 Summary for Decision Makers

In this section, we present a series of challenges that decision makers are likely to face when developing floating offshore wind energy ports on the West Coast and outline potential solutions to help overcome these challenges. These challenges and solutions draw from the analysis presented in this report along with input from stakeholders and industry experts and are summarized in the following sections.

Challenge #1: Existing Port Infrastructure Is Inadequate for Commercial-Scale Floating Wind Build-Out

High-level summary: There is insufficient existing capability in West Coast ports to support floating offshore wind energy deployment and developing these capabilities will be time-consuming and capital-intensive.

Table 4. Actions, Relevant Organizations, and Potential Outcomes To Address Port Infrastructure Challenges

Action	Relevant Organizations	Potential Outcome
Identify the most viable sites and leverage existing studies to understand required investment	• Local, state, federal governments • Community representatives • Port owners[10]	Port investments are made efficiently to leverage existing strengths and community perspectives
Consider funding and incentive mechanisms to encourage investment, including grants, private investment, tax credits, state budget allocations, and funds from BOEM bidding credits	• Local, state, federal governments • Private investment firms • Project developers • Manufacturers • Port owners	Initial investments in port infrastructure are supported through cost-sharing mechanisms that reduce investment risk
Leverage experience from fixed-bottom port development on the East Coast	• Port owners • Port tenants[11]	Lessons learned from developing fixed-bottom ports streamlines the funding, planning, and development process for West Coast ports
Maintain communication to make sure that ports can support next-generation wind turbine systems	• Port owner • Manufacturers • Developers • Port tenants	Ports are designed with sufficient flexibility to accommodate various wind turbine ratings and floating platform designs without significant additional investment

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[10] In this report, we broadly define “port owner” to include public port authorities and private port owners.

[11] In this report, we broadly define “port tenant” to include organizations such as vessel owners, fabricators, labor unions, and equipment operators that could conduct floating offshore wind activities at the port either in addition to or as part of a project developer’s scope.

Action	Relevant Organizations	Potential Outcome
Coordinate between port owners and project developers to understand how installation and repair scheduling can impact port design	- Port owners - Developers - Port tenants	Enough ports are designed and built to operate at high utilization rates without adversely affecting project installation or repair schedules
Explore alternative technologies that could reduce the demand for conventional port infrastructure	- Technology providers - Federal government - State governments - Port owners - Research institutions	The potential benefits and risks of alternate technologies are available to decision makers for strategic planning; alternative technologies could include novel floating platform designs, floating ports/dry docks, or at-sea installation or maintenance methodologies

Challenge #2: Developing an Efficient West Coast Port Network Will Require Effective Communication Between Different Stakeholder Groups

High-level summary: Developing a West Coast floating offshore wind energy ports network will involve a huge number of stakeholders, which will require effective communication and coordination between these groups coupled with strategic planning from an authorized decision-making entity.

Table 5. Actions, Relevant Organizations, and Potential Outcomes To Address Communication Challenges

Action	Relevant Organizations	Potential Outcome
Create an intergovernmental steering committee to coordinate port decision-making along the West Coast, communicate with individual ports, establish roles and responsibilities for ports and other stakeholders, and guide port investments to fit into a broader regional strategy	- State governments - Tribal governments - Federal government	A transparent strategy for port locations, development time frames, and investment mechanisms provides guidance for ports and other organizations that want to support floating wind energy infrastructure on the West Coast. The strategy would need to be regularly updated to accommodate new state policies or targets, perspectives from stakeholders (e.g., port owners, industry, organized labor), and new floating wind or port technologies.
Provide objective technical support to the steering committee to	- Coastal engineering firms - Economic and environmental consultancies - National laboratories	Strategic plans developed by the steering committee are based on transparent and/or quantitative estimates of their impact on port

Action	Relevant Organizations	Potential Outcome
systematically inform decision-making	• Industry advisory groups	cost, offshore wind energy project cost, local communities, environmental resources, and other relevant factors. The committee could engage regularly with industry advisory groups (e.g., project developers, port authorities or port associations, organized labor).
Develop and maintain broader communication channels beyond the decision-making steering committee to share best practices and lessons learned	• State/local governments • American Association of Port Authorities • State and local economic development agencies • State and local regulatory and permitting agencies • Project developers • Port owners • Port tenants	Strategic port plans are efficiently implemented by state and local agencies that communicate effective approaches to working with stakeholders, permitting, construction, and other development activities
Encourage port owners to engage with tribes and local communities to present opportunities, schedules, and risks associated with floating wind energy port development	• Port owners • Port tenants • Community representatives • Tribal governments • Local governments	Port communities are fully aware of development plans and have opportunities to provide input and shape the development process to create attainable local benefits. This engagement could establish clear time frames, messages, and a vision for development for port communities.
Stakeholders determine how they can contribute to and benefit from offshore wind port development through strategic plans at individual community levels	• Community representatives • Tribes • West Coast	Community members have a clear vision for how offshore wind energy projects could impact them and are empowered to provide actionable input to port development processes

Challenge #3: A Significant Workforce Will Be Required To Construct and Operate West Coast Floating Wind Energy Ports

High-level summary: Many workers will be required to construct and operate West Coast ports, but there are currently not enough of these workers in respective port development regions.

Table 6. Potential Actions To Address Workforce Demand

Action	Relevant Organizations	Potential Outcome
Develop new training programs (and expand existing ones) to create good-paying offshore wind jobs that meet the demand of port development	• Organized labor • Manufacturers • Project developers • State and local economic development agencies • Tribes • Community representatives	A consistent pipeline of workers is available when needed for West Coast port development. Workers are paid and trained appropriately so that they remain in the industry, leading to more efficient operations over time.
Coordinate with port communities to convey the workforce opportunity at West Coast ports	• Organized labor • Manufacturers • Project developers • State and local economic development agencies • Tribes • Community representatives	Port communities have a clear understanding of how they can contribute to the workforce needed at offshore wind ports and what steps they need to take to fill worker demand (e.g., training).
Develop and publicize long-term plans for port construction, manufacturing, staging and integration, and operations and maintenance workforce needs	• Organized labor • Manufacturers • Project developers • Construction companies	Tribes, states, regions, and communities are aware of the long-term demand for workers and can coordinate activities so that an appropriate number of workers are hired and trained for port development.

Challenge #4: Permitting and Regulatory Requirements Can Be Uncertain and/or Time-Consuming

High-level summary: Offshore wind energy ports on the West Coast will need to navigate a complex and time-consuming permitting process. These permits are necessary to minimize adverse impacts on the environment and various stakeholder groups, but providing greater transparency and certainty around the approval process would help with strategic planning. We provide greater detail about port permitting in Appendix J.

Table 7. Potential Actions To Address Port Permitting and Regulatory Challenges

Action	Relevant Organizations	Potential Outcome
Understand the resources that permitting and regulatory agencies would require to efficiently and transparently review permits	• Federal, state, local regulatory agencies	Decision makers that guide budgets and funding opportunities understand how investing in staffing, training, and planning activities affects port development time frames and the resulting impact on communities, tribes, and the environment.
Port developers engage relevant groups, community stakeholders, and agencies at early stages of the project	• Port authorities • Tribes • Environmental groups • Energy justice groups • Federal, state, local regulatory agencies • Community representatives	Port development projects have a clear understanding of the range of permits they need to obtain, needs and sensitivities within the local community, and best practices and approaches to resolving challenges and conflicts during the development process.

Challenge #5: A Floating Wind Vessel Fleet Will Need To Be Developed In Parallel With the Port Network

High-level summary: A West Coast port network will need a significant fleet of vessels to install and service offshore wind energy projects, but the requirements for this fleet are unclear and may present a challenge for U.S. shipbuilding capacity.

Table 8. Potential Actions To Address the Need for a Floating Wind Vessel Fleet

Action	Relevant Organizations	Potential Outcome
Maintain communication between key groups to ensure that newly built vessels can accommodate next-generation wind turbines and installation methods while complying with at-berth emissions standards	• Project developers • Manufacturers • Port owners • Vessel operators • Shipyards	Newly built vessels are designed to efficiently accommodate relevant technologies through at least 2045 with little or no need for retrofits or modifications.
Consider how novel funding mechanisms could de-risk investment in new vessels	• Vessel operators • Financial institutions • State and federal governments	The cost/benefit trade-offs between different funding mechanisms are well-understood by potential investors, such as backstop programs, shared investment between multiple developers, and allocation of state clean energy revenue.

Action	Relevant Organizations	Potential Outcome
Conduct a gaps analysis between the long-term demand for floating wind vessels and the availability of shipyards over the next decade	• Shipyards • Vessel operators • Project developers	The floating wind industry understands achievable time frames and investment costs for U.S.-flagged vessels to facilitate strategic planning.

5 Conclusions and Future Work

Developing a robust, impactful, efficient, and equitable floating wind energy industry in the United States is synonymous with creating a thriving and comprehensive port network that can support the manufacturing, installation, and maintenance needs of the sector. As the floating wind deployment pipeline continues to expand and the first commercial-scale projects aim to be built around 2030, ports will have to develop in parallel to realize the significant benefits that this new industry could provide. This system of port infrastructure on the West Coast would require roughly \$5–\$30 billion of investment to meet or exceed existing state deployment targets, in addition to further funding for manufacturing facilities, vessel construction, workforce training, community engagement, and the cost of the offshore wind energy projects themselves.

This significant investment could be made more impactful if states, planning agencies, communities, tribes, labor unions, and the offshore wind industry can strategically plan and communicate effectively to determine the most beneficial solutions and highest marginal value ways to allocate funds. This report is intended to provide these key decision-makers with some of the information they will need to consider when developing these strategies. We also suggest that further studies or activities could be conducted to provide more detailed information in several important areas, including:

- Outreach and coordination with West Coast port owners to better understand their interest in offshore wind energy and investment challenges or risks that they perceive
- Engagement with tribes to reduce adverse impacts on cultural, natural, and economic resources due to port development
- A detailed assessment of vessel needs and shipbuilding capabilities that considers uncertainty around which floating platforms will gain dominant market share on the West Coast
- A comparative analysis of different technologies and processes for accelerating staging and integration activities to achieve higher deployment rates
- A comparative analysis of different floating wind operations and maintenance strategies and the subsequent impact on port requirements
- A thorough workforce skills assessment covering port construction, component manufacturing, and floating wind installation and maintenance
- A life cycle assessment of floating offshore wind environmental impacts, including port construction and component manufacturing and transportation, installation, and maintenance
- A broad classification of the major risks facing offshore wind energy projects and how they could drive financing and project insurability.

Glossary

Air draft. The vertical clearance above the water line required to transport a floating wind turbine or component

Berth. A place in which a vessel is moored alongside a wharf within the port (also referred to as a quay)

Breakwater. An artificial offshore structure that protects a harbor from ocean waves

Draft. The amount of water required for a vessel to float without touching the bottom

Port. A maritime facility comprising terminals where vessels load and unload cargo

Site. A self-contained area within a port that includes sufficient infrastructure for its intended operation, such as a terminal, wharf, or upland area

Terminal. A berthing location within the port for loading and unloading cargo

Uplands. A storage area adjacent to a wharf for storing cargo

Wet storage. A location in a port's harbor where an assembled floating platform (with or without an integrated wind turbine) can be stored prior to installation

Wharf. A structure running parallel to the shore for securing and then loading/unloading vessels within the port

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Appendix A. Previous and Ongoing Assessments of West Coast Ports

There have been a series of recent studies that have considered the viability of West Coast ports supporting the floating wind energy industry. In this appendix, we identify these studies, highlight several key findings from each, and describe how this report complements and expands upon previous work.

Determining the Infrastructure Needs To Support Offshore Floating Wind and Marine and Hydrokinetic Facilities on the Pacific West Coast and Hawaii

Porter and Philipps (2016) conducted a seminal study that screened West Coast ports and assessed their viability for offshore wind energy operations. The authors concluded that:

- Existing wharfs and vessels are generally not ready to support commercial-scale floating wind deployment.
- Ports with land availability and no air-draft restrictions typically have more challenging navigation channel restrictions.
- A demonstration-scale staging and integration port is not likely to be used for commercial-scale deployment.
- Ports along the Columbia River and in the San Francisco Bay are good candidates for manufacturing ports but not for staging and integration due to air-draft restrictions.

Coos Bay Offshore Wind Port Infrastructure Study

Mott Macdonald (2022) identified the constraints, opportunities, needs, and high-level costs needed to prepare the Port of Coos Bay to support floating offshore wind energy activities in Southern Oregon. The authors conclude that:

- Coos Bay has the physical characteristics to serve as a manufacturing, staging and integration, and/or operations and maintenance port for floating offshore wind, primarily including a deep-draft navigation channel and available upland space seaward of bridges.
- Investments in the port that would be required to support staging and integration activities would likely be at least \$235−\$950 million.
- The port is located close to an airport, which would require coordination with the Federal Aviation Administration and Coos County Airport District to understand how offshore wind tow-out operations could coexist with aviation traffic.

Port of Coos Bay Infrastructure Assessment for Offshore Wind Energy Development

Trowbridge et al. (2022) evaluated the infrastructure at Coos Bay and conducted extensive outreach to prospective West Coast floating wind developers to understand the port facility requirements for the West Coast and screened individual sites within the port for different offshore wind activities. The key findings of this report include:

- The Port of Coos Bay has multiple good and moderate sites for manufacturing, staging and integration, and operations and maintenance activities.

- Investments in staging and integration capabilities align with the estimates provided by Mott Macdonald (2022). Additional estimates for manufacturing on the east side of the port ranged from $130−$520 million.
- The United States Army Corps of Engineers’ Proposed Channel Modification Project will be required to improve the channel to support floating wind energy activities.
- The Port of Coos Bay represents the best option (across metrics) for supporting floating wind activities in Oregon (instead of investing in new greenfield facilities).

Central Coast Emerging Industries Waterfront Siting and Infrastructure Study

Porter and Gostic (2022) investigated the regional opportunities to expand or develop new port infrastructure to jointly support the offshore wind energy and aerospace industries on the central coast of California (proximate to the Morro Bay lease areas). They conducted a screening exercise to identify likely ports that meet criteria to act as small facilities (likely operations and maintenance and staging of some components) or large facilities. They also conducted a further assessment of Diablo Canyon and the Port of San Luis to convey the construction requirements to build a large facility at these locations. Porter and Gostic (2022) find that:

- There are no existing wharves on the U.S. West Coast that can support floating offshore wind energy integration, and a network of ports will likely be required to support overall industry deployment.
- Offshore wind energy developers prefer port facilities located close to the offshore wind plant.
- Developing a new large facility (such as a staging and integration port) at Diablo Canyon or the Port of San Luis could cost between $1.3 and $6.2 billion.
- Coordination between the ports; the city of Morro Bay; San Luis Obispo and Santa Barbara counties; and the state of California is required to define the need, time frame, and investment in new or upgraded port facilities.

California Floating Offshore Wind Regional Ports Assessment

Trowbridge et al. (2023a) evaluated existing port capabilities in California to understand the number and capabilities of ports that would be required to support varying deployment scenarios through 2050. Offshore wind energy deployment ranged from a low scenario of 0.5 gigawatts (GW)/year (11 GW installed by 2050) to a high scenario of 2.5 GW/year (55 GW installed by 2050). The authors also conducted a detailed screening of California ports, including outreach to port owners and tenants. Trowbridge et al. (2023a) determined that:

- Many port sites exist in California that could meet the state’s offshore wind energy goals, although significant investment in existing ports would be required for the necessary upgrades.
- The ports of Humboldt, Los Angeles, and Long Beach are good candidates for staging and integration sites based on available space, deep navigation channels, and no air-draft restrictions. Nine ports were identified as good manufacturing sites (the Port of Humboldt, Port of Benicia, Port of Stockton, Port of Richmond, Port of San Francisco, Port of Redwood City, Port of Los Angeles, Port of Long Beach, and Port of San Diego) and six sites were identified as good operations and maintenance sites (the Crescent City Harbor District, Port

of Humboldt, City of Morro Bay, Diablo Canyon Power Plant, Port of San Luis, and Port of Hueneme).
- The ports of Los Angeles and Long Beach may be needed for decommissioning up to 23 oil-and-gas platforms that are currently located off the coast of California, which could affect the available capacity for offshore wind energy activities.

Alternative Port Assessment To Support Offshore Wind

Trowbridge et al. (2023b) conducted a feasibility assessment for the region between San Francisco and Long Beach, California, to determine the opportunities and limitations for creating new alternative port locations beyond existing sites considered in Trowbridge et al. (2023a). The study focused on staging and integration and operations and maintenance ports. The authors also provided high-level construction cost estimates and time frames for developing these possible greenfield sites. The key findings of the study include the following:

- There are 11 potential sites that could be candidates for staging and integration ports, with the Port of San Luis, China Harbor, and Gato Canyon ranked as the most promising due to environmental, engineering, and workforce considerations. Developing these sites could cost around $2 billion (with a range of –20% to –50% on the low end and +30% to 100% on the high end).
- Building a staging and integration port at one of these three locations could take 10 to 15 years to permit, partially due to the time required to develop a new port authority and conduct appropriate environmental studies.
- There are 13 potential sites that could be candidates for operations and maintenance ports. The authors did not rank these sites, but classified them by the level of investment required (either $1−$10 million or $10−$50 million).

AB 525 Port Readiness Plan

Lim and Trowbridge (2023) conducted a follow-on study to Trowbridge et al. (2023a) that evaluated the feasibility of port upgrades and estimate construction costs and time frames for the sites identified in the *California Floating Offshore Wind Regional Port Assessment.* The findings from this report, Lim and Trowbridge (2023), and (indirectly) the other studies listed in this appendix will be incorporated into the Seaport and Workforce chapter of California's AB 525 Strategic Plan, which will be developed in 2023 (California Legislature 2021). Lim and Trowbridge (2023) report that:

- Staging and integration ports are the most critical infrastructure that need to be identified and developed because of the limited number of suitable locations in California. Between three and five port sites would likely be required to install 25 GW by 2045.
- The Port of Humboldt, Port of Los Angeles, and Port of Long Beach appear to have the most cost-effective sites to develop.
- At least 12 manufacturing sites would be required to fabricate blades, towers, nacelles, floating foundations, and floating foundation subassemblies. These sites could maximize economic benefits and job creation.
- Between 9 and 16 berths would be required to support operations and maintenance vessels.

Summary

A summary of the reports described in this appendix is provided in Table A1.

Table A1. Summary of Previous and Ongoing West Coast Port Assessments

		Porter and Philipps (2016)	Mott Macdonald (2022)	Moffatt and Nichol (2022)	Porter and Gostic (2022)	Trowbridge et al. (2023a)	Trowbridge et al. (2023b)	Lim and Trowbridge (2023)
Funding agency		Bureau of Ocean Energy Management (BOEM)	TotalEnergies SBE US Oregon Business Development Department	BOEM	San Luis Obispo County Santa Barbara County City of Morro Bay	BOEM	California State Lands Commission	California State Lands Commission
Lead authors		Mott Macdonald	Mott Macdonald	Moffatt and Nichol	Mott Macdonald	Moffatt and Nichol	Moffat and Nichol	Moffatt and Nichol
Publication year		2016	2022	2022	2022	2023	2023	2023
Port region		West Coast and Hawai`i	Coos Bay	Coos Bay	California Central Coast	California	California Central Coast	California
Content	Site screening	X	X	X	X	X	X	
	Greenfield port design				X		X	
	Existing port redesign		X	X	X			X
	Economic impact					X		
	Strategic planning		X	X		X	X	

		Porter and Philipps (2016)	Mott Macdonald (2022)	Moffatt and Nichol (2022)	Porter and Gostic (2022)	Trowbridge et al. (2023a)	Trowbridge et al. (2023b)	Lim and Trowbridge (2023)
	Regulatory assessment				X	X	X	
	Stakeholder coordination				X	X	X	

This study has been designed to complement the published and ongoing work referenced in Table A1 by using consistent methodologies and assumptions that we then apply to the entire West Coast. An important goal of this report is to not only provide messaging that is consistent with other studies, but to introduce additional considerations and assessments that could influence how ports could develop to support the floating wind energy industry.

Appendix B. Design Requirements for Floating Offshore Wind Energy Ports

This section defines the requirements and design criteria for different types of offshore wind energy port sites. These criteria are the same as those used by Trowbridge et al. (2023b) to evaluate port requirements for floating wind energy in the state of California; some tables in this section are reproduced from Trowbridge et al. (2023b). We consider the following types of sites in this study:

- **Manufacturing/fabrication (MF) site.** A MF site produces major offshore wind energy components, such as wind turbine blades, nacelles, towers, cables, or floating substructures, from raw materials that are transported to the port via road, rail, or barge. The site would likely feature factories, warehouses, and storage space for completed components; further descriptions of these types of sites are provided in Shields et al. (2023).
- **Staging and integration (S&I) site.** A S&I site stages major offshore wind components for assembly and installation activities. The site needs sufficient laydown space to store a buffer of components, quayside assembly capabilities including heavy-lift cranes, reinforced wharves, deep berths, and a navigation channel that allows fully assembled floating wind turbines to be transported out to sea. We also assume that major repairs and replacements for operational wind turbines are conducted at a S&I site (after the wind turbine is disconnected from its moorings and electrical cables and towed back to the port).
- **Operation and maintenance (O&M) site.** An O&M site is a base for service vessels that conducts regular trips to one or more offshore wind energy projects for maintenance activities. The site may include warehouses, spare part storage, offices, and facilities for vessel provisioning. Typical types of O&M vessels include crew transfer vessels, which take day trips to the wind project for visits and inspections, and service operation vessels, which can spend several weeks at the wind project to provide on-site accommodations for the repair crew.

Other vessels, such as tugboats, barges, and cable-lay vessels will be required for various phases of floating offshore wind energy projects but typically do not drive design requirements.

Wind Turbine Size

The offshore wind energy industry has seen significant growth in wind turbine rating in recent years, with 15-megawatt (MW) wind turbines now commercially available (Musial et al. 2022). Increasing wind turbine rating has the potential to reduce the levelized cost of energy for a project because it requires fewer machines for a given project capacity, thereby realizing economies of scale and size that reduce unit costs (Shields et al. 2021). However, the rapid growth of turbine size could also conceivably increase costs if continual shifting to the newest technology prevents manufacturers from meaningfully advancing along the learning curve and if new investments in infrastructure are required to accommodate larger machines. As a result, there is significant uncertainty about the size of wind turbines that will be used for West Coast floating wind energy projects. This challenge is exacerbated by the dozens of conceptual designs for floating wind platforms, each of which could have different port requirements (ABS Group 2021).

Given the technology risk facing the floating wind industry, port development would benefit by considering the broadest possible design envelope (meaning, the largest potential wind turbine and substructure sizes) to facilitate market growth and competition between different technologies. With this in mind, we consider floating wind turbine dimensions corresponding to a 25-MW machine even though the technology pathways we consider in this report only include 15- and 20-MW wind turbines. The dimensions used for the 25-MW wind turbine system were derived by Trowbridge et al. (2022) through extensive industry outreach. These dimensions are listed in Table B1.

Table B1. Approximate Dimensions for a Conceptual 25-MW Wind Turbine Used To Conservatively Size Port Design Requirements

	Approximate Dimensions
Substructure width	Up to 130 meters (m)
Draft (before wind turbine integration)	4.5 to 7.5 m
Draft (after wind turbine integration)	6 to 15 m
Hub/nacelle height (from water level)	Up to 183 m
Tip height (from water level)	Up to 335 m
Rotor diameter	Up to 305 m

Types of Floating Substructures

Figure B1 shows floating wind archetypes. Although these archetypes are some of the more common floating platform designs, they do not cover the dozens of possible concepts being developed by different technology providers.

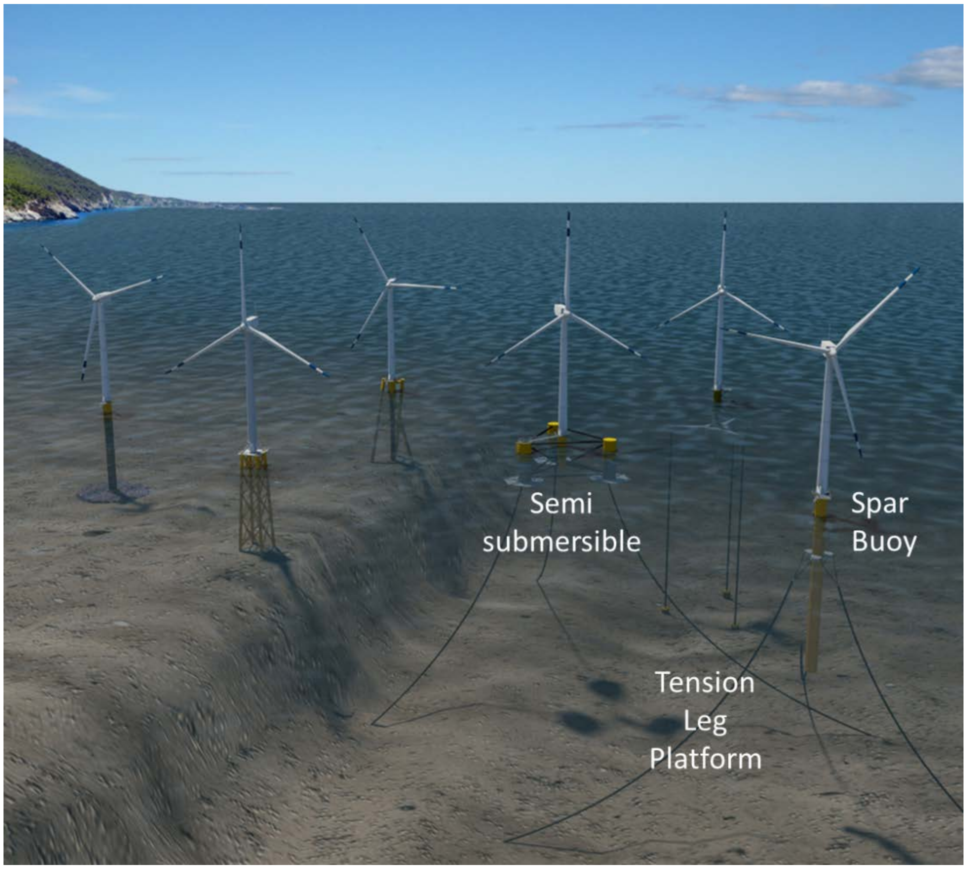

Figure B1. Common archetypes for floating wind technology. ***Illustration by Josh Bauer, National Renewable Energy Laboratory***

These floating design concepts have been proven to support offshore drilling operations by the oil-and-gas industry under a variety of extreme weather conditions, and are being adapted into new designs to accommodate the different dynamic forces involved with supporting wind turbines. The semisubmersible is the most common substructure selected by developers because it is most easily adapted to existing port infrastructure. It uses significant buoyancy and water plane area to maintain static stability and is stable in the water after wind turbine assembly at quayside. It has a relatively shallow draft that allows it to be towed out to its open-ocean operating site with a minimal amount of expensive labor at sea. It can be disconnected from its moorings at sea and towed to shore for maintenance, avoiding the use of a highly specialized wind turbine installation vessel.

The tension-leg platform (TLP) gets its static stability from mooring-line tension and is unstable unless additional buoyancy is added. This makes TLPs more difficult to fully assemble at quayside and could increase labor costs. They also require high-capacity vertical load anchors that can add cost. While TLPs are more difficult to deploy, they are very stable once installed and are beneficial because they have a much smaller footprint on the seabed. There have been no megawatt-scale offshore wind turbine TLPs to date, but these substructures could be advantageous in the deeper waters of the U.S. western Outer Continental Shelf where smaller footprints may be desired.

The spar buoy is statically stabilized by ballast but as a result has a deeper draft penetrating farther below the water surface (Musial et al. 2022). The world's first commercial floating wind power plant was a five-turbine, 30-MW facility deployed by Equinor in October 2017 off Peterhead, Scotland, using spar technology. The deep draft of the spar prevents it from being a practical option in most existing U.S. ports without significant modifications. Promising hybrid options are being developed that combine the best features of these major archetypes (Stiesdal 2023).

B.3 Port Requirements

Trowbridge et al. (2022) develop a series of port design requirements for West Coast floating wind ports based on discussions with industry and port operators. This section summarizes their findings, which we adapt for use in this report. The design requirements are provided in Table B2, and are described in more detail in the following sections.

Table B2. Port Infrastructure Requirements. ***Adapted from Trowbridge et al. (2022)***

	Approximate Criteria for S&I Sites	Approximate Criteria for MF Sites	Approximate Criteria for O&M, Mooring Line and Anchor Storage, and Construction Support Sites	Approximate Criteria for Electrical Cable Laydown Sites
Acreage, minimum	30 to 100 acres	30 to 100 acres	**O&M:** 5 to 10 acres **Others:** 10 to 30 acres	20 to 30 acres
Wharf length	1,500 feet (ft)	800 ft	300 ft	500 ft
Minimum draft at berth	38 ft	38 ft	20 to 30 ft	30 to 35 ft
Draft at sinking basin*	40 to 100 ft	Not applicable (N/A)	N/A	N/A
Wharf loading	> 6,000 pounds per square foot (psf)	> 6,000 psf	**O&M:** 100 to 500 psf **Others:** 500 psf	1,000 psf
Uplands/yard loading (for wind turbine generator components)	> 2,000 to 3,000 psf	> 2,000 to 3,000 psf	N/A	1,000 to 2,000 psf

*Options for transferring a floating foundation from land to water include use of semisubmersible barge and sinking basin, ramp system, or direct transfer methods (lifting portions or complete foundation units from land into water).

Air-Draft Restrictions

S&I sites have air-draft restrictions, meaning they cannot be located upstream of bridges or power lines, so that fully integrated wind turbines can be towed out to sea from the port. These wind turbines may need 335 meters of clearance above the water line to transit from the port to the project site. For reference, this means that floating wind turbines would not fit under the Golden Gate Bridge in the San Francisco Bay. These air-draft restrictions do not apply to MF or O&M sites.

Port Wharf and Loading Requirements

A S&I wharf needs enough space for the delivery of components at one berth and for at least two adjacent wind turbine assemblies. These three berths require a quayside length of 450 meters. MF and O&M sites do not require the same quayside length and depend on the type of vessel (and type of component) being used at the site.

S&I and MF sites require a bearing capacity of 2,000–3,000 pounds per square foot (psf) at laydown areas to support massive offshore wind components. Reinforced wharves (where a heavy-lift crane will likely be used to load/unload components or assemble the wind turbine components on a floating platform) will require a higher capacity of 6,000 psf. O&M facilities do not stage or lift these heavy components, and would only require 100–500 psf at the quayside.

Project developers and component manufacturers prefer a site size of 30 to 100 acres for MF and S&I sites, although they may be able to use smaller sites if necessary. A risk of smaller sites is that fewer components can be stored, which could lead to delays and bottlenecks in the installation process. O&M facilities require a minimum of 5–10 acres, although larger O&M facilities (10–30 acres) could potentially be designed to service multiple projects. In this report, we consider the smaller sites that can be located in more areas along the West Coast.

Wet Storage Requirements

Wet storage space is also required at S&I sites (and could be used at some MF sites) in addition to the upland acreage and water frontage. Ports must have locations where floating foundations or integrated wind turbines can be safely moored to mitigate the risk of weather downtime, vessel traffic, entrance channel congestion, and other transportation hazards. This space also allows the developers to store and test the completed units and floating foundations to ensure they can deliver to the lease area on time. The size of the wet storage area depends on the developer's strategy, deployment schedule, downtime risk, and available port space.

Additional Port Requirements

MF and S&I sites require some capability to transfer components from a fabrication or assembly area into the water. Multiple options exist for these activities. Components could be fabricated on semisubmersible barges, which are then submerged so that the floating platform (and integrated wind turbine) can float off. Wharves could have inclined ramps or lifts to transfer components from dry land assembly areas into the water. Some early-stage demonstration projects in Europe have used dry docks to assemble floating platforms, but these are unlikely to be built at West Coast ports due to the size and cost of these systems. MF and S&I sites need roll-on/roll-off capabilities at the wharf and laydown area to allow components to be transported within a facility.

New port terminals must have the appropriate infrastructure to meet state and federal green port initiatives, which may include port electrification and alternative fuels for vessels. Conventional fueling sources will likely still be required in the short term as the alternate fuel vessel fleet is built. Other vessel services include the need for potable water, shore power, and security requirements.

Design Life

New marine structures at offshore wind ports must be designed with a 50-year service life, which is the time period that a properly built and maintained structure should be able to operate without major replacement or repair. It will also be necessary to anticipate sea-level rise when determining the elevation of the port infrastructure.

Governing Codes, Standards, and References

See Section 2.4 of Trowbridge et al. (2023b) for a list of codes, standards, and references for the design of port infrastructure and offshore wind vessels.

Technology Sensitivities

The results in this study are based on the concept of "conventional" port designs that could accommodate floating wind activities. Novel technologies have been proposed that could reduce the need for this type of infrastructure and potentially (and significantly) reduce the magnitude of infrastructure investment needed. A nonexhaustive list of some of these concepts includes:

- Floating drydocks that can be delivered to a conventional port via road, assembled on-site, and towed to deeper water to launch a floating wind turbine
- Floating ports that can conduct manufacturing or integration activities outside of a sheltered harbor
- Alternate floating platform designs that significantly reduce the laydown and quayside space required at ports
- Refined supply chain methodologies designed to minimize assembly times at the S&I port (such as transporting towers in a single section to reduce tower integration and cable pull-in times).

We do not directly evaluate these technology pathways in this report, although there is merit in understanding the value proposition of these concepts. The conventional port concepts that we outline in this report effectively represent a low-risk pathway to commercializing floating wind energy, but come with a significant level of required investment and stakeholder engagement. A disruptive technology could potentially reduce the cost or time required to build these ports, but would have to demonstrate a level of feasibility, safety, and reliability that is similar to a conventional port design.

Appendix C. Offshore Wind Energy Deployment Scenarios

The amount of floating offshore wind energy being deployed along the West Coast will drive the demand for port facilities (and, conversely, the number of port facilities will enable the installation and operation of different levels of offshore wind deployment). We define the following three levels of offshore wind deployment by 2045:

- Twenty-five gigawatts (GW) of offshore wind energy projects are built exclusively in California
- Thirty-five GW of offshore wind energy projects are built in California and Oregon
- Fifty-five GW of offshore wind energy projects are built in California, Oregon, and Washington.

The 25-GW deployment scenario focuses on the 25-GW planning goal established by California's Assembly Bill No. 525 (California Legislature 2021). Oregon has an Intergovernmental Renewable Energy Task Force, active Call Areas, and a goal of developing up to 3 GW of floating wind energy projects by 2030 (Bureau of Ocean Energy Management n.d. (a); Oregon State Legislature 2021). We therefore add 10 GW of capacity in Oregon waters by 2045 in the 35-GW scenario to reflect this interest. Finally, the 55-GW deployment scenario includes higher deployment levels in California and Oregon (33 GW and 16 GW, respectively) as well as 6 GW deployed in Washington. Washington has received an unsolicited lease area request but does not have an established task force or Call Area (Trident Winds 2022); therefore, we assume that offshore wind energy will only be built in Washington in this latter scenario.

In addition to the overall deployment targets for each scenario, we estimate the annual deployment rate in five West Coast regions: central California, northern California, southern Oregon, central Oregon, and southern Washington. These regions approximately reflect the existing lease areas, Call Areas, and unsolicited lease area requests along the West Coast. We further assume that each project will have a nameplate capacity of 1,000 megawatts. As the actual offshore wind energy deployment pipeline develops, project locations and capacities will vary based on marine spatial planning, stakeholder and tribal input, developer design choices, and technology evolution; however, estimating these details is outside the scope of this study. The offshore wind energy project deployment schedule is plotted over time for each scenario in Figure C1.

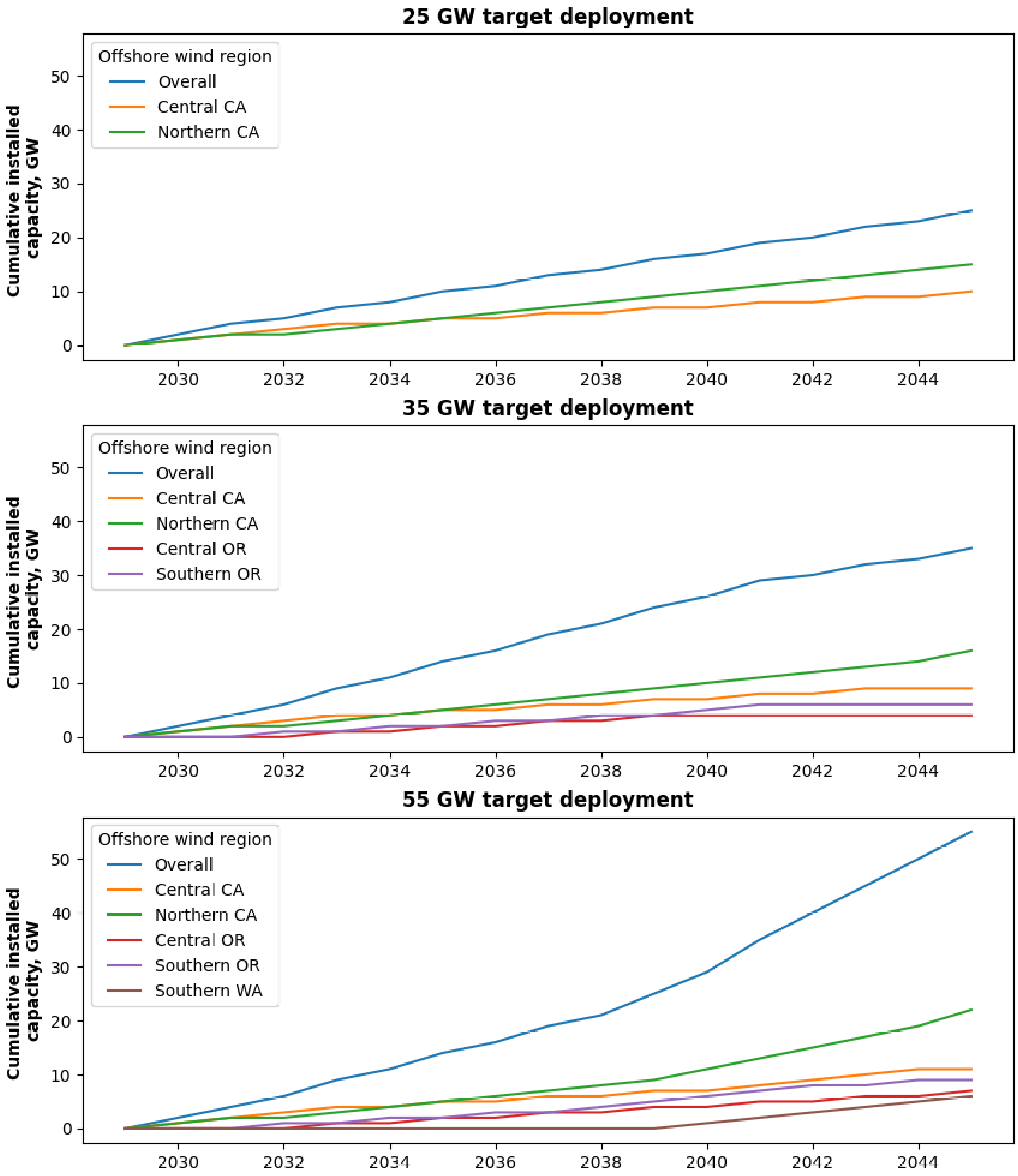

Figure C1. Regional floating offshore wind energy deployment for the 25-GW, 35-GW, and 55-GW deployment scenarios

Appendix D. Port Construction

Any potential port site on the West Coast would require significant infrastructure upgrades to serve the offshore wind energy industry. In this section, we describe the rough order of magnitude cost estimates that would be required to expand the port sites from their current state to a facility suitable for specific phases of offshore wind activity. These costs focus on the improvements to the port infrastructure itself—specifically, dredging of the sinking basin, creation of a suitable heavy-lift wharf, and clearing and preparing an upland area. Individual ports would have to make additional decisions about specific technologies and equipment that would be needed for floating wind operations. These considerations could include the method for transferring an assembled substructure into wet storage, which could use semisubmersible barges, inclined ramps, lift gates, or other equipment,[12] or the type of crane that would be needed to integrate the wind turbine onto the assembled platform. We do not consider these cost estimates in this study because they would be specific to individual ports and the preferred technologies selected by developers (including the platform type and turbine rating).

Port Screening

We screened existing ports along the West Coast to determine their suitability for the three different phases of floating wind energy projects. This process involved a desktop evaluation of existing port capabilities, such as available upland area, number and size of wharves, and width and depth of navigation channels, which we compared against the floating wind port requirements listed in Appendix B. Most port sites do not currently meet the required criteria, so we had to judge which sites are more likely to be developed for the different phases of offshore wind deployment. We further downselected port sites based on our understanding of existing operations at the ports (for example, if the port is sufficiently busy that it is less likely to pivot toward offshore wind activities). As part of the AB 525 work conducted by Lim and Trowbridge (2023), we conducted outreach to California ports to review the findings and incorporate their perspectives of their own capabilities. Similar outreach to Oregon and Washington ports could be conducted as a follow-on study.

Results of the port screening are provided in Tables D1–D4 for Washington state, the Columbia River Basin, the Oregon Coast, and California.

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[12] Although drydocks have been used for early demonstration-scale floating wind energy projects in Europe, they are not likely to be developed for commercial-scale West Coast ports due to prohibitive size and cost.

Table D1. Results From Washington State Port Screening for Staging and Integration (S&I), Manufacturing/Fabrication (MF), and Operations and Maintenance (O&M) Activities

Port Location	Capabilities			Notes
	S&I	MF	O&M	
				Puget Sound
Bellingham	X	X		Not much available land
Anacortes				Deep channels, not much available land
Port Townsend				Not much available land, shallow water depth, too far from ocean
Everett	X	X		Land currently in use, but may be available in future
Port of Seattle	X	X		One terminal currently not in use
Port of Tacoma	X	X		Deep draft channel, large empty lot near turning basin
Olympia		X		Bridge restriction, currently in use by another industry, but may have available land in future
				Washington Coast
Port Angeles		X	X	Not much available land
Neah Bay				Channel is USACE maintained, but not a lot of industrial land available
Grays Harbor	X	X	X	Lots of land available, closer to projects than Puget sound/Olympic peninsula
Westport			X	Columbia River has several small harbors that can support O&M
Willapa Bay/Peninsula				USACE 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 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).

USACE = U.S. Army Corps of Engineers

Table D2. Results From the Columbia River Basin Port Screening for S&I, MF, and O&M Activities

Port Location	Capabilities			Notes
	S&I	MF	O&M	
Ilwaco (WA)			X	Not much space available, shallow water depth
Chinook (WA)			X	Not currently fully utilized
Hammond Boat Basin (OR)			X	USACE maintains channel, not much space available
Warrenton (OR)		X	X	Water depth can accommodate barges
Astoria (OR)			X	Not much land available, adequate water depth for O&M vessels
Cathlamet (WA)	🟥	🟥	🟥	Not much space available, shallow draft
Wauna (OR)	🟥	🟥	🟥	Currently in use, no land available, adjacent industrial site included in ~10–15 private terminal line item
Port of Longview (WA)		X		Lots of industrial land, adequate draft
Port of Kalama (WA)		X		Multiple sites available, adequate water depth
Port of Columbia County (OR)		X		Industrial land, deep-draft access, multiple sites
Woodland (WA)		X		Zoned for deep-draft vessel terminals, greenfield site
Vancouver (WA)		X		Lots of industrial land right on the channel
Port of Portland (OR)		X		Multiple sites
Up river (east) from I-5 bridge		X		After the bridge, the channel is barge only. There are ~5–10 barge-only private terminal sites that could be used for MF. The I-5 bridge is located on the Columbia River spanning between Vancouver and Portland.
~10–15 private terminal sites along the Columbia River and Willamette River		X		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 between Vancouver and Portland.

Green indicates a good candidate site, yellow indicates a moderate 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).

Table D3. Results From the Oregon Coast Port Screening for S&I, MF, and O&M Activities

Port Location	Capabilities			Notes
	S&I	MF	O&M	
Nehalem	🟥	🟥	🟥	No maintained channel
Tillamook Bay/Garibaldi			🟨 X	18 feet (ft) deep, CTV only for O&M, not as close to wind energy areas
Depoe Bay	🟥	🟥	🟥	Entrance channel not adequate for O&M
Yaquina River/Toledo/Newport		🟨 X	🟩 X	USACE maintains channel, potentially up to 40 acres available
Waldport	🟥	🟥	🟥	No maintained channel
Siuslaw River/Florence	🟥	🟥	🟥	No land available
Umpqua River/Reedsport		🟨 X	🟩 X	Shallow water depth in channel
Coos Bay	🟩 X	🟩 X	🟩 X	Best option (challenges with airport)
Bandon			🟨 X	Coquille River depth is 13 ft, CTV only for O&M site
Port Orford	🟥	🟥	🟥	No protected harbor
Rogue River			🟨 X	CTV only due to channel depth
Brookings Harbor/Chetco			🟨 X	CTV only due to channel depth

Green indicates a good candidate site, yellow indicates a moderate 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)

CTV = crew transfer vessel

Table D4. Results From the California Port Screening for S&I, MF, and O&M Activities

Port Location	Capabilities			Notes
	S&I	MF	O&M	
Crescent City Harbor			🟩 X	Identified in BOEM California Floating Offshore Wind Regional Ports Assessment
Humboldt	🟩 X	🟩 X	🟩 X	Identified in BOEM California Floating Offshore Wind Regional Ports Assessment
West Sacramento	🟥	🟥	🟥	Identified in BOEM California Floating Offshore Wind Regional Ports Assessment
Stockton		🟩 X		Identified in BOEM California Floating Offshore Wind Regional Ports Assessment
Benicia		🟩 X		Identified in BOEM California Floating Offshore Wind Regional Ports Assessment
Richmond		🟩 X	🟨 X	Identified in BOEM California Floating Offshore Wind Regional Ports Assessment
Oakland		🟨 X	🟨 X	Identified in BOEM California Floating Offshore Wind Regional Ports Assessment

Port Location	Capabilities			Notes
	S&I	MF	O&M	
Alameda		X	X	Identified in BOEM California Floating Offshore Wind Regional Ports Assessment
Redwood City		X		Identified in BOEM California Floating Offshore Wind Regional Ports Assessment
San Francisco		X	X	Identified in BOEM California Floating Offshore Wind Regional Ports Assessment
Bay Area Private Terminals (Two Sites)		X		Identified in AB 525 Port Readiness Plan
Pillar Point Harbor			X	Identified in CSLC Alternative Port Assessment
Santa Cruz Wharf			X	Identified in CSLC Alternative Port Assessment—CTV only for O&M
Santa Cruz Small Craft Harbor			X	Identified in CSLC Alternative Port Assessment—CTV only for O&M
Moss Landing			X	Identified in CSLC Alternative Port Assessment—cannot support SOVs for O&M
Monterey Harbor			X	Identified in CSLC Alternative Port Assessment—cannot support SOVs for O&M
China Harbor	X			Identified in CSLC Alternative Port Assessment—no existing port authority, significant environmental impact and cost
Morro Bay Harbor			X	Identified in BOEM California Floating Offshore Wind Regional Ports Assessment
Diablo Canyon PP			X	Identified in BOEM California Floating Offshore Wind Regional Ports Assessment
Port San Luis Pier/Cal Poly Pier	X		X	Identified in BOEM California Floating Offshore Wind Regional Ports Assessment—no existing port authority, significant environmental impact and cost; CTV and SOV only for O&M
Vandenberg Barge Berth			X	Identified in CSLC Alternative Port Assessment—CTV only for O&M
Gato Canyon	X			Identified in CSLC Alternative Port Assessment—no existing port authority, significant environmental impact and cost
Ellwood Pier			X	Identified in CSLC Alternative Port Assessment—CTV and SOV only for O&M
Santa Barbara Harbor			X	Identified in CSLC Alternative Port Assessment—CTV only for O&M
Stearns Wharf			X	Identified in CSLC Alternative Port Assessment—CTV and SOV only for O&M
Hueneme			X	Identified in BOEM California Floating Offshore Wind Regional Ports Assessment
Los Angeles	X	X		Identified in BOEM California Floating Offshore Wind Regional Ports Assessment

Port Location	Capabilities			Notes
	S&I	MF	O&M	
Long Beach	X	X		Identified in BOEM California Floating Offshore Wind Regional Ports Assessment
San Diego		X		Identified in BOEM California Floating Offshore Wind Regional Ports Assessment- Foundation MF at NASSCO and steel component fabrication and ship repair services at BAE Systems

Green indicates a good candidate site, yellow indicates a moderate 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)

BOEM = Bureau of Ocean Energy Management, CSLC = California State Lands Commission (CSLC), SOV = service operation vessel,

Port Upgrade Cost Estimates

Modeling Approach and Assumptions

All cost estimates were developed to meet the Association for the Advancement of Cost Estimating Class 5 accuracy (-50%/+50%). These cost estimates include the necessary port infrastructure upgrades required to meet the offshore wind port requirements listed in Appendix B. Note that these construction cost estimates exclude any above-grade construction (i.e., warehouses and buildings) to facilitate fair cost comparisons as each developer will determine the necessary above-grade construction for each site.

The general improvements required for staging and integration (S&I) and manufacturing/fabrication (MF) sites, which are included in the cost estimates, are summarized here:

- Preparation of 80 total acres at each site
- Demolition of existing wharf
- Construction of a new wharf
    - A 485-meter (m)-by-45-m heavy-lift wharf with a bearing capacity of 6,000 pounds per square foot (psf) at combined S&I and MF sites
    - A 240-m-by-45-m heavy-lift wharf with a bearing capacity of 6,000 psf at MF-only sites
    - Thirty-inch-diameter steel pipe piles that support the wharf
    - A 1-m-deep layer of dense-graded aggregate topping surface
- Preparation of upland area
    - Grading and compaction of upland soils
    - A 1-m-deep layer of dense-graded aggregate topping surface
    - Installation of utilities, such as stormwater, electrical, and water systems

- Dredging of harbor area
    - Dredge berth pocket to 11.5 m below the mean lower low water line[13]
    - Dredge a 182-m-by-300-m sinking basin with a depth between 18 m and 30.5 m at S&I and foundation manufacturing sites.

We use these general improvements to identify a pathway for developing port capabilities that could effectively support floating offshore wind energy operations. Additional upgrades and investments could be required for specific technologies; alternatively, disruptive innovations or technology solutions could reduce the demand for port infrastructure. Because of the uncertainty in the developing floating wind energy industry, we outline these general port improvements to provide a reasonable baseline that would create a robust network of S&I, MF, and O&M ports and enable commercial-scale floating wind deployment.

The costs that we report are total overnight construction costs (with contingency), which includes direct costs, indirect costs, and contingencies:

- **Direct cost.** Material, labor, and equipment costs developed based on historical and current data using in-house sources, information from previous studies, and budget price quotations solicited from local suppliers and contractors. All costs are in 2023 U.S. dollars and do not include escalation.
- **Total construction cost**. Direct costs to complete the work plus indirect costs including contractor supervision (general conditions), corporate overhead and profit, and bonds and insurance costs.
- **Total construction cost (with contingency).** Total construction cost plus a project contingency of 50%. The contingency amount has been included to cover undefined items, due to the level of engineering performed at this time. The contingency is not a reflection of the accuracy of the estimate but covers items of work that must be performed, and elements of costs that will be incurred, but which are not explicitly detailed or described due to the level of investigation, engineering, and estimating completed today. A contingency of 50% is a common assumption for this level of design for marine structures.

The development timelines for infrastructure improvements at the identified sites have also been estimated and are summarized in Table D5.

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[13] The mean lower low water line is the average of the lowest of the two daily low tides over a specified datum period, usually 19 years.

Table D5. Estimated Availability Dates for Port Sites in West Coast Regions

Region	Site Type	Assumed Start Date	Years to Plan, Permit, and Construct	First Site Available for Use
Puget Sound and Washington Coast	S&I	2028	Approximately 8–16 years	2036–2044
Columbia River Basin	MF	2026	Approximately 8–13 years	2034–2039
Oregon Coast	S&I	2028	Approximately 8–16 years	2036–2044
California	S&I	2023	Approximately 8–16 years	2031–2039
	S&I (central coast)[14]	2023	Approximately 20–25 years	2043–2048
	MF	2023	Approximately 8–13 years	2031–2036
All	O&M	2023	Approximately 7–10 years	2030–2033

Port Construction Cost Estimates

We developed cost estimates (in $2023) for individual port sites within the Puget Sound region, Columbia River Basin, Oregon Coast, northern California, San Francisco Bay, central California, and southern California. These cost estimates can vary for sites used for MF, S&I, or operations and maintenance (O&M) activities. We then averaged the results for all port sites within each region to provide a representative upgrade cost for the area. We determined that this approach was reasonable because the individual port upgrade costs did not vary drastically within a region, and by using the aggregated costs we can estimate the overall investment needed to develop a West Coast port network without specifying particular ports or losing significant accuracy. The representative port site upgrade costs are provided in Table D6.

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[14] S&I sites identified in central California in existing ports and brownfield and greenfield sites may require more investment, pose greater environmental impacts, and have longer development schedules than those within existing large ports.

Table D6. Summary of Port Site Construction Costs for Different West Coast Regions. Sinking Basin Costs Are in Addition to the Average Site Cost. Costs are reported in $2023.

Region	Site Type	Average Site Cost	Sinking Basin Costs		
			18 m	24 m	30.5 m
Puget Sound and Washington Coast	S&I/MF	$665 million/80 acres	Not applicable (N/A)	N/A	N/A
Columbia River Basin	MF[15]	$229 million/40 acres $458 million/80 acres	N/A	N/A	N/A
Oregon Coast	S&I	$713 million/80 acres	$125 million	$250 million	$500 million
Northern California	S&I	$700 million/80 acres	$200 million	$350 million	$600 million
San Francisco Bay	MF	$350 million/40 acres $525 million/80 acres[16]	N/A	N/A	N/A
Central California	S&I	$2,800 million/80 acres	$70 million	$200 million	$400 million
Southern California	S&I	$1,100 million/80 acres	N/A	N/A	$35 million
All	O&M	$25 million	N/A	N/A	N/A

Cost Estimates in Washington, Oregon, and the Columbia River Basin

We considered the Port of Seattle and the Port of Tacoma in the Puget Sound region for S&I / MF activities. These sites have deep existing berth pockets and navigation channels, meaning that dredging is not required for the navigation channel or sinking basin. Grays Harbor on the Washington Coast would also be a suitable S&I/MF facility, although it would require dredging of the navigation channel and sinking basin, which could add $100–$500 million depending on the depth of the basin.

The only feasible location for S&I/MF in Oregon is within Coos Bay. Because Coos Bay does not have deep enough existing berth pockets or navigation channels, dredging is required. Dredging for a sinking basin is also needed. Additionally, existing wetlands on the site will need to be filled to grade. Mott Macdonald (2022) describe how the proximity to the Southwest Oregon Regional Airport presents a challenge and would require coordination with the Federal Aviation Administration to permit towing operations.

There are several adequate sites for MF along the Columbia River, on both the Washington and Oregon sides, that could support the offshore wind energy industry. However, the Columbia River does not have deep enough berth pockets or navigation channels, therefore dredging is required. We consider the ports along the Columbia River to be some of the best-suited for offshore wind component manufacturing because of the number of sites with existing industrial land. Sites such as the Port of Longview (Washington), Port of Kalama (Washington),

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[15] Note that MF-only sites include a wharf length of 800 feet (ft) so these costs cannot be directly compared to the costs for the S&I/MF sites because these sites include 20 ft of wharf per acre = 20 * 80 acres = 1,600 ft.

[16] Not all sites in the San Francisco Bay have 80 acres available.

Vancouver (Washington), and Port of Portland (Oregon) are well-suited for MF activities due to the existing industrial land available and deep-water draft in some areas, with potential for deep draft by dredging in other areas.

O&M sites have the simplest requirements out of the different floating wind port types and are most preferable when they are in close proximity to offshore wind energy projects. Sites such as Port Angeles (Washington), Astoria (Oregon), Yaquina River/Toledo/Newport (Oregon), and Umpqua River/Reedsport (Oregon) are well-suited for O&M activities due to their proximity to Oregon offshore wind Call Areas, available port space, and navigation channels maintained by the U.S. Army Corps of Engineers.

Cost Estimates in California

We obtained the site cost estimates for California ports from Moffat and Nichol's published and ongoing work to support the state of California's and Bureau of Ocean Energy Management in developing port feasibility studies (Trowbridge 2023a, Lim and Trowbridge 2023).

The Port of Humboldt has already begun development as a terminal project that could incorporate S&I, and potentially MF and O&M activities. The Port of Los Angeles and the Port of Long Beach in southern California are additional S&I/MF options, and Long Beach has announced their intent to develop a 400-acre floating wind energy installation site. These latter two ports would require a significant amount of fill to create land for uplands storage space. This fill would likely be obtained by dredging the harbors to around a 25-m depth and would then be used to build the terminals. We include these cost estimates in the average cost for southern California S&I/MF sites.

Humboldt, Los Angeles, and Long Beach are established industrial port locations in California. An alternative approach would be to develop a new (or significantly expanded) S&I site on the central coast. Several potential options have been considered in Porter and Gostic (2022) and Trowbridge et al. (2023b). These sites would be significantly closer to the Morro Bay offshore wind lease areas; however, they would need to establish a new navigation channel and breakwater. The build-out of these sites could take 20–25 years to go through the design, permitting, and construction process and (possibly) establish a new port authority to manage the port. These alternative port sites may require more investment, pose higher environmental risk to the coastal marine ecosystem, and have longer development schedules than those within existing large ports. See Appendix J for a discussion of the California Coastal Act of 1976 and its potential impacts on permitting for new ports in the region.

There are several sites that could be used as MF-only sites in California, with a particular concentration in the San Francisco Bay Area. The Port of San Francisco, Port of Stockton, Port of Oakland, and Port of Richmond, as well as private industrial terminals identified in Antioch and Pittsburg, have adequate channel and berth draft and sufficient available acreage to support floating offshore wind energy manufacturing activities. The Port of Benicia and Port of Redwood City are not included as both sites do not have a minimum of 30 acres. The City of Alameda site is not included as it does not have direct access to the waterfront.

Sites with waterfront structures that can be readily converted to O&M sites with the addition of such features as floats, davits, gangways, and/or localized structural rehabilitation will likely require an investment of $1 to $10 million. Sites with this level of investment may have limited operationality due to wave exposure (e.g., Ellwood Pier), require coordination with other users, or have site geometry constraints (e.g., Diablo Canyon due to the harbor size).

Sites that require improvements such as new waterfront structures—such as pile-supported wharves or a pier expansion—and/or dredging of navigation channels, such as with Morro Bay, will require an investment of $10 to $50 million. Sites with this level of investment are intended to support crew transfer, CTVs, and in some cases SOV moorage, depending on the size of the SOV. In Table D6, we select an average value of $25 million per O&M site.

Appendix E. Energy Justice Considerations in Port Communities

Ports play a critical role in the U.S. energy sector and economy more broadly, but "while ports are critical, they are likely places to look for signs of environmental inequity" (Greenberg 2021). In many cases, the areas near ports are home to environmental justice communities that tend to be low income and/or majority nonwhite and bear the brunt of harmful impacts from port activities (U.S. Environmental Protection Agency [EPA] 2020). The West Coast offshore wind energy industry, anchored by the ports discussed in this study, has the potential to provide new investment and economic opportunities—benefits that are important to port communities. But while the offshore wind industry is likely to provide significant benefits to the West Coast region more broadly, "there is a risk that members of port communities may become disproportionately burdened by supply chain activities, as has often occurred with other industries operating at ports" (Shields et al. 2023).

Living near port activities such as trucking, ship traffic, and industrial activities means that port communities are exposed to disproportionately high levels of air pollutants, resulting in increased incidence of health conditions such as heart and lung disease, cancer, and premature mortality (EPA 2020). Notably, of the U.S. counties that have currently or previously failed to meet the National Ambient Air Quality Standards, 30% either include or are adjacent to major ports (Gillingham and Huang 2021). This pollution often has particularly high impacts on the health of nonwhite residents of port communities (Gillingham and Huang 2021); for example, Black residents of Long Beach, California, are hospitalized with asthma at eight times the rate of white residents (Hagerty 2021). Other issues include a lack of economic investment, displacement from housing due to expanding port activities, isolation from basic necessities due to infrastructure surrounding ports (e.g., highways, railroads), exposure to noise and light pollution, and high vulnerability to coastal climate impacts (EPA 2022a). The disproportionate environmental, health, and quality-of-life burdens placed on port communities "can be compounded when they do not receive the same level of benefits from port activities – such as jobs and economic growth – that are enjoyed regionally" (EPA 2022a).

Many ports on the West Coast are also located near tribal lands and/or in places with cultural, historical, economic, and environmental significance to tribes, thus another important consideration for energy justice. Like many port community members, Indigenous people may experience significant environmental health and economic burdens, compounding the harms brought to their historical and cultural resources by port activities. Important factors to consider in offshore wind port decision-making include impacts to tribal resources, tribal consultation, mitigation of negative impacts, and creation of economic and workforce opportunities for tribes. These topics are addressed in greater detail in Appendix K.

In Shields et al. (2023), the National Renewable Energy Laboratory established a framework of metrics and indicators that can be used to evaluate equity in each stage of offshore wind energy supply chain projects. These metrics included contextual, procedural equity, and socioeconomic impact equity indicators (Shields et al. 2023). In this study, we apply and expand on this framework to develop two indicators that can be used to become familiar with West Coast port communities and assess the impacts of port development: community vulnerability and workforce accessibility. While these indicators are by no means meant to capture the many nuances of energy justice and equity, they can help decision makers anticipate challenges and opportunities related to port communities. Having a deeper understanding of the impacts of offshore wind port development on nearby communities through data collection and engagement will allow decision makers to begin mitigating and compensating for negative impacts.

Modeling Approach and Assumptions

We created the following two indicators that can be used to consider energy justice impacts on port communities:

- The **community vulnerability indicator** quantifies the existing burdens faced by port communities. This indicator can be used to understand baseline community context and to anticipate potential health and environmental impacts of port development.
- The **workforce accessibility indicator** examines the ability of port communities to access workforce opportunities offered by port development. This indicator can be used to understand baseline community context as it relates to workforce and education.

Based on a review of literature and discussion with community engagement experts, we define port communities as census tracts lying (partially or fully) within a 5-mile radius of ports. While most impacts resulting from port development will likely be felt by communities beyond the 5-mile radius, this definition allows us to focus our analysis on those who are most impacted by port activity. Studies have found that the populations that live the closest to ports experience greater impacts than those at a slightly greater distance. One study of the 50 largest U.S. ports found that, compared to populations living within a 5- or 10-mile radius of ports, populations living within a 2-mile radius were predominately people of color, more socioeconomically disadvantaged, had less formal education, and had higher exposure to air pollutants and other environmental risks (Greenberg 2021).

The community vulnerability and workforce accessibility indicators are comprised of data found in the publicly available Climate and Economic Justice Screening Tool (CEJST) created by the United States White House Council on Environmental Quality. The CEJST pulls from other federal databases such as the EPA's EJScreen tool and the U.S. Census Bureau's American Communities Survey. We prioritized the use of publicly available data to allow for future work that calculates these metrics for ports not considered in the present study. While we report these metrics on a regional level for the port regions considered in this study, we encourage decision makers to use the CEJST to collect data on specific port communities. Shields et al. provide additional metrics that can be incorporated into energy justice analyses and decision-making (Shields et al. 2023).

Assessment Metrics

Community Vulnerability

Port communities tend to experience economic, environmental, and health burdens that can exacerbate or interact with each other in ways that increase their sensitivity to port activities. For example, higher levels of poverty within port communities may make it difficult for community members to relocate or seek healthcare to mitigate health issues caused by air pollution. In this study, we refer to the burdens experienced by port communities as community vulnerability.

For each of the ports considered in this study, we calculated port community vulnerability metrics based on data from the CEJST. Using guidance from the EPA Ports Primer (Environmental Protection Agency 2020), we selected eight key metrics from the CEJST that are highly relevant to port communities. These metrics are:

- PM2.5 exposure (level of inhalable particles that are 2.5 micrometers or smaller)
- Diesel particulate matter exposure
- Transportation barriers (average relative cost and time spent on transportation)
- Proximity to National Priorities List (Superfund) sites
- Current asthma rates among adults aged greater than or equal to 18 years
- Percent of individuals below 200% of the federal poverty line
- Wastewater discharge exposure (based on measurements of toxic concentrations in nearby stream segments)
- Low median household income as a percent of area median income.

For each of the census tracts in the United States, the CEJST provides percentile values for these measurements. For each census tract, we calculate the community vulnerability indicator as the sum of the eight metrics listed earlier. The portwide community vulnerability indicator is calculated by averaging the metrics across all census tracts comprising the port community. The individual port metrics are normalized across all ports. Portwide vulnerability indicators can range 0 from to 1, with a score of 1 indicating the highest estimated vulnerability. In this study, we chose to determine low, medium, and high community vulnerability thresholds relative to the calculated scores, and we assigned scores to port regions. Regions with scores higher than 0.6 are considered highly vulnerable, regions scoring between 0.4 and 0.6 are moderately vulnerable, and region with scores below 0.4 have low vulnerability.

Barriers to Workforce Accessibility

Ensuring that disadvantaged communities, particularly port communities significantly impacted by development, are benefitting from the offshore wind energy industry is crucial to creating an equitable industry and supply chain. It is difficult to predict how various port sites will provide workforce benefits and opportunities to port communities because these outcomes depend on voluntary actions taken by those involved in port decision-making, hiring, and workforce development. Given this uncertainty, we instead assess the relative ability of communities in the vicinity of offshore wind port development to access jobs once they become available.

Using the CEJST, we determined whether communities surrounding a port considered in the scenarios were considered to have high barriers to workforce accessibility. The CEJST classifies a census tract as being workforce disadvantaged if it meets these criteria:

- At or above the 90th percentile for linguistic isolation **or** low median income **or** poverty, **or** unemployment
- **And** more than 10% of people aged 25 or older have less than a high school education (i.e., do not have a high school diploma or equivalency diploma [GED]) (CEJST 2022).

Most job roles in the offshore wind energy industry have a minimum education requirement of a high school diploma or GED, although some roles at offshore wind ports, such as longshoreman and laborer roles, may not require a high school education (Stefek et al. 2022). A workforce assessment focused on offshore wind ports could help more precisely identify how education level factors into access to workforce opportunities.

Our study designated a port as having high barriers to workforce accessibility if any census tract within a 5-mile radius of the port was designated by CEJST as workforce disadvantaged. Because this metric is meant to evaluate the ability of communities directly surrounding the ports to access offshore wind port jobs, the radius is smaller than if we were considering the broader workforce availability for the port across a larger region. A workforce assessment study of port locations may be warranted to understand the broader workforce impact of port development.

For each region, if less than 35% of the ports in each scenario were designated as workforce disadvantaged, that region was scored as having low barriers to workforce accessibility. If the region had between 35% and 60% of the ports falling into the disadvantaged category, the region was rated as moderate. Finally, if 60% or more of the ports in the region were designated as workforce disadvantaged, the region was scored as having high barriers to workforce accessibility.

It is important to note that the workforce accessibility score is not a statement on whether a port site should be developed in a certain location, as the score does not indicate that there is no workforce available to support the port; rather, it highlights areas where investment and coordination may be needed to ensure jobs are accessible to port communities.

Constraints and Limitations

Workforce Accessibility Percentages

To analyze workforce barriers, we use a percentage of the total number of ports in a region to determine the favorability score, but it does not demonstrate the absolute impact. For example, one region with only five ports that all have high barriers to workforce accessibility score would be classified as high, but another region that includes an additional 25 ports could be classified as low. The indicator is meant to demonstrate the overall impact of development within a region. However, individual port impacts should be studied further to identify specific impacts and needs.

Size of Census District and Distance From Port Considered in Indicators

For consistency across the West Coast, this study uses data from federal sources (CEJST). This federal-level data has detail down to the census-tract level. Census tracts are not uniform in geographic size or population. According to the Census Bureau, tracts generally have 1,200–8,000 people and vary similarly in geographic size.

Selection of Vulnerability Metrics

We selected vulnerability metrics based on the priority topics identified by the EPA's Port Community Collaborative and Ports Initiative and the metrics that are available in federal data sets (EJScreen and CEJST) and share a common format across the West Coast. We chose metrics that highlight vulnerabilities that are of specific significance to port communities, like diesel particulate matter, as well as to encompass general vulnerability metrics, like the percent of the population below 200% of the federal poverty line. However, the metrics do not represent all aspects of vulnerability and, depending on the specific context of each port community, there may be other metrics worth considering. Additionally, all metrics were weighted equally in this study.

Regional Energy Justice Evaluations

Community Vulnerability Results

In this section, we report the community vulnerability scores calculated for each port considered in the scenarios. Because the community vulnerability indicators for each port are related to their communities' distinct histories, we found that evaluating the metrics on a regional basis is more meaningful than doing so on a scenario basis (see Figure E1).

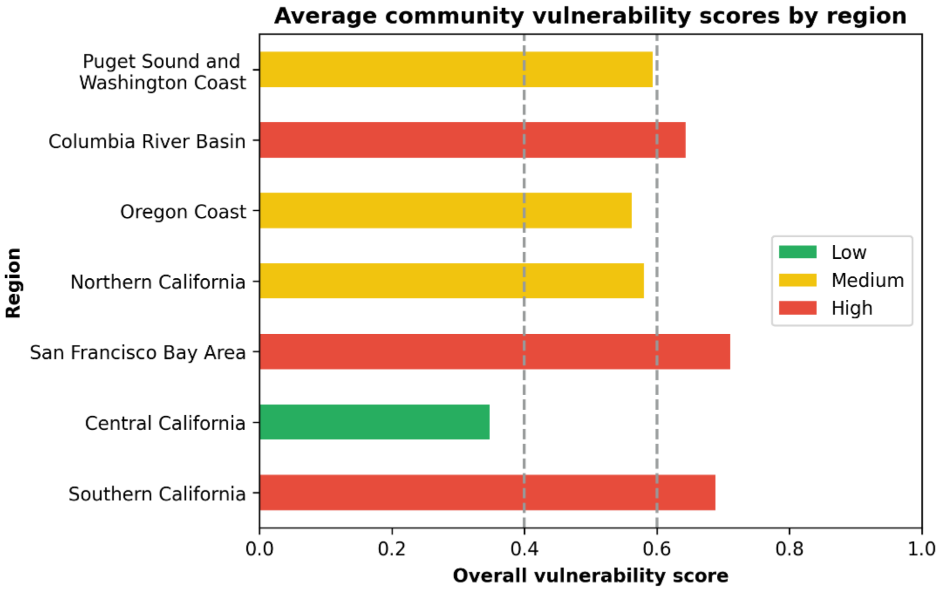

Figure E1. Community vulnerability indicators by region. Scores below 0.4 are considered low, and scores above 0.6 are considered high.

Our analysis revealed regional differences in vulnerability that are summarized in Figure E1. Ports in urban or more densely populated regions—most notably the Columbia River Basin, San Francisco Bay Area, and southern California—are often surrounded by highly vulnerable communities, whereas port communities in rural or less densely populated regions generally face low and moderate levels of vulnerability. Urban and rural port communities also face different drivers of their vulnerability levels; for example, urban port communities face higher exposures to poor air quality and proximity to Superfund sites, whereas vulnerability scores for more rural communities in northern California and on the Oregon coast are driven by low income and high poverty levels rather than environmental health metrics. As the offshore wind energy industry expands into ports on the West Coast, these differences in vulnerability levels and drivers of vulnerability among rural and urban regions will be important to weigh with other factors discussed in this report, such as workforce accessibility and the impact of port proximity on project cost and timeline. The relative contributions of each metric to overall vulnerability is broken down by region in Figure E2.

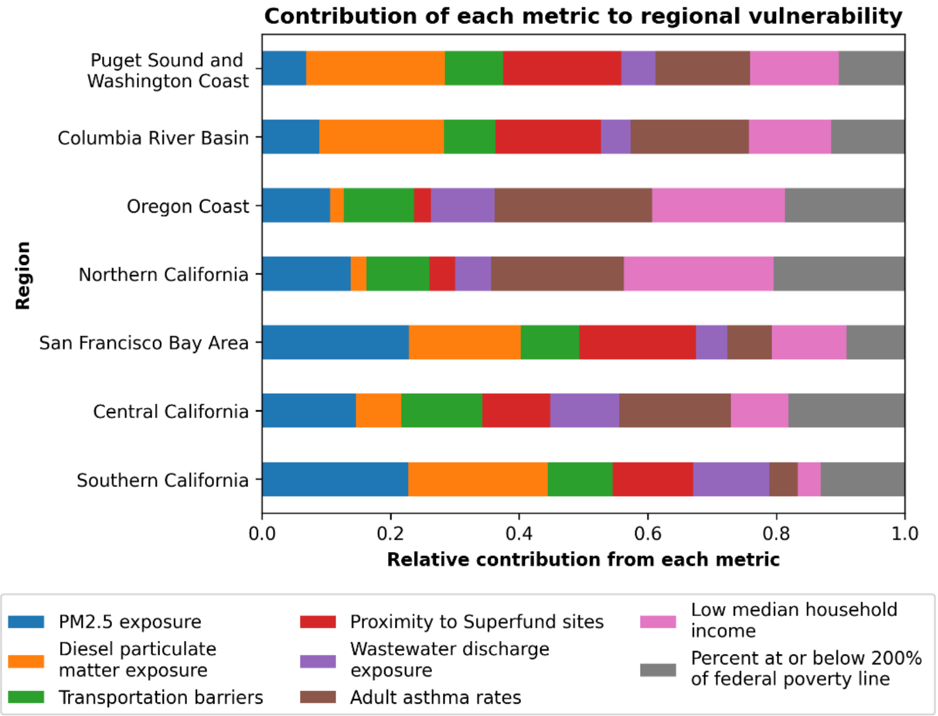

Figure E2. Proportion of vulnerability metrics by region. This chart can be used to examine which indicators drive community vulnerability across the regions considered in this study.

Since different regions are involved to varying degrees across the port network scenarios developed in this study, these regional indicators can help inform the study's overall results. For instance, it is important to note that the San Francisco Bay Area, which was found to have the highest vulnerability across all regions in this analysis, is involved across all scenarios outlined in Section 3.5. Community vulnerability in California ports could vary significantly depending on whether a second port is added in central California (low vulnerability) or southern California (high vulnerability). Expanding staging and integration activities to Oregon and Washington, however, would engage communities with similar levels of vulnerability to those already engaged in northern California. Finally, expanding manufacturing into the Columbia River Basin would include additional communities, but they face vulnerability levels that are similar to communities in the San Francisco Bay Area. These conclusions highlight the importance of analyzing each involved community on an individual basis as plans develop for floating offshore wind deployment. Because every community faces a unique combination of economic, environmental, and health burdens, decision makers should avoid assuming that any offshore wind energy project will impact all communities similarly.

Figure E3 shows the vulnerability indicators for the 32 ports considered in this analysis: 3 ports (9.4%) have low vulnerability, 15 (46.9%) are considered moderately vulnerable, and 14 (43.8%) are considered highly vulnerable. As mentioned previously, every scenario relies on a combination of high-, moderate-, and low-vulnerability ports, so overall scenario indicators do not tell the full story and should mainly be used as points of comparison between scenarios. Regardless of where offshore wind ports are established, developers should consider how they can ensure that development alleviates, rather than exacerbates, the vulnerabilities of surrounding communities.

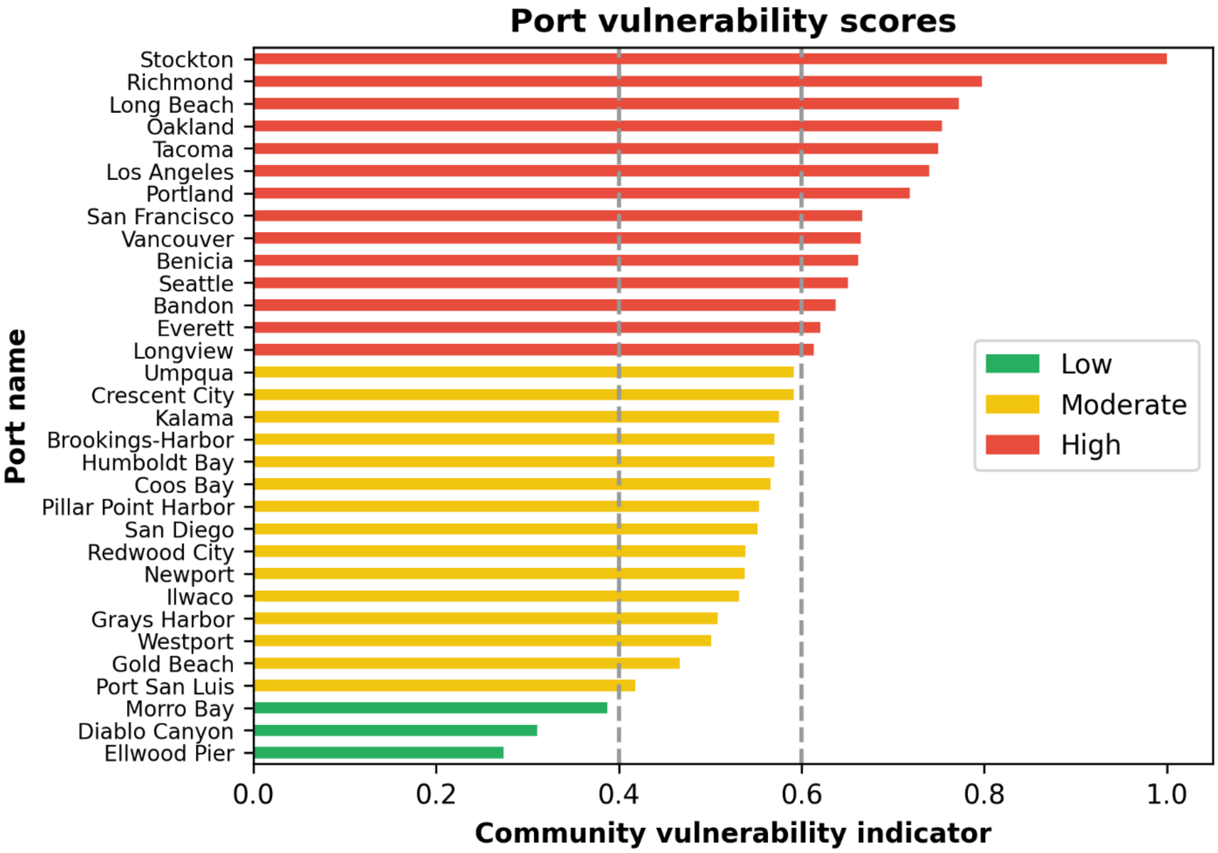

Figure E3. Distribution of community vulnerability indicators across all ports considered in this study (32 total)

Barriers to Workforce Accessibility Results

While quantifying baseline vulnerability of port communities is important as we consider different development options, understanding a community's capacity to capitalize on the promised benefits of development is also crucial. The barriers-to-workforce-accessibility analysis considered a port to be workforce disadvantaged if it had a census tract within 5 miles that was designated as workforce disadvantaged in the CEJST (at or above the 90th percentile for linguistic isolation, low median income, poverty, or unemployment **and** more than 10% of people ages 25 or older have less than a high school education (i.e., did not graduate with a high school diploma). Across the ports considered in the scenarios, 18 ports or 58% were classified as having high barriers to workforce accessibility in the surrounding census tracts (at least one census tract within 5 miles).

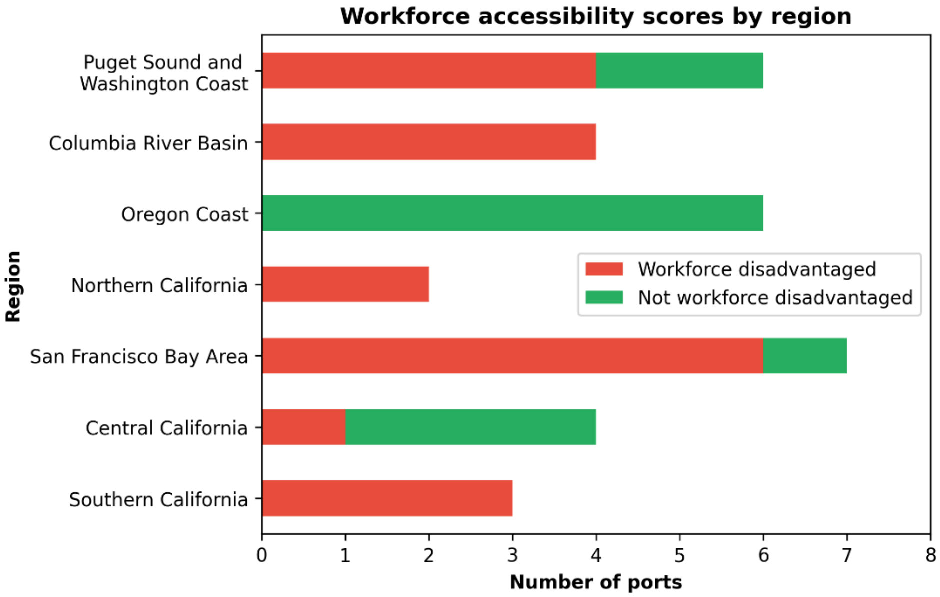

Figure E4. Barriers to workforce accessibility summary by region

The analysis classified workforce accessibility by regions (see Figure E4). Although this report does not provide data at a port-by-port level, the regional trends are important to consider when planning offshore wind port development. All but one port in the San Francisco Bay Area, Columbia River Basin, and southern California regions were classified as being workforce disadvantaged. While northern and central California have split results, the Oregon Coast has no ports with the workforce disadvantaged designation.

Table E1. Port Workforce Disadvantage Designation

Ports Identified As Being Workforce Disadvantaged (20)	Ports NOT Identified As Being Workforce Disadvantaged (12)
Benicia, Crescent City, Ellwood Pier, Everett, Humboldt Bay, Ilwaco, Kalama, Long Beach, Longview, Los Angeles, Oakland, Portland, Redwood City, Richmond, San Diego, San Francisco, Seattle, Stockton, Tacoma, and Vancouver	Bandon, Brookings-Harbor, Coos Bay, Diablo Canyon, Gold Beach, Grays Harbor, Morro Bay, Newport, Pillar Point Harbor, Port San Luis, Umpqua, Westport

Regions where ports are primarily located in urban areas, such as southern California and the San Francisco Bay Area, tended to have higher barriers to workforce accessibility, whereas regions with ports located in more rural areas had lower barriers to workforce accessibility. As shown in Figure E5, the individual barriers contributing to workforce inaccessibility also vary by region. While poverty levels and high school attainment levels (i.e., percentage of those 25 and older without high school diploma) are similar across all regions, more urban regions such as the San Francisco Bay Area and southern California tend to experience relatively high levels of linguistic isolation compared to more rural regions like northern California and the Oregon Coast. Workforce barriers in these more regional regions, however, are driven by low median income.

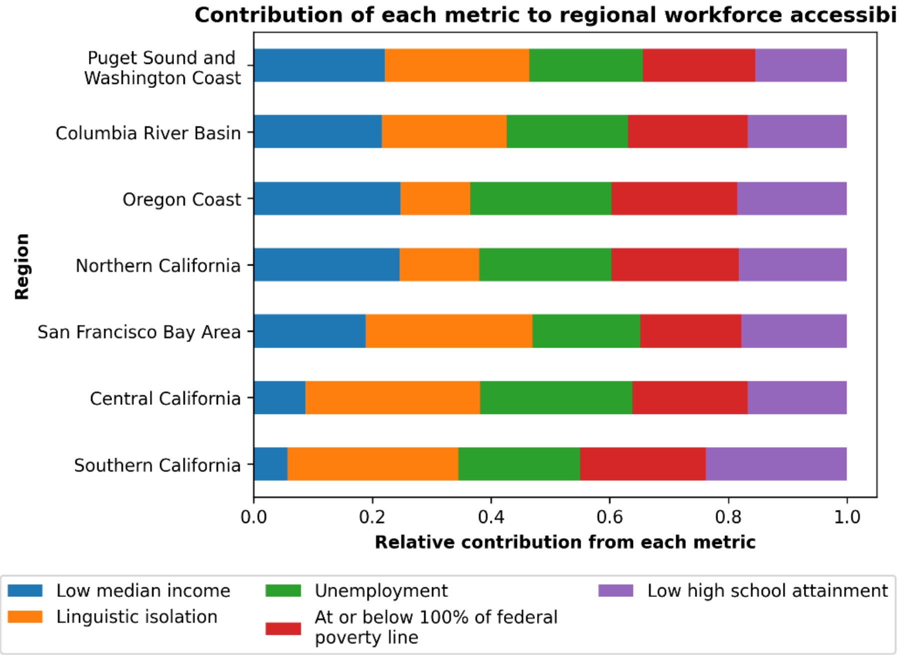

Figure E5. Average proportion of each metric considered in workforce accessibility

These classifications can help provide a better understanding of local capacity to capitalize on workforce opportunities and ensure local residents can benefit from job creation. These results are not intended to make decisions about where to develop port sites but rather to highlight regions where port communities face higher barriers to accessing the jobs created by port development. If port decision makers and developers wish to provide equitable access to workforce opportunities, it may be necessary for them to support workforce development and invest in port communities experiencing higher barriers to workforce accessibility.

Appendix F. Offshore Wind Energy Project Cost and Logistics

In this appendix, we examine how port availability affects the costs and logistics of installing and operating a wind power plant. We consider the installation and operational phases separately, focusing on the staging and integration (S&I) port during the installation phase and the operation and maintenance (O&M) port—supported by an S&I port for major component replacements—during the operations phase. We measure cost using the levelized cost of energy (LCOE), which represents the dollar amount that an offshore wind power plant owner would need to receive for each megawatt-hour of electricity to exactly meet their capital, financing, and operational costs.

Offshore wind energy project costs are affected by site parameters such as wind speed and water depth, and by access to onshore infrastructure including ports. In this study, ports primarily influence cost through their proximity to an offshore wind site. More granular factors such as specific port capabilities, facility costs, and availability will also play a role in port selection for individual projects, but port development in support of offshore wind energy on the West Coast is at too early a stage to make meaningful comparisons of these factors within the subset of sites that have been identified as potential S&I or O&M ports. Regional offshore wind development scenarios include a variety of site conditions and port distances that represent potential locations for offshore wind energy development on the West Coast. Because of this range of conditions, much of the cost variation that we model occurs within scenarios rather than between them. In this section, we analyze the effect of port proximity independent of site conditions and discuss cost and installation times across scenarios.

Methodology

Installation Phase Cost and Logistics

We used the National Renewable Energy Laboratory's (NREL's) Offshore Renewables Balance of station and Installation Tool (ORBIT) model (Nunemaker et al. 2020) to estimate capital costs and installation times for offshore wind energy development on the West Coast. ORBIT is a process-based model that produces high-level cost and sizing estimates for all major balance-of-system components (the floating platform, station-keeping system, and electrical system) and then simulates the installation of an offshore wind project on an hourly timescale. ORBIT tracks delays that occur when hourly wind or wave conditions exceed the operational limits of a vessel, crane, or process. It also tracks delays related to imbalances in the assembly and integration process; for example, if a vessel is available but must wait for a wind turbine integration process to complete before beginning the tow to the project site.

Capital expenditures (CapEx) are subdivided into:

- Turbine CapEx: the cost associated with the purchase of each wind turbine.
- System CapEx: the cost associated with the remainder of the wind plant components, excluding the turbines. System CapEx includes floating platforms, moorings and anchors, electrical cables, and offshore substation(s).
- Installation CapEx: the cost associated with the installation of each turbine and corresponding subsystem. It is based on the simulated installation time, which accounts for

weather delays during the installation process. The total cost depends on the day rates for the ports and vessels involved in each installation phase.

- Soft CapEx: additional project-level costs associated with commissioning, decommissioning, and financing of the project. For the present study, we used default cost factors for these categories as derived by Stehly and Beiter (2019).

The component design choices modeled in ORBIT are listed in Table F1. Each component has an associated design module that computes the cost of each item based on equations that relate total cost to input parameters such as water depth or wind turbine spacing. The design modules also output component weights and dimensions as inputs to the installation module for each system.

Table F1. Component Technology Selection

Component	Technology Type
Array Cables	Cross-linked polyethylene 500 millimeter (mm) 132 kilovolt (kV)
Export Cables	High-voltage direct current 2,000 mm 320 kV
Mooring System	Three-line with drag embedment anchor
Offshore Substation	Floating
Substructure	University of Maine VolturnUS-S[17]
Wind Turbine	International Energy Agency 15 megawatts

The installation phases in ORBIT include installing the mooring system, export cable, floating substation, floating wind turbine, and array cables. Each phase is described in detail, accompanied by a complete list of processes and their associated weather constraints. Highlighted processes are deemed suspendable (i.e., they are suspended when wind or wave conditions exceed operational limits). All other processes with weather constraints must wait for a continuous window in which weather conditions remain within the limits. This distinction allows suspendable processes, which are usually lengthier, to reach completion without excessive weather delays. The process times in Tables F2–F5 are primarily based on input from vessel operators and project developers, although it is worth noting that weather limits could be increased to DNV standards for weather-unrestricted towing (which could increase significant wave height to 5 meters [m]). More permissive operational limits would reduce weather downtime during installation activities, but may be nonconservative for West Coast floating wind energy operations.

Mooring System Installation

This phase models loading the mooring chain, rope, and anchors onto an anchor handling tug supply (AHTS) vessel at the S&I port, transiting to the project site, and installing the system

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[17] The University of Maine VolturnUS-S is a reference steel semisubmersible platform designed by Allen et al. (2020).

prior to the hookup with the floating wind turbine. The AHTS must travel back and forth to the port many times to install the station-keeping components for a full project. Detailed process times are listed in Table F2. The AHTS used for mooring system installation is described in Table F7.

Table F2. Mooring System Installation Process Times

Process	Description	Value	Wind Speed Constraint (meters per second [m/s])	Wave Height Constraint (meters [m])
Load Mooring System	Load mooring system onto anchor handling tug supply vessel	5 hours (hr)	-	-
Transit	Transit between port and site	10 kilometers (km)/hr	20	3
Position On-Site	Position the vessel at site	2 hr	20	3
Perform Mooring Site Survey	Perform site survey prior to mooring system installation	4 hr	20	3
Install Drag Embedment Anchor	Install a drag embedment anchor	Calculated based on depth	20	3
Install Mooring Line	Install a mooring line	Calculated based on depth	20	3

Export Cable Installation

This phase models loading a carousel of cable onto a cable lay vessel (CLV) at a location at or near the S&I port, pulling the cable into the landfall site, laying the cable out toward the floating substation, and connecting to the substation. We assume that part of the export cable is buried but that the section closest to the floating wind plant is suspended in the water column. The CLV can typically carry all of the export cable in one trip. Typically, CLVs would transit from a cable factory instead of the S&I port; however, because we do not specify the cable facility location in ORBIT, we assume the distance is the same as the S&I port location. A more detailed breakdown of the phase with durations associated with each process is presented in Table F3. The CLV used for this phase is described in Table F7.

Table F3. Export Cable Installation Process

Process	Description	Time or Speed	Wind Speed Constraint (m/s)	Wave Height Constraint (m)
Load Cable	Load cable on to the array cable installation vessel	6 hr	-	-
Tow Plow	Tow plow at landfall site	5 km/hr	25	2
Pull Winch	Pull cable onshore through the previously dug trench	5 km/hr	25	2
Prepare cable	Prepare cable for pull-in	1 hr	25	2
Pull In Cable	Pull cable into the onshore trench	5.5 hr	25	2
Terminate Cable	Terminate and test cable connection	5.5 hr	25	2
Lower Cable	Lower cable to seafloor at landfall	1 hr	25	2
Lay/Bury Cable	Lay and bury a cable section	0.3 km/hr	25	2
Raise Cable	Raise unspliced cable from seafloor	0.5 hr	25	2
Splice Cable	Splice cable at sea	48 hr	25	2
Transit	Transit between port and site	11.5 km/hr	25	2

Floating Substation Installation

This phase starts after the export cable installation is 25% complete. This phase models the substation being assembled at a shipyard, towed to the project site using an AHTS, and hooked up to mooring lines. A detailed breakdown of the phase with durations associated with each process is presented in Table F4. The AHTS used for this phase is described in Table F7.

Table F4. Floating Substation Installation Process

Process	Description	Time or Speed	Wind Speed Constraint (m/s)	Wave Height Constraint (m)
Substructure Assembly	Assemble substation substructure quayside	336 hr	-	-
Attach Topside	Attach topside	24 hr	-	-
Tow Substation to Site	Tow substation to site using floating substation installation vessel	6 km/hr	20	3
Position On-Site	Position the vessel at site	2 hr	20	3
Ballast to Operational Draft	Ballast completed assembly to operational draft	6 hr	15	2.5
Perform Mooring Site Survey	Perform a mooring system survey	4 hr	20	3
Install Suction Pile Anchor	Install a suction pile anchor	Calculated based on depth	20	3
Install Mooring Line	Install a mooring system line	Calculated based on depth	20	3
Connect Mooring Lines	Connect mooring lines	22 hr	15	2.5
Check Mooring Lines	Check mooring lines and connection	12 hr	15	2.5
Transit	Transit from site to port	10 km/hr	20	3

Floating Wind Turbine Installation

This phase starts after 40% of the mooring system installation has completed. This phase models the assembly of the floating platform at the S&I port, integration of the wind turbine and floating platform, wet storage at port, towing the floating system to the project site, and connecting to the mooring lines. The floating platform assembly is effectively the time between launches of each successive platform, and implicitly assumes that multiple platforms can be built in parallel at the assembly site to achieve this production rate. The towing operation is conducted using a towing group of one AHTS and two support tugboats. A detailed breakdown of the phase with durations associated with each process is presented in Table F5. The AHTS and support tugboats used for this phase are described in Table F7.

Table F5. Floating Wind Turbine Installation Process

Process	Description	Time or Speed	Wind Speed Constraint (m/s)	Wave Height Constraint (m)
Substructure Assembly	Assemble a mooring substructure quayside	168 hr	-	-
Move Substructure	Move completed mooring substructure to wind turbine assembly line	8 hr	-	-
Prepare for Turbine Assembly	Prepare mooring substructure for turbine assembly	12 hr	-	-
Lift and Attach Tower Section	Lift and attach tower section at quayside	4 hr	15	-
Lift and Attach Nacelle	Lift and attach nacelle at quayside	12 hr	15	-
Lift and Attach Blade	Lift and attach turbine blade at quayside	3.5 hr	12	-
Mechanical Completion	Perform mechanical completion work at quayside	24 hr	18	-
Electrical Completion	Perform electrical completion work quayside including precommissioning	72 hr	18	-
Ballast to Towing Draft	Ballast completed assembly to towing draft	6 hr	15	3
Tow Substructure	Tow completed assembly to site	5.5 km/hr	15	3
Position Substructure	Position completed assembly at site	2 hr	15	2.5
Ballast to Operational Draft	Ballast completed assembly to operational draft	6 hr	15	2.5
Connect Mooring Lines, Pretension and Prestretch	Connect mooring lines to ballasted assembly	20 hr	15	2.5
Check Mooring Lines	Check mooring lines	6 hr	15	2.5
Transit	Transit from site to port	14 km/hr	15	3

Array Cable Installation

This phase starts after 80% of the floating wind turbine installation is complete. This phase models loading a carousel of cable onto a CLV at a location at or near the S&I port, transiting to the project site, and connecting the cable to individual wind turbines. We assume that the array cable floats in the water column at a depth of 300 m below the surface. Typically, CLVs would transit from a cable factory instead of the S&I port; however, because we do not specify the cable facility location in ORBIT we assume the distance is the same as the S&I port location. A detailed breakdown of the phase with durations associated with each process is presented in Table F6. The CLV used for this phase is described in Table F7.

Table F6. Array Cable Installation Process

Process	Description	Time or Speed	Wind Speed Constraint (m/s)	Wave Height Constraint (m)
Load cable	Load cable on to the array cable installation vessel	6 hr	-	-
Transit	Transit between port and site	11.5 km/hr	25	2
Position On-Site	Position the vessel at site	2 hr	25	2
Prepare Cable	Prepare cable for pull-in	1 hr	25	2
Pull In Cable	Pull cable into offshore substructure	5.5 hr	25	2
Terminate Cable	Terminate and test cable connection	5.5 hr	25	2
Lower Cable	Lower cable to seafloor	1 hr	25	2
Lay/Bury Cable	Lay and bury a cable section	0.4 km/hr	25	2

The different vessel types used are listed in Table F7. Note that the wind speed and wave height weather constraints are transit-related and can be overridden by process-specific requirements.

Table F7. Vessel Types for Different Installation Phases

Vessel Type	Day Rate ($/day)	Transit Speed (km/h)	Wind Speed Limit (m/s)	Wave Height Limit (m)	Storage Limit (tonnes)
Cable Lay Vessel (Export Cable)	300,000	11.5	25	2	13,000
Cable Lay Vessel (Array Cable)	225,000	11.5	25	2	13,000
Anchor Handling Tug Supply Vessel (Mooring System Installation)	100,000	14	15	3	5,000
Support Tugboat	35,000	14	15	3	-
Anchor Handling Tug Supply Vessel (Floating Turbine Tow-Out)	100,000	14	15	3	-
Floating Substation Installation Vessel	100,000	10	20	3	-

Our simulations with ORBIT make the following assumptions:

- Each offshore wind energy project has access to a single S&I site (with one platform assembly station and one integration crane)
- The wet storage capacity is assumed to be five substructures for all ports except southern California, which is assumed to have a wet storage capacity of 20 substructures. The simulated installation times were not very sensitive to wet storage limits, and consequently, a wet storage sensitivity study is not performed.
- Weather forecasting is perfect (i.e., when searching for a feasible window of operations based on vessel constraints, the simulation does not consider any probability that the weather profile is inaccurate).
- Operational failures of any kind do not occur in any of the vessels throughout the lifetime of the project.
- Array and export cables are laid in a straight line, ignoring geotechnical considerations.
- Substations maintain the same spacing as the wind turbines.
- The same monthly rate for use of port facilities is assumed across all ports.
- A mature supply chain exists on the West Coast, and there is sufficient labor and facilities to install commercial-scale projects.

Operations Phase Cost and Logistics

We estimated operational expenditures and energy production using NREL's Windfarm Operations and Maintenance cost-Benefit Analysis Tool (WOMBAT) (Hammond and Cooperman 2022). WOMBAT uses a discrete event simulation approach to model scheduled and unscheduled maintenance during the lifetime of a wind power plant. Each component of the plant (including wind turbines, power cables, and substations) is represented as a collection of subsystems that have specific maintenance requirements. These requirements include preventive maintenance at regular intervals as well as different types of failures that occur at random intervals according to a probability distribution. Every failure or maintenance task has its own duration, materials cost, and vessel type that is needed to perform the task. Vessels are dispatched by WOMBAT's repair manager, which evaluates vessel availability subject to constraints on working hours and the maximum safe wave heights and wind speeds for each vessel.

WOMBAT uses site-specific wind and wave time series to identify weather windows and estimate power production based on a wind turbine power curve. For this study, we used ERA5 reanalysis data (Hersbach et al. 2020) and the International Energy Agency 15-megawatt reference wind turbine power curve (Gaertner et al. 2020). Power production is suspended when a wind turbine is undergoing maintenance.

Maintenance tasks are divided into four categories: inspections (including preventive maintenance), minor and major repairs, and major component replacements. Frequency, cost, and labor hours for these tasks are listed in Table F8, based on inputs from COREWIND (2021). In addition to direct maintenance costs, we also include a flat annual operating cost of \$30/kilowatt (kW) that accounts for items such as lease payments, land-based facilities, insurance, and management (Stehly and Duffy 2022).

Our cost estimates assume that service operations vessels (SOVs) or crew transfer vessels (CTVs) are available year-round to carry out most maintenance tasks. These vessels could be owned by the wind plant operator or leased under a long-term contract. We assume that CTVs are used in cases where the O&M site is located within 112 kilometers (km) (70 miles) of the reference wind plant site, otherwise an SOV is the primary O&M vessel. Additional vessels are chartered as needed for specific repairs or inspection campaigns.

Major component replacements are relatively infrequent maintenance events (occurring at a rate of approximately once every 10 years for each wind turbine in this study) that can have a large impact on wind turbine availability and total maintenance costs. Replacing a large component typically requires a crane capable of lifting tens of tons to a height of approximately 150 m. The O&M sites modeled in this study are generally not assumed to have access to a suitable crane for major component replacements. We assume that replacements are carried out at S&I sites under a tow-to-port strategy.

Table F8. Maintenance and Repair Parameters. All Costs are Reported in $2023.

System	Task Description	Service Interval (years)*	Service Time (h)	Materials Cost ($)	Vessel Type
Wind Turbine (67 per gigawatt [GW])					
	Annual inspection	1.0	24	$2,500	CTV or SOV
Main Shaft	Minor repair	4.3	10	$1,200	CTV or SOV
	Major repair	38.5	36	$16,800	CTV or SOV
	Replacement	111.1	144	$278,400	Tow to port
Power Converter	Minor repair	1.9	14	$1,200	CTV or SOV
	Major repair	3.0	28	$8,400	CTV or SOV
	Replacement	13.0	170	$66,000	Tow to port
Electrical system	Minor repair	2.8	10	$1,200	CTV or SOV
	Major repair	62.5	28	$6,000	CTV or SOV
	Replacement	500.0	54	$60,000	Tow to port
Generator	Minor repair	1.8	13	$1,200	CTV or SOV
	Major repair	33.3	49	$17,200	CTV or SOV
	Replacement	111.1	244	$283,800	Tow to port
Pitch System	Minor repair	1.2	18	$600	CTV or SOV
	Major repair	5.6	38	$2,280	CTV or SOV
	Replacement	1,000.0	75	$16,800	Tow to port
Rotor Blades	Minor repair	2.2	18	$6,000	CTV or SOV
	Major repair	100.0	42	$51,700	CTV or SOV
	Replacement	1,000.0	864	$534,000	Tow to port
Yaw System	Minor repair	6.2	10	$600	CTV or SOV

System	Task Description	Service Interval (years)*	Service Time (h)	Materials Cost ($)	Vessel Type
	Major repair	166.7	40	$3,600	CTV or SOV
	Replacement	1,000.0	147	$15,000	Tow to port
Floating Platform (67 per GW)					
	Annual inspection	1.0	24	$720	CTV or SOV
	Subsea inspection	2.0	6	$600	Diving support vessel
	Marine growth removal	8.3	40	$1,800	CTV or SOV
Ballast Pump	Minor repair	100.0	8	$1,200	CTV or SOV
Mooring Line	Major repair	66.7	240	$24,000	CTV or SOV
	Replacement	80.0	360	$162,000	Anchor handling tug supply (AHTS)
Anchor	Major repair	66.7	240	$90,000	CTV or SOV
	Replacement	80.0	360	$614,000	AHTS
Buoyancy Module	Replacement	30.3	40	$120,000	CTV or SOV
Cables (67 Array Cables + 1 Export Cable per GW)					
Array Cable	Major repair	40.0	240	$18,000	Cable lay vessel
	Replacement	62.5	360	$132,000	Cable lay vessel
Export Cable	Inspection	2.0	12	$375	Diving support vessel
	Major repair	150.0	360	$250,000	Cable lay vessel
Offshore Substation (1 per GW)					
	Inspection	1.0	24	$600	CTV or SOV
	Minor repair	5.0	12	$2,400	CTV or SOV
	Major repair	100.0	60	$120,000	CTV or SOV

* Service interval is the time between scheduled preventive maintenance tasks or the mean time between failures. Individual subsystem failures are modeled to occur at random intervals chosen from a Weibull distribution with a shape parameter of 1 and a scale parameter equal to the mean time between failures.

The annual energy production output from WOMBAT only includes losses due to wind plant equipment downtime; as a postprocessing step we also consider the additional losses listed in Table F9.

Table F9. Loss Assumptions for Estimating Annual Energy Production

Description	Value
Environmental Loss	1.6%
Technical Losses	1.2%
Electrical Losses	4%
Wake Losses	8%
Total	**14%**

The levelized cost of energy depends on CapEx, operational expenditures (OpEx), financing costs expressed as a fixed charge rate (FCR), and annual energy production (AEP). We obtain CapEx for each reference site using ORBIT and OpEx and AEP from WOMBAT. We model an FCR of 5.1%, consistent with NREL's 2022 Annual Technology Baseline (NREL 2022). LCOE is calculated using the following equation:

$$LCOE = \frac{FCR \times CapEx + OpEx}{AEP}$$

Constraints and Limitations

ORBIT and WOMBAT are not intended to provide a precise picture of real-world project cost estimates, but rather to draw comparisons between difference scenarios and identify trends therein. ORBIT and WOMBAT are medium fidelity in their ability to replicate real-world project costs, installation times, and downtime. Some limitations with our modeling approach include:

- ORBIT and WOMBAT do not directly account for credits or subsidies from the Inflation Reduction Act of 2022 or other incentive programs. We consider some of these benefits as part of the supply chain evaluation in Appendix G and combine them with the LCOE assessment described in this section to compare different scenarios.
- Although costs associated with financing and insurance are considered, they may not fully capture the subtlety associated with risk related to topics such as nascent technology, towing distances, weather conditions and associated damage and delays, geopolitical issues, and so on.
- The same technology is assumed for each project without considering alternate foundation types, mooring systems, turbine ratings, and so on. Therefore, the capital costs are relatively similar between the different reference projects.
- Component failure rates and maintenance intervals are assumed to be constant over time. Operational expenditures modeled in WOMBAT do not consider increases in failure rates over time (i.e., as the wind turbines age) or how technological innovations such as condition-based monitoring or improvements in component reliability could decrease failure rates.

Scenario Results

To provide cost estimates for the West Coast offshore wind energy deployment and port network scenarios considered in this report, we modeled five 1-gigawatt (GW) reference projects at representative locations. Key parameters for each of these reference sites are listed in Table F10. In California, we evaluated different combinations of S&I ports under the Baseline and Moderate deployment scenarios. We also considered a range of O&M ports for each project location. We chose the points of interconnection based on previously published studies (Beiter et al. 2020; Novacheck and Schwarz 2021).

Table F10. Reference Site Parameters

Project Location	Mean Wind Speed (m/s)	Water Depth (m)	Distance to S&I Port (km)	O&M Port Distances (km)	Distance to Export Cable Landfall (km)
Central California	9.3	1,013	111 (central California) 433 (southern California) 657 (northern California)	91, 97, 222 249 (central California)	97 (Diablo Canyon)
Northern California	9.3	832	43 (northern California) 755 (central California)	43, 96 (northern California), 441, 450 (San Francisco Bay Area)	43 (Humboldt)
Southern Oregon	10.5	602	148 (Oregon coast)	42, 48, 115 (Oregon coast)	132 (Fairview)
Central Oregon	9.2	595	50 (Oregon coast)	56, 128 (Oregon coast)	97 (Wendson)
Southern Washington	8.3	913	89 (Washington coast)	78, 110 (Washington coast)	89 (Grays Harbor)

CapEx estimates from ORBIT are shown in Figure F1. These estimates are intended to provide a high-level comparison between different project locations and have not been fully adjusted to account for recent cost increases due to macroeconomic factors and supply chain constraints that have affected the offshore wind industry. There is minimal variation in the overall CapEx among the different reference sites. Part of this consistency arises from assuming the same wind turbine, floating platform, and soft costs across all sites. Costs for additional major components such as the offshore substation and array cables vary only slightly between sites. The most significant differences in system CapEx between sites are observed for the mooring system (dependent on water depth) and export cable (dependent on distance to landfall), which are relatively small contributors to the total. Installation CapEx also varies between sites as a result of varying port distance and other site parameters such as water depth that increase the time or complexity of installation processes.

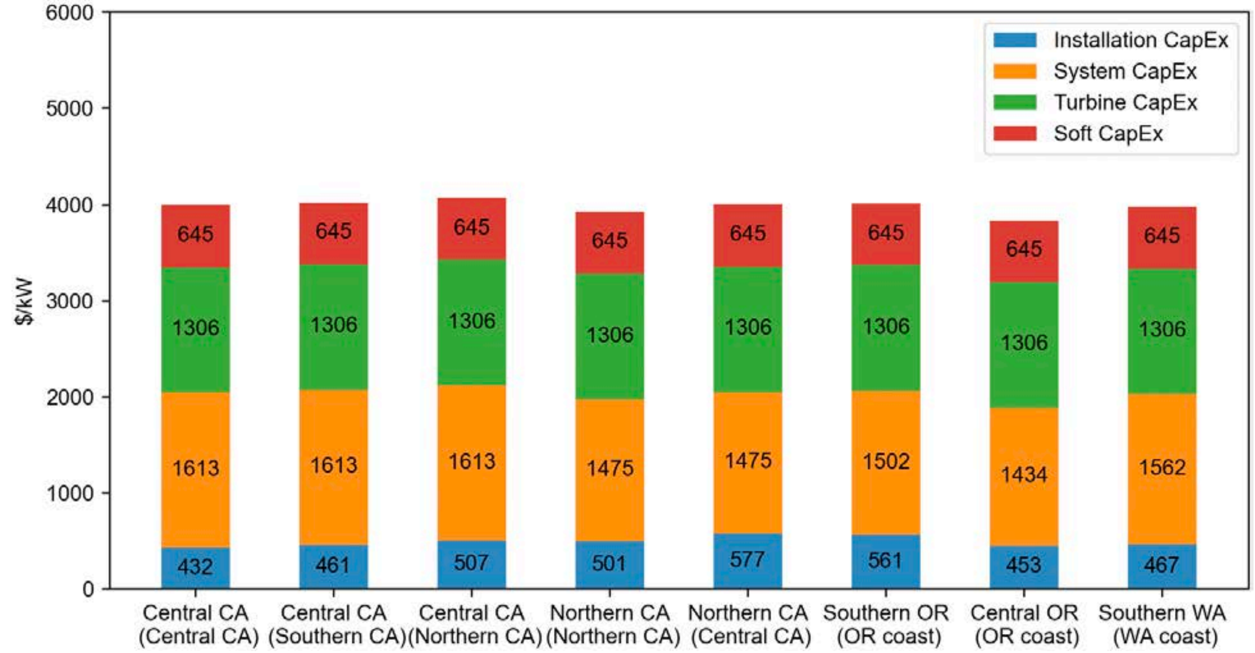

Figure F1. Breakdown of capital costs for reference sites (associated S&I port regions) in Table F10

The total installation time (based on a weather profile starting January 1, 2020) for each scenario in Figure F1 is shown in Table F11. ORBIT models an overall installation time of approximately 2 to 3 years for each site. Longer installation times correspond to longer distances from the S&I ports, driven primarily by mooring system installation, which requires multiple trips between the site and the port. Cable installations make up a considerable part of the installation process and offer an opportunity to reduce the overall installation time by optimizing the sequencing of phases. Wind turbine installation tends to experience significant delays primarily driven by slow turbine assembly times at the port. Consequently, unless the S&I port is extremely far away (e.g., northern California offshore wind site with S&I port in central California), the most effective method to reduce turbine installation times in ORBIT is by adding a second assembly line. Changes to other parameters such as increasing the wet storage, adding more vessels, or reducing the distance to the port have little impact on the turbine installation times.

Table F11. Total Installation Times

Project Location	S&I Site Location	Distance to S&I Site (km)	Installation Time (days)
Central California	Central California	111	707
	Southern California	433	774
	Northern California	657	905
Northern California	Northern California	43	877
	Central California	755	964
Southern Oregon	Oregon Coast	148	927
Central Oregon	Oregon Coast	50	760
Southern Washington	Washington Coast	89	801

Breakdowns of the installation time for each reference project and S&I site are shown in Figures F2–F9. Dates refer to the wind and wave time series beginning January 1, 2020, that was used to model weather delays. In addition to the installation phases discussed in the Methodology section, the breakdown includes various delays experienced during the simulation of the installation process. The different sources of delays captured by the ORBIT simulation are:

- Weather delays, which can affect the vessel operations as well as on-site operations
- Delays due to no completed substation assembly resulting in an idling floating substation installation vessel
- Delay due to lack of availability of substructures that are required to commence turbine assembly
- Delay in idling floating turbine installation groups, resulting from incomplete turbine assemblies
- Wind turbine and substructure assembly delays resulting from not enough wet storage.

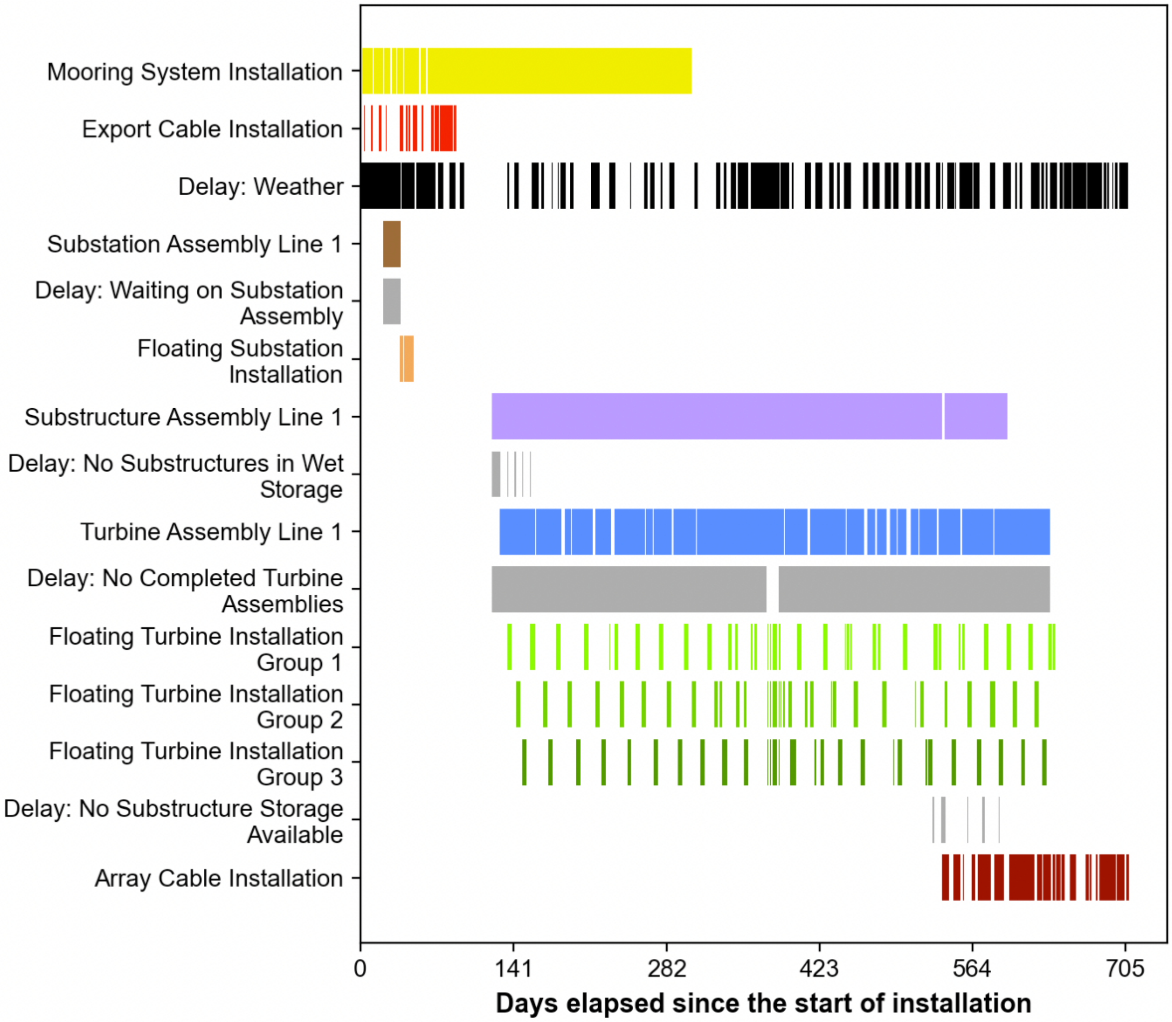

Figure F2. The installation process times for the central California reference project with a central California S&I site. On the left are the various installation phases considered in the simulation. The gaps in the various installation phases indicate a delay.

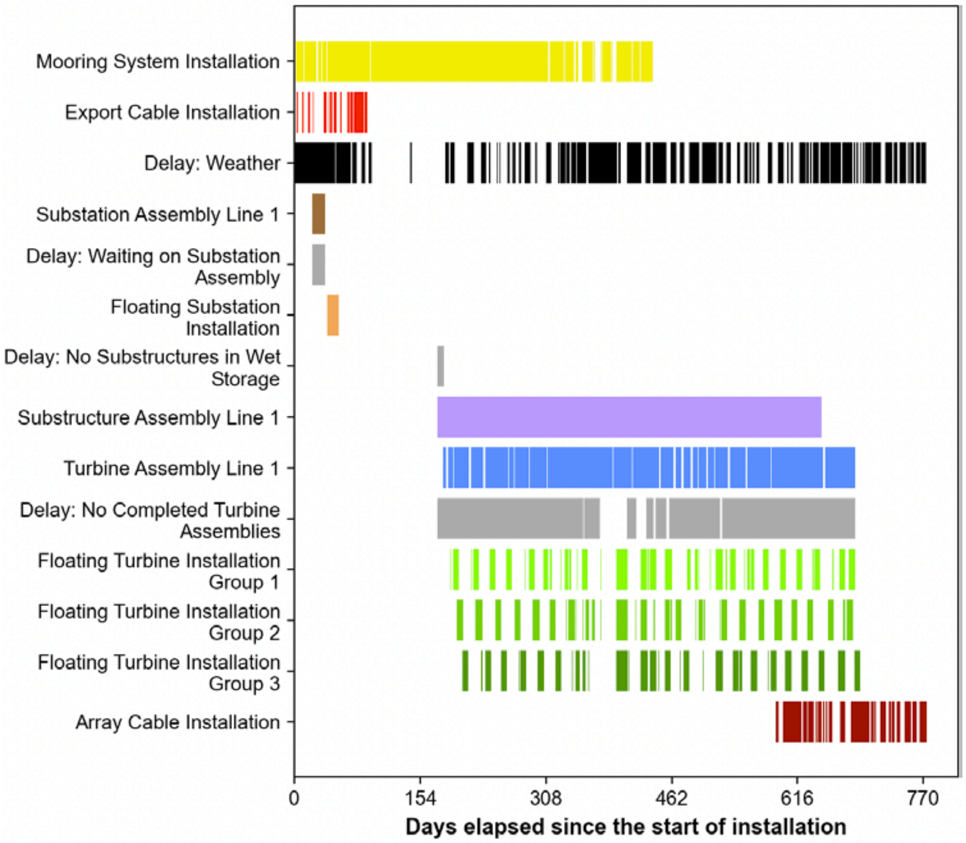

Figure F3. The installation process times for the central California reference project with a southern California S&I site. On the left are the various installation phases considered in the simulation. The gaps in the various installation phases indicate a delay.

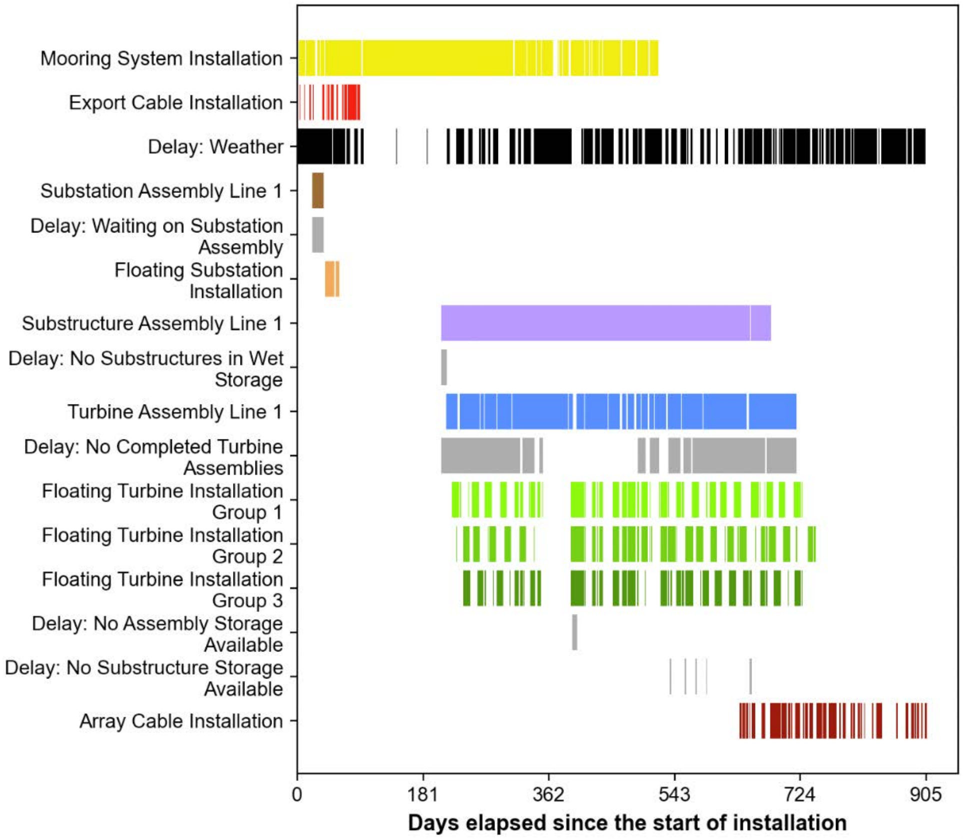

Figure F4. The installation process times for the central California reference project with a northern California S&I site. On the left are the various installation phases considered in the simulation. The gaps in the various installation phases indicate a delay.

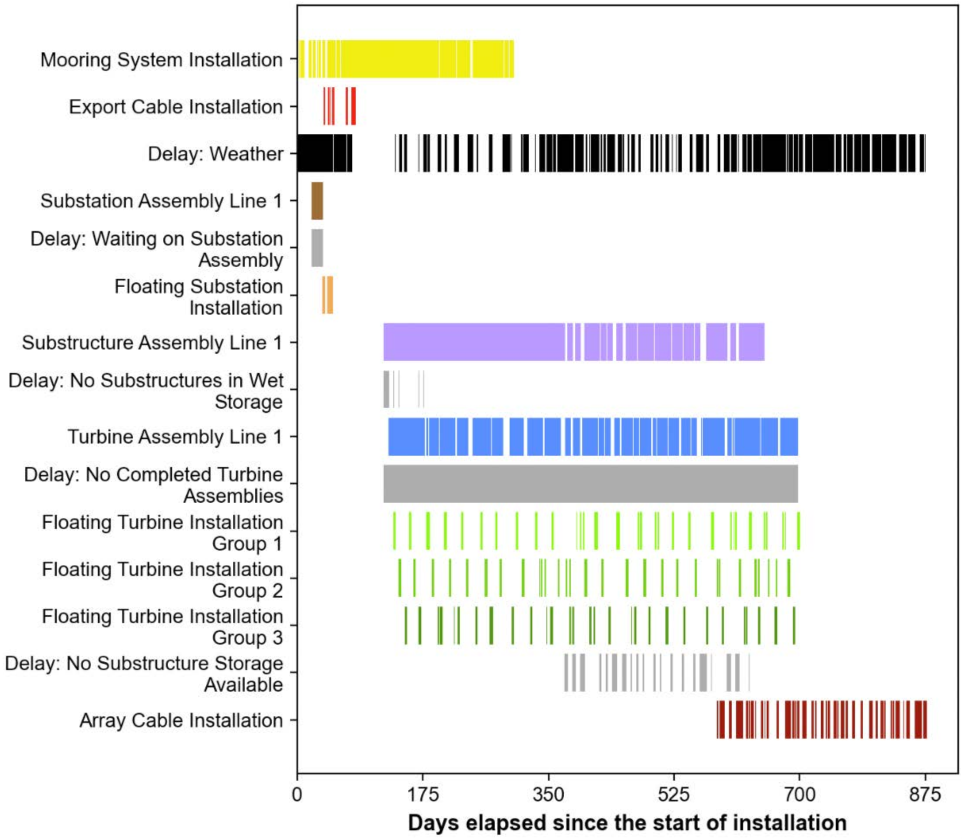

Figure F5. The installation process times for the northern California reference project with a northern California S&I site. On the left are the various installation phases considered in the simulation. The gaps in the various installation phases indicate a delay.

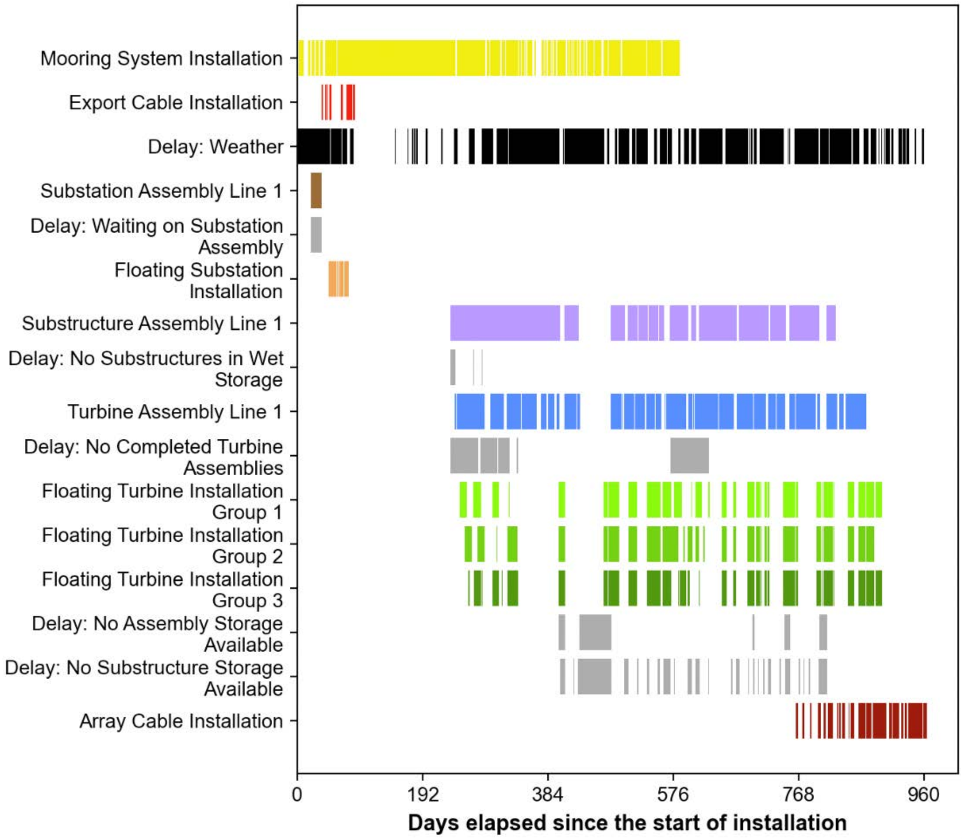

Figure F6. The installation process times for the northern California reference project with a central California S&I site. On the left are the various installation phases considered in the simulation. The gaps in the various installation phases indicate a delay.

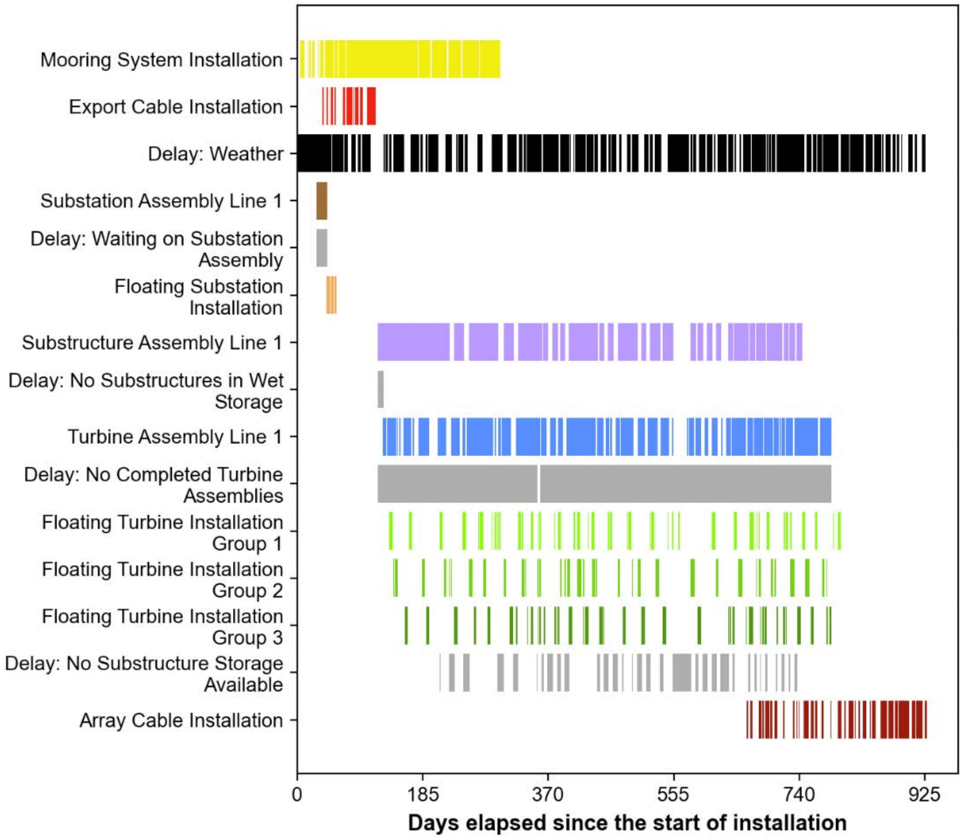

Figure F7. The installation process times for the southern Oregon reference project with an Oregon S&I site. On the left are the various installation phases considered in the simulation. The gaps in the various installation phases indicate a delay.

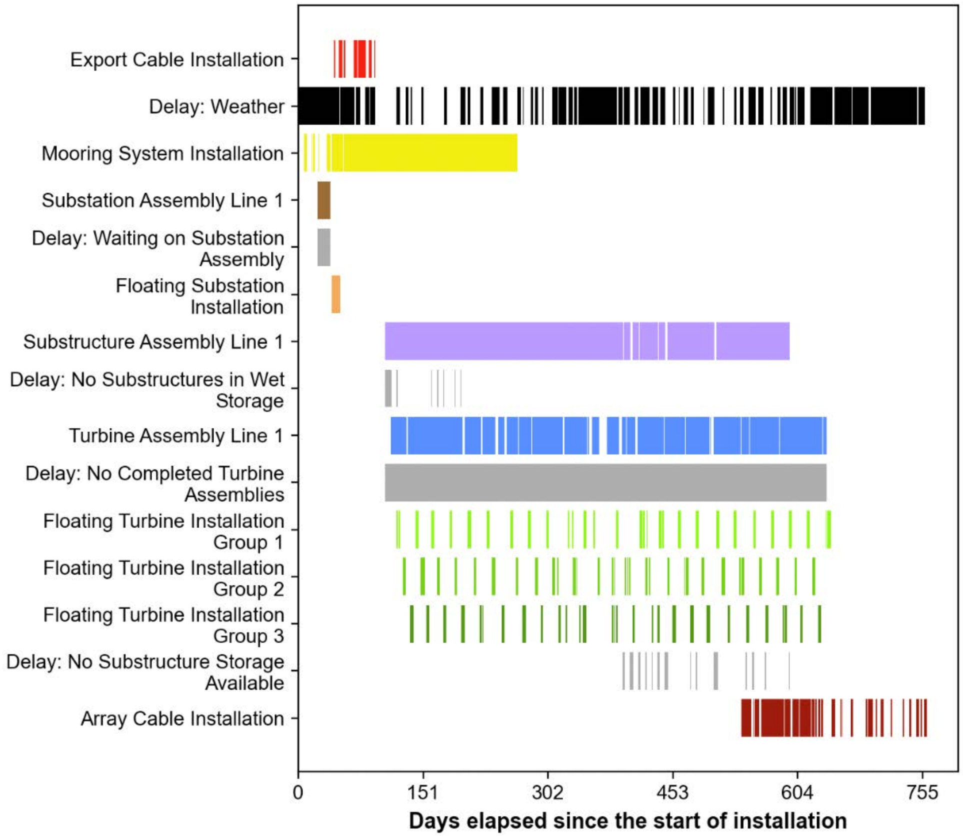

Figure F8. The installation process times for the central Oregon reference project with an Oregon S&I site. On the left are the various installation phases considered in the simulation. The gaps in the various installation phases indicate a delay.

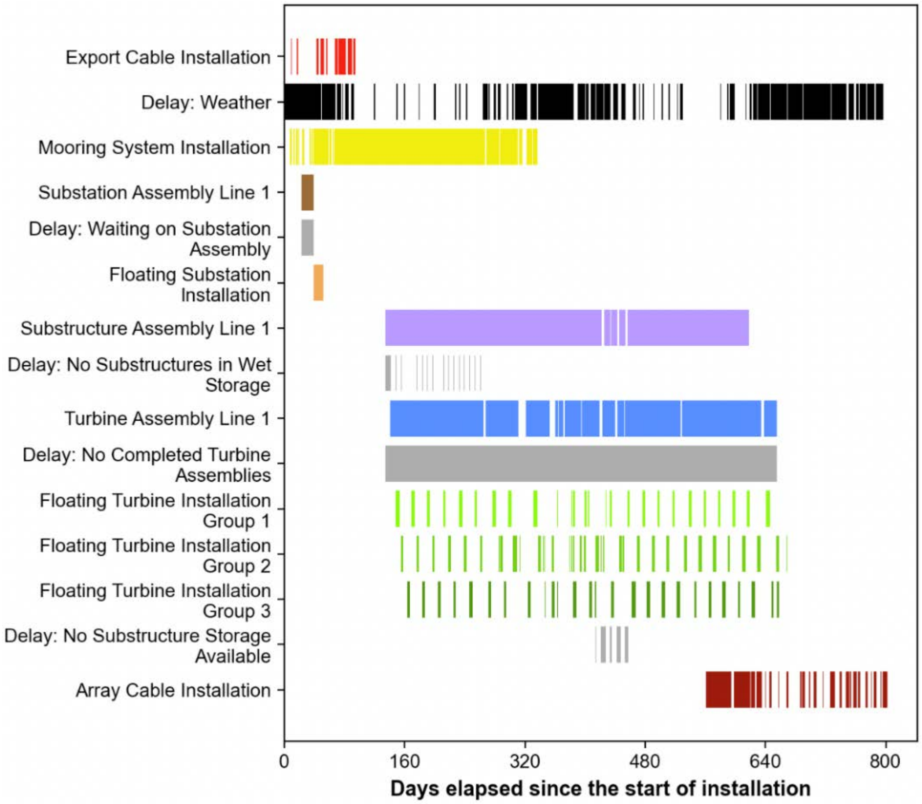

Figure F9. The installation process times for the southern Washington reference project with a Washington S&I site. On the left are the various installation phases considered in the simulation. The gaps in the various installation phases indicate a delay.

Figure F10 includes the annual OpEx for each combination of reference project location and O&M site distance. We provide these results for Baseline, Moderate, and Expanded levels of O&M port sites, corresponding to 25-, 35-, and 55-GW offshore wind deployment levels. OpEx costs can be more than 50% higher for a given site when the O&M site is located far from the offshore wind plant. The highest costs in central and northern California are associated with O&M site distances of 250 km and 450 km, respectively. See Table F10 for a complete list of the O&M port site distances considered for each reference site. Annual OpEx is also affected by the wave climate; for two project locations with similar port distances, WOMBAT models higher costs for the location with higher mean significant wave heights.

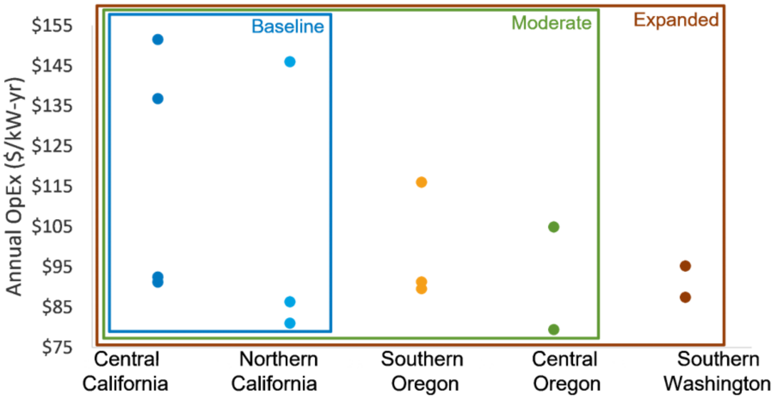

Figure F10. Annual OpEx for different O&M sites servicing each reference project. Large rectangles indicate which reference projects are included in each deployment scenario. Baseline, Moderate, and Expanded rectangles correspond to the O&M sites needed for 25-, 35-, and 55-GW levels of offshore wind deployment.

Figure F11 shows the distribution of LCOE results for each deployment scenario. Because LCOE is projected to evolve over time as the floating offshore wind energy industry develops, and our study scenarios are not tied to specific deployment dates, Figure F11 reports normalized LCOE relative to the average across all scenarios. Within each region, different combinations of S&I and O&M ports produce the observed range of LCOE values, which is discussed in more detail in the Port Proximity section. Differences in LCOE between regions are primarily driven by AEP, with higher mean wind speeds corresponding with lower LCOE. Site conditions contribute to regional differences in CapEx (Figure F1) and OpEx (Figure F10); however, they make a smaller contribution to the variation in LCOE.

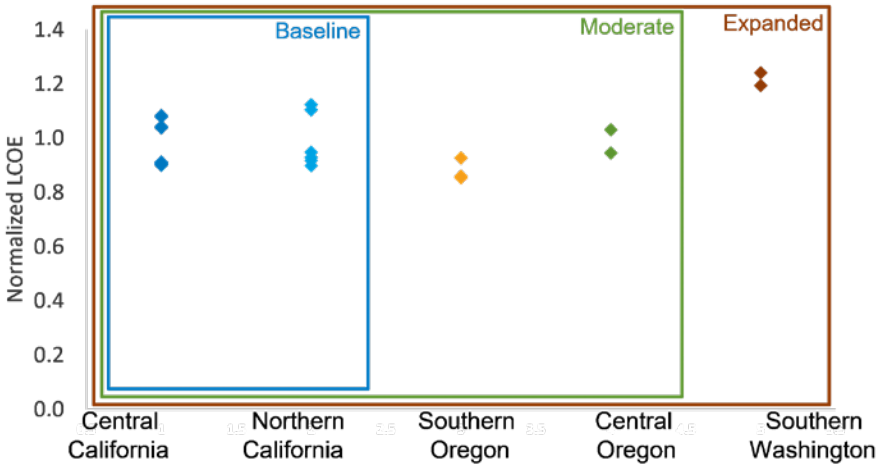

Figure F11. Normalized LCOE for each reference site under different port scenarios. Rectangles indicate which reference sites are included in each deployment scenario. Baseline, Moderate, and Expanded rectangles correspond to the O&M sites needed for 25-, 35-, and 55-GW levels of offshore wind deployment.

Port Proximity

To investigate the effects of port proximity, we consider three distances to S&I ports (50, 100, and 400 km) and three distances to O&M ports (5,0, 100, and 200 km). Assuming that the O&M port distance is less than or equal to the S&I port distance gives us six combinations to model. We use ORBIT and WOMBAT to simulate the installation and operation of a 1-GW floating wind energy project using 15-MW turbines and site conditions representative of the California Central Coast. The resulting LCOE, CapEx, and OpEx are presented in Figure F12 and Table F12.

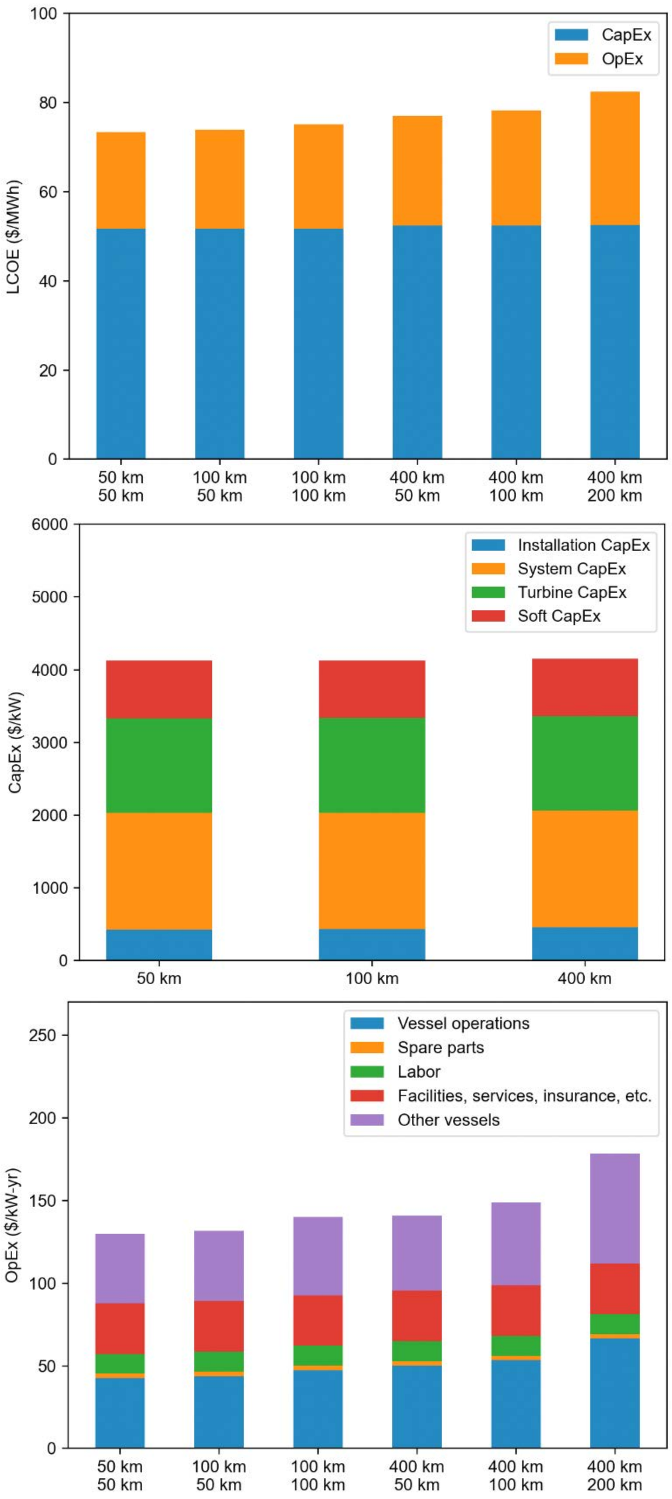

Figure F12. Levelized cost of energy, CapEx, and OpEx

Table F12. Port Proximity
(Results corresponding to two assembly lines and cranes are in parentheses)

O&M Port Distance	km	50	50	100	50	100	200
S&I Port Distance	km	50	100		400		
LCOE	$/megawatt-hour	$73	$74	$75	$77	$78	$82
Installation							
Vessel + Port Costs	$ million	429 (353)	433 (355)		460 (383)		
Project Installation Time	Days	700 (611)	707 (614)		770 (641)		
Turbine Installation Time	Days	515 (271)	519 (276)		521 (302)		
Weather Delays During Turbine Install	% of total install time	25 (25)	27 (28)		40 (44)		
O&M							
Annual Vessel Cost	$/kW-year (yr)	$42	$44	$47	$50	$54	$67
Annual Tow-to-Port Cost	$/kW-yr	$2	$3	$3	$11	$11	$11
Tow-to-Port Frequency	Avg. # of turbines/yr	5.3	5.4	5.3	5.8	5.7	5.9

Figure F12 indicates that the LCOE of a floating wind energy project increases by 5%–15% as the distance to the S&I port increases from 50 km to 400 km. The increase in costs is primarily due to additional vessel costs associated with O&M. The annual tow-to-port cost required to transport wind turbines to the S&I port for major repair increases by a factor of five as the port distance goes from 50 to 400 km. Simulated failures in WOMBAT result in a tow-to-port event approximately once every 10 years for each wind turbine, or an average of 5–6 turbines being towed to port per year over the lifetime of a 1-GW project. Increasing the distance to the O&M port also results in higher costs for CTVs or SOVs to perform regular maintenance activities, further contributing to higher O&M costs. Wind plant capital costs show a negligible dependency on port proximity. Installation time and costs increase slightly but represent a relatively small fraction of the overall project cost.

In Table F12, we include the installation times and costs for a project that uses two sites (with their own substructure assembly station and turbine integration crane) at the same S&I port. This scenario decreases the turbine installation time for the near port (50 km from the project site) to 261 days, which then increases by around 20% if the distance to the port increases to 200 km. The installation costs of the greater port distance are around 15% more expensive than the shortest distance, and both are lower than the single-site scenario (even though we increase the port rental rate by 50% to account for the second production line). Although we do not report them here, we find similar results if we reduce the process times for substructure assembly and turbine integration to a total of around 1 week with one production line.

We present the outputs of the ORBIT installation simulation in Figures F13–15 for S&I port site distances of 50 km and 400 km. These charts show the times when each installation phase is active and when there are delays due to weather or imbalances in the production schedule; for example, when a vessel arrives at port before wind turbine integration is complete. Regardless of whether the project is located 50 km or 400 km away from the port, nearly all of the wind turbine installation phase (which encompasses the substructure assembly line and the turbine assembly line in Figures F13–15) experiences a continuous delay from having no completed turbines assembled and ready for tow-out. In other words, any time a vessel arrives at port it must wait for a turbine to complete the integration process with the substructure before the installation can continue. This result means that the port operations are a more significant bottleneck than the distance to the project. Although not plotted here, we performed towing group sensitivity studies with the number of towing groups reduced to two. We observed no difference in installation times, and the delay in port operations continues to be the bottleneck. Note, however, that for extremely large tow distances (northern California project location with S&I site in central California), port operations cease to be a bottleneck.

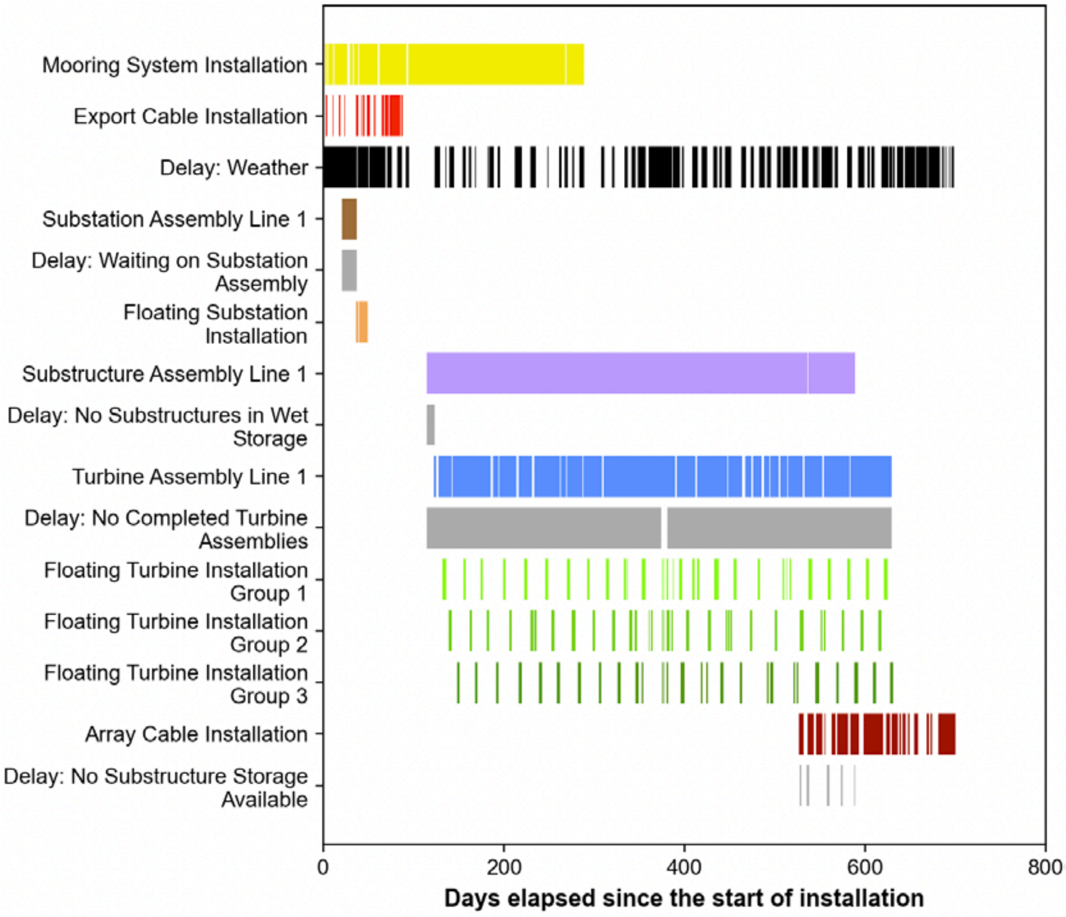

Figure F13. Simulated installation schedule for a 1-GW offshore wind energy project located 50 km from a staging and integration port site with one assembly line

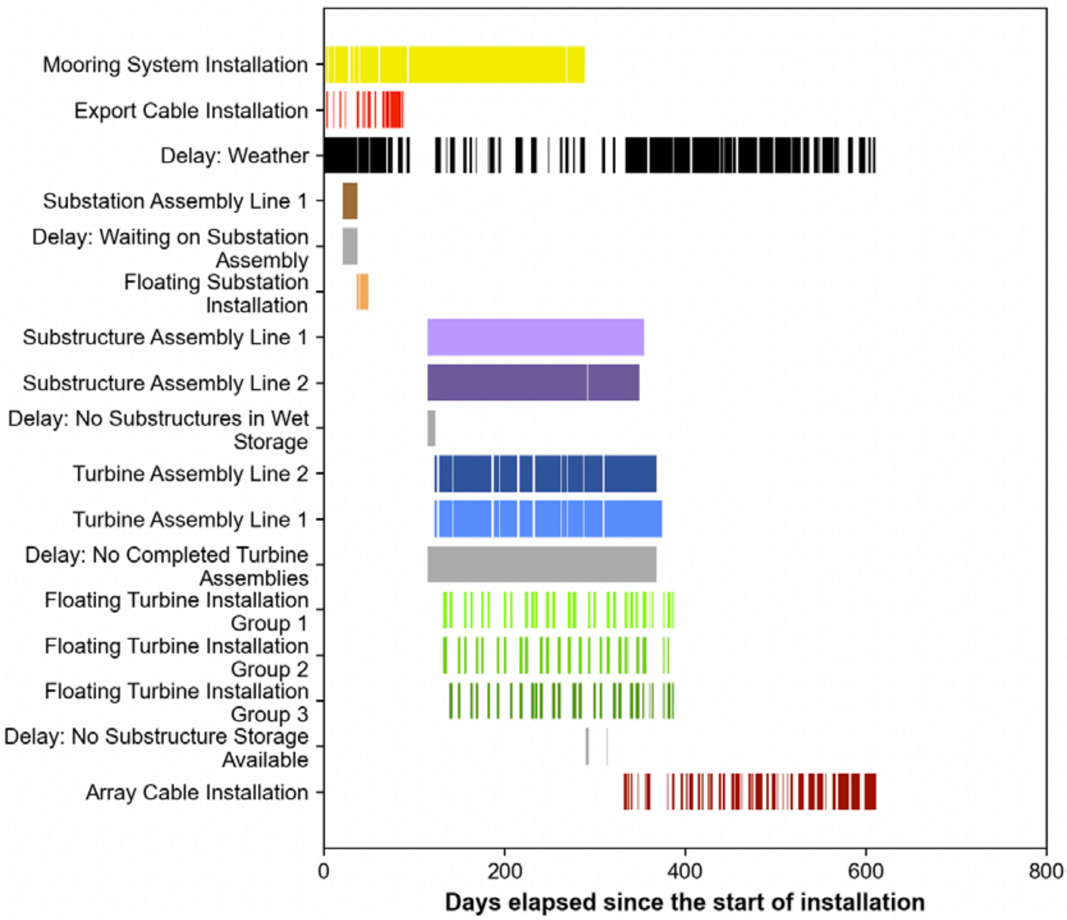

Figure F14. Simulated installation schedule for a 1-GW offshore wind energy project located 50 km from a staging and integration port site with two assembly lines

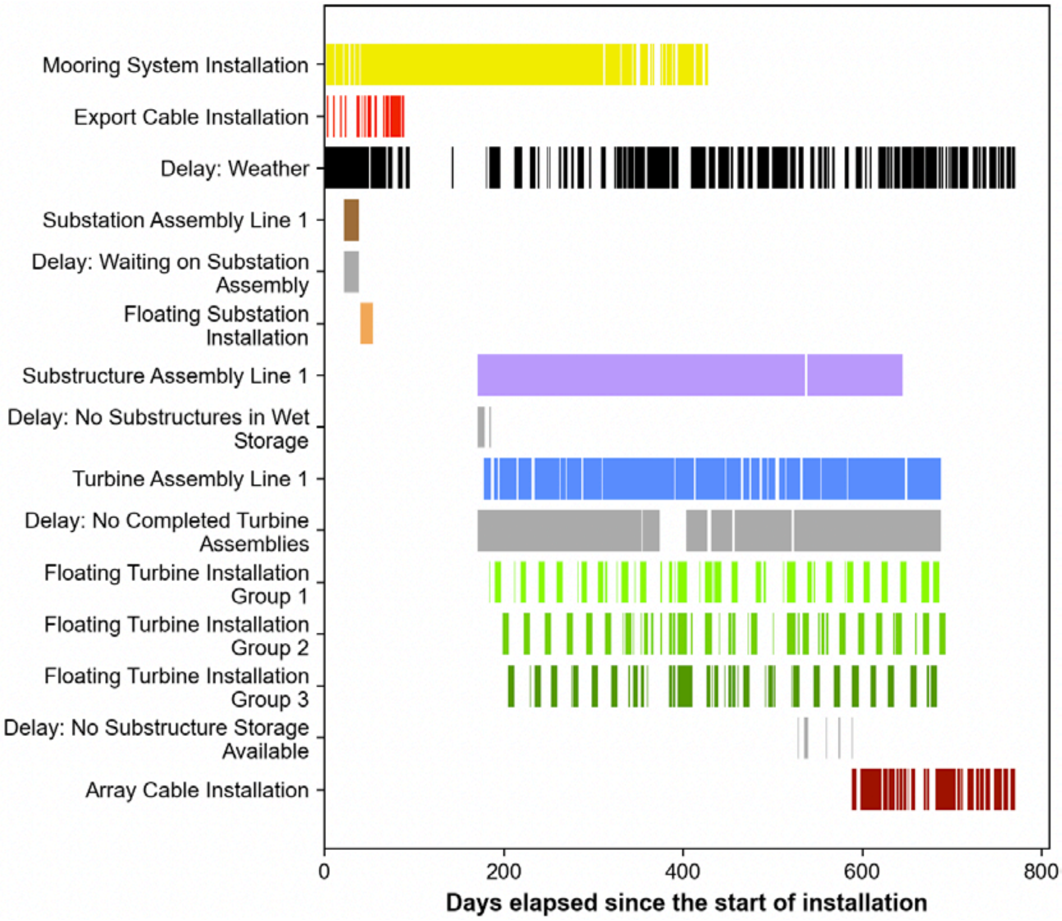

Figure F15. Simulated installation schedule for a 1-GW offshore wind energy project located 400 km (bottom) from a staging and integration port site with one assembly line

The insensitivity of wind turbine installation times and costs to port proximity is a counterintuitive result that requires further justification. The critical port processes that we use in this analysis (which are listed in Tables F2–F6) include assembling the floating platform; integrating multiple tower sections, the nacelle, and the blades; performing cable pull-in and electrical completion; and conducting mechanical completion and precommissioning work. Altogether, this process takes around 2 weeks to complete (roughly 1 week between launches of each newly assembled floating platform[18] and 1 week for wind turbine integration). These time frames already assume a level of industrialization and mass production beyond what the current industry can achieve. If the duration of port operations per turbine could be further reduced—

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[18] A benchmark of assembling one floating platform per week is often used to envision a commercialized floating offshore wind industry. It may be possible to reach this assembly rate, but it is more likely that an industrialized assembly site achieves an average rate of one unit per week by having enough space for multiple build positions with staggered schedules for each substructure. In this scenario, the one-per-week target is effectively the average production rate of the facility (not the average assembly time per unit). In other words, the one-per-week target measures the time between launches of successive floating platforms. In this report, we assume that the floating platform assembly sites have sufficient space for these parallel build positions to achieve an average production rate of one unit per week.

either by further industrializing the production process or by using multiple S&I sites or integration positions at the port—then we would expect to see greater sensitivity of the installation time to port proximity.

It is possible that other factors could affect LCOE as a project gets further from port; for example, insurance premiums may be higher to account for increased risk of weather delays or damage during a longer tow. However, because floating wind energy is still a new industry, the insurance market for these activities is not well-developed and the magnitude of these premiums is unclear. Because installation represents only on the order of 5% of the overall project capital costs, even if premiums doubled the installation costs, then LCOE would only increase by ~1%. There could be additional costs associated with contingencies, additional support or safety vessels, or other unknown needs that could introduce additional costs to projects. Financing and insurance for floating wind energy projects will evolve as the industry grows, and it will be important to understand their impact on the viability and insurability of the projects.

To summarize this simple case study, the proximity of the offshore wind energy project to the S&I port can significantly increase LCOE by 5%–15% as the distance increases from 50 km to 200 km. This impact is primarily driven by O&M costs. Wind turbine installation times and costs would not be impacted by this distance unless the time at port could be reduced to around 1 week for floater assembly and wind turbine integration, at which point the transport and installation time for a vessel group towing a wind turbine to the site could be shorter than the time taken for the next turbine to be ready for installation. This decrease in installation time could be achieved through improved production times or by using additional port resources such as more assembly or integration stations. This second option would lead to higher costs for the project developer. In either case, the impact on LCOE would be relatively minor because the wind turbine installation costs are on the order of 5% of the overall project capital costs. Further analysis is required to fully capture the cost/benefit trade-offs and project risks associated with port operations, vessel spreads, insurance rates, and distance to offshore wind energy projects.

Conclusions

As the floating wind energy sector begins to strategically plan the location of major ports on the West Coast, it will be important to consider both the required infrastructure investment and how the location and capabilities of this enabling infrastructure impacts the cost of floating wind projects. Ultimately, higher costs of energy are likely to be passed on to the ratepayer and may make floating wind less viable in a competitive energy market. We show that these costs could increase as the distance between a project and its supporting ports grows, and these cost differences could be magnified when considering actual port characteristics (e.g., achievable throughput, rental fees at the port). Decision makers should consider leveraging the results of this report to conduct detailed cost/benefit trade-off studies that investigate port solutions with the highest marginal value to offshore wind energy projects, port operators, and port communities.

Appendix G. Supply Chain

As project developers/owners prepare to establish offshore wind energy on the West Coast they have two distinct component sourcing options at their disposal—import components from overseas or establish a domestic manufacturing presence that can support projects throughout the region. The overseas components would likely be built using a relatively mature southeast Asian supply chain that would already be supplying projects within that region. While importing components from these facilities could reduce labor and material costs, it can also increase transportation time, costs, and emissions that could offset savings while increasing the environmental impact related to the sourcing of offshore wind components. These sourcing and supply chain choices will ultimately impact component and project cost as well as limit local investments, jobs, and other revenue opportunities that can be created through the domestic production of offshore wind energy components.

Modeling Approach and Assumptions

The scenarios that we present in Section 3.5 include different supply chain pathways. One pathway involves an international supply chain centered in southeast Asia where all major offshore wind energy components are imported to the West Coast. The other pathway focuses on a domestic supply chain that could be developed on the West Coast for the new floating wind industry. Throughout this section, we estimate the impact of these different scenarios on the landed capital cost of components for a 1-gigawatt (GW) floating wind project and describe the cost factors that drive the cost differences along with our approach to modeling them.

We focus on the 10 highest cost components of a floating wind project: blades, nacelles, towers, floating platforms, mooring rope, mooring chain, anchors, offshore substations, and dynamic cables. We then use the National Renewable Energy Laboratory’s Offshore Renewables Balance-of-system and Installation Tool (ORBIT) cost model (Nunemaker et al. 2020) to establish a baseline capital cost (which we break down into labor and materials) for these components. ORBIT models costs assuming a mature, generic U.S. supply chain; therefore, we develop a series of scaling factors to adjust the baseline costs to reflect the different international and domestic scenarios. The following sections summarize the key cost factors we use for each scenario.

Labor and Materials

Supply chains located in different global regions could have significant differences in labor and raw material costs. One potential value of using a southeast Asian supply chain is the opportunity to reduce these costs. Each country in the region has its own economic characteristics; however, for this simplified analysis, we have selected aggregated labor and material scaling factors (relative to the ORBIT baseline costs). We estimate that labor costs in southeast Asia are half of those in the United States (The Conference Board 2018), and steel prices are two-thirds of those in the United States (Organisation for Economic Co-operation and Development 2022). Copper prices are approximately equal to those in the United States (World Bank 2023), so no scaling factor was applied. The steel scaling factor is applied to the material costs of the tower, floating platform, anchors, mooring chain, and substation topside. While cost differences for other materials may exist (i.e., glass fiber, carbon fiber, and so on) and could impact cost differences for blades and other components, more data are needed to understand the extent of these differences.

Labor rate data from the Bureau of Labor Statistics for production employees on manufacturing payrolls showed a negligible difference between California and the Columbia River Basin (Bureau of Labor Statistics 2022). Therefore, we use the baseline labor and material costs from ORBIT for a U.S. supply chain with no further adjustment. The labor and material scaling factors are listed in Table G1.

Table G1. Relative Labor Rates and Raw Material Costs for Southeast Asian Supply Chains Relative to a Mature U.S. Supply Chain

Component	Labor	Raw Material
Blade	0.5	1
Nacelle	0.5	1
Tower	0.5	0.67
Floating Platform Subassembly	0.5	0.67
Floating Platform Final Assembly	0.5	1
Mooring Rope	0.5	1
Mooring Chain	0.5	0.67
Anchor	0.5	0.67
Substation	0.5	0.67
Dynamic Export Cable	0.5	1
Dynamic Array Cable	0.5	1

New Factory Amortization

The domestic manufacturing of many floating offshore wind energy components will require facilities that are designed and constructed specifically for these purposes. As such, it is important to account for the cost, often hundreds of millions of dollars, that are needed build these facilities. Manufacturers can offset these investments by adding a cost premium to components that is ultimately passed on to the customer (the project developer, and then the ratepayer). Because some facilities in southeast Asia have already been constructed and are recouping these costs, we conservatively considered these investments depreciated within the scenario. More detailed amortization assumptions and methodologies that were used in this report can be found in Shields et al. (2023). The cost premiums that are passed on to blades, nacelles, towers, and floating platforms are partially offset by the advanced manufacturing production tax credits from the Inflation Reduction Act (IRA); however, because these incentives expire in 2032 (and it is unlikely that major component manufacturing will be available on the West Coast before 2030), the benefit of the tax credits is relatively minor for floating wind components. The relevant factory assumptions and resulting cost premiums are provided in Table G2.

Table G2. Component Assumptions for the Factory Payback Cash Flow Model (Adapted from Shields et al. 2023)

Parameter	Units	Blade	Nacelle	Tower	Dynamic Array Cable	Dynamic Export Cable	Moor-ing Chain	Moor-ing Rope	Floating Platform
Cost Premium	% of baseline cost	9.3	5.4	7.0	14.4	14.8	5.0	4.5	4.2
Facility Construction Cost	$ million	300	250	250	350	350	500	50	100
Cost per Unit	$ million	1.46	5.94	3.99	0.44 ($million/km)	0.94 ($ million/km)	0.85	0.11	10.73
Production Capacity	#/year	200	275	125	550	250	2,000	2,000	50
Manufacturing Production Credit	$/unit	0.02	0.05	0.03	0	0	0	0	0.04
Wind Turbine Rating	mega-watts	15							
Facility Technical Life	years	25							
Depreciation Asset Life	years	7 (asset class 33.4 or 34.0)							
Maintenance CapEx Share of Sales	%	2							
Debt Share	%	70							
Interest Rate	%	4							
Debt Life	years	20							

IRA Domestic Content Bonus

The IRA provides incentives to individual energy projects in addition to the advanced manufacturing production tax credits for newly manufactured components. These benefits include the production tax credit (PTC) and investment tax credit (ITC) for individual projects along with potential 10% bonuses for meeting sufficient levels of domestic content and for locating the project in an energy community. Any offshore wind energy project could claim either the PTC or ITC, but to claim the domestic content bonus a project would have to source 20%–55% of manufactured products from the United States[19]. If a project also meets prevailing wage and workforce training requirements, the ITC domestic content bonus would be worth an additional 10% of the project cost. We include this 10% bonus credit (which assumes the wage and workforce requirements are satisfied) in the comparison between domestic and international supply chains to show the relative cost difference that it could drive; however, we do not include

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[19] Projects that begin construction before 2025 need to meet a 20% domestic content threshold, which ramps up to 55% for projects that begin construction after 2027.

the overall ITC or PTC value in the comparative analysis because projects could qualify for these regardless of the source of components.

Raw steel imports are subject to Section 232 tariffs that impose a 25% tariff on the base price of the component. We include a case study that assumes the United States does not have sufficient steel production and therefore adds a 25% cost premium to components built primarily out of steel, including the floating platforms, towers, mooring chains, anchors, and substations. In addition to Section 232 tariffs, steel and/or steel components can also be subject to antidumping duties or countervailing duty orders. These duty orders vary depending on country of origin and the type of steel and/or steel product and are intended to offset unfairly traded imports (U.S. Department of Commerce 2017).

Transportation Cost

Whether imported or domestically produced, offshore wind energy components will need to be transported from manufacturing facilities to staging and integration ports prior to being assembled for deployment. Components will likely be delivered from manufacturing facilities by deck carrier vessels with a deck space of 3,600 square meters (m^2) and capacity of 10,000 tons. The total number of components that we assume can be delivered on a single voyage varies depending on the component:

- Twelve blades
- Five to seven nacelles
- Four to six towers
- Two complete floating platforms
- All subassemblies for two floating platforms
- Cargo containers of mooring chain that are 100 by 75 cubic meters (m^3) (corresponding to around 25 kilometers of chain)
- Fifty anchors.

Given these restrictions, most components will require multiple trips to complete deliveries for a single project. We estimate the cost premium for transportation based on the number of trips required and the overall distance from a manufacturing facility to the staging and integration (S&I) port. As shown in Table G3, a trip from southeast Asia to the United States could last 66 days compared to the 3–4 days it takes to travel from the San Francisco Bay or Columbia River Basin to a S&I site in northern California.

Table G3. Travel Parameters for Transporting Components From Different Supply Chain Hubs to a Staging and Integration Port in Northern California

Supply Chain Hub Location	Distance to Northern California (kilometers)	Travel Time to Northern California (days)
Southeast Asia	11,000	66
San Francisco Bay	430	3
Colombia River Basin	630	4

It is important to note that interarray and export cables are likely to be delivered straight to the site for installation using a cable-laying vessel. With this in mind, the cost premium for cables is based on the day rates of a cable-laying vessel instead of an oceangoing barge. The cost assumptions used in this report for transportation can be found in Shields et al. (2023).

Constraints and Limitations

The high-level nature of the supply chain comparison within this report used high-level assumptions for labor, materials, and insurance premiums. As a result, the supply chain analysis using more detailed cost data could be beneficial moving forward. This analysis could use specific labor rates for individual workers to better understand how labor changed depending on which component is being manufactured, whether a facility is in an urban area versus a rural area, and the overall difference between union labor rates and a state's average labor rate for manufacturing. It could also include specific rates for materials beyond steel and copper to better quantify cost differences for other materials that are used to produce wind energy components (e.g., carbon fiber, glass fiber, resin, balsa). Additionally, we did not conduct a detailed assessment related to any insurance cost differences but suggest a future study to determine if insurance differences and capital-expenditure-related impacts exist.

Impacts of Domestic and International Supply Chains

Cost differences

Figure G1 compares the total landed cost[20] for components for a 1-GW floating wind energy project sourced from supply chains in southeast Asia or the U.S. West Coast. We estimate that sourcing components from a supply chain in southeast Asia could be around 15% less expensive than a mature West Coast supply chain, but qualifying for the domestic content bonus from the IRA reduces this gap to only 5%. The landed costs of these cases are similar because the lower labor and material costs of the supply chain in southeast Asia are offset by the lower transportation costs for a West Coast supply chain.

Additionally, Figure G1 shows that steel sourcing also plays an important role in West Coast manufacturing cost. Along with not qualifying for IRA domestic content incentives, West-Coast-produced components for a floating offshore wind energy project that use imported steel face tariffs that add a 25% premium to material costs. This results in floating offshore wind components for a 1-GW floating offshore wind project that are 25% more expensive than those produced in southeast Asia.

The results in Figure G1 assume that the capabilities of the factories in southeast Asia and the West Coast are identical; in reality, it will take time for U.S. facilities to be permitted and constructed, and there will be further time required for these new facilities to reach full production capacity as workers learn skills for a new industry. This lead time may result in early-stage floating wind projects needing to source some components from international suppliers to meet project schedules, and may make it difficult for U.S.-produced components to qualify for

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[20] The landed cost refers to the cost to procure and transport components from the manufacturing facilities to the staging and integration port. This cost does not include project installation costs (which do not depend significantly on the supply chain source).

advanced manufacturing production tax credits which expire in 2032. However, it will be important for the U.S. supply chain to evolve in parallel with these early projects so that it can be well-positioned to support the overall floating wind energy pipeline.

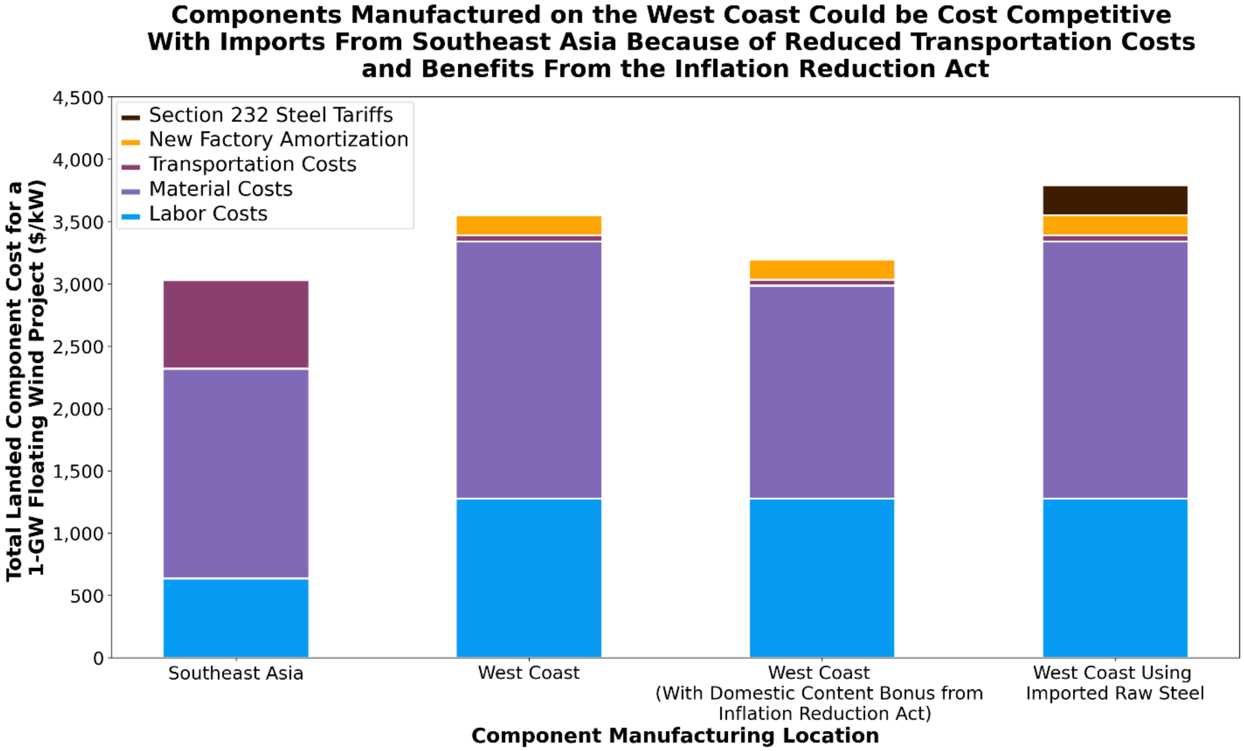

Figure G1. Comparison of the landed cost of components for a 1-GW floating offshore wind power plant that sources components from southeast Asian or U.S. West Coast supply chains. The West Coast supply chain case also includes results that demonstrate the additional benefit from the 10% domestic content bonus from the Inflation Reduction Act and the additional costs that would be incurred by sourcing raw steel from international suppliers. All costs are reported in $2023.

Jobs and facility investment

While deployment scenarios drive total components needed to meet capacity demand, jobs and facility investment are also tied to whether components are domestically produced or imported. As deployment goals expand, additional factories will be needed to meet that demand, which will require additional jobs and investment. Using component-specific production capacities from Shields et al. (2023) that were then modified to align with likely technology and supply chain pathways specific to the West Coast through 2045, we estimated that a supply chain sized to meet the demand of 25 GW on the West Coast would require 16 facilities and a corresponding 3,440 direct manufacturing jobs (see Table G4). Additionally, $3.15 billion of facility investments would be needed (beyond the manufacturing port upgrades summarized in Section 3.5). As shown in Table G5, a 35-GW deployment scenario would require 21 facilities and a corresponding 4,410 direct manufacturing jobs. Additionally, $3.9 billion of facility investments would be needed to support this scenario. A 55-GW deployment scenario would need 28 facilities, resulting in 6,170 direct manufacturing jobs and requiring a $5.2-billion investment (see Table G6). If components are imported, those jobs and facility investments will not be realized.

Table G4. Total Number of Domestic Manufacturing Facilities, Jobs, and Investment on the West Coast To Support the Low (25 GW) Deployment Scenario. (Costs are based on findings from Shields et al. (2023) and are reported in $2022).

25-GW Deployment Scenario			
Component	**# of Facilities**	**Total Jobs**	**Facility Investment ($ millions)**
Blades	2	1,000	$600
Towers	2	580	$500
Nacelle Assembly	2	460	$500
Floating Platform	3	720	$300
Floating Platform Subcomponents[21]	2	Not applicable (N/A)	N/A
Substation[22]	2	N/A	N/A
Mooring Rope	1	110	$50
Mooring Chain	1	110	$500
Anchor[23]	N/A	N/A	N/A
Array Cables	1	230	$350
Export Cables	1	230	$350
Total	**16**	**3,440**	**$3,150**

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[21] For this report, we assume 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.

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

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

Table G5. Total Number of Domestic Manufacturing Facilities, Jobs, and Investment on the West Coast To Support the Mid (35 GW) Deployment Scenario. (Costs are based on findings from Shields et al. (2023) and are reported in $2022).

35-GW Deployment Scenario			
Component	**# of Facilities**	**Total Jobs**	**Facility Investment ($ millions)**
Blades	3	1,500	$900
Towers	2	580	$500
Nacelle Assembly	2	460	$500
Floating Platform	4	960	$400
Floating Platform Subcomponents	3	N/A	N/A
Substation	2	N/A	N/A
Mooring Rope	1	110	$50
Mooring Chain	1	110	$500
Anchor	N/A	N/A	N/A
Array Cables	1	230	$350
Export Cables	2	460	$700
Total	**21**	**4,410**	**$3,900**

Table G6. Total Number of Domestic Manufacturing Facilities, Jobs, and Investment on the West Coast To Support the High (55 GW) Deployment Scenario. (Costs are based on findings from Shields et al. (2023) and are reported in $2022).

55-GW Deployment Scenario			
Component	**# of Facilities**	**Total Jobs**	**Facility Investment ($ millions)**
Blades	5	2,500	$1,500
Towers	3	870	$750
Nacelle Assembly	2	460	$500
Floating Platform	5	1200	$500
Floating Platform Subcomponents	4	N/A	N/A
Substation	3	N/A	N/A
Mooring Rope	1	110	$50
Mooring Chain	1	110	$500
Anchor	N/A	N/A	N/A
Array Cables	1	230	$350
Export Cables	3	690	$1,050
Total	**28**	**6,170**	**$5,200**

As part of this analysis, we looked at the potential distribution of manufacturing facilities under each deployment scenario to locate a single manufacturing facility in ports identified as suitable for manufacturing. We began the search in California before expanding into Oregon and Washington. Using this guideline, each port in the West Coast region that is suitable for offshore wind manufacturing would have one manufacturing facility before a second manufacturing facility would be located in any given port. In no way was this effort meant to portray how manufacturing will be distributed, but to better understand the limitations and opportunities for manufacturing throughout the West Coast.

While each region has numerous ports that could support floating offshore wind energy manufacturing, it is unlikely that any single state could support all of the domestic manufacturing needed for any of the West Coast deployment scenarios. We estimate that California has 10 capable manufacturing sites, whereas Oregon and Washington could support nine facilities each (see Tables D1–D4 in Appendix D). Some ports may prioritize S&I activities over manufacturing, which could further reduce this available number. Under the 35-GW deployment scenario, two ports would need to develop multiple manufacturing sites to meet the demand. Under the 55-GW deployment scenario, a total of nine ports would require multiple manufacturing sites. The various land and permitting constraints for existing port infrastructure means a multi-facility per port solution is unlikely without additional upland clearing and site expansion. Without these improvements, the region will need to lean heavily upon the exiting 19 ports (see Tables D1–D4 in Appendix D) that are suitable for floating offshore wind component manufacturing. Given the capabilities of ports along the West Coast and the demand for numerous manufacturing facilities for a floating offshore wind supply chain, a regional spread of manufacturing would likely occur if expanded deployment goals were fully sourced through a West Coast supply chain.

Risks Associated With International Supply Chains

A reliance on insecure supply chains with geopolitical risks could mean components and materials are being sourced from countries with social instability, unfair trade practices, or human rights issues, such as child or forced labor (U.S. Department of Energy 2022). An additional risk related to a component or material's country of origin involves environmental standards. Internationally sourced components or materials may originate from countries with environmental standards that are lower than the United States, which could adversely impact nearby resources and communities. Sudden supply chain interruptions like those experienced due to COVID-19 and the Russia-Ukraine war are additional risks that could be mitigated by having a higher proportion of domestic supply (Shields et al. 2023).

The longer time at sea for transportation of components from southeast Asia (shown in Table G3) means there are increased opportunities for accidents that create an additional safety risk for at-sea personnel. Additionally, vessels can encounter extreme weather that can result in travel delays or components incurring noticeable external damage or lost at sea. Extended time at sea also leaves transported components an extended opportunity to incur internal damage that will go unnoticed until the wind plant is operational. Transportation and supply chain delays can also be a scheduling risk that can impact workforce and equipment cost and/or availability, which could impact deployment. Finally, longer transport will create higher levels of emissions, which we discuss further in Appendix I.

Appendix H. Offshore Wind Energy Pipeline Deployment

The capabilities of a West Coast port network will dictate the level of offshore wind energy deployment that can realistically be achieved. These deployment levels will depend on the throughput that each port can achieve, the number of vessels available to perform installation activities, available weather windows, and the number of offshore wind energy projects in the pipeline. We use the National Renewable Energy Laboratory's Concurrent ORBIT for shared Resource Analysis Library (CORAL) model to simulate the deployment of the pipelines we define in Appendix C with different staging and integration (S&I) port configurations listed in Section 3.5 (Figure 5). We used the CORAL model for a similar assessment of the fixed-bottom pipeline on the East Coast by Shields et al. (2023) that was expanded to incorporate floating wind energy deployment logistics for this report.

Modeling Approach and Assumptions

CORAL defines a configuration for each project in the offshore wind energy pipeline that includes project characteristics (such as project capacity, planned construction dates, wind turbine rating, and substructure and mooring design choices), port logistics (such as the times required for individual processes during substructure assembly and wind turbine integration), and site conditions (such as water depth, distance to port, and weather time series). The model also includes a shared library of port and vessel resources. Each port can have distinct capabilities, including the number of parallel production lines (which includes substructure assembly, turbine integration, and wet storage space). Port and vessel resources can be added at future dates in the simulation as new resources are built for the offshore wind energy industry. Individual projects require a set of port and vessel resources to begin construction. If any these resources are unavailable at the intended installation start date, the project is delayed until sufficient resources become available. A primary output of the CORAL model is a Gantt chart showing project delays, actual construction dates, and the total installed capacity at the target date. These charts also display the cumulative port investment for each scenario that is presented in Section 3.5.

The CORAL simulations presented in this section use the deployment schedules and port resources defined in Section 3.1.

We make the following assumptions in the simulation:

- Each wind turbine system (the integrated floating platform and wind turbine) requires one anchor handling tug supply (AHTS) vessel and two tugboats to be towed from port to project site. We iteratively solved for the size of the fleet required to eliminate vessel delays, and report these results in this section.
- An offshore wind energy project is staged out of a S&I site in its own region; for example, a project in northern California stages out of a north California S&I site.
    - The only exception to this assumption is for central California projects that could stage out of central coast or southern California sites, depending on the specified scenario.
- We focus exclusively on the wind turbine system installation in the CORAL simulation because this activity will require an S&I site. Cable installation will likely be based out of the

manufacturing site or an alternate laydown facility. Mooring and anchor installation could be based out of a S&I site or a manufacturing yard, but would not require the heavy-lift capabilities of a S&I site. Offshore substation installation will likely be based out of the shipyard where the substation is constructed. These installation phases can be staggered with the turbine system installation (as we describe in Appendix F) and therefore have a relatively small impact on the overall deployment by 2045.

- There are no delays due to upstream component supply (i.e., there are always components at the S&I site that are ready to be assembled and installed).
- Six weeks per summer are reserved for operations and maintenance (O&M) activities at the S&I port when a turbine system is towed back from a commissioned project for maintenance or repair that requires a quayside crane. CORAL does not simulate these activities, but blocks out this time so that no installation activities can take place. CORAL sensitivity studies indicate that increasing the time per summer reserved for O&M activities beyond 6 weeks begins to impact the overall pipeline deployment. We further discuss O&M activities, including failure rates for major repairs and replacement, in Appendix F.
- We do not specify the infrastructure or equipment needed for assembling the floating platform or integrating the wind turbine. Different options could include semisubmersible barges, lift gates, or on-land assembly with roll off or inclined ramps. Drydocks are not expected to be widely developed on the West Coast due to their size and expense. Each of these technologies could be selected by individual port developers and could impact the process times we use in this study.
- Installation process times are consistent for all S&I ports considered. Specific infrastructure decisions or natural features of the ports (such as the accessibility of the navigation channel) could lead to differences in production rates between ports.

The CORAL model is intended for comparative analysis between different scenarios, and should not be interpreted as a prediction of when specific projects will be installed. The goal is to understand how port and vessel investment can enable increased offshore wind energy deployment.

Simulated Pipeline Deployment for Each Scenario

We used the CORAL model to estimate the total offshore wind capacity that could be installed by 2045 for each S&I port scenario listed in Figure 5. The S&I scenarios include:

- 25 gigawatts (GW) (central coast)
    - Two S&I sites in northern California that come online in 2029 and 2030
    - One S&I site in central California that comes online in 2037 (potential ports identified by Trowbridge et al. (2023a) in the central coast do not have sufficient space for two sites)
- 25 GW (southern California)
    - Two S&I sites in northern California that come online in 2029 and 2030
    - Two S&I sites in southern California that come online in 2031
- 35 GW
    - Two S&I sites in northern California that come online in 2029 and 2030

  - Two S&I sites in southern California that come online in 2031
  - Two S&I sites on the Oregon coast that come online in 2031 and 2038
- 55 GW
  - Two S&I sites in northern California that come online in 2029 and 2030
  - Two S&I sites in southern California that come online in 2031
  - Two S&I sites on the Oregon coast that come online in 2031 and 2038
  - One S&I site in central California that comes online in 2037
  - Two S&I sites on the Washington coast that come online in 2035.

Figure H1 shows the target capacity, installed capacity, and level of investment in S&I ports required for each relevant scenario. In the two 25-GW scenarios, 95% of the pipeline is installed by 2045 with a second port (with two S&I sites) in southern California, whereas only 71% of the pipeline is developed by 2045 with a port on the central coast because this port could likely take significantly longer to permit and construct and likely only has space for one S&I site (Porter and Gostic 2022; Trowbridge et al. 2023b). The overall estimated investment in S&I ports is relatively similar for the two scenarios, but the $4.2 billion required for the 25-GW (southern California) scenario enables four sites to be built, whereas the $5.2 billion for the 25-GW (central coast) scenario only results in three; furthermore, the third site is not available until the late 2030s.

Although a southern California S&I port could enable another 5 GW to be installed by 2045 relative to a central coast port, this analysis does not consider the potential impact of port proximity on the cost and viability of the offshore wind energy projects. We discuss this trade-off further in Section 3.3 and Appendix F.

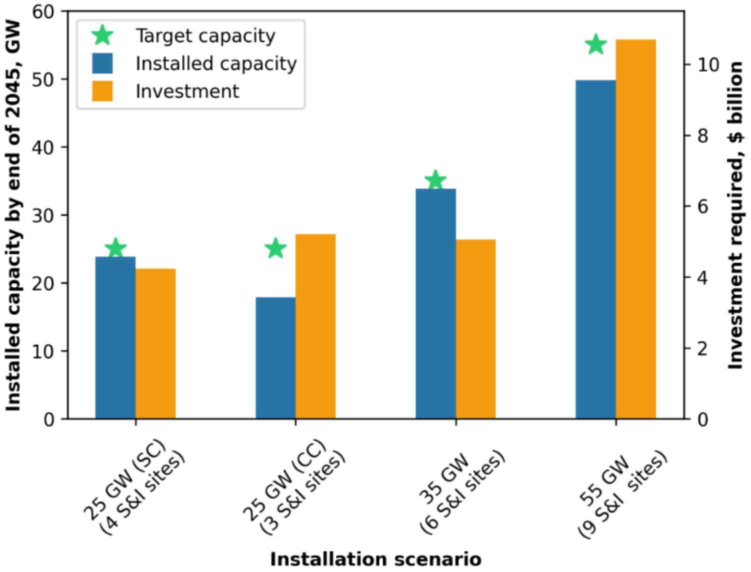

Figure H1. Target capacity, installed capacity, and investment required for different port network scenarios. Costs are reported in $2023.

SC = southern California, CC = central coast (of California)

The 35-GW scenario, which includes two S&I ports in California (with two northern California sites and two southern California sites) and one port in Oregon (with two S&I sites), could deploy around 97% of the target pipeline. Achieving this level of deployment could require a $5.1-billion investment in these S&I ports. The 55-GW scenario indicates that five S&I ports and a total of nine sites in California, Oregon, and Washington would enable around 50 GW—or 91% of the target pipeline—to be installed by 2045. We select a third California port in the central coast for this scenario, although this level of deployment could also be achieved by adding a third S&I site in southern California or on the Washington coast. This scenario would require around $10.7 billion to be invested in S&I ports along the West Coast.

The detailed CORAL simulation results for each scenario are provided in Figure 7. These charts show the delays experienced by individual projects per region for the different S&I port availability.

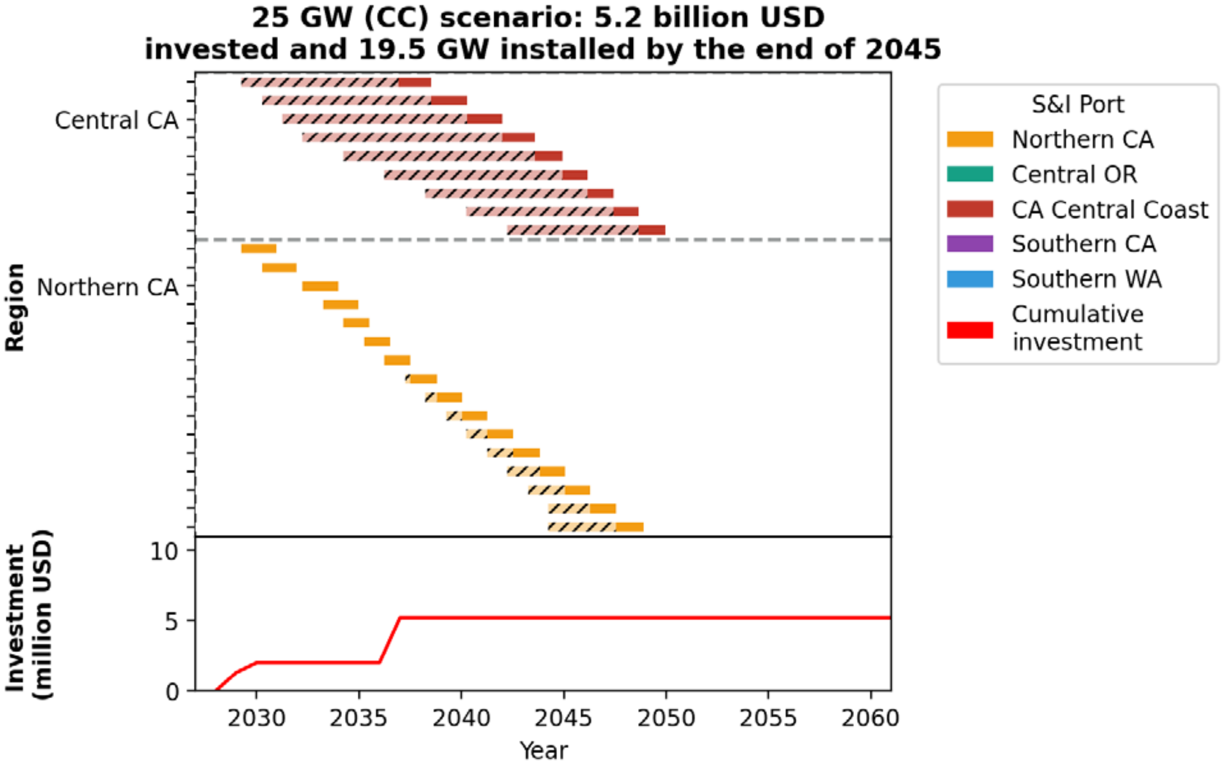

Figure H2. The pipeline installation schedules for the 25-GW scenario with ports in northern California and on the central coast of California. Offshore wind energy projects are concentrated in central and northern California, and the S&I port region for each project is identified in the legend. Cumulative investment costs in S&I ports are also shown in $2023.

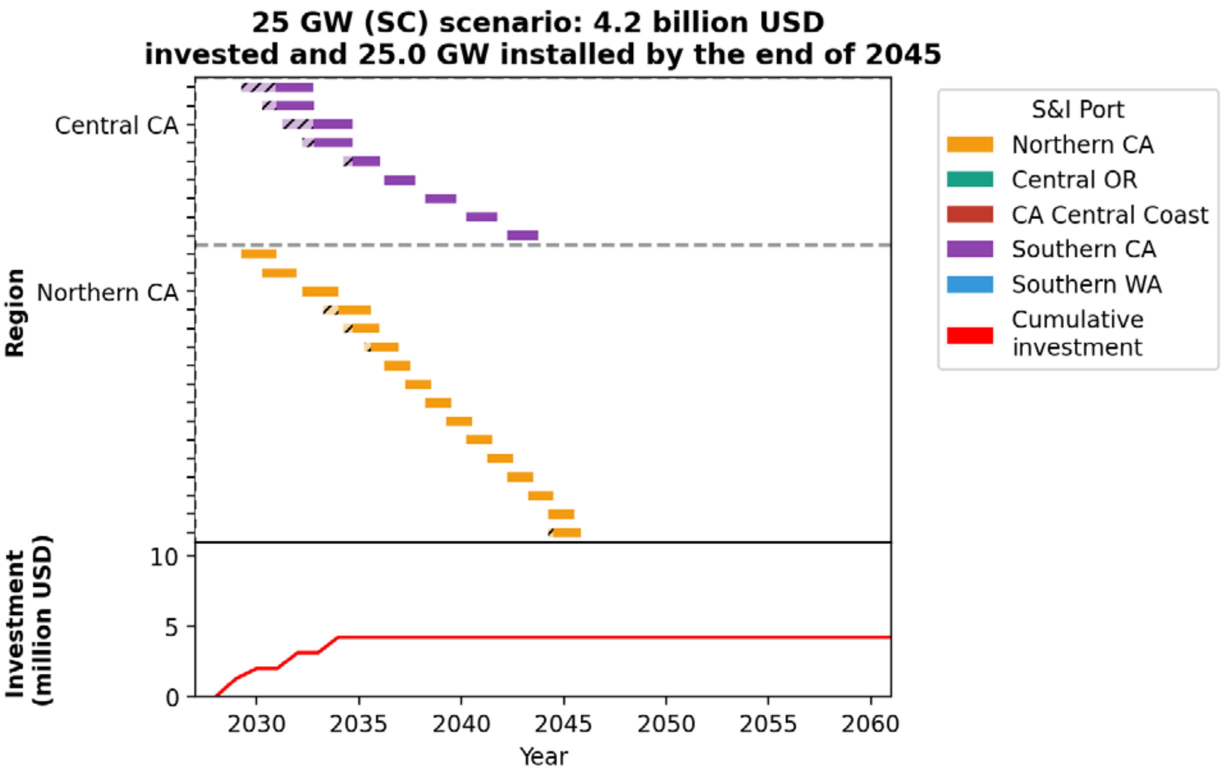

Figure H3. The showing pipeline installation schedules for the 25-GW scenario with ports in northern and southern California. Offshore wind energy projects are concentrated in central and northern California, and the S&I port region for each project is identified in the legend. Cumulative investment costs in S&I ports are also shown in $2023.

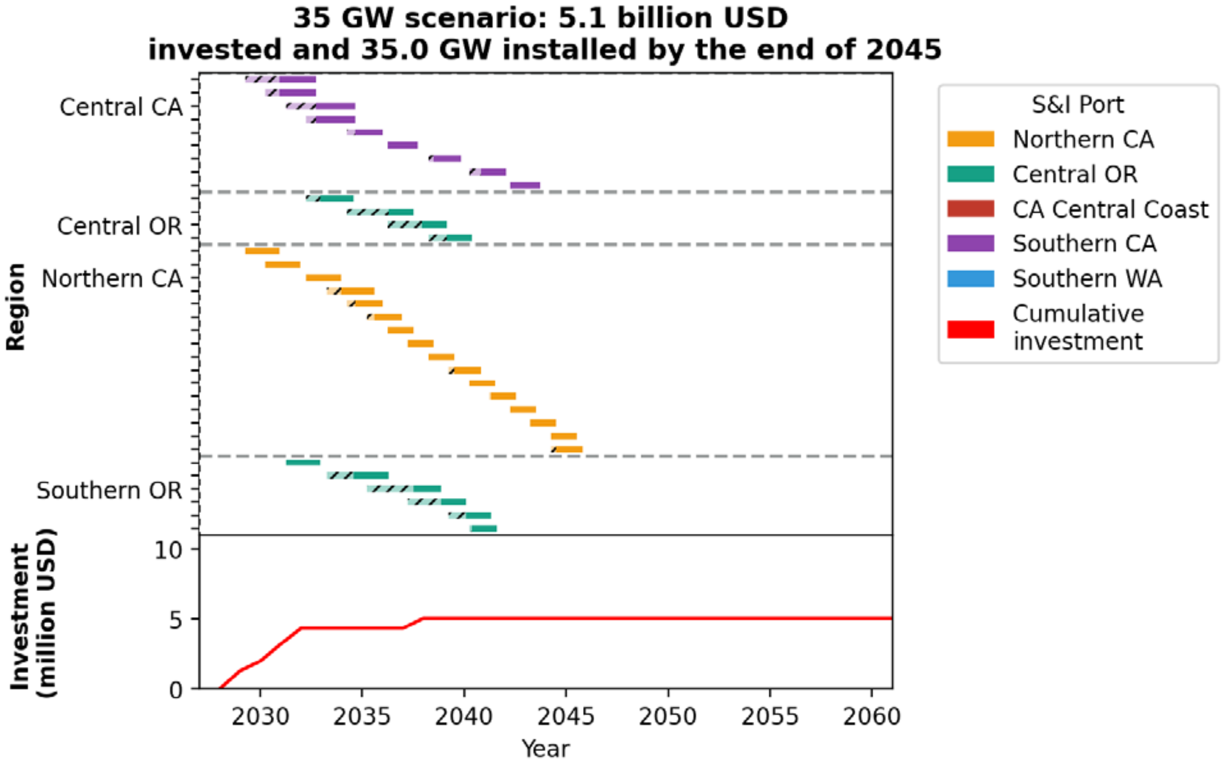

Figure H4. The pipeline installation schedules for the 35-GW scenario with ports in northern and southern California and the Oregon coast. Offshore wind energy projects are concentrated in central and northern California and Oregon, and the S&I port region for each project is identified in the legend. Cumulative investment costs in S&I ports are also shown in $2023.

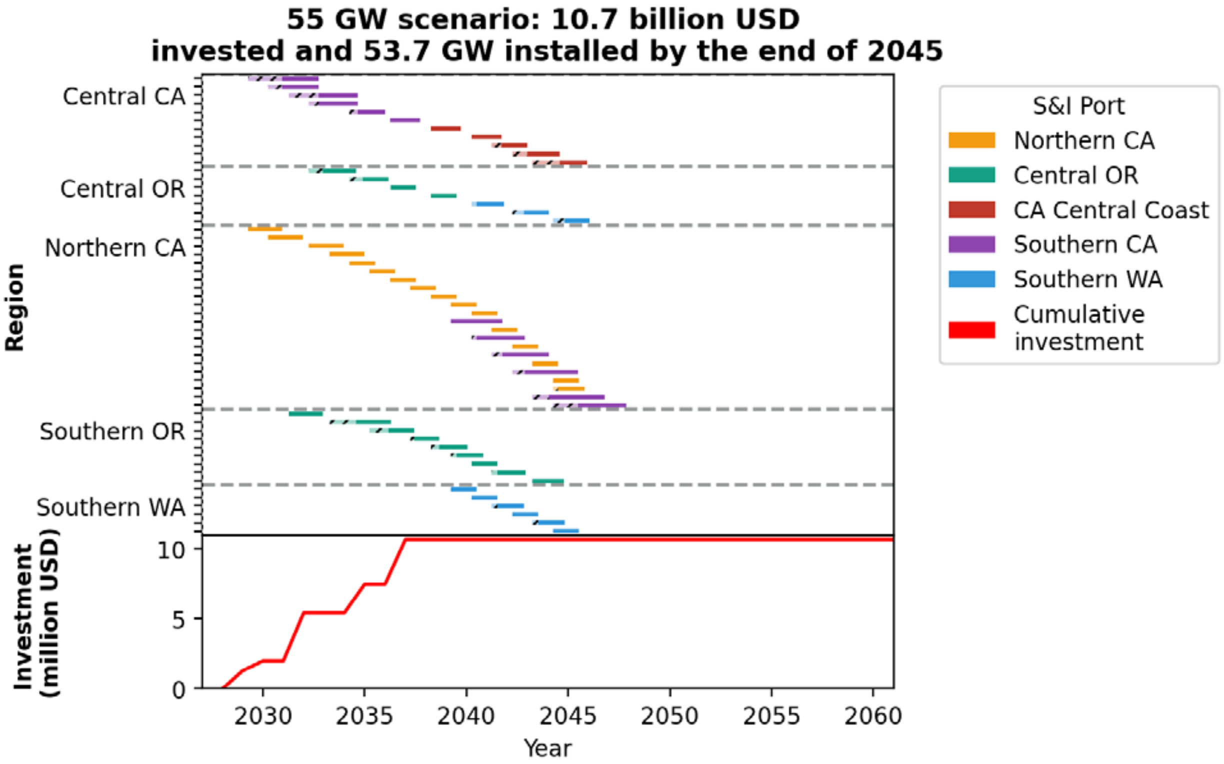

Figure H5. The pipeline installation schedules for the 55-GW scenario with ports in northern and southern California, the central coast, Oregon coast, and Washington coast. Offshore wind energy projects are concentrated in central and northern California, Oregon, and Washington, and the S&I port region for each project is identified in the legend. Cumulative investment costs in S&I ports are also shown in $2023.

Significant delays are noticeable in the 25-GW (CC) scenario because the intended construction dates of the offshore wind energy projects in the central coast lease areas are much earlier than a port in the region could become available. Although the installation time frames for projects staged out of a southern California port (25-GW (SC) scenario) are somewhat longer and may require more vessels, the reduced delays allow for a higher deployment level. The 35-GW scenario shows that a S&I port in Oregon could support 10 GW of deployment by 2045 if it could come online in the early 2030s and add a second S&I site in the mid-to-late 2030s. Finally, the 55-GW scenario is around 5 GW short of the target. About 3 GW of these delayed projects are assigned to a northern California port, although projects based out of southern and central California, Oregon, and Washington also experience some delays. Although adding additional port resources could help reach the target scenario, the marginal value of investing around a billion dollars in a new site to enable a few gigawatts of deployment may not be economically viable.

Number of Required Vessels for CORAL Simulations

CORAL models individual towing groups, each comprising one AHTS vessel and two tugboats that move substructure and wind turbine assemblies around the port and between project and port sites. Table H1 lists the minimum number of vessels that we used in the CORAL simulations to eliminate deployment bottlenecks. Further study is required to understand the vessel fleet required for varying levels of floating wind build-out on the West Coast, particularly because some vessels may be able to support different project phases (for example, AHTS can install anchors and mooring lines and may also be able to tow out turbine systems if they have sufficient towing capacity). Additional work is necessary to understand the need for semisubmersible barges that can help transfer floating platforms and/or wind turbine systems from quayside to wet storage or tow-out. There is currently an insufficient supply of U.S.-flagged semisubmersible barges that could be used for these activities, but the demand for these vessels will depend on preferred approaches from port owners, project developers, and technology providers.

Table H1. Minimum Number of Vessels Needed for Each Type to Eliminate Vessel Bottlenecks Across All Scenarios. These Are Also the Vessel Numbers Used in the CORAL Simulations.

Scenario	AHTS (Turbine Tow-Out)	Tugboats
25 GW (SC)	12	24
25 GW (CC)	9	18
35 GW	15	30
55 GW	27	54

Considerations for Floating Platform Assembly Time

The deployment levels that we estimate in Figures H1–H5 assume that a newly assembled floating platform is ready for wind turbine integration at the S&I site every week. . This 1-week time frame is typically referenced by the floating wind industry as a target for an industrialized production rate (James and Wang 2018; Borisade 2019). The target of 1 week per floater refers to the time between units, not the assembly time per unit. This assumption is reflected in our models.

At this time, precommercial levels of production require several months to assemble a single floating platform. Therefore, the industry is making a concerted effort to design floating platforms with serialized production in mind to allow easier fabrication at U.S. port facilities (U.S. Department of Energy Office of Energy Efficiency and Renewable Energy 2022). The exact pathways that this industrialization process will take are not yet known, but could involve some combinations of platform design concepts (such as using pins or bolts instead of welds) and facility design (such as setting up parallel assembly lines with automated process integrated where possible). Both approaches come with challenges. In the former case, it would be critical to design the floating platforms for rapid assembly from the beginning of the process. In the latter case, it would be difficult to find enough ports with a sufficient amount of space to enable parallel manufacturing to bring the average throughput up to one platform per week (and would greatly increase the cost to construct these ports). The time frame for progressing from the precommercial to commercial stage is uncertain and will likely require proof-of-concept testing by building units for demonstration projects. Solving this problem will be critical to implementing a commercially viable manufacturing and installation floating wind ecosystem on the West Coast.

Appendix I. Vessel Emissions

Transport, installation, and operations and maintenance (O&M) vessels could potentially emit greenhouse gases within the life cycle of a floating offshore wind power plant. As a result, development of the vessel fleet will need to comply with the emissions standards of West Coast states and ports, which aim to lessen the air quality impacts of port activity on nearby communities (Environmental Protection Agency [EPA] 2022b; California Air Resources Board 2020a).

Vessel emissions could disproportionately impact port communities that are already burdened by high exposure to pollutants such as nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter (PM), and volatile organic compounds (VOCs) (EPA 2020). Acute respiratory symptoms, heart and lung disease, increased cancer risk, and premature mortality are all associated with exposure to these pollutants (EPA 2020). Developing port and offshore wind energy project strategies that reduce total vessel emissions is a way to minimize harm to port communities.

We used the results from the Windfarm Operations and Maintenance cost-Benefit Analysis Tool (WOMBAT) and Concurrent ORBIT for shared Resource Analysis Library (CORAL) models (described in Appendix F and H) to calculate the level of emissions from vessel activity in each of the deployment scenarios. These results are only meant to serve as an additional point of comparison between the deployment scenarios and are not to be interpreted as a full-scale life cycle assessment.

Vessel Emissions Estimates

To maintain simplicity, we chose to calculate only the carbon dioxide (CO_2) emissions occurring at port and sea due to offshore wind energy development activities – we define these as the direct CO_2 emissions because they do not include drilling, refining, or other processing. The combustion of marine diesel fuel also emits NO_x, SO_x, particulate matters, and additional greenhouse gases—many of which are subject to port, state, and international regulations. Because our CO_2 estimates are based on vessel use hours, we assume that other types of emissions would scale according to the proportions listed in Table I1; however, we do not apply these proportions in the remainder of the report.

Table I1. Conversion Factors Between Carbon Dioxide (CO_2) Emissions and Other Pollutants Associated With Marine Diesel Fuel Combustion (Smith et al. 2014)

Pollutant	grams/ton CO_2	Pollutant	grams/ton CO_2
CO_2	1,000,000	**CO**	864.005
CH_4	18.715	**Non-methane volatile organic compounds**	960.699
N_2O	46.787	**PM**	318.153
NO_x	27,214.598	**SO_x**	823.456

The vessel emissions metric is intended to represent the emissions of existing maritime vessels that are used in the scenarios outlined in this report. Therefore, these estimates do not consider the emissions reductions standards imposed on vessels by individual ports, states, the EPA, or the International Maritime Organization: many of these standards would require vessels to plug into shore power while at berth, use cleaner fuels, or employ on-deck capture-and-control technologies like exhaust "bonnets" (California Air Resources Board [CARB] 2020a). As a result, emissions occurring due to "idling at berth" activities are likely overestimates of actual emissions.

To align with this report's analyses on different installation and O&M strategies, we also chose to focus emissions estimates on maritime vessels. Due to their significant size and weight, we assume that floating offshore wind components will primarily be manufactured at port sites and/or transported to assembly sites by deck carrier vessels, rather than on-road vehicles. Therefore, estimates do not consider emissions from trucks or trains. However, a broader assessment of portwide emissions occurring from floating offshore wind activities should also consider that emissions from on-road vehicles (including drayage trucks) and manufacturing heavily burden port communities (EPA 2020).

At-Berth Vessel Emissions Standards

Since 2014, CARB has regulated at-berth vessel emissions for container, passenger, and refrigerated cargo ships visiting the ports of Los Angeles, Long Beach, San Diego, Oakland, San Francisco, and Hueneme (CARB 2020b). An updated regulation, which will lead to a 90% reduction in pollution from 2014 levels by 2030, extends emissions standards to roll-on/roll-off vessels and tankers. From conversations with maritime industry experts, we anticipate that other West Coast states are likely to adopt similar regulations to limit pollution, and its adverse health impacts, at ports.

In this analysis, we assume that deck carrier vessels (DCVs), a type of ocean-going barge recently classified by DNV (Rüde 2023), will be used to transport floating offshore wind components from manufacturing sites to assembly and installation sites. Due to a lack of information on how CARB's at-berth emissions standards will apply to DCVs, as well as unknowns about future regulations in Oregon and Washington, we chose not to factor CARB's at-berth standards in our estimates of vessel emissions from component transportation. However, in commissioning or building vessels to serve floating offshore wind energy in the West Coast, developers should consider using shore power, alternative fuels, or capture-and-control technologies to comply with at-berth emissions standards (CARB 2020a).

Vessel Emissions Methodology

Both the *2019 EMEP/European Environment Agency Air Pollutant Emission Inventory Guidebook* and the *Third International Maritime Organization Greenhouse Gas Study 2014* calculate vessel fleet emissions using a bottom-up approach, which is based on vessel specifications and activities (De Laurentis et al. 2019; Smith et al. 2014). For this study, we follow these methodologies closely and use them to calculate vessel emissions from component transportation, project installation, and O&M for each of our modeled scenarios presented in Section 3.5. Because each of our assessed scenarios represent different combinations of supply chain, installation, and O&M strategies, we first calculate emissions associated with each individual strategy and then combine them to obtain scenariowide emissions estimates.

The bottom-up approaches outlined by the *EMEP/European Environment Agency Air Pollutant Emission Inventory Guidebook* and the *Third International Maritime Organization Greenhouse Gas Study 2014* include calculating individual emissions factors (mass of CO_2 per hour) for every vessel and activity of interest. These emissions factors are then applied to vessel fleet data describing the time spent by each vessel performing each activity. In this section, we describe how we obtained these data for each of the supply chain, installation, and O&M strategies. Next, we describe our approach for calculating individual emissions factors and lastly, we report the results obtained from applying these emissions factors to each scenario.

Supply Chain Hours

Floating offshore wind energy components are assumed to be transported from the manufacturing site to the staging and integration (S&I) port by DCVs. We calculated transit hours based on the distance between the supply chain location (either southeast Asia or the U.S. West Coast) and the S&I ports used in the scenario. We use a transport speed of 7 kilometers per hour, which corresponds to the average cruising speed of a representative DCV (United Wind Logistics n.d.). Because maneuvering and idling hours are assumed to be constant across all supply chain scenarios, we only consider transit emissions for DCVs in this analysis.

Installation and O&M Hours

Transit, maneuvering, and idling hours for all vessels involved in floating offshore wind energy were calculated from results of the WOMBAT modeling—used to simulate three O&M strategies—and the CORAL modeling—used to simulate different deployment pipelines. In addition to allowing us to calculate the emissions associated with each vessel and activity in the project pipeline, this approach enables us to distinguish between emissions occurring at sea and at port.

We make the following assumptions about vessel activity hours in the CORAL and WOMBAT modeling:

- Because CORAL and WOMBAT do not specify maneuvering activities, 10% of transit time is designated as maneuvering time
- When idling at port due to delays, vessel engines are kept running for 25% of total delay time
- One O&M port can serve up to 3 gigawatts of offshore wind energy projects.

Emissions Factors

We consider 10 basic vessel types used to support floating offshore wind projects. To estimate the emissions contribution of each vessel type, we chose to calculate emissions factors based on the engine specifications of actual vessels that are or will be used for American and European offshore wind projects. These emissions factors are further broken down by transit, maneuvering, and idling activities to account for the variation in engine load factor during different modes of operation. A full list of vessel types and specifications can be found in Table I2.

Table I2. Representative Vessel Types and Specifications

Vessel Type	Representative Vessel	Propeller Engine Rating (kilowatts [kW])	Auxiliary Engine Rating (kW)	Specification Sheet Source(s)
Scour protection vessel (SPV)	Bravenes (Van Oord)	Main: 6,200 Thrusters: 7,000	3,194	Van Oord (2021)
Crew transfer vessel (CTV)	CTV1 (Patriot)	2,088*	50*	Patriot Offshore Maritime Services, EPA (2023a)
Cable lay vessel (CLV)	Leonardo da Vinci (Prysmian Group)	Main: 6,200 Thrusters: 7,000	3,194	Prysmian Group (n.d.)
Anchor handling tug supply (AHTS)	Normand Sagaris (Solstad Offshore)	17,400	8,400	Solstad Offshore (n.d.)
Tugboat	EPA tugboat classification	2,536	191	EPA (2022g)
Service operations vessel (SOV)	T60-18 (IHC)	5,720	5,370	IHC Offshore Energy (2021)
Feeder barge (FB)	Superfeeder (MiNO Marine)	Main: 7,500 Thrusters: 2,400	6,800	Moore (2020)
Heavy lift vessel (HLV)	Bokalift 2 (Boskalis)	Main: 10,000 Thrusters: 20,400	34,560	Boskalis (2022)
Wind turbine installation vessel (WTIV)	Charybdis (Seajacks)	Main: 12,800 Thrusters: 11,100	34,560**	Seajacks (2023)
Deck carrier vessel (DCV)	Boldwind (UWL)	Main: 5,280 Thrusters: 700	Not considered	United Wind Logistics (n.d.); Ship Technology (2019)

*Engine power ratings are unspecified; these numbers were obtained from the EPA ports emissions inventory.

**Auxiliary engine power ratings are unspecified; this number was approximated using the heavy-lift vessel auxiliary engine rating.

For each vessel type and activity, emissions factors (in tons of CO_2 per hour) are calculated based on engine power (kilowatt [kW]), load factor, fuel carbon intensity (grams of CO_2 emitted per gram of fuel combusted), and specific fuel consumption rate (gram of fuel combusted per kilowatt-hour [kWh]). A summary of these constants can be found in Tables I3 and I4. To consider the emissions from stationary vessel activities, such as wind turbine assembly or crew transfers, we chose to calculate the emission factors on a per-hour, rather than per-mile, basis.

Table I3. Engine Constants Used in Emissions Factor Calculations

Activity	Propeller Engine Load Factor	Auxiliary Engine Load Factor
Transit	0.6–0.8*	0.4
Maneuvering	0.2 0.3*	0.6
Idling at port	0	0.17–0.22*
Idling at sea	0	0.1

*Ranges are reported for activities in which load factor is dependent on vessel type.

Source: EPA (2009)

Table I4. Fuel Consumption Rates Used in Emissions Factor Calculations

Fuel Type	Used by	CO_2 Intensity (grams CO_2 Emitted per gram of Fuel Combusted)	Specific Fuel Consumption (grams of Fuel Combusted per Engine kWh)
Marine diesel oil	All	3.206	**Slow Speed Diesel (SSD)**: 185 **Medium Speed Diesel (MSD)**: 205 **High Speed Diesel (HSD)**: 217
Heavy fuel oil	Deck carrier vessel	3.114	**MSD**: 227 **HSD**: 227

Sources: Smith et al. (2014); Hawkins et al. (2019).

Vessel emissions factors are calculated using Eq. I1:

$$\boldsymbol{EF_{vessel,\ activity} = \sum_{engines} P_{engine} \times LF_{activity} \times FC_{engine,\ fuel} \times CI_{fuel}} \tag{I1}$$

Where $EF_{vessel,\ activity}$ is the emissions factor (grams of CO_2 emitted per hour) for a specific vessel and activity, P_{engine} is the power rating (kW) of each vessel engine, $LF_{activity}$ is the engine load factor specific to each activity, $FC_{engine,\ fuel}$ is the specific fuel consumption (grams of fuel combusted per kWh of output) for each engine and fuel type on the vessel, and CI_{fuel} is the carbon intensity (gram of CO_2 emitted per gram of fuel combusted). The resulting emissions factors can be found in Table I5.

Table I5. Emissions Factors (Tons of CO_2 per Hour) by Vessel Type and Activity

Vessel	Transit	Maneuvering	Idling at Port	Idling at Sea
SPV	4.149	3.936	0.444	0.222
CTV	1.112	0.433	0.007	0.003
CLV	4.149	2.556	0.444	0.222
AHTS	11.486	6.937	1.169	0.584
Tugboat	1.387	0.580	0.027	0.013
SOV	4.502	3.369	0.747	0.374
FB	4.561	4.582	0.804	0.473
HLV	14.875	20.420	4.809	2.404
WTIV	16.347	19.138	4.809	4.809
DCV	2.082	0.0*	0.0*	0.0*

*We only considered transit emissions for deck carrier vessels.

Vessel Emissions

We use the emissions factors in Table I5 to estimate the total CO_2 emissions from the simulated transport, installation, and O&M hours of the different deployment scenarios. While these CO_2 estimates describe only one aspect of potential environmental impacts due to vessel traffic (others include emissions of additional pollutants and greenhouse gases, disturbances to marine animals, and the risk of fuel and toxin leaks), they are useful as points of comparison between the scenarios outlined in this report. The results of this analysis are summarized in Figure I1.

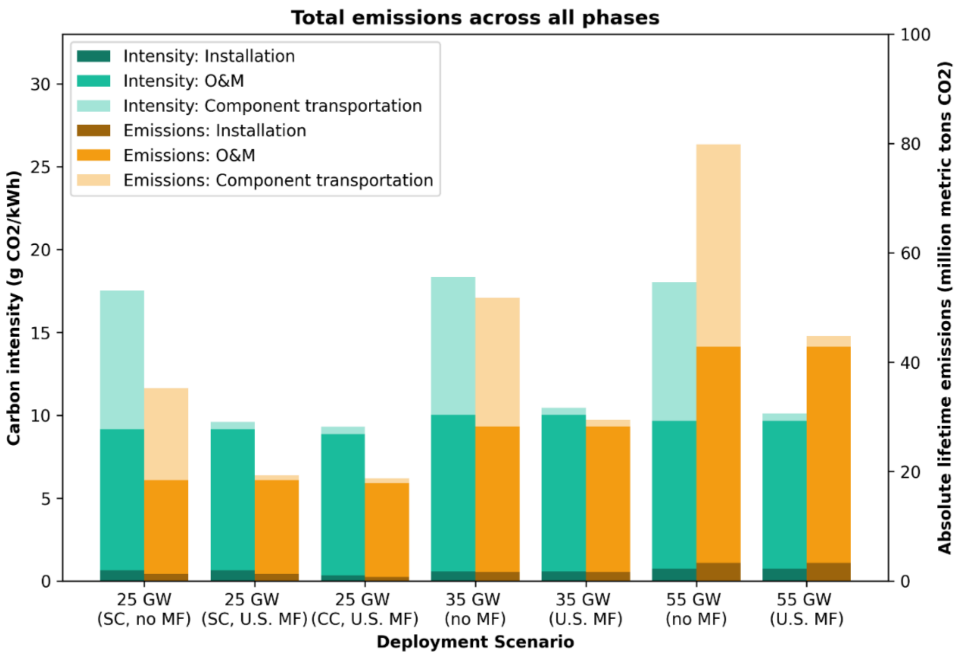

Figure I1. Complete emissions results, broken down by wind plant life cycle stage

SC = southern California; MF = manufacturing/fabrication

Vessel emissions installation activities are typically less than 1 gram of CO_2 per kWh. Differences among scenarios are primarily driven by distances between projects and the S&I port. Anchor handling tug supply vessels and tugboats make many trips between the project site and port, so total installation emissions are particularly sensitive to the distances traveled by these vessels. Therefore, scenarios involving few S&I ports and/or S&I ports that are far away from project sites experience the highest installation emissions. These results only capture the installation of the floating wind turbine systems; stationkeeping and cable installation would increase these emissions, but not to a level as significant as O&M or international transport.

Vessel emissions due to O&M activities are similar across all 10 scenarios, ranging from 8.5 to 8.8 grams of CO_2 per kWh. Of the vessels involved in O&M activities, anchor handling tug supply vessels make the largest contribution to total emissions, creating between 5.6 and 5.9 grams of CO_2 per kWh. Similar to the emissions from installation activities, we model anchor handling tug supply vessels making frequent trips between the project and port, so scenarios involving relatively large distances experience relatively high emissions.

Emissions due to the transportation of components from the manufacturing site to the S&I port range from 0.4 to 8.3 grams of CO_2 per kWh. This range, which is much larger than that of the installation and O&M emissions, is driven by the distances between manufacturing facilities and S&I ports for each scenario. In our models, deck-carrier vessels transporting components from facilities located on the West Coast travel an average of 530 kilometers per trip. Vessels carrying components from facilities in southeast Asia, however, travel an average of 11,000 kilometers per trip—over 20 times farther. As a result, scenarios relying on an international supply chain cause nearly double the emissions of scenarios relying on a domestic supply chain.

The component transportation, installation, and O&M activities for the highest-emitting scenario are found to contribute around 80 million metric tons' worth of CO_2 throughout its projects' 20-year lifetimes. While this number seems high at first glance, it is less than 1% of the 9,878 million metric tons of CO_2 emitted by an equivalent capacity of coal power plants over the same time period (U.S. Energy Information Administration n.d.).

Vessel Emissions at Port

This analysis estimates vessel emissions for each scenario by tracking the time that vessels spend in four activities: transit, maneuvering, idling at port, and idling at sea. This strategy enables us to provide a breakdown of emissions occurring at port and at sea, which is of particular interest from an energy justice perspective. Emissions created from all "idling at port" activities are considered to occur at port, and all remaining emissions are considered to occur at sea. A summary of this breakdown is provided in Figure I2. The results indicate that most emissions are associated with vessels transit.

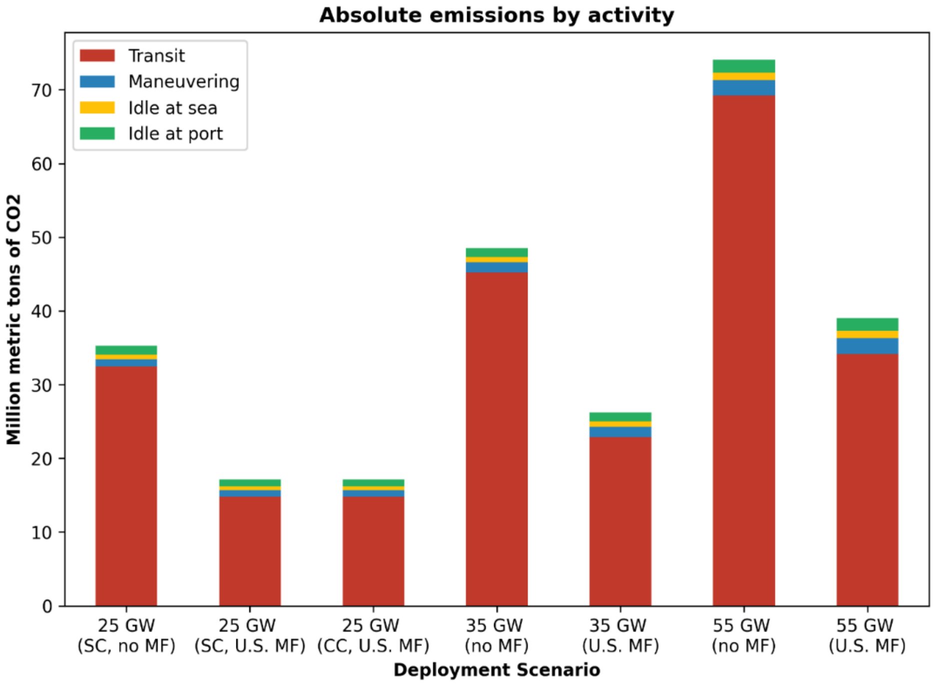

Figure I2. Scenario emissions broken down by vessel activity. Emissions from idling at port have the most direct impact on adjacent port communities.

Strategies To Mitigate Vessel Emissions

At present, zero-emissions vessels (powered by electricity, hydrogen, or methanol) with capabilities for floating offshore wind energy activities are nonexistent on the West Coast. While some emissions are inevitable, many strategies exist to mitigate emissions. The use of slow steaming (reducing vessel transit speeds) and very low sulfur fuel oils are two strategies that are relatively inexpensive and easy to implement (Chu Van et al. 2019; Faber et al. 2017). More advanced strategies, such as integrating shore power systems or retrofitting vessels to install capture-and-control "bonnets" require greater investments, but can be highly effective in reducing at-port emissions (EPA 2022g; CARB 2018).

Appendix J. Port Permitting

Developing port facilities requires an understanding of permitting requirements and processes at different levels of government. The most effective way for a port developer to become aware of all requirements is to work directly with the federal, state, tribal, and local governments that are involved in regulating coastal activities in a given area, as the required permits may differ depending on the project's specifications and location. Thus, this section is intended not to identify every permit that will be required but rather to introduce the stakeholders, policies, and processes that should be considered when planning a port project on the West Coast.

Federal Level

The National Environmental Policy Act (NEPA) of 1970 requires federal agencies to assess the environmental impacts of federal actions such as permit approvals, construction of publicly owned facilities, and allocation of federal funding (U.S. Environmental Protection Agency [EPA] 2022c). If an offshore wind energy port project receives federal funding or permits, it is likely that NEPA regulations will be triggered. The federal agency or agencies carrying out the federal action will need to conduct either an environmental impact statement (EIS) or an environmental assessment (EA), depending on the extent of the action's impacts to human health and the environment. Across federal agencies, the average time to complete an EIS has been found to be 4.5 years, so time may be a relevant consideration for projects that trigger NEPA regulations (Council on Environmental Quality [CEQ] 2020). Additional support for the NEPA process may come from federal, tribal, state, or local agencies chosen to serve as cooperating agencies, often due to their special expertise or jurisdiction by law concerning the geographic area or a specific environmental issue (EPA 2022c).

Federal agencies are required to consider environmental justice under NEPA, which may be done through actions like engaging the public and incorporating environmental justice analysis into an EIS or EA (EPA 2023a). Agencies may also conduct a Health Impact Assessment as part of the NEPA process, although this is not required (EPA 2023a). Given that communities living around ports tend to experience environmental justice burdens, such health and environmental justice analyses would likely factor into the NEPA process related to an offshore wind energy port project.

The Coastal Zone Management Act (CZMA) of 1972 established the National Coastal Zone Management Program, which has the participation of 34 coastal states, including the three West Coast states considered in this study. State or local agencies are responsible for carrying out federal consistency review. Federal consistency "requires that federal actions, within and outside the coastal zone, which have reasonably foreseeable effects on any coastal use (land or water) or natural resource of the coastal zone be consistent with the enforceable policies of a state's federally approved coastal management program" (National Oceanic and Atmospheric Administration Office for Coastal Management n.d.). In other words, under CZMA, federal actions like agency activities, permits, and financial assistance activities, some of which could be involved in offshore wind port development, must be consistent with state coastal management policies (NOAA Office for Coastal Management n.d.).

The Clean Water Act of 1972 established "the basic structure for regulating discharges of pollutants into the waters of the United States and regulating quality standards for surface waters" (EPA 2022d). Under Section 401 of the Clean Water Act, a federal agency may not issue a permit for an activity that may result in discharges into waters of the United States unless a Section 401 water quality certification is issued or the requirement is waived (EPA 2022e). States and authorized tribes where the discharge originated are responsible for issuing these certifications.

Under the National Historic Preservation Act of 1966, tribal consultation is required with each step of the process "when a federal agency project or effort may affect historic properties that are either located on tribal lands, or when any Native American tribe or Native Hawaiian organization attaches religious or cultural significance to the historic property, regardless of the property's location" (U.S. General Services Administration 2023). The Section 106 consultation process applies to a "federal or federally assisted undertaking," or a project, activity, or program that is under the jurisdiction of a federal agency, receives federal financial assistance, or requires federal permits or approvals (Suagee 2018). The federal agency involved in an undertaking may consult tribes and use tribal expertise when developing ways to avoid, minimize, or mitigate negative impacts to historic properties. Section 106 consultation is only required for federally recognized tribes, but federal agencies may choose to include non-federally recognized tribes as additional consulting parties (Advisory Council on Historic Preservation 2018).

The Rivers and Harbors Act of 1899 prohibits unauthorized obstructions to the navigable capacity of U.S. waters (U.S. Army Corps of Engineers [USACE] n.d. [a]). Under Section 14 of this law, any project that would modify, alter, or occupy an existing USACE Civil Works project—such as a levee, dam, channel, or navigable waterway—must first be approved by USACE as part of the Section 408 program (USACE n.d. [b]). Alterations could include "improvements to the projects, relocation of part of the project, or installing utilities or other non-project features" (USACE n.d. [b]).

Under the Ports and Waterways Safety Act of 1972, the U.S. Coast Guard has a statutory responsibility to ensure the safety and environmental protection of U.S. ports and waterways (U.S. Coast Guard n.d.). Though not directly involved in permitting processes for port facilities, the Coast Guard is involved in port activities like developing safety standards and monitoring vessels. Therefore, port developers might consult the Coast Guard and consider its policies in their planning and decision-making.

Under the Endangered Species Act of 1973, federal agencies must consult with the U.S. Fish and Wildlife Service "to ensure that actions they fund, authorize, permit, or otherwise carry out will not jeopardize the continued existence of any listed species or adversely modify designated critical habitats" (U.S. Fish and Wildlife Service n.d.). Through the Section 7 review process, the U.S. Fish and Wildlife Service conducts analysis to determine possible impacts to an endangered species and recommends measures to reduce impacts. For a port project on the West Coast, endangered or threatened species that might be considered in Section 7 review include killer whales, salmon, and several species of seabirds (National Oceanic and Atmospheric Administration Fisheries n.d.).

State Level

The port permitting process differs between California, Oregon, and Washington, as these states have different agency structures, environmental laws and standards, and processes for determining federal consistency and leading state environmental review. The following is intended to provide a brief overview of each state's laws, processes, and considerations.

In California, the lead agency involved in a port project would most likely be the California Coastal Commission (CCC) or the San Francisco Bay Conservation and Development Commission, both of which are part of the California Natural Resources Agency and responsible for administering the California Coastal Management Program. Depending on the location of the project, either of these two commissions could lead federal consistency review for the project. The California Coastal Act of 1976 established policies for habitat protection, water quality, human impacts, and other activities in the coastal zone (CCC n.d. [b]). Under Section 8 of the California Coastal Act, existing commercial port districts are encouraged to construct new facilities within their boundaries to reduce the need to create new ports in other parts of the state (California Public Resources Code 2023). In other words, it is not impossible to build a new port outside of an existing port district, but such a development would face more challenges in state permitting processes than a development at an existing port.

Another consideration is California Environmental Quality Act (CEQA) review, which requires a state, regional, or local agency to evaluate the potential environmental impacts of a project it is carrying out, financing, or permitting. There are opportunities for coordination between CEQA and NEPA reviews, such as using a federal EIS if it meets CEQA requirements, which can help make both processes more efficient (California Governor's Office of Planning and Research 2014). Other considerations in California include Section 401 water quality certification and waste discharge requirements, which are under the purview of the California Water Boards. The state Department of Fish and Wildlife might also be involved due to its authority over wetland resources associated with rivers, streams, and lakes.

In Oregon, the lead agency for a port project would most likely be the state Department of Land Conservation and Development (DLCD), which oversees the Oregon Coastal Management Program. The program would lead federal consistency review for the project. Channel modification would require a variety of permits, such as Section 401 water quality certification from the Department of Environmental Quality and fish passage authorization through the Department of Fish and Wildlife. If the project had any adverse impacts on fishing industries, mitigation or other actions in consistency with state fisheries protections policies would be required. Finally, Oregon has statewide land use planning goals, two of which (Goals 16 and 17) are focused on estuarine resources and coastal shorelands; though not mandatory, these goals are used to guide local planning (DLCD n.d. [b]). Some activities involved in port development, such as dredging, could require a goal exception under the statewide planning goals.

In Washington, the lead agency involved in a port project would most likely be the Washington Department of Ecology, which oversees the Washington Coastal Zone Management Program. The program would lead federal consistency review for the project. The Shoreline Management Act of 1971 set policies for shoreline use, environmental protection, and public access to shoreline areas (Washington Department of Ecology n.d. [b]). Another consideration is the State Environmental Policy Act process, which requires state and local agencies to evaluate the environmental impacts of a proposed project (including carrying out, financing, or permitting a public or private construction project) as well as potential mitigation measures (Washington Department of Ecology n.d. [a]). As in California and Oregon, Section 401 water quality certifications would be necessary and issued by the Department of Ecology. The state Department of Fish and Wildlife might become involved in some cases; for example, the department issues approvals for hydraulic projects, which are activities that impact the flow or bed of any state waters (Washington Department of Fish and Wildlife n.d.).

Tribal Governments

In some cases, permits and approvals for port development may come from tribal governments. Across the United States, there are 573 sovereign tribal nations that are federally recognized and have a formal nation-to-nation relationship with the federal government. Some of these tribes may have land in trust status or otherwise have jurisdiction over coastal lands near existing ports or potential port sites. For example, in 2022, five tribes in California reclaimed their right to manage 200 miles of coastal land and will form management agreements with the state through the Tribal Marine Stewards Network (Austin 2022).

The EPA is authorized to treat federally recognized tribes in a similar manner as states for the implementation of certain environmental programs (EPA 2022f). For example, these tribes may manage Clean Water Act programs such as water quality certifications and dredge and fill permitting (EPA 2022f). Thus, depending on the location and context, a tribal government could be responsible for some of the required permits for an offshore wind energy port project.

As is true with federal, state, and local governments, tribal governments may have overlapping responsibilities with other governments concerning coastal areas and/or tribal resources impacted by port development. Port decision makers should familiarize themselves with the roles that tribes may play in permitting and land management in a given port context, as well as consult tribes about potential impacts; tribal consultation is discussed in Appendix K.

Local Level

Local-level permitting or planning approvals can be performed by a variety of entities, including municipal or county governments and port governing bodies. Port policies and plans are best understood on an individual port level, so this section focuses on the role of municipal and county governments in coastal planning and permitting.

In California, the 76 cities and counties in the state’s coastal zone use planning tools called Local Coastal Programs to guide development in coastal areas (CCC n.d. [c]). Once adopted by a city or county governing body, a Local Coastal Program must be certified by the California Coastal Commission. A certified Local Coastal Program is given the authority to issue Coastal Development Permits to developments in the coastal zone; however, the CCC still has “permanent ongoing responsibilities” to oversee coastal development (CCC n.d. [a]). The ports that are established as commercial port districts within the State of California by the California Coastal Act are the Port of Hueneme, Port of Long Beach, Port of Los Angeles, San Diego Unified Port District, and the Humboldt Bay Harbor, Recreation, and Conservation District (California Public Resources Code 2023). These ports, with the exception of Humboldt Bay, have Port Master Plans that have been certified by the CCC (CCC n.d. [a]) and encounter different state processes for new projects or developments than other ports in the state (California Public Resources Code 2023).

In Oregon, the seven counties and 33 cities in the coastal zone are all considered local partners in the Oregon Coastal Management Program (DLCD n.d. [a]). Statewide Planning Goals 16 and 17, which are focused on estuaries and coastal shorelands, respectively, are both implemented primarily through local planning (include estuary plans and comprehensive plans) and zoning (DLCD n.d. [a]). Channel modification for a port project would require obtaining a Land Use Compatibility Statement from the local jurisdiction, which may in turn require other permits, such as conditional use or floodplain development permits (Oregon Department of Environmental Quality n.d.).

In Washington, the 39 counties and about 250 municipalities with lake, stream, wetland, and marine shorelines are required by the Shoreline Management Act to establish Shoreline Master Programs (Washington Department of Ecology n.d. [b]). The Department of Ecology helps local governments create and update their Shoreline Master Plans, which are local policies and regulations that guide both public and private use of the state's shorelines. Local jurisdictions then have the authority to issue permits, make decisions about exemptions, and enforce regulations related to their shorelines; shoreline permits include substantial development permits and conditional use permits.

Appendix K. Engaging With Tribes

As with offshore wind energy projects themselves, offshore wind port development and supply chain activities on the West Coast will likely impact environmental, historical, economic, and cultural resources that hold significance to tribes. In order to minimize these impacts and deliver benefits to tribes, offshore wind port decision-making must involve considering impacts to tribal resources and lands, consulting tribes, addressing negative impacts, and creating economic and workforce opportunities for Indigenous people on the West Coast.

Many of the existing ports on the West Coast are in places that have been key cultural centers for tribes for thousands of years, and the same may be true of any new proposed port locations. Thus, there is often significant historical context that port decision makers must become familiar with to understand an offshore wind energy port project's potential impacts on Indigenous communities. In addition to consulting tribes about the port project and the history of the area, decision makers may need to conduct studies on coastal archaeology to identify tribal resources at or near port sites. In one example, the State of Washington discovered a tribal village, thousands of artifacts, and a burial ground of the Kllalam people in 2003 during construction of a port project in Port Angeles, leading members of the Lower Elwha Klallam Tribe to persuade the state to move the project to a new site (Mapes 2009). Port decision makers must be willing to meaningfully incorporate tribes' concerns and input into all stages of decision-making—particularly early stages—as well as being willing to adjust their plans when new information is discovered, as occurred in the case of Port Angeles.

Depending on a port's proximity to tribal lands and/or lands with significance to tribes, port developers may be required to engage in Section 106 tribal consultation under the National Historic Preservation Act, which is described in greater detail in Appendix J. Regardless of whether Section 106 consultation is deemed necessary for a given project, it is important for decision makers to consult with tribes in a way that is proactive, involves two-way communication, meaningfully supports tribes' ability to participate (e.g., provision of funding), uses tribal expertise (e.g., tribes leading technical reviews), and allows tribal input to shape project outcomes. Consultation approaches may need to be altered if tribes deem them inadequate or inequitable; for example, in response to perceived subpar engagement from the Bureau of Ocean Energy Management, the Confederated Tribes of the Coos, Lower Umpqua and Siuslaw Indians passed a resolution in 2022 calling upon the bureau to engage in meaningful government-to-government consultation with the tribe about offshore wind energy development off of Oregon's coast (Gaines 2022). Finally, beyond the early project stages and formal consultation processes, it is valuable to form and maintain long-term relationships with tribes, as ports can benefit from tribal input and partnership throughout their operations.

If negative impacts to tribes are anticipated or observed from a port project, tribal consultation will allow developers to work with tribes to determine the best ways to address those impacts. Addressing negative impacts can take different forms, depending on the situation and the preferences of the tribes engaged in consultation; for example, one mitigation hierarchy that may be used consists of avoiding, minimizing, and compensating. Avoiding or minimizing impacts could be achieved by engaging tribes in the earliest stage of port siting decisions so that a location can be selected that has no or few negative impacts to tribal resources. Compensating for impacts might look like establishing community benefit agreements that provide financial compensation to tribes or supporting workforce development for Indigenous people to enter the offshore wind energy industry. Though such actions may add extra cost or time to port projects, they play a key role in creating better project outcomes and ensuring “developers and Indigenous host communities can share the benefits of new infrastructure while simultaneously addressing the burdens that local and marginalized people may face” (Mirza et al. 2023).

Finally, tribal communities may face barriers to accessing the significant economic and workforce opportunities provided by the offshore wind industry. To ensure that there is equitable access to educational and training opportunities for Indigenous people, there is a need to expand offshore wind energy programs at tribal colleges and universities and other tribal-serving educational institutions, strengthen apprenticeship programs in and near Indigenous communities, and increase awareness of opportunities in the industry (Mirza et al. 2023). One effort already underway on the West Coast is a partnership between the Yurok Tribe, Cal Poly Humboldt, and College of the Redwoods to form an offshore wind energy workforce training initiative (Cal Poly Humboldt 2023). According to Yurok Vice Chairman Frankie Myers, initiatives like this help the tribe continue their stewardship of the North Coast region and also “provide great potential for generational transformation for our young people, providing good-paying jobs and economic security for Native Americans in all of California and beyond” (Cal Poly Humboldt 2023).

Appendix L. Insurability for Floating Offshore Wind Energy Projects

Floating offshore wind energy projects are likely more challenging to insure than fixed-bottom offshore wind projects due to the relative infancy of the floating offshore wind industry. Insufficient data are available to fully understand the risks associated with the construction and operation of large-scale floating offshore wind plants. Although insurance premiums will likely represent a relatively small percentage of the overall capital costs of an offshore wind energy project (Stehly and Duffy 2022), having access to appropriate policies could be a make-or-break financial decision for project developers, lenders, and tax equity investors, who will be less willing to accept the risk of lack of insurance for damage or loss of revenue for a multibillion-dollar project. Therefore, the insurance market will have to evolve in parallel with the technology and infrastructure development of floating offshore wind.

The more mature fixed-bottom offshore wind energy market has established insurance policies that could be a baseline for floating offshore wind. A common approach is using a Construction All Risk policy that is taken out by the developer to cover construction and all subcontractors (such as marine logistics companies) involved in the project. Each subcontractor would agree to a deductible for damage or loss to project assets that would be agreed upon with the overall policyholder (the developer); in other words, risk is distributed throughout the subcontractor network for each project. This type of policy would likely be appropriate for floating offshore wind energy projects; however, the fundamental differences from fixed-bottom offshore wind projects mean that insurance underwriters will have a hard time pricing the risk of new technology and installation methods. Furthermore, the operational performance of floating wind projects (which is directly linked to energy production, revenue, and profitability) is more uncertain than fixed-bottom projects; if an insurance company is unsure that a floating wind project can operate damage- and defect-free for the duration of the policy (which may be less than the lifetime of the wind plant), then it may decide that the entire project is uninsurable.

Ultimately, insurance companies are focused on the likelihood that a project can be built as planned with no damage to insured infrastructure and operated within its planned design envelope. Some of the key factors that floating wind projects will have to demonstrate to underwriters include:

- A robust approach to risk management
- A reliable supply chain that can deliver components on schedule
- Adequate installation and maintenance vessel availability
- The use of technology with low risk of defects ideally backed by adequate defect warranty coverage under supply contracts
- Adequate certification from a reputable certifier
- Suitably proficient contractors
- An operations and maintenance strategy that can safely and reliably keep the wind energy power plant operating within its design envelope
- An installation strategy that mitigates risk of damage or loss.

The final two points are an important consideration for identifying the staging and integration port locations that will support floating wind projects on the West Coast of the United States.

The insurance market for floating wind energy projects is not sufficiently mature to understand exactly how port capabilities and location could impact insurance premium; however, several key factors that could impact insurance premiums and insurability include:

- Floating offshore wind project developers will likely have to pay a higher premium than fixed-bottom offshore wind developers to insure installation; however, these costs will remain a relatively low percentage of the overall capital investment (on the order of 1%).
- The biggest risk to floating offshore wind projects is not the cost of insurance but the risk that all or parts of a project are uninsurable. Existing policy frameworks such as fixed-bottom offshore wind Construction All Risk policies are a good base for floating offshore wind transport and installation, but ongoing modification to these policies will be necessary to adapt to floating offshore wind projects.
- Insuring the tow phase of a floating offshore wind project is not necessarily related to the distance between a port and the project site, although tow distance has yet to be fully evaluated by insurers, but is more focused on the project-specific risk factors along the tow. These factors include the risk of catastrophic weather events, the availability of safe harbor ports where a vessel (and wind turbine) could shelter during a storm, and the availability of qualified vessels to conduct the installation.
- Insuring other phases of a floating offshore wind project will depend on the availability of a reliable supply chain, vessels low risk of defects, appropriate certifications, and developing reliable and safe operations and maintenance strategies.

Given the uncertainty around the cost of insurance premiums for floating offshore wind projects, and the relatively low contribution of these premiums to project costs, in this study we hold insurance costs constant throughout all scenarios regardless of the distance to ports. However, it is important to understand that the insurance market and floating offshore wind technology development need to evolve in parallel so that appropriate policies can be put in place that cover all phases of project development and operation. Without these policies, floating wind projects may be uninsurable and unlikely to be constructed.

Appendix M. Challenges and Opportunities for West Coast Port Development

The analysis conducted in Section 3 and in complementary California and Oregon port studies have described some of the challenges to developing ports along the West Coast (Porter and Phillips 2016; Porter and Gostic 2022; Trowbridge et al. 2023a, 2023b). In this section, we summarize specific challenges, group them into major categories, and outline potential solutions and relevant organizations that could help to overcome these barriers. These challenges and actions also incorporate suggestions and perspectives from this project's stakeholder advisory committee. The intent of this summary is to provide a concise and actionable information that West Coast decision makers can incorporate into strategic planning exercises.

Challenge #1: Existing Port Infrastructure Is Inadequate for Commercial-Scale Floating Wind Build-Out

High-level summary: The existing capabilities of West Coast ports to support floating offshore wind deployment are insufficient and developing these capabilities will be time- and capital-intensive.

Any Potential Port Site Will Require Significant Financial Investment and Development Time

The West Coast has dozens of active ports but the requirements for floating offshore wind projects are beyond existing capabilities. Upgrading existing facilities or developing greenfield facilities would be time- and capital-intensive, and it is not clear how these investments could be spent more efficiently. The United States Department of Transportation Maritime Administration's Port Infrastructure Development Program has awarded grants of up to $48 million to offshore wind ports (U.S. Department of Transportation Maritime Administration 2022) but (as we show in Section 3.1) this level of investment is less than 10% of the anticipated investment in a staging and integration (S&I) site. Additional state and/or private capital investment will likely be required to finance West Coast floating wind ports.

Several actions that could address this challenge are listed in Table M1.

Table M1. Actions, Relevant Organizations, and Potential Outcomes To Address Port Investment

Action	Relevant Organizations	Potential Outcome
Identify the most viable sites and leverage existing studies to understand required investment	• Local, state, and federal governments • Community representatives	Port investments are made efficiently to leverage existing strengths and community perspectives
Consider funding and incentive mechanisms to encourage investment, including grants, private investment, tax credits, state budget allocations, and funds from Bureau of Ocean Energy Management bidding credits	• Local, state, and federal governments • Private investment firms • Project developers • Manufacturers	Initial investments in port infrastructure are supported through cost-sharing mechanisms that reduce investment risk
Leverage experience from fixed-bottom port development on the East Coast	• Port authorities and operators	Lessons learned from developing fixed-bottom ports streamlines the funding, planning, and development process for West Coast ports

Ports Need To Be Designed To Support a Range of Potential Floating Wind Energy Technologies and Operations

Floating wind energy is at a nascent development stage and it is not clear what types of floating platforms or stationkeeping systems (if any) will gain a dominant market share by 2045 (ABS Group 2021). Furthermore, wind turbines have grown rapidly in recent years and the future trajectory of turbine ratings is uncertain. Larger turbines will require bigger cranes, larger laydown areas, deeper navigation channels, and larger balance-of-system components; however, the advantages of continuing to upsize wind turbines may be outweighed by the benefits of industrializing a single design. Finally, the frequency at which turbines are towed back to a S&I port for repair, the duration of repair activities, and how these activities will be coordinated with installation work has not been fully established. It is unlikely that S&I ports will have dedicated repair berths because of the additional cost and intermittent need to conduct major repairs at port, so the sequencing between installation and operations and maintenance activities will potentially affect the port design. These uncertainties make it difficult to design ports because of the wide potential design envelope.

Several actions that could address this challenge are listed in Table M2.

Table M2. Actions, Relevant Organizations, and Potential Outcomes To Address Technology Uncertainty

Action	Relevant Organizations	Potential Outcome
Maintain communication to make sure that ports can support next-generation wind turbine systems	• Port owners • Manufacturers • Developers	Ports are designed with sufficient flexibility to accommodate various wind turbine ratings and floating platform designs without significant additional investment
Coordinate between port owners and project developers to understand how installation and repair scheduling can impact port design	• Port owners • Developers	A sufficient number of ports are designed and built to operate at high utilization rates without adversely affecting project installation or repair schedules
Explore alternative technologies that could reduce the demand for conventional port infrastructure	• Technology providers • Federal government • State governments • Port owners • Research institutions	The potential benefits and risks of alternate technologies are available to decision makers for strategic planning; alternative technologies could include novel floating platform designs, floating ports/dry docks, or at-sea installation or maintenance methodologies

Engagement With Tribes

We provide a high-level description in Appendix K of how both existing ports and proposed greenfield ports along the West Coast could be located at sites with immense historical or cultural significance to tribes, as well as impacting tribal practices like fishing and coastal management. Developing the dozens of ports needed to support a floating wind industry on the West Coast could potentially disrupt or damage these sites and cause irreparable harm to tribes. Many individual port authorities and communities actively engage with local tribes; however, a more systematic approach to working with and consulting tribes across the region needs to be established as part of the discussions around port planning and permitting. Additional studies could also be undertaken to understand the potential risks of disrupting cultural resources at potential port locations along the West Coast. For example, coastal archaeology studies could identify burial grounds, settlements, or other resources that are unknown to current port owners. These studies could be managed or led by tribal representatives and could identify risks, mitigation strategies, or alternate approaches to port development to minimize adverse impacts to tribes. Additionally, Indigenous community members may face greater barriers to accessing workforce and other economic opportunities created by offshore wind ports, which is another subject deserving more dedicated attention in equity and workforce development efforts.

Challenge #2: Developing an Efficient West Coast Port Network Will Require Effective Communication Between Different Stakeholder Groups

High-level summary: Developing a West Coast floating wind ports network will involve a huge number of stakeholders, which will require effective communication and coordination between these groups coupled with strategic planning from an authorized decision-making entity.

There Is No Single Decision-Making Authority That Governs Port Planning or Investment Within West Coast States or for the Overall Region

Creating a strategic plan for a port network on the West Coast will be complicated by the wide range of agencies, governments, and stakeholders that need to be consulted, including state and local governments, sovereign tribal governments, community representatives, regulatory agencies, and port owners. Without clear leadership, it will be difficult for these individual groups to effectively share their perspectives on port development and decide how funding and resources should be allocated. A dedicated intergovernmental steering committee or working group with a mandate to establish strategic plans that incorporate viewpoints from all relevant stakeholders could help overcome this barrier. The committee would need the ability to coordinate with the various entities within the region, which may include:

- Tribal leadership in potential port development locations
- The California Office of Planning and Research, which manages the California Environmental Quality Act
- The California Coastal Commission
- The California State Lands Commission
- The Oregon Coastal Management Program
- The Washington Department of Ecology
- The Washington Department of Commerce
- City and county permitting and zoning authorities
- Harbor districts, port commissions, and state/regional port associations (such as the California Ports Association and the Pacific Northwest Waterways Association)
- The U.S. Environmental Protection Agency
- The U.S. Department of Transportation
- Offshore wind project developers
- Organized labor.

The committee would be responsible for engaging with these groups, developing strategic plans for port development, and helping ports navigate the permitting and approval process.

Several actions that could address this challenge are listed in Table M3.

Table M3. Actions, Relevant Organizations, and Potential Outcomes To Address a Lack of Decision-Making Authority

Action	Relevant Organizations	Potential Outcome
Create an intergovernmental steering committee to coordinate port decision-making along the West Coast, communicate with individual ports, establish roles and responsibilities for ports and other stakeholders, and guide port investments to fit into a broader regional strategy	• State, tribal, and federal governments	A transparent strategy for port locations, development time frames, and investment mechanisms provides guidance for ports and other organizations that want to support floating wind infrastructure on the West Coast. The strategy would need to be regularly updated to accommodate new state policies or targets, perspectives from stakeholders, and new floating wind or port technologies.
Provide objective technical support to the steering committee to systematically inform decision-making	• Coastal engineering firms • Economic and environmental consultancies • National laboratories	Strategic plans developed by the steering committee are based on transparent and/or quantitative estimates of their impact on port cost, offshore wind project cost, local communities, environmental resources, and other relevant factors. The committee could engage regularly with industry advisory groups (e.g., project developers, organized labor).
Develop and maintain broader communication channels beyond the decision-making steering committee to share best practices and lessons learned	• Western Governors' Alliance • American Association of Port Authorities • State and local economic development agencies • State and local regulatory and permitting agencies • Project developers • Port owners • Vessel operators	Strategic port plans are efficiently implemented by state and local agencies that communicate effective approaches to working with stakeholders, permitting, construction, and other development activities.

Local Communities Will Be Impacted by Port Development and Should Be Involved in the Planning and Decision-Making Process

Offshore wind energy port development has the potential to create a significant number of jobs and economic benefits for host communities; however, in order for these positive impacts to be realized, communities need to be engaged early and consistently in the planning and development processes (Shields et al. 2023). Some local governments on the East Coast have voiced opposition to port development in their communities because of a perceived lack of accountability and transparency in the decision-making process (Smith 2021). In some port communities on the West Coast, there have been significant histories of environmental injustice stemming from disproportionately high pollution exposure, health burdens, and community disenfranchisement. Meaningfully incorporating local representation (including local governments, community leaders, and community-based organizations) into decision-making processes could help tailor development activities to suit the needs and preferences of the community. This type of engagement is time- and resource-intensive and would need to be appropriately budgeted for to be fully effective.

Several actions that could address this challenge are listed in Table M4.

Table M4. Actions, Relevant Organizations, and Potential Outcomes To Address Impacts on Local Communities

Action	Relevant Organizations	Potential Outcome
Encourage port owners to lead engagement with tribes and local communities to present opportunities, schedules, and risks associated with floating wind port development	• Port owners • Community representatives • Tribes	Port communities are fully aware of development plans and have opportunities to provide input and shape the development process to create attainable local benefits. This engagement could establish clear time frames, messages, and vision for development in port communities.
Stakeholders determine how they can contribute to and benefit from offshore wind energy port development through strategic plans at individual community levels	• Community representatives • Tribes	Community members have a clear vision for how offshore wind energy projects could impact them and are empowered to provide actionable input to port development processes.

Challenge #3: A Significant Workforce Will Be Required To Construct and Operate West Coast Floating Wind Ports

High-level summary: Many workers will be required to construct and operate West Coast ports, but there are not currently enough of these workers in potential port development regions.

There is an insufficient number of trained workers in likely offshore wind port development regions that can construct and operate new facilities. Many of the ports that could play major roles in West Coast offshore wind energy development, such as Humboldt and Coos Bay, are far from major population centers. The relatively small port communities may not be able to provide all of the workers needed to construct and operate the ports, and the long distances to major cities makes it unrealistic for workers to commute on a daily basis. Furthermore, there are different types of jobs that will be required at ports—construction jobs are likely to be relatively short term (several years), traditional maritime and port-related work will be ongoing, and operation jobs are likely to be long term (the lifetime of the port). These types of jobs could attract different types of workers and require different types of training programs. Many of these workers will be hired by existing U.S. companies that act as subcontractors to project developers.

Creating sustainable jobs that benefit port communities will require forethought and planning at individual ports and throughout the entire West Coast.

Several actions that could address this challenge are listed in Table M5.

Table M5. Actions, Relevant Organizations, and Potential Outcomes To Address Workforce Needs

Action	Relevant Organizations	Potential Outcome
Develop new training programs (and expand existing ones) to create high-prestige, good-paying offshore wind jobs that meet the demand of port development	• Organized labor • Manufacturers • Developers • State and local economic development agencies • Tribal governments	A consistent pipeline of workers is available when needed for West Coast port development. Workers are paid and trained appropriately so that they remain in the industry, leading to more efficient operations over time.
Coordinate with port communities to convey the workforce opportunity at West Coast ports	• Organized labor • Manufacturers • Developers • State and local economic development agencies • Tribal governments • Community representatives	Port communities have a clear understanding of how they can contribute to the workforce needed at offshore wind ports and what steps they need to take to fill worker demand (e.g., training).

Uncertain Port Construction Time Frames and Schedules Could Lead to Significant Variability in the Annual Number of Required Jobs

Upgrading or constructing an offshore wind port could require hundreds or thousands of jobs at a given time (depending on the size of the port). Overlapping construction windows for multiple ports could create an unreasonable demand for workers; conversely, years with less construction would reduce worker demand and could lead to layoffs. The nature of constructing a West Coast ports network will inherently require a series of short-term jobs in different locations (and states). Understanding how the demand for construction workers varies over time could help companies plan for hiring, training, and possibly relocation needs.

Several actions that could address this challenge are listed in Table M6.

Table M6. Actions, Relevant Organizations, and Potential Outcomes To Address Workforce Scheduling

Action	Relevant Organizations	Potential Outcome
Develop and publicize long-term plans for port construction, manufacturing, staging and integration, and operations and maintenance workforce needs	• Organized labor • Manufacturers • Developers • Construction companies	Tribes, states, regions, and communities are aware of the long-term demand for workers and can coordinate activities so that an appropriate number of workers are hired and trained for port development.

Challenge #4: Permitting and Regulatory Requirements Can Be Uncertain and/or Time-Consuming

High-level summary: Offshore wind ports on the West Coast will need to navigate a complex and time-consuming permitting process. These permits are necessary to minimize adverse impacts on various stakeholder groups, but providing greater transparency and certainty around the approval process would help with strategic planning.

Offshore wind projects face a lengthy and complex permitting process, highlighting the need for a more streamlined and transparent regulatory process. The Bureau of Ocean Energy Management has presented a regulatory roadmap to clarify the steps and time frames for developing an offshore wind energy facility (Bureau of Ocean Energy Management 2022b). Port development on the West Coast faces similar permitting challenges and could also benefit from additional transparency about permitting time frames. Streamlining regulatory processes should not be construed as an attempt to avoid or circumvent required permits, which are intended to protect environmental, community, tribal, and other considerations. However, the massive and interconnected scope of developing a series of ports along the three West Coast states will require a coordinated effort to understand how and when resources can best be invested to maximize benefits and minimize harm to local communities while also enabling broad offshore wind energy deployment. Understanding exactly what permits are required (covering both land and waterway development) and having a reasonable expectation of how long it will take to obtain these permits would simplify port planning processes.

Several actions that could address this challenge are listed in Table M7.

Table M7. Actions, Relevant Organizations, and Potential Outcomes To Address Permitting and Regulatory Challenges

Action	Relevant Organizations	Potential Outcome
Understand the resources that permitting and regulatory agencies would require to efficiently and transparently review permits	• Federal, state, and local regulatory agencies • Tribes	Decision makers that guide budgets and funding opportunities understand how investing in staffing, training, and planning activities affects port development time frames and the resulting impact on communities, tribes, and the environment.
Port owners and operators engage relevant groups and agencies at early stages of the project	• Port authorities • Tribes • Environmental groups • Energy justice groups • Federal, state, and local regulatory agencies • Community representatives	Port owners and operators have a clear understanding of the range of permits they need to obtain, needs and sensitivities within the local community, and best practices and approaches to resolving challenges and conflicts during the development process.

Challenge #5: A Floating Wind Vessel Fleet Will Need To Be Developed in Parallel With the Port Network

High-level summary: A West Coast port network will need a significant fleet of vessels to install and service offshore wind energy projects, but the requirements for this fleet are unclear and may present a challenge for U.S. shipbuilding capacity.

Uncertainty in Future Floating Wind Turbine Technology Presents an Investment Risk for New Vessels

The dozens of potential floating wind energy technologies that will be competing for a dominant market share over the next few decades do not only create a challenge for port design and development (ABS Group 2021), but vessel owners need to understand the business case for investing in a new ship. This investment could depend on the technologies and methodologies that become most common on the West Coast. For example, some floating wind system designs may rely exclusively on towing out the integrated system from the port; others may prefer that the wind turbine be installed at sea using a dynamically positioned wind turbine installation vessel; and others may pursue a hybrid approach with some at-sea operations that use a less sophisticated vessel. The vessel needs translate directly to port design requirements so that the ports can accommodate the safe navigation, maneuvering, and quayside operations of each vessel. Although most floating wind support vessels are likely to be less expensive than the approximately half-billion-dollar wind turbine installation vessels that will be required for fixed-bottom projects (Shields et al. 2023), high-bollard pull anchor handling tug supply could still cost more than $100 million each to build (Shields et al. 2022). Without a reasonable idea of the long-term demand for new vessels, investors may be hesitant to invest in a new fleet.

Several actions that could address this challenge are listed in Table M8.

Table M8. Actions, Relevant Organizations, and Potential Outcomes To Address Investment Risk in New Vessels

Action	Relevant Organizations	Potential Outcome
Maintain communication between key groups to ensure that newly built vessels can accommodate next-generation wind turbines and installation methods	• Developers • Manufacturers • Port owners • Vessel operators	Newly built vessels are designed to efficiently accommodate relevant technologies through at least 2045 with little or no need for retrofits or modifications.
Consider how novel funding mechanisms could de-risk investment in new vessels	• Vessel operators • Financial institutions • State and federal governments	The cost/benefit trade-offs between different funding mechanisms are well-understood by potential investors, such as backstop programs, shared investment between multiple developers, and allocation of state clean energy revenue.

Constrained Shipbuilding Capacity in the United States Could Limit the Number of Available Coastwise Qualified Vessels

Many of the vessels that could be required for floating wind energy installation and maintenance, such as anchor handling tug supply tugboats, and semisubmersible barges, could be subject to the Jones Act, which requires vessels that transport merchandise between U.S. ports to be U.S.-flagged. Fixed-bottom wind turbine foundations have been classified as ports by the U.S. Customs and Border Protection, requiring transportation vessels to be coastwise qualified[24] (Musial et al. 2022). The U.S. Customs and Border Protection has not issued guidance on floating foundations, but many project developers are prudently assuming that the same rules that apply to vessels used in fixed-bottom offshore wind energy projects will be in place for floating offshore wind projects. The shipyard capabilities required to build these vessels are not as complex as those required for wind turbine installation vessels; however, many shipyards have existing commitments that could limit their availability to build the expansive fleet needed for the floating wind energy industry. Some vessels, such as crew transfer vessels and service operation vessels, will be needed for both fixed-bottom and floating offshore wind projects, which could create an additional bottleneck for these ships.

Several actions that could address this challenge are listed in Table M9.

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[24] Both U.S.-flagged and foreign-flagged vessels can operate in U.S. waters and be compliant with the Jones Act, depending on the type of activities they are conducting. We use the term "coastwise qualified" to refer to vessels that are U.S.-built, U.S.-owned, U.S.-crewed, and can transport merchandise between U.S. ports.

Table M9. Actions, Relevant Organizations, and Potential Outcomes To Address Constrained Shipbuilding Capacity

Action	Relevant Organizations	Potential Outcome
Conduct a gaps analysis between the long-term demand for floating wind vessels and the availability of shipyards over the next decade	• Shipyards • Vessel operators • Developers	The floating wind energy industry understands achievable time frames and investment costs for coastwise qualified vessels to facilitate strategic planning.

Appendix N. Recommended Future West Coast Port Studies

Throughout this report, we identified several areas that need further study to better understand the impact on port development, offshore wind energy projects, and host communities. We conclude this report by summarizing the following recommended next steps.

Outreach and Coordination With West Coast Port Owners

The port screening activities presented in Appendix D indicate how the existing capabilities of ports on the West Coast could be suited for different offshore wind energy activities. The results are based on a desktop study of the port capabilities and the authors' understanding of individual ports' interest in offshore wind. Ultimately, a port's decision to invest in offshore wind energy is a business decision that will depend on the risks and benefits perceived by that port's decision makers. California port owners were surveyed about the results of this screening as part of the AB525 study (Trowbridge et al. 2023a) and had the opportunity to provide feedback on the findings. It will be critical to conduct this same outreach and engagement with specific ports in Oregon and Washington to confirm this report's characterization of their capabilities and to understand their position on investing in offshore wind. The results of this study, coupled with the ongoing development of the offshore wind energy industry, can help provide information to frame these discussions.

Detailed Vessel and Shipbuilding Assessment

A floating wind port network will be intricately linked to the operating vessel fleet. In this report, we conducted a preliminary assessment of the needs of vessel for various levels of offshore wind deployment, including anchor handling tug supply vessels and support tugboats. The assessment provided in Appendix H relies on several high-level assumptions about deployment rates, port logistics, project sizes, technology choices, and vessel spreads per project. Furthermore, it does not consider how specific vessels could be used for multiple installation phases and requires more detail about how one vessel could transition between projects. Finally, additional vessels need to be considered, specifically the demand for semisubmersible barges at individual ports. We suggest that a detailed vessel gaps assessment should be conducted that explores a range of technology, deployment, and logistics scenarios to better understand the range of vessels needed for commercial-scale floating wind deployment, the time frame when these vessels need to be available, the cost and construction times for different vessels, and the capability and capacity of U.S. shipyards to meet this demand.

Detailed Assessment of Floating Wind Staging and Integration Port Logistics

One of the important findings within this report is that platform assembly and wind turbine integration activities at a staging and integration (S&I) port represent some of the most significant schedule bottlenecks for a floating offshore wind energy project. There are many parameters that influence installation schedules, including process times, number of available S&I sites at a port, weather, distance to the lease area, vessel capabilities, supply chain reliability, and wet storage space. Investing in any of these areas could accelerate commercial-scale floating offshore wind project deployment, but the opportunity cost between different pathways is not clear (and may vary between regions, ports, or technology choices). A cost/benefit trade-off study between different alternatives that highlights the most impactful ways to increase throughput at S&I sites could point the industry toward making the most useful investments.

Detailed Assessment of Floating Wind Operations and Maintenance Strategies

In this report, we conduct a basic assessment of the impacts of port proximity on offshore wind project cost, and find that the majority of the increase in levelized cost of energy is driven by operations and maintenance (O&M) costs. In this analysis, we assume that the wind turbines are towed back to a S&I port for major repair; however, this may not be the best strategy for commercial-scale floating wind projects. There is a need for a more detailed O&M study that presents cost/benefit trade-offs between various strategies and considers parameters such as port availability, vessel demand, uncertainty in failure rates, weather, human safety, and novel technologies or strategies to reduce downtime.

West Coast Ports Workforce Skills Assessment

The supply chain assessment that we describe in Section 3.4 identifies the number of manufacturing jobs that could be created by a domestic supply chain; however, we do not estimate the number of construction workers or port workers that would be required to build and operate new ports on the West Coast. This study provides several scenarios for where manufacturing/fabrication, S&I, and O&M ports could be located in California, Oregon, and Washington. An important next step would be to look at the individual port sites and estimate the construction and maritime workforce required to build the work, the number of workers needed to conduct offshore wind operations, and the specific skill sets and qualifications these workers need. This workforce demand should then be compared against the skill set of existing workers in West Coast states, tribes, and labor unions to understand the gaps between workforce supply and demand and identify pathways needed to train new workers to fill these gaps. Such a skills assessment should consider how to make these thousands of jobs available to port communities that will be affected by the development of the offshore wind energy industry.

Life Cycle Assessment of Floating Offshore Wind Energy

In the present study, we outline a methodology for estimating the vessel emissions associated with the transportation, installation, and O&M of floating offshore wind projects. While these estimates serve as useful points of comparison for the assessed scenarios, they do not fully capture the total emissions that might occur at or near ports as a result of floating offshore wind activities. The manufacturing of offshore wind turbine components, which often occurs at port, includes energy-intensive processes such as fabrication of steel plates, splicing and welding of steel components, and casting and forging of large components (Shields et al. 2023). Thus, manufacturing activities have the potential to contribute significant emissions and should be considered when assessing the impacts of offshore wind energy on life, land, and sea. Furthermore, developing offshore wind ports can have significant environmental impacts (particularly dredging channels near protected marine areas) and should be accounted for within the life cycle environmental impact. A thorough life cycle assessment of floating offshore wind energy projects (including infrastructure and supply chain considerations; decommissioning; and repowering) could help decision makers understand the impacts of various technologies or deployment levels on greenhouse gas emissions, pollutants, water use, resource depletion, marine ecotoxicity, and terrestrial ecotoxicity. Such a study could also present cost/benefit trade-offs for emission reduction strategies such as electric or alternate fuel vessels, or emission capture-and-control technologies.

Floating Wind Risk Assessment and Project Insurability

The levelized cost of energy analyses conducted in this report (as well as most other floating wind energy assessments) typically assume that project insurance and financing are reasonably similar to fixed-bottom offshore wind projects; however, insurance underwriters and financing organizations have concerns about supply chains, technology maturation, component manufacturing, project certification, and logistics strategies for floating wind projects that could lead to higher costs of capital or, in an extreme case, premiums that are so prohibitively high that a project is effectively uninsurable. A study that characterizes and presents the major floating offshore wind risks, estimates their potential impact on financing and insurability, and evaluates various mitigation strategies (such as technology maturation or novel insurance mechanisms) would help provide a common perspective for the industry to build on.