Floating Offshore Wind Energy Infrastructure

Karina Nielsen and Bryson Robertson, Editors

Introduction

The Rationale for Development of Floating Offshore Wind Energy Along the U.S. West Coast

Karina Nielsen and Bryson Robertson

The policy goal of limiting climate change by decarbonizing and electrifying the energy sector is driving rapid development and innovation of offshore wind energy technologies, including floating offshore wind. The U.S. West Coast is an attractive location for development of offshore wind energy because of its strong and reliable offshore winds (Figure 1).

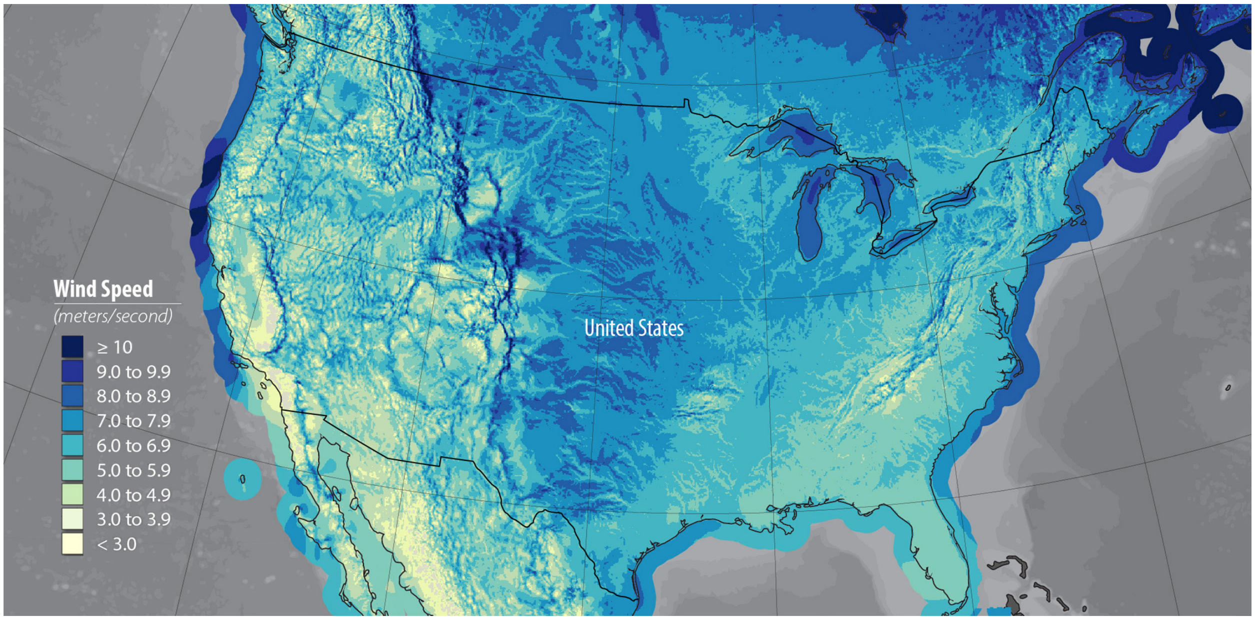

Figure 1. Annual average wind speed at 100 m (328 ft.) above the surface of the contiguous United States and the adjacent 50 nautical mi. (57.5 mi.; 92.6 km). Modified from a figure produced by the National Renewable Energy Laboratory (www.nrel.gov/gis/assets/images/wtk-100-north-america-50-nm-01.jpg).

Accessing these winds, which are over ocean waters much deeper than 60 m (197 ft.), will require the use of floating offshore wind (FOSW) energy instead of fixed-bottom technologies (Figures 2, 3). Wind turbines deployed at sea are classified as either fixed-bottom or floating. Fixed-bottom offshore wind turbines are attached to foundations that are rigidly affixed to the seafloor. In contrast, floating offshore wind turbines are attached to floating foundations that are held in place by mooring lines connected to anchors on the seafloor.

As of 2024, the four FOSW arrays in operation worldwide are off the coasts of Scotland, Portugal, and Norway (173.5 MW of generating capacity). The arrays are WindFloat Atlantic (8 MW; Windfloat Atlantic n.d.), Hywind Scotland (30 MW; Equinor n.d. a), Kincardine Offshore Wind Farm (47.5 MW; Principle Power n.d.), and Hywind Tampen (88 MW; Equinor n.d. c). They are from 15 to 140 km (8 to 76 nautical mi.) offshore at depths of 60 to 300 m (197 to 984 ft.) and represented 0.2 percent of global offshore wind generating capacity in 2023. The cumulative generating capacity of all offshore wind installations in 2023, most of which are in Europe and Asia (GWEC 2024) and use fixed-bottom technologies (Figure 3), was 75,200 MW (72.5 GW).

Figure 2. General locations off the coast and within lakes of the United States where water depth (maximum 1300 m [4265 ft.]) and wind speeds are sufficient for installation of fixed-bottom (yellow) and floating (blue) wind energy turbines. Image does not consider potential siting constraints. Modified from a graphic by Philipp Beiter, National Renewable Energy Laboratory.

Although no FOSW arrays currently operate in U.S. federal waters, in 2022 the Bureau of Ocean Energy Management sold the first five U.S. leases for FOSW along the West Coast near Humboldt Bay and Morro Bay, California (BOEM n.d. a). Since then, the Bureau of Ocean Energy Management engaged with federal, state, and local agencies and tribal governments through the Oregon Intergovernmental Renewable Energy Task Force to identify additional lease areas off the coast of Oregon.

The Bureau of Ocean Energy Management planned to hold an auction to sell two more lease areas in U.S. federal waters near Coos Bay and Brookings, Oregon (BOEM n.d. b), in October 2024. However, on 27 September 2024, the Bureau of Ocean Energy Management postponed the lease auction due to insufficient bidder interest (BOEM 2024). Simultaneously, Governor Kotek withdrew Oregon from the Oregon Intergovernmental Renewable Energy Task Force. In a letter to the Bureau, the Governor cited the need to complete the Oregon Offshore Wind Energy Roadmap before a lease sale; concerns of tribes, sectors, and the public; the risks that a failed lease process would pose to Oregon's developing supply chain industry; and potential risks to offshore ecosystems; while also stating her confidence "that offshore wind holds exciting promise to be part of our nation's clean energy future" (Kotek 2024). The Bureau of Ocean Energy Management intends to continue working with federal, state, and local agencies and tribal governments and to support the state-led offshore wind energy roadmap process, as directed by Oregon House Bill 4080 (passed in 2024), to determine opportunities for a future lease sale.

The potential development of FOSW off the coast of Oregon has prompted a range of responses, opinions, questions, and concerns from Oregonians and tribes (Informal Offshore Wind Work

Group 2024). In this chapter, we explore why FOSW is being pursued off the U.S. West Coast, describe the floating offshore infrastructure being considered, and examine potential interactions of this infrastructure with the ocean environment and coastal human communities. The scope of our exploration includes the at-sea infrastructure, supporting port infrastructure, and shore-based transmission stations. The many other infrastructure topics that are beyond the scope of this chapter include inland transmission, storage, supply chain, manufacturing, procurement, and the vessels needed to support deployment. Our discussion of environmental interactions with FOSW infrastructure focuses on wind-driven upwelling, underwater sound, electromagnetic fields, entanglement hazards, and fishes. The chapter also explores public perceptions, energy and environmental justice, and community benefit plans related to FOSW. Environmental and societal topics that also were beyond the scope of this chapter include potential effects of FOSW on birds, bats, marine mammals, fisheries, tribal cultural resources, and tribal federal trust and treaty rights.

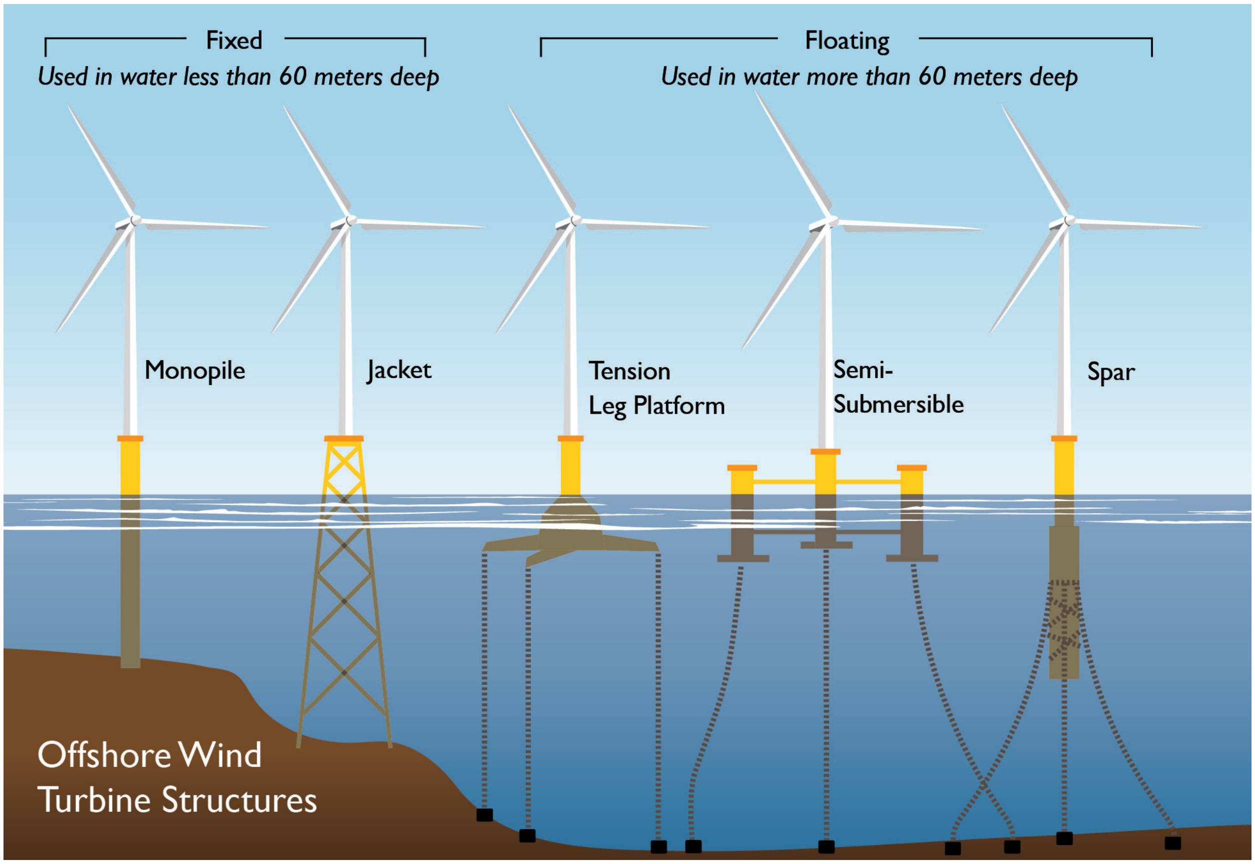

Figure 3. Fixed-bottom and floating offshore structures for wind turbines. Graphic by Allison Walkingshaw.

International and National Efforts to Limit Climate Change

Several substantive international, national, and state-level policies are contributing to actions and innovations to decarbonize the energy sector and reduce greenhouse gas emissions with the goal of limiting climate change. The United States is a party to the Paris Agreement, an international treaty to limit climate change that was adopted in 2015 (UNFCCC n.d. a). Members of the Paris Agreement were required to submit a national climate action plan, also known as a Nationally Determined Contribution (UNFCCC n.d. b), in 2020, and must update the plan every five years. In its first submission, the United States set an economy-wide target of reducing its net greenhouse gas emissions by 50–52 percent below 2005 levels by 2030 (United States 2021). In setting this target, the United States described taking an all-of-government and sector-by-sector approach to reducing greenhouse gas emissions by decarbonizing the energy sector, increasing carbon sink capacity and reducing greenhouse gas emissions from natural and agricultural systems, and reducing emissions of greenhouse gases other than carbon dioxide.

Achieving its energy sector decarbonization goal will require the United States to rapidly deploy solar and wind technologies while reducing the percentage of energy derived from fossil fuels and increasing the percentage of electricity produced by non-carbon emitting sources to at least 75 percent by 2030 (NASEM 2021). The International Energy Agency's Net-Zero Roadmap further clarifies that rapid deployment of commercially available technologies and widespread use of technologies that are not commercialized yet will be required to reach the net zero carbon goal by 2050 (IEA 2021). About 45 percent of the reduction in carbon dioxide emissions necessary by 2050 relies on extant technologies that need to be commercialized.

In 2021, the White House issued Executive Order 14008, which directed the Secretary of the Interior and other relevant federal administrators and agencies to increase renewable energy production on public lands and offshore waters. The executive order included a goal of doubling "offshore wind by 2030 while ensuring robust protection for our lands, waters, and biodiversity and creating good jobs." Offshore wind energy is a relatively mature wind technology, and the United States has set ambitious and aggressive goals to advance and deploy wind energy in support of energy sector decarbonization. In 2021, the White House set the goal of deploying 30 GW of offshore wind by 2030 (The White House 2021), and in 2022, it added another 15 GW to its floating offshore wind energy goal for 2035 (The White House 2022).

The U.S. federal government made an unprecedented commitment to and investment in the modernization and decarbonization of the U.S. energy system through the Infrastructure Investment and Jobs Act of 2021 (House Bill 3684; commonly called the Bipartisan Infrastructure Law) and Inflation Reduction Act of 2022 (House Bill 5376). The Congressional Budget Office estimated that total support for the climate and clean energy programs, tax credits, and other incentives authorized through the two acts will exceed $430 billion from 2022 through 2031 (Steinberg et al. 2023).

The Inflation Reduction Act includes multiple provisions related to offshore wind leasing, transmission planning, and tax credits (CRS 2022). One of the provisions set a new limit on the Bureau of Ocean Energy Management's authority to issue offshore wind leases through 2032: it may not issue a lease for offshore wind development unless it has also offered at least 60 million acres (93,750 mi^2 or 242,800 km^2) for oil and gas leasing on the outer continental shelf during the previous year. Given this constraint, and the 2024 postponement of the planned lease sale by the Bureau of Ocean Energy Management, the next opportunity for a lease sale off the Oregon coast will occur in 2026. 2026 is the year after the next proposed offshore oil and gas lease sale on the Bureau's leasing schedule for the outer continental shelf. The combination of these provisions, the administration's goals for offshore wind energy, and the substantial federal investments and provisions approved by Congress has been driving the rapid and constrained timeline for the Bureau of Ocean Energy Management to complete its planned offshore wind lease auctions.

The White House also projects that its policies to develop a U.S. offshore wind industry will deliver social and economic benefits including jobs, domestic manufacturing and supply chains, and improvements in port infrastructure, and will contribute to addressing historical inequities in energy development (Biden 2023, Ocean Policy Committee 2023). A study of the social and economic effects of European offshore wind energy arrays developed since 2010 indicated that the economic benefits of the local offshore construction stage were substantially overestimated due to imported labor and skills (Glasson et al. 2022). Other economic benefits over the offshore wind lifecycle, including onshore construction and, especially, the 20–25 years of the operation and management stage, were underestimated (Glasson et al. 2022). The data on social effects were much more limited; the overall impact on well-being was positive, but effects on aspects of social capital were less positive (Glasson et al. 2022). Although it is too soon to analyze the economic benefits of offshore wind array development in the United States, land-based wind energy installations in the country have meaningful employment and earnings impacts that extend beyond the construction phase (Gilbert et al. 2024). Earnings and employment among workers who were male, Black, or without a high school or college degree were higher within 32 km (20 mi.) of a project (Gilbert et al. 2024). However, the increases in spending and investment were lower than is typical of other industries.

Several technical value propositions support the development of offshore wind energy. These include the ability of offshore wind turbines to generate large amounts of reliable power. Because no mountains or buildings obstruct wind flow over water, wind speeds tend to be higher and more consistent, and wind less turbulent, over water than on land (Wilson and Zimmerman 2023). Additionally, many areas suitable for offshore wind energy arrays tend to have stronger winds in the afternoon and evening than in the morning (although this diurnal effect diminishes farther offshore). Therefore, offshore wind arrays continue generating power in the evening and in winter, when solar energy generation decreases. This characteristic of offshore wind aligns with daily power demand cycles and can complement other variable or intermittent renewable energy sources, such as solar and land-based wind.

As the energy sector is decarbonized, the percentage of variable or intermittent renewables in the energy sector portfolio, also referenced as their penetration, will increase. For energy and electricity demand to be met reliably and consistently, the increasing penetration of renewables must be complemented by a suite of baseload and dispatchable energy sources and energy storage. Baseload generation has a consistent power output and its production does not increase or decrease over short periods of time. Examples of baseload generators include coal-fired generators and nuclear facilities. Production by a dispatchable energy source can be increased or decreased on demand to adjust the power output supplied to the electrical grid. Examples of non-variable dispatchable generators include natural gas generators and hydroelectric, hydrogen-generated, and some geothermal power sources, albeit the dispatchability of hydropower depends on the amount of water stored behind the dam. Furthermore, hydropower is vulnerable to climate change given evolving operational restrictions related to riverine ecosystems and projected future extreme storms, droughts, and asynchronous timing of changes in supply and demand (Kao et al. 2022). As penetration of wind and solar energy sources increases and use of baseload coal declines, use of dispatchable natural gas is increasing to fill the gap (EIA 2023). Interest in expanding nuclear energy capacity to meet energy needs is also growing (Mandler 2024, Plumer 2024, Sierra 2024). Other sources of clean energy and energy storage lag in coming to market.

An emerging and substantive concern is that the demand for energy is increasing faster than previously projected. Five-year growth projections almost doubled, from 2.6 to 4.7 percent, between 2022 and 2023 (Wilson and Zimmerman 2023). New data centers (including cryptocurrency and artificial intelligence) and industrial facilities (primarily semiconductors, batteries, and automotive, but also hydrogen) are two of the main drivers of this sudden growth in energy load (Wilson and Zimmerman 2023). Building and transportation electrification (e.g., heat pumps, electric vehicle chargers) are also increasing demand over longer periods of time, but are less volatile. The combination of demand increases, decarbonization targets, and a limited number of new low-carbon technologies for energy generation creates uncertainty in the future of Oregon's electricity sector.

Oregon's Energy Sources

In 2021, nearly half of the electricity that supplied Oregon's demand was generated via the combustion of fossil fuels (Table 1). Natural gas accounted for the largest percentage of fossil fuels (24.5 percent), followed by coal (21.8 percent) (ODOE 2022). Hydropower, wind, and nuclear generated 38.4, 9.3, and 3.1 percent of Oregon's electricity, respectively. There is a cost to generating electricity regardless of the energy source, but not all sources of energy incur costs. Most forms of renewable energy, such as wind and sun, are free and abundant. Therefore, the costs of electricity generated from most renewable sources are relatively stable. By contrast, fossil fuels must be mined, processed, and transported. As a result, they have a cost and their availability can be constrained, causing the costs of electricity generated from fossil fuels to be more variable than the costs of electricity generated from renewables. Costs of electricity generated from fossil fuels can also be volatile and high if and when supply-chain constraints cause fossil fuels to become scarce. Another, non-monetary cost of fossil fuels is the greenhouse gases they emit when combusted.

Resource	Percentage	Millions of MWh
Hydropower	38.4	22.10
Natural gas	24.5	14.07
Coal	21.8	12.55
Wind	9.3	5.37
Nuclear	3.1	1.76
Solar	1.7	0.98
Biomass	0.6	0.35
Other non-biogenic	0.1	0.08
Biogas	0.1	0.07
Geothermal	0.1	0.06
Petroleum	0.1	0.05
Other biogenic	0.1	0.04
Waste	0.1	0.03

Table 1. Oregon electricity resource mix for investor- and consumer-owned electric utilities serving Oregon in 2021. MWh, megawatt-hours. Source: www.oregon.gov/energy/energy-oregon/pages/electricity-mix-in-oregon.aspx.

Oregon's clean electricity law (House Bill 2021), passed in 2021, requires that Oregon's two largest investor-owned utilities, Portland General Electric and PacifiCorp, and the state's electricity service suppliers reduce the greenhouse gas emissions from the electricity they use to meet Oregon demand by 80 percent below the baseline by 2030, 95 percent by 2035, and 100 percent by 2040.

In 2021, via House Bill 3375, the Oregon Legislature set a state goal to plan for the development of up to 3 GW of floating offshore wind within the federal waters off the Oregon coast by 2030, but it has neither set a state deployment target nor mandated or created specific incentives for procurement of floating offshore wind by Oregon utilities. The 2022 Floating Offshore Wind Study by the Oregon Department of Energy (as charged by the legislature in House Bill 3375) concluded, "Achieving Oregon's economy-wide decarbonization and clean electricity policies will require developing a tremendous scale of new renewable generation projects." Land-based wind and solar renewable resources remain the lowest cost and fastest growing renewable energy resources in Oregon, as other renewable generation technologies are not yet commercially mature, scalable, and deployable.

FOSW offers many advantages and challenges. Key benefits identified by the Oregon Department of Energy reflect national findings and include the reliably strong and consistent winds off the Oregon coast, FOSW's complementarity to other renewables, its potential to offset land-use impacts related to the development of onshore renewable energy sources, and its potential to enhance power system reliability, local energy resilience, and economic development, especially for coastal communities. The major challenges include concerns about adverse effects on coastal communities, existing industries, and the environment and cultural resources; siting and permitting approvals; technology readiness and costs of commercial-scale deployment; upgrades to port infrastructure needed to support initial construction and ongoing operations and maintenance; necessary improvements to transmission infrastructure; and commitments to procure the power.

In contrast to California and other regions of the United States, the Pacific Northwest (Idaho, Montana, Oregon, and Washington, as defined by the 1980 Pacific Northwest Electric Power Planning and Conservation Act [Senate Bill 885]) does not have a centralized and independent regional transmission provider or a centralized power market. Instead, the many transmission and power providers in the Pacific Northwest each conduct their own local transmission and power planning and generally contract bilaterally for transmission and power services. In other regions, Regional Transmission Organizations and Independent System Operators provide centralized transmission planning and operate centralized power markets, both of which help to optimize power and transmission planning and procurement to serve regional loads more efficiently and cost effectively. Additionally, unlike several East Coast states, neither Oregon nor California has created specific incentives for offshore wind or mandated its procurement through state policies, such as a state-wide power purchase agreement or offshore wind renewable energy certificates, to support explicit offshore wind procurement goals. To realize gigawatt-scale FOSW development to serve Pacific Northwest customers, Pacific Northwest utilities would likely need to collaborate with each other or cooperate with utilities outside the region to plan and commit to the necessary procurement agreements and transmission infrastructure investments (Sierman et al. 2022).

West Coast Energy Policies and Strategies

Jason Sierman, Joni Sliger, and Stephanie Kruse

The states of Oregon, Washington, and California have mid-twenty-first century goals for economy-wide decarbonization and 100 percent clean electricity. As of 2021, the populations of Oregon, Washington, and California were 4.3, 7.7, and 39.2 million, respectively. California's large population, associated demand for energy, and clean energy and climate policies are currently the primary motivations for pursuing development of floating offshore wind (FOSW) along the West Coast.

California Assembly Bill 525, passed during the 2021–2022 legislative session, directed the California Energy Commission to establish state policy targets for FOSW development and produce a government-wide strategic plan to help meet those targets. In 2022, the California Energy Commission established a state target of developing 2 to 5 GW of FOSW by 2030 and 25 GW by 2045. California has also committed to making the port and transmission infrastructure investments that are prerequisites to deploying several gigawatts of FOSW projects. California's actions have significant effects on the opportunities and challenges for deploying FOSW anywhere along the West Coast, including ocean areas adjacent to Oregon and Washington.

Oregon Clean Energy and Climate Policies

To reduce emissions of greenhouse gases and mitigate climate change and its effects, Oregon has enacted some of the most aggressive economy-wide decarbonization and renewable and clean energy goals in the nation. These include several major bills passed by the legislature in 2007 (House Bill 3543), 2016 (Senate Bill 1547), and 2021 (House Bill 2021) and Executive Order No. 20-40, issued by Governor Kate Brown in 2020. House Bill 3543 established Oregon's goal of reducing greenhouse gas emissions to 75 percent below 1990 levels by 2050. Senate Bill 1547 increased Oregon's Renewable Portfolio Standard, requiring Oregon's largest consumer-owned utilities to achieve 25 percent renewables by 2025 and its largest investor-owned utilities to achieve 50 percent renewables by 2040. Senate Bill 1547 also requires investor-owned utilities to remove coal power costs from rates by 2030. House Bill 2021 requires Oregon's two largest investor-owned utilities and its electricity service suppliers to provide 100 percent non-greenhouse gas-emitting electricity by 2040. Executive Order 20-40 called for the state to reduce its greenhouse gas emissions by at least 80 percent below 1990 levels by 2050. The latter mandate led to the Oregon Department of Environmental Quality's ongoing rulemaking to establish the state's Climate Protection Program, which proposes to require a 50 percent reduction in greenhouse gas emissions from fossil fuels used in Oregon by 2035 and a 90 percent reduction by 2050.

Oregon Offshore Wind Policies

The Oregon Legislature passed bills regarding FOSW in 2021 (House Bill 3375) and 2024 (House Bill 4080). House Bill 4080 directs the Oregon Department of Land Conservation and Development to lead engagement with and gather input from diverse interested parties, tribes, communities, and state agencies to develop a state offshore wind roadmap that supports public engagement; coastal communities; new economic opportunities and sustained existing economies; a local, trained, housed and equitable FOSW workforce; protection of tribal cultural and archaeological resources, viewsheds, and other tribal interests; protection of the environment and marine species; and achievement of state energy and climate policies, including energy diversity, reliability, and resilience of state and regional energy systems. A report on the roadmap and related standards must be submitted to the Oregon Legislature by 1 September 2025.

House Bill 4080 also includes three state policies. The first supports engagement among developers, stakeholders, and communities. The second supports the interconnection of FOSW projects in ways that promote reliability and resilience of Oregon's power grid. The third supports economic diversification and quality workmanship in the development and operation of FOSW and port infrastructure projects by requiring and defining strong labor standards.

House Bill 3375 directed the Oregon Department of Energy to study and report on the benefits and challenges of integrating up to 3 GW of FOSW into Oregon's power grid by 2030. This study and the report were completed in 2022. The bill also set two state policy goals for offshore wind: a goal to plan for the development of up to 3 GW of FOSW within the federal waters off the Oregon coast by 2030, and a goal that the planning be conducted in a manner that maximizes benefits to Oregon while minimizing conflicts among FOSW projects, the ocean ecosystem, and ocean users. The former goal is not an explicit deployment target and does not designate an entity to procure the power. House Bill 3375 does not direct the state (or any state agency) to conduct the strategic planning necessary to mobilize the capital investments required to deploy FOSW at a gigawatt scale. Nor does it mandate or create incentives for procurement of FOSW by Oregon utilities. Given this context, the first planning goal has not been interpreted as a minimum or maximum bound on potential FOSW development off Oregon's coast.

In response to the two state policy goals for FOSW planning, the Oregon Department of Energy added offshore wind-related data into its development of the Oregon Renewable Energy Siting Assessment mapping tool. The Oregon Department of Energy also submitted comments to the

Bureau of Ocean Energy Management supporting the bureau's identification of ocean areas capable of accommodating up to 3 GW of FOSW development and participated in several studies exploring the potential transmission infrastructure necessary to connect gigawatts of FOSW to the regional power grid.

Oregon's Energy Strategy

As directed by House Bill 3630 (pased in 2023), the Oregon Department of Energy is developing a comprehensive state energy strategy that identifies optimized pathways to achieving the state's energy policy objectives. The department has reached out to tribes and engaged with the public, data holders, and other state agencies to ensure that the strategy is informed by Oregon-specific data and the real-world experiences of Oregonians, communities, businesses, and industry. Development of the strategy is ongoing and will be completed by 1 November 2025.

In summer 2024, the Oregon Department of Energy began to quantitatively model and assess the ability of candidate clean electricity technologies, including FOSW, to contribute to reliably and affordably meeting state and regional demands for clean electricity. The modeling will include scenarios that explore different pathways to meet Oregon's energy policy objectives by considering and evaluating different risks and uncertainties, such as constraints to interstate transmission. The analysis will examine resource development, cost, and other effects associated with different potential futures. Complementary technical analyses will assess how each scenario could affect jobs, household energy costs, and public health. The next phase of the Oregon Energy Strategy process will draw on the results of the modeling and technical analyses to inform policy recommendations.

Jurisdictional Boundaries, Regulations, and Permits

Jeff Burright

The regulatory and permitting process associated with an offshore wind project is complex, involving multiple entities at multiple levels of government. Components of the project, such as shoreside support facilities, navigation channel modifications, transmission infrastructure improvements, and the offshore installation itself, generally are distinct permit actions that may require separate but interdependent permitting processes.

Numerous federal, state, and local permits, authorizations, and consultations are required before an offshore wind project installation is allowed to proceed (Table 2). The primary authorizations for a project in federal waters are a Construction and Operations Plan from the Bureau of Ocean Energy Management and a permit issued by the U.S. Army Corps of Engineers under the Clean Water Act and Rivers and Harbors Act. These federal authorizations also trigger the need for an assessment of environmental impacts under the National Environmental Policy Act of 1969 and state federal consistency review under the Coastal Zone Management Act of 1972.

Under the Coastal Zone Management Act, federally approved state coastal programs have the authority to review federal actions (including federal licenses and permits for offshore wind) that may affect coastal resources and uses with respect to the actions' consistency with state enforceable policies. In Oregon, these policies are drawn from existing state statutes and rules, the 19 Statewide Planning Goals, and the local embodiment of the goals in city and county plans and codes.

Oregon's review authority has been approved by the National Oceanic and Atmospheric Administration's Office for Coastal Management to extend into a portion of federal jurisdictional

Authority	Agency	Application	Format of decision	Purpose
Federal regulatory	Bureau of Ocean Energy Management	Construction and operations plan	Approval to develop	Approve a use of the Outer Continental Shelf to produce energy
	U.S. Army Corps of Engineers	§404 (Clean Water Act)	Permit	Regulate discharges to waters of the United States and permit construction of structures in or over any navigable water of the United States
		§10 (Rivers and Harbors Act)	Permit	
Federal consultation	National Oceanic and Atmospheric Administration; National Marine Fisheries Service	Magnuson-Stevens Fishery Conservation and Management Act; Marine Mammal Protection Act	Biological opinion	Conserve essential habitat for federally managed fishes; protect marine mammals
	U.S. Fish and Wildlife Service	Endangered Species Act consultation	Biological opinion	Ensure that the action shall not jeopardize listed species or designated critical habitat
	U.S. Army Corps of Engineers	National Historic Preservation Act §106 Consultation	Report	Protect historical properties and archaeological resources
Subject to federal consistency review				
Federal authority delegated to the state	Department of Environmental Quality	§ 401 Clean Water Act beneficial use	§ 401 certification	Protect water quality standards
	Department of Land Conservation and Development, Oregon Coastal Management Program	Consistency certification and necessary information	Federal consistency	Ensure that federal licenses and permits are fully consistent with state enforceable policies
State agency regulatory authority	Department of State Lands	Removal-fill	Permit	Protect wetlands and waters for home, commercial, wildlife habitat, public navigation, fishing, and recreational uses
		Proprietary lease	Lease	Manage state submerged and submersible lands in the public trust
	Oregon Parks and Recreation Department	Ocean shore	Permit	Approve ocean shore alterations and protect the free and uninterrupted use of ocean shores
	Oregon Parks and Recreation Department-State Historic Preservation Office	Archaeological resources	Permit	Protect historical properties and archaeological resources
State consultation	Oregon Department of Fish and Wildlife		Consultation	Optimally manage fishes caught for human consumption; protect wildlife
	Oregon Department of Energy		Consultation	
Local government	City or county	Permit (conditional use)	Land use	Ensure that shoreside portions of projects are consistent with Oregon Statewide Planning Goals

Table 1. Regulatory overview of an offshore wind energy installation.

waters for marine renewable energy projects, recognizing that a project in federal waters has reasonably foreseeable effects on state coastal resources and uses. The review authority for marine renewable energy projects (defined by a Geographic Location Description, one of which Oregon maintains for renewable energy projects; DCLD n.d.) extends to approximately 32–80 km (20–50 mi.) offshore and is delineated by the 500-fathom (914.4 m or 3000 ft.) depth contour. The portions of projects within state jurisdiction, such as those related to water quality, uses of the seafloor, effects on the ocean shore, and effects on estuaries, shorelands, and uplands within local jurisdiction, also are subject to permits and authorizations.

The Oregon Department of Land Conservation and Development is the lead state agency for these federal consistency reviews. The Oregon Coastal Management Program within the Department of Land Conservation and Development coordinates with other local, state, and federal agencies and consults with tribal nations in the review of any proposed project. This networked program, which is federally approved under the Coastal Zone Management Act, includes the authorities, policies, and subject-matter expertise of 11 state agencies, 8 counties, and 33 cities in the coastal zone. The program incorporates over 3,000 enforceable policies that apply to federal actions with coastal effects. At the conclusion of the review, the Coastal Management Program may concur that the activity is consistent, concur with conditions, or object on the grounds that the activity is inconsistent with the state's enforceable policies. If a review of a federally permitted project results in an objection, the federal agency will not issue the permit to the applicant. The applicant may appeal an objection to the U.S. Secretary of Commerce.

Offshore wind projects require the development of offshore transmission infrastructure that crosses state waters, port infrastructure, and onshore transmission infrastructure that connects the project to Oregon's onshore grid. Each of these infrastructure developments requires permitting reviews from local, state, and federal authorities. Federal consistency review also applies to development activities within state waters, such as routing subsea transmission cables and onshore connection infrastructure. Any alteration to Oregon's shoreline, estuaries, wetlands, or navigation channels to facilitate the deployment of offshore wind projects also is subject to federal consistency review.

The full permitting process for an offshore wind project may take years of coordinated effort, with a high burden of information. The construction, installation, and decades of operation of floating offshore wind in Oregon are novel uses in a region that prioritizes protection of its living renewable ocean resources. Uncertainties about the individual and cumulative effects of development on natural, economic, and social systems are of great concern to potentially affected communities.

Floating Offshore Wind Energy Infrastructure, Transmission, and Ports

Floating Offshore Wind Infrastructure

Bryson Robertson and Travis Douville

Offshore wind systems are generally classified as fixed-bottom or floating (Figure 3). Most global offshore wind deployments are fixed-bottom, whereas those off the U.S. West Coast will be floating. Fixed-bottom offshore wind turbines are attached to foundations that are rigidly affixed to the seafloor through an embedment monopile or a jacket foundation. The installation machinery and structural members of fixed-bottom systems require water depths less than about 60 m (200 ft.). The ocean floor along the U.S. West Coast is much deeper, and therefore cannot support fixed-bottom systems. For example, the current Oregon wind energy areas have water depths of 600 m (1970 ft.) to 1300 m (4265 ft.).

A floating offshore wind (FOSW) system has four major subsystems: the turbine subsystem, which includes the rotor blades, hub, nacelle, and tower; floating platform subsystem; mooring and anchoring subsystem, and balance of plant, which includes the grid connection, cables, and electrical components (Figure 4).

Wind Turbine Subsystem

The wind turbine rotor blades, hub, and nacelle (which houses the generators, converters, transformers, controllers, and potentially gearboxes) harness ocean winds to create lift on the blades. This lift creates the forces necessary for rotation of the hub to drive the generator within the nacelle and create electrical power. Although land-based and offshore wind turbines are substantially similar, offshore blades, hubs, and nacelles are significantly larger than those on land.

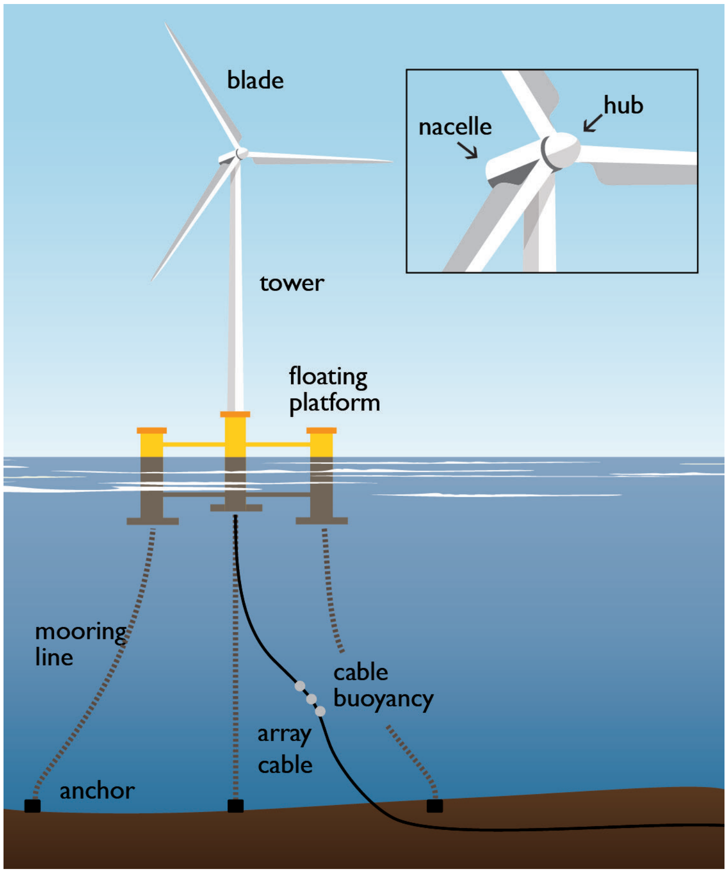

Figure 4. Components of a floating offshore wind system. Graphic by Allison Walkingshaw.

The comparatively large size of offshore rotor blades is driven by higher and more consistent wind speeds and lower turbulence and boundary layer effects offshore, the ability to transport larger blades by sea than on land, continuous improvements in the composite materials from which the blades are constructed, and the ability to increase the capacity factor (a metric that indicates the efficiency of the system) and reduce overall costs of energy by maximizing the energy produced at each turbine. Major offshore wind turbine components are manufactured by international companies such as Vestas, Siemens Gamesa, and General Electric. The diameter of a Vestus 15 MW offshore wind turbine, which is often cited as a potential system for Oregon, is 236 m (774 ft.). This diameter results in a rotor swept area (the area enclosed by rotation of the rotor blades) of 44,000 m^2 (430,556 ft.^{2}). Each blade of the turbine is more than 100 m (328 ft.) long and the hub is about 150 m (492 ft.) above sea level (Vestas 2024).

The blade, hub, and nacelle subsystems are actively controlled to improve power production within a load envelope that is consistent with the operational and service plans for the FOSW array. Based on wind direction and speed sensor input, the turbine controller activates motors that drive yaw rings to enable constant positioning of the rotor to receive the desired amount of wind energy for power conversion while maintaining acceptable structural loads through the blades, hub, drivetrain, and tower. When the rotor is yawed into the prevailing wind, the turbine controller pitches blades into and out of the wind through hydraulic actuation and large pitch bearings.

A master power plant controller communicates with the turbine controllers to guide the array's active and reactive power output, maintain performance through grid disturbances, and potentially establish grid voltage and frequency. Siemens generators use direct drive technology, which does not require a gearbox, and thereby avoids the associated losses and maintenance, but requires a heavy and costly low-speed generator. In contrast, current Vestas and General Electric generators include gearboxes that translate the low rotational speed of the rotor into the higher rotational speeds needed for a much smaller, high-speed electrical generator. Permanent magnet generators coupled with four-quadrant electrical converters enable the machines to match electrical output to characteristics at the plant substation with the point of connection to the main electrical grid (detailed below). Transformers in the nacelle or tower convert low voltage power at the generator (typically less than 1 kilovolt) to the medium voltage of the collector system.

Towers are composed of cylindrical, rolled-steel cone sections that are bolted together with internal flanges. Although base sections may have large diameters and therefore are difficult to ship by land, the modular nature of tower subcomponents simplifies the shipping of components to port. Tower sections can be manufactured to precise standards of original equipment manufacturers by a greater number of suppliers and in more locations around the world than other turbine components. Original equipment manufacturers commonly leverage this greater diversity in the supply chain to save costs on a given project.

Floating Platforms

FOSW facilities along the U.S. West Coast will be constructed in deeper waters than conventional fixed-bottom offshore wind arrays along the U.S. East Coast and in Europe. Wind turbines in water depths up to 60 m (200 ft.) typically have fixed foundations. In contrast, wind turbines on the West Coast will be in waters with depths of about 600–1300 m (1970–4265 ft.), necessitating the use of floating platforms and robust mooring systems to maintain the turbines' position while operating. The floating platform provides a stable foundation or virtual ground onto which the turbine tower is mounted. The tower must be structurally sufficient to bear the dynamic motion and weight of the nacelle, blades, and hub; resilient to vibrations and oscillatory flow from system operation; and lightweight enough to maintain hydrodynamic stability of the entire floating platform.

A wide variety of floating platforms has been developed, with many more concepts in development at lower technology readiness levels. The fundamental objectives of the platform are to float the weight of the tower, blades, hub, and nacelle; maintain hydrodynamic stability in variable sea states; and allow for efficient and robust turbine aerodynamics by keeping the platform stable in all six degrees of freedom. The most common platform designs are the tension leg platform, semi-submersible, and spar buoy (Figure 3).

A tension leg platform is a vertically moored system: mooring lines extend vertically downward from the platform to the sea floor. The platform's excess buoyancy is counteracted by the mooring lines to maintain the platform's position below the surface. As discussed below, the need to counteract the excess buoyancy and associated forces can create significant design constraints for the mooring and anchoring system. The tension leg platform system is stable in heave (upward and downward) and rotational motion (pitch and roll), yet often requires bespoke mooring and anchor systems.
The semi-submersible system generally features three or four shallow draft columns that are connected by a lattice or similar structure to maintain the relative position and structural integrity of the column locations. In most cases, each column has a large, flat heave plate on its lower (deeper) end. The heave plate creates additional hydrodynamic damping and viscous drag to help stabilize the platform. Additionally, many semi-submersible platforms have active ballasting systems and can pump water between columns to maintain stability under different wind and wave conditions.

Semi-submersible platforms are relatively stable in isolation from their mooring system, but the area between construction ports and offshore turbines must be deep and wide. The Principle Power WindFloat design, described below, is an illustrative example of a semi-submersible platform.

The spar buoy is a simple structure. Its one major cylindrical spar is stabilized by ballasting the hollow core with water or other weight. However, construction of that cylinder requires deep port and navigation channels. For example, the spar buoys for the 6 MW turbines installed at Hywind Scotland penetrate about 80 m (262 ft.) below the surface (Equinor n.d. b). Spar buoys are generally towed to the project location in a position parallel to the water surface and then ballasted until the platform becomes vertically oriented. This process eliminates the opportunity to install turbines, blades, and nacelles in ports with shallow or medium water depths.

Anchors and Mooring Lines

Moving downward through the floating offshore wind system, the next subsystems are the mooring and anchoring subsystems. Each platform is anchored to the sea floor by mooring lines, and platforms are connected by electric power cables suspended in the water column.

The mooring and anchoring systems' objective is to keep the floating platform in a specific location or, in the case of a tension leg platform system, to provide a reaction force to the excess buoyancy. A wide range of mooring and anchoring systems are possible, and selection depends heavily on the platform, operational water depths, meteorological and physical oceanographic conditions, and seafloor and sediment composition. Mooring lines are generally composed of synthetic lines, sections of chain, and mid-water column or surface floats that have high strength-to-weight ratios.

The seafloor and sedimentary conditions strongly affect what anchors are feasible. Most anchors can be classified as embedment, suction, gravity, or pile systems. If the sediment allows embedment, or penetration, then a drag embedment, micro-pile, or suction bucket anchor may be effective. For example, to create a suction bucket anchor, giant upside-down steel buckets are sunk directly onto the seabed. A suction pump then removes the water and air from inside the bucket, which creates negative pressure inside the bucket and drives the foundation down into the seabed. If the seafloor sediment is much firmer (more consolidated), then gravity foundations or pile anchors might be more appropriate. The massive weight of gravity anchors provides a reaction mass or force for the mooring systems, whereas pile anchors are drilled into the seafloor and create a rigid connection between the seafloor and the mooring system.

Balance of Plant and Electrical Transmission

Travis Douville

Balance of plant generally refers to all the other, mainly electrical, components of the floating offshore wind (FOSW) system, including the collector system, substations, and export cables (Figure 5). Numerous technological components in addition to the individual turbine, platform, and moorings systems are required to complete the power plant and are critical to its operation. After alternating current (AC) power is transformed to medium voltage in the nacelle or tower, it is transmitted on a collector system of AC electrical cables typically rated between 66 and 132 kV. These cables usually run from one turbine to another three to five turbines on an electrical feeder line before they connect to the plant substation. On the shore-side of the substation connection, the design of these balance of plant systems is classified as high voltage alternating current (HVAC) or high voltage direct current (HVDC).

Most land-based wind energy projects use HVAC substations and overhead cables to their points of interconnection to the bulk utility electricity system. However, some FOSW systems are sufficiently far from points of interconnection that they require more-efficient HVDC transmission. Although HVDC cables are more expensive than HVAC cables per unit length, they lose less electricity and avoid the need for reactive power compensation equipment. For these reasons, there is a break-even distance between HVAC and HVDC cable costs. A comparison of the costs of offshore transmission technologies suggested that beyond 100 km (62 mi.), the costs of HVDC are lower than those of HVAC (Beiter et al. 2016). Another analysis indicated that beyond 186 km (116 mi.), the cost of 320 kV HVDC fell below that of 220 kV HVAC (Larsson 2021). As plant size increases, HVDC may be cheaper even at shorter distances (DNV 2022).

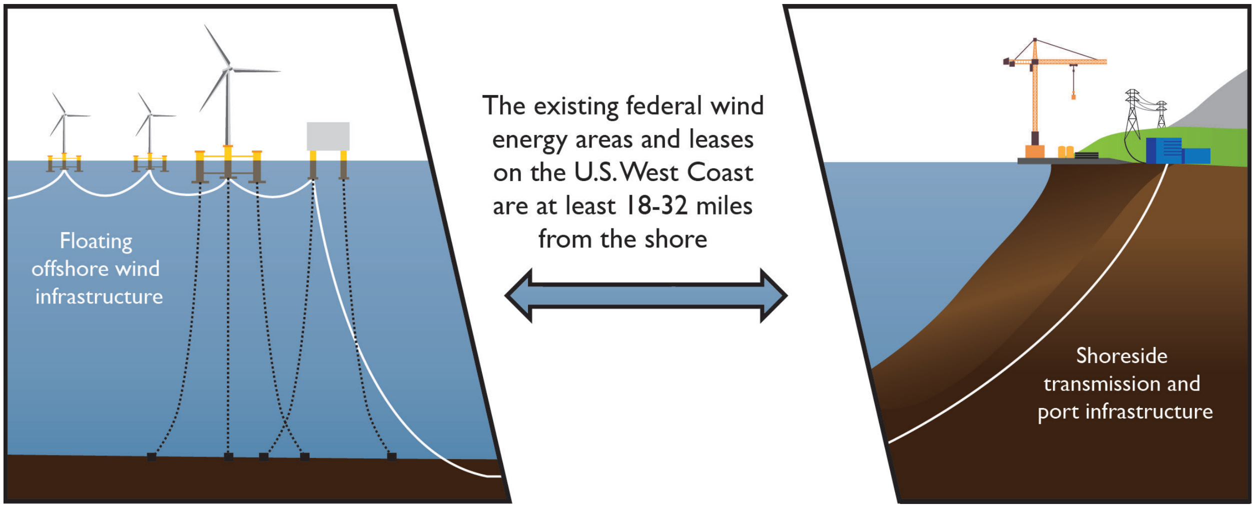

Figure 5. Floating offshore wind energy infrastructure, balance of plant, and electrical transmission systems. The closest point of the wind energy and lease areas established by the Bureau of Ocean Energy Management on the West Coast range from 29–51 km (18–32 mi.) offshore. Graphic by Allison Walkinshaw. Accurately scaled visual simulations of the coastal viewshed under a range of meteorological conditions, with and without hypothetical offshore wind arrays, from six key observation points in Oregon are available at www.boem.gov/renewable-energy/state-activities/oregon-offshore-wind-visual-simulation.

The collector system cables of HVAC systems terminate in an offshore AC substation near the turbines (Figure 6). On the west coast of the United States, these substations must float given the water depths in the vicinity of the lease areas and high-quality winds (Figures 3, 5). In the AC substations, voltage again is increased to that of the export cable, which is rated for long-distance transmission (export cables are currently expected to be rated at 230 kV or 400 kV). The export cable connects to land under the beach and terminates in an onshore AC substation. Onshore, the voltage again may be adjusted to meet the needs of the onshore grid (transmission system). HVAC transmission over land, whether above-ground or underground, links the onshore AC substation to the point of interconnection with the transmission system, which is approved on a project-by-project basis by the grid system operator.

Four types of floating substations, semi-submersible, spar, tension leg platform, and barge, are under development for FOSW. The turbine platforms and mooring and anchoring systems of these substations are similar to those of offshore wind turbines. A key difference between turbine and substation platforms is the weight that must be supported. The components of the substation that are above the water's surface can be 2000–4500 metric tons (MT) heavier than the wind turbines.

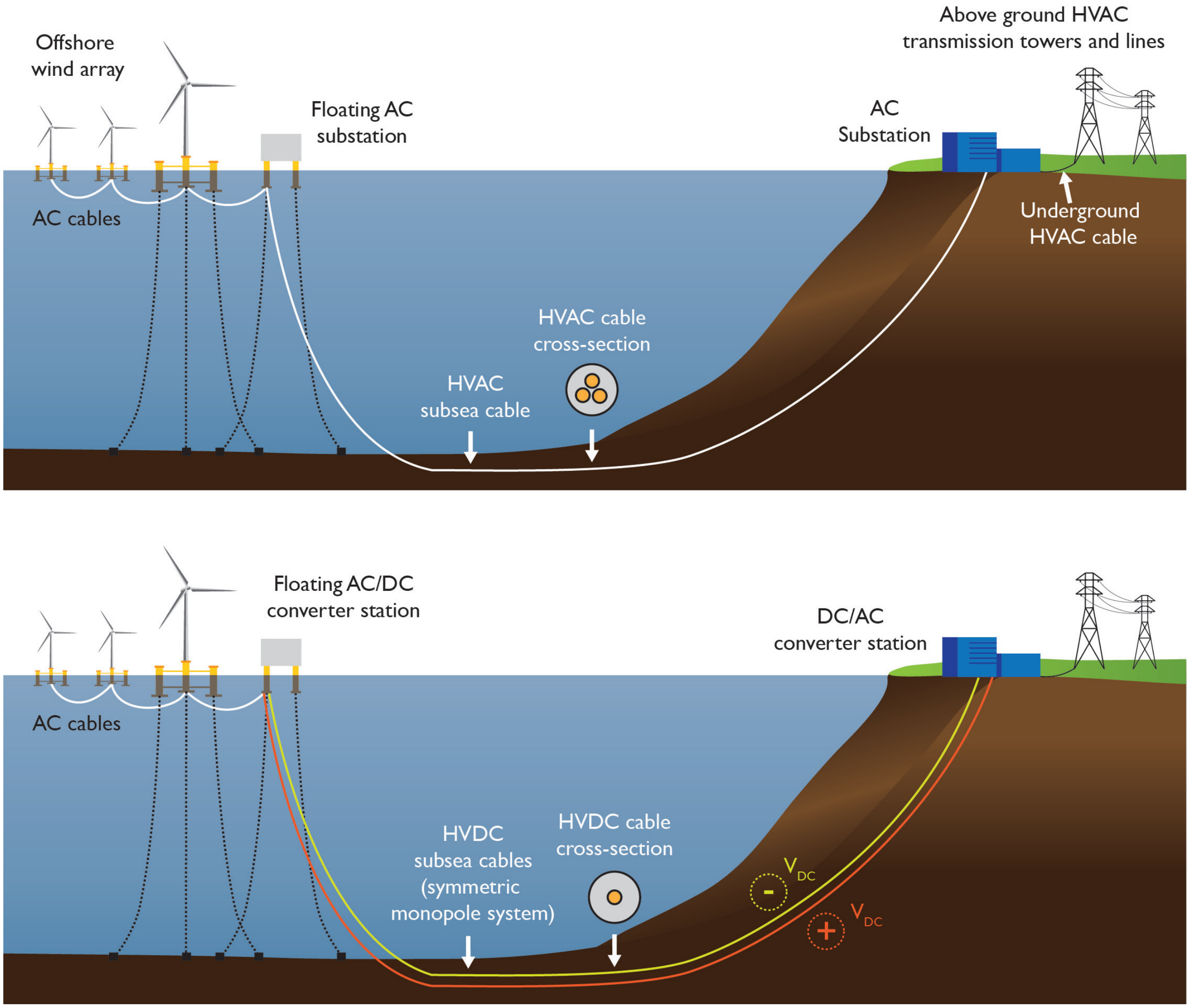

Figure 6. High voltage alternating current (HVAC) (top) and direct current (HVDC) (bottom) subsea transmission systems depicted from the floating offshore wind array to the point of interconnection with the land-based grid transmission system. HVAC subsea cables carry three-phase AC power via a tri-core of conductors (see Figure 7) and are more economical for shorter transmission distances (see text). HVDC subsea cable systems can have different configurations (asymmetric monopole, symmetric monopole [shown in figure], or bipole) and use single core subsea cables to carry direct current (see Figure 7). HVDC subsea cables are more cost effective over longer transmission distances.

The above-water components also have lower centers of gravity, which affects their stability and could require platform and mooring designs different than those of floating turbines. Additionally, the substation platforms must accommodate multiple subsea cable connections and the motion between cables and the platform (DNV 2022).

Borrowing from decades of work in the oil and gas industry, floating AC substation designs are under development by major vendors such as Hitachi, General Electric, and BW Ideol (Huang et al. 2023, Buljan 2024, GE Vernova 2024). The following three designs have been publicized, and others are underway. Ideol and Atlantique Offshore Energy's Damping Pool design traps sea water within an inner ring to dampen dynamic movements of the substation. The design is modular (in 200–300 MW segments) and can scale to 1000 MW (Richard 2019). Semco Maritime, ISC Consulting Engineers, and Technip Energies have introduced a three-column design with 400 MW capacity that weighs 6,500-7,500 tons (Semco Maritime 2022, Huang et al. 2023). Siaipem and Siemens Energy plan a 500 MW floating substation with a semisubmersible structure (Chadderdon 2022).

The HVAC export cables that leave the floating substation are typically three-core extruded cross-linked polyethylene (XLPE) and qualified up to 400 kV (Figure 7). However, current commercially available cables do not bend or move as would be necessary for FOSW arrays. The depth of the water along the West Coast necessitates vertical cables that run from the floating platforms through the water column to the seafloor. These vertical sections of cable, like the mooring cables, will move as the floating turbine moves. Design and testing to accommodate these movements has not yet been completed at the 230 kV or 400 kV rating.

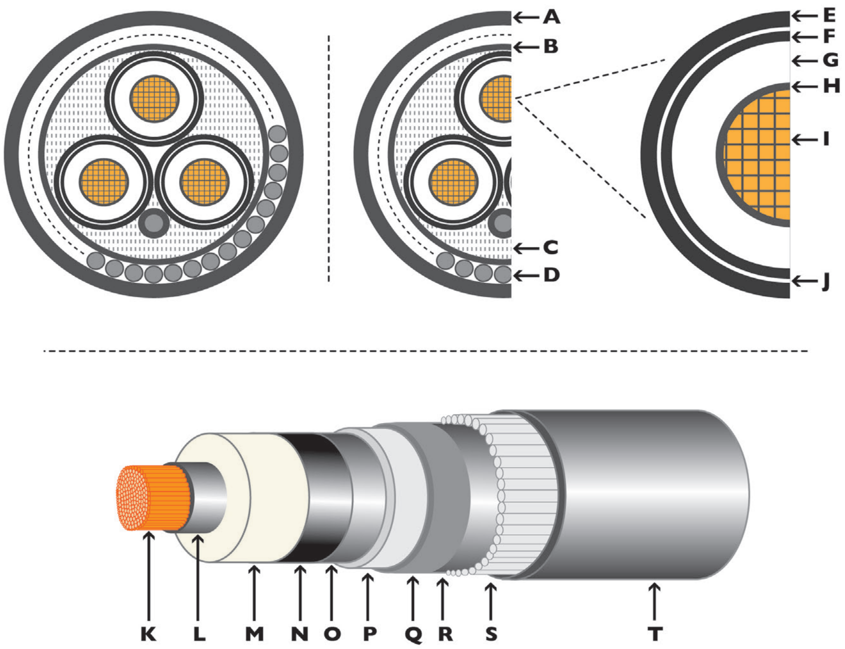

Figure 7. High voltage alternating current (HVAC) (top) and direct current (HVDC) (bottom) subsea cables. Subsea cables may also incorporate optical fiber for data transmission. **HVAC cable components:** Polypropylene yarn serving (A) and polypropylene yarn bedding (B) protect the steel armoring that helps prevent against magnetic field losses (D). Polypropylene yarn filler (C) surrounds the three copper conducting cores that carry three-phase HVAC power (I). The spaces between the copper wires within the conducting core are filled with a swellable tape to limit migration of water along the cable and minimize the repair length should the cable become physically damaged on the seafloor. The copper wires are encased in a conductor shield (H), a layer of cross-linked polyethylene (XLPE) insultation (G), an insulation shield (F), a metallic (lead) shield that prevents intrusion of water (J), and an anticorrosion polyethylene shield (E). **HVDC cable components:** The single copper or aluminum conducting core (K) is surrounded by an inner semi-conduction layer (L), XLPE insultation (M), outer semiconducting layer (N), swellable tape (O), and a metallic (lead) sheath (P). These are surrounded by a polypropylene inner sheath (Q). The outermost sheath of polypropylene yarn (T) and the polypropylene bedding (R) protects the armoring layer (S). Graphic by Allison Walkingshaw, adapted from Sumitomo Electric (global-sei.com/power-cable-business/products/submarinecable/) (HVAC) and Anatolia Technologies (anatoliacom.com/extruded-dc-up-to-525-kv) (HVDC).

Like most fixed-bottom offshore wind arrays, FOSW uses HVAC transmission. However, HVDC designs for offshore wind plants soon will be operational. The first such project in the United States, Sunrise Wind (924 MW, fixed-bottom, with a 161 km [100 mi.] HVDC export cable into Long Island), is projected to be operational in 2025 (Sunrise Wind 2021). Tennet, a German transmission system operator, is planning projects with a modular 2 GW HVDC design (Tennet n.d.). On the West Coast, initial electrical transmission connections, particularly those closer to coastal points of FOSW interconnection, such as the Morro Bay leases, are expected to proceed with HVAC cables. However, HVDC systems may be necessary to reach more remote FOSW arrays off the Oregon and California coasts in the 2030s.

For interconnections exceeding one GW or export cables longer than about 161 km (100 mi.), HVDC technology is often

Case Study: Principle Power Semi-submersible Platform

Bradley Ling

Principle Power’s WindFloat® semi-submersible floating foundation has a track record of pre-commercial deployments in Europe. Nine WindFloat units have been deployed in Portugal and Scotland with wind turbine generators up to 9.5 MW, and three more are under construction in France. The WindFloat is designed to be compatible with any commercial wind turbine generator.

The WindFloat is a triangular, semi-submersible, column-stabilized offshore platform that uses water plane stiffness to counteract large, wind-induced overturning moments. Damping heave plates at the bottom of each column provide additional hydrodynamic inertia by increasing the volume of displaced water and adding viscous damping to the system in roll, pitch, and heave motions. The platform also includes a closed-loop hull trim, or ballasting, system that moves water ballast among the three columns to counteract variable thrust loads on the blades, hub, and nacelle that result from changes in the average wind speed and direction and to minimize loads and optimize power production. The WindFloat is in its fourth generation and is fully modular to enable different execution plans.

The WindFloat has two variants, both steel semi-submersibles (Figure 8). The WindFloat T has columns suitable for tubular construction. The WindFloat F has columns and pontoons suitable for flat panel construction.

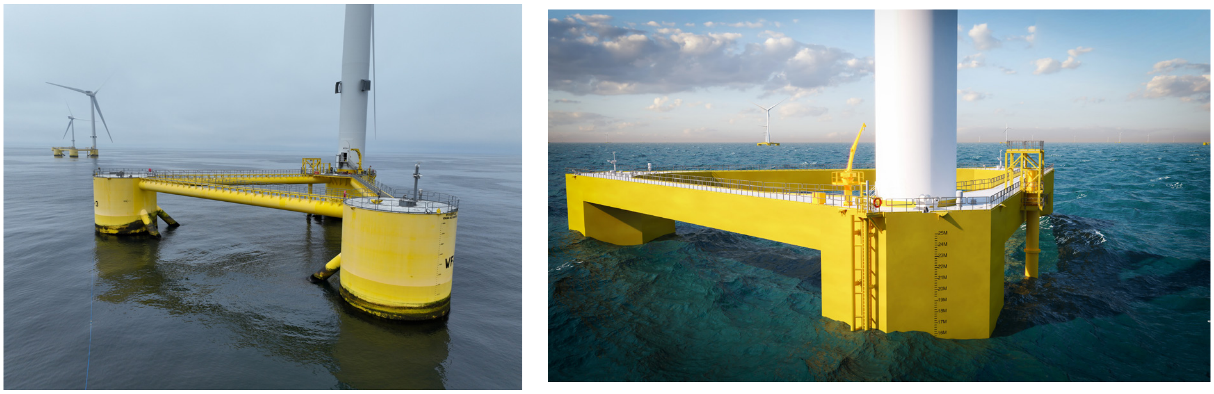

Figure 8. WindFloat T (left) and WindFloat F (right) offshore platforms. Photograph of the WindFloat Atlantic project courtesy of Principle Power and Ocean Winds.

With two variants, the platform can be tailored to local supply chain capabilities and project constraints. For example, the tubular design may be preferable in the U.S. Gulf of Mexico due to the local supply chain’s ability to fabricate tubular structures similar to jackets used in the oil and gas sector. The tubular design also may be better suited to water depths greater than 11–13 m (36–43 ft.). Due to the relatively low effort required for its final assembly, this variant also may be more favorable for projects where components are fabricated at different locations and the platform is fabricated at a relatively small site.

Alternatively, for the U.S. West Coast, the flat panel design may be less expensive for new, purpose-built facilities capable of automated, indoor manufacturing of large, stiffened panel components. The flat panel design may be preferable for sites with more restrictive draft constraints (<8–10 m [26–33 ft.]) at the quay (loading platform) where the wind turbine and tower are integrated with the floating foundation. This variant may also be less expensive when fabrication is centralized at a shipyard or other large site with permanent equipment and a stable workforce that can run the final assembly process.

The WindFloat principal dimensions (column diameter, column spacing, and column height) are adjusted to meet specific project meteorological and oceanographic conditions and generator and logistical constraints. Platforms have been deployed around the world in meteorological and oceanographic conditions similar to those off the Oregon coast.

Mooring systems for the WindFloat vary across project sites. The relatively deep water in the proposed Oregon lease areas (>200 m [656 ft.]) would likely require a semi-taut or taut mooring design in which a long, synthetic rope in the water column is connected to a shorter chain that is attached to the anchor. An anchor that can resist vertical loading, such as a suction pile, probably would be most suitable, although the final selection of anchor type will depend on the seabed sediment type and other geological attributes.

Depending on how the wind turbine is integrated and how the platform is fabricated for a specific project, the generator, hub, blades, and tower can be integrated with the floating foundation at the location of the platform's final assembly and launch or at a separate location (Figure 9). Integration should occur as close to the project site as possible to minimize weather-related risks and delays in platform assembly. The integration operation has the most demanding port infrastructure requirements. Methods of integrating the wind turbine components and platform include use of a shore-based crane, a crane and temporary buoyancy aids to reduce platform draft, a crane with the platform grounded to integrate the generator on the platform while it floats alongside quay, or a jack-up vessel equipped with a crane either alongside quay or in a sheltered environment (Figure 9). Once fully integrated, the system is towed to the project site, where it is attached to the mooring lines and inter-array electrical connection cable.

Figure 9. Integration of wind turbine components with a crane (tower [left], nacelle [middle], and blade [right]). Photograph of the WindFloat Atlantic project courtesy of Principle Power and Ocean Winds.

advantageous. After the AC power is collected at the plant, it is sent through HVAC to HVDC converter stations (Figure 6). These stations also must float. From the stations, HVDC export cables carry power at high voltages, typically 320–525 kV, to the landing point. The export cable terminates in an onshore HVDC converter station, where the power is prepared for connection to the bulk energy system at the point of interconnection to the transmission system. The interconnection has been approved by the transmission system operator.

Voltage source converters, a relatively new technology that allows full directional flow and control of power quality (voltage and frequency signals), connection of high-capacity power flows to weak grids, and the ability to establish grids after a disruption, commonly are used to convert AC power to DC or vice versa. These converters are well suited to the multiple-terminal direct current systems that are likely to emerge in the future. HVDC export cables are designed for asymmetric monopole, symmetric monopole (Figure 6), or bipole systems. They usually are single core conductors with extruded XPLE, mass-impregnated paper, or paper-polypropylene laminated insulators (Figure 7). XPLE insulators are less susceptible to leakage than the two latter types of insulators, and therefore are the most common for offshore applications.

At 320 kV and when arranged in a symmetric monopole configuration, HVDC subsea cables can transmit 1300 MW of power. At 525 kV and when arranged in a bipole configuration, they can transmit 2000 MW of power. Unlike AC lines, DC lines do not have a theoretical power transmission length limit. However, technology risks are associated with DC transmission, including an unstable supply chain and limited supply of DC circuit breakers. The DC circuit breakers will be necessary to isolate faults in the case of networked transmission.

The four major types of FOSW systems are undergoing rapid and global innovation and development. Floating offshore wind arrays have not yet been built in the United States, but are in early planning phases in California and the Gulf of Maine. Commercial projects (those with a minimum capacity of 50 MW) are under development in South Korea (Ocean Winds n.d.) and France (Offshore 2024). Development is based heavily on the experience of the offshore oil and gas industry in deep water and from European and East Coast deployments of fixed bottom offshore wind systems. Building floating offshore wind on the West Coast will require adapting the experience from other regions and industries to the demanding wave and depth conditions of the coastal Pacific Ocean. As early FOSW projects mature, information about their system performance and manufacturability can be used to design projects and build a West Coast supply chain.

Offshore Wind Port Requirements

Aubryn Cooperman

Ports and vessels enable the transportation of equipment, materials, and people to and from an offshore wind site or among suppliers, and allow for the construction of floating offshore wind (FOSW) systems. Different vessels, port sites, and port types can support offshore wind projects. Vessels used to deploy offshore infrastructure and transportation of components, parts, and people must comply with the Jones Act (Merchant Marine Act of 1920 [Section 27]). Within the United States, there are few Jones Act-compliant options for vessels that can support FOSW in Oregon.

Ports can be classified as staging and integration, manufacturing, or operations and maintenance. At staging and integration ports, the largest ports, all wind turbine components are integrated with floating platforms before being towed to an offshore site (Figure 10). Staging and integration ports are primarily used during the installation phase of a project but may also serve as a base for heavy maintenance after a wind array becomes operational. The size

Port location	**Capabilities**			**Notes**
	S&I	**MF**	**O&M**	
Hammond Boat Basin			🟨 X	U.S. Army Corps of Engineers maintains channel. Not much space available.
Warrenton		🟨 X	🟨 X	Water depth can accommodate barges
Astoria			🟩 X	Not much land available. Adequate water depth for operations and maintenance vessels.
Wauna	🟥	🟥	🟥	Currently in use, no land available
Port of Columbia County		🟨 X		Industrial land, deep-draft access, multiple sites
Port of Portland		🟩 X		Multiple sites
Nehalem	🟥	🟥	🟥	No maintained channel
Tillamook Bay at Garibaldi			🟨 X	4.5 m (18 ft.) deep, crew transfer vessel only for operations and maintenance, not as close to wind energy areas
Depoe Bay	🟥	🟥	🟥	Entrance channel not adequate for operations and maintenance
Yaquina River/ Toledo/Newport		🟨 X	🟩 X	U.S. Army Corps of Engineers maintains channel. A maximum of 16 ha (40 acres) may be available.
Waldport	🟥	🟥	🟥	No maintained channel
Siuslaw River at Florence	🟥	🟥	🟥	No land available
Umpqua River at Reedsport		🟨 X	🟩 X	Shallow water depth in channel
Coos Bay	🟩 X	🟩 X	🟩 X	Best option, but airport and dredging create challenges
Bandon			🟨 X	Coquille River depth is 4 m (13 ft.). Crew transfer vehicle only for operations and maintenance site.
Port Orford	🟥	🟥	🟥	No protected harbor
Rogue River (Gold Beach)			🟨 X	Crew transfer vessel only due to channel depth
Brookings Harbor at Chetco			🟨 X	Crew transfer vessel only due to channel depth

Table 3. Oregon port capabilities for offshore wind. Green, yellow, and red indicate good, moderate, and unlikely candidate sites, respectively. S&I, staging and integration; MF, manufacturing and fabrication; O&M = operations and maintenance. Adapted from Shields et al. 2023.

and weight of the offshore wind components staged at these ports lead to demanding specifications for facilities (Porter and Phillips 2016, Trowbridge et al. 2022, Lim and Trowbridge 2023, Shields et al. 2023). Requirements include high bearing-capacity wharves long enough to accommodate FOSW platforms and vessels transporting large components; space for component storage, including mid- to high bearing capacity upland areas and sheltered harbor areas for wet storage of floating components; heavy-lift cranes and load-handling equipment such as self-propelled modular transporters (as noted in the Principle Power case study); navigation channels and berths with sufficient depth and width for FOSW systems and large vessels (a key challenge in Oregon); and at least 305 m (1000 ft.) of clearance above navigation channels to allow passage of fully integrated floating wind systems.

Figure 10. Floating offshore wind turbines at assembly ports. Top: Floating wind turbine (9.5 MW) for Scotland's Kincardine Offshore Wind project at a port in The Netherlands. Bottom: Floating platform for an 8.4 MW Floating wind turbine for Portugal's WindFloat Atlantic project along a quay in Spain (for scale, note the figure in red coveralls at the top right side of the floating platform). Photographs courtesy of Principle Power.

Manufacturing or fabrication ports host factories and facilities for assembly of major offshore wind energy components and subsystems. Many of these components are too large for transportation over land, so they must be manufactured at a port with access to a navigable waterway. There may be more flexibility in the requirements for manufacturing ports than for staging and integration ports. For example, manufacturing ports can be located farther from offshore wind installations and, depending on the type of component (e.g., blades, nacelles, towers) they produce, may not require a channel depth, width, or air clearance as great as that needed for a fully assembled floating wind system.

Operations and maintenance ports serve offshore wind arrays throughout their operational life. Typical onshore facilities include offices for operational monitoring and management, space for vessel provisions, warehouses for storage of spare parts, and workshops for repairing small components. Berth requirements depend on the type of vessels used for day-to-day maintenance of the wind array. Crew transfer vessels are typically used when travel time to the operations and maintenance port is within two hours, allowing for daily return to port (ACP 2023). Service operations vessels, which are likely to be used for larger or more distant wind arrays, require larger berths and a deeper channel than crew transfer vessels.

Existing ports on the U.S. West Coast could serve as each type of FOSW port (Shields et al. 2023; Table 3). The Port of Coos Bay, which has engaged in initial scoping activities related to offshore wind (Trowbridge et al. 2022), is the only good candidate for staging and integration. Several ports along the Columbia River and the Pacific coast are potential candidates for manufacturing and fabrication. A greater number of ports can support operations and maintenance, although several would be limited to crew transfer vessels rather than the larger service operations vessels.

Floating Offshore Wind Infrastructure and the Environment

State of the Science

Andrea Copping and Hayley Farr

Understanding of the potential environmental effects of floating offshore wind (FOSW) energy is limited. Research and monitoring at Hywind Scotland and Kincardine (Scotland), Hywind Tampen (Norway), Principle Power Windfloat Atlantic (Portugal), and smaller demonstration projects are just beginning to build the evidence base. However, data from coastal development, land-based wind, fixed offshore wind, wave and tidal energy, and other industries provide some insights into FOSW's potential environmental effects, monitoring priorities, and strategies for mitigating undesirable effects (Copping and Hemery 2020, Farr et al. 2021, Maxwell et al. 2022, Rezaei et al. 2023).

The potential environmental effects of FOSW, like those of other offshore renewables, can be examined with a stressor-receptor framework (Boehlert and Gill 2015). Stressors are the parts of a FOSW array (e.g., turbines, cables) or its lifecycle (e.g., operational sound, vessel traffic) that may cause harm or stress to receptors, such as marine animals, their habitats, and ecological processes. Diverse potential stressor-receptor interactions, or risks, are associated with offshore wind energy's siting, construction, operations and maintenance, and decommissioning (SEER 2022). Below we summarize some of the common concerns and key risks.

Ecosystem Dynamics. Like many offshore industries, FOSW development can change coastal, benthic, and pelagic ecosystems. For example, the installation of anchors, cables, and scour protection can disturb or alter benthic systems. However, these effects are often localized and may be temporary. Throughout their lifecycle, floating offshore wind turbine substructures, moorings, and anchors may act as artificial reefs, potentially increasing the species richness and abundance of some marine fishes and other taxonomic groups while increasing the size or quality of foraging and sheltering areas for others (Hemery 2020, SEER 2022; see *Effects on Fishes*, this chapter). There is some concern that the development of large FOSW arrays affects ocean dynamics, such as coastal upwelling, by reducing wind energy at the surface (Raghukumar et al. 2023; see *Wind-driven Upwelling*, this chapter).

Underwater Sound. Underwater sound is generated throughout the lifecycle of a floating offshore wind array. Construction sound associated with vessel traffic, mooring and anchor installation, and cable burial is localized and temporary, but may disrupt some communication, navigation, or other uses of acoustic signals by marine mammals or fishes (SEER 2022). During operations, sound and vibrations from FOSW turbines are transmitted via the turbine, substructure, and moorings. Acoustic data from Hywind Scotland and Kincardine suggest that operational sound from floating wind turbines is similar to sound from fixed-bottom wind turbines, which does not typically exceed background sound levels and is considered to be a low risk (Burns et al. 2022, Risch et al. 2023) (see *Underwater Sound*, this chapter).

Entanglement and Collisions with Vessels. Although accidental entanglement in fishing gear is a major threat to marine animals, the likelihood of entanglement with FOSW moorings and cables is extremely low (Benjamins et al. 2014, Garavelli 2020, SEER 2022). These structures have large diameters and are spaced far apart; marine animals generally have the sensory capacity to avoid these potential hazards. There is little to no evidence that marine animals might become entangled by debris caught on offshore wind moorings and cables (but see *Secondary Entanglement Hazards*, this chapter). Collision of marine mammals and sea turtles with wind array construction and maintenance vessels is another concern. These risks are generally mitigated by use of onboard protected-species observers, reducing vessel speeds, and route restrictions (SEER 2022).

Electromagnetic Fields. Electromagnetic fields are generated around power export cables on the seafloor, inter-array cables draped between floating turbines, and offshore substations that service floating offshore wind platforms. Depending on the amount of power transmitted, electromagnetic fields may affect the behavior of some crustaceans (e.g., crabs, lobsters) and elasmobranchs (e.g., sharks, skates, rays). The effects of anthropogenic electromagnetic fields on marine animals appear to be minor (Gill and Desender 2020, 2023; Hutchison et al. 2020b; SEER 2022) (see *Electromagnetic Fields*, this chapter).

Effects on Birds and Bats. Risks of FOSW developments to birds and bats include disturbance from construction activities, displacement from habitat or migration routes, and collision with turbine blades. Depending on the wind array's location, layout, and other characteristics, some bird species may be attracted to or avoid the array. Bat activity may be lower offshore than on land. Animals that are attracted to either land-based or offshore wind turbines may be susceptible to injury or death.

As with all major new technological developments, additional research and monitoring are needed to better understand the likelihood and magnitude of the range of risks from FOSW arrays and potential cumulative effects of FOSW and other human activities.

Effects on the Physical Environment of the Coastal Ocean

Wind-Driven Upwelling

John A. Barth and Kaustubha Raghukumar

Winds blowing along coastal regions can move seawater up (upwelling) or down (downwelling), which can deliver or remove nutrient-rich water that feeds a rich ecosystem. Wind-driven upwelling is responsible for much of the primary productivity in the California Current, which is one of the world's most productive ocean ecosystems (Figure 11). The California Current extends southward from British Columbia, Canada, to Baja California, Mexico, delivering cool, nutrient-rich waters to the west coast of North America. The extraction of wind energy by an offshore wind array can reduce wind speeds downwind of the array, which in turn can affect local or regional wind-driven upwelling, nutrient delivery, and ecosystem dynamics. Here we review the possible effects of floating offshore wind arrays on coastal upwelling.

Oregon's coastal waters are strongly influenced by southward, upwelling-favorable winds in spring, summer, and early autumn, and by intermittent storms with strong northward winds in late autumn and winter (Huyer 1983). The upwelling season runs from April or May through mid-October.

A typical southward wind event lasts two to five days and reaches about 20 knots (10 m s^{-1}) in strength. The force that moves surface waters and results in upwelling is the stress generated by the interaction of the wind with the surface of the sea. Stress is a measure of force tangential to a surface. It is expressed in units of newtons (N) per square meter (m^{2}) of surface area (N m^{-2}). A 20 knot (10.3 m s^{-1}) wind blowing over the surface of the sea surface generates a stress of 0.18 N m^{-2}. This stress moves surface waters offshore in a process called Ekman transport (in this example, the transport is 1.8 m^{2} s^{-1}). The Bakun upwelling index can be related to this quantity by multiplying by one in the form 100 m per 100 m of coastline in the along-coast direction: in this case, 180 m^{3} s^{-1} per 100-m-coastline. To balance mass, water upwells from below to replace the surface water driven offshore by wind. If this upwelling is distributed over the continental shelf out to, for example, 18 km offshore (9.7 nautical mi.), the deeper water upwells to the surface at a vertical velocity of 0.0001 m per second (1 x 10^{-4} m s^{-1}). This is an extremely low vertical velocity that cannot be measured directly with a current meter, but when summed over a day, results in about 8.6 m of upwelling for a 20-knot wind. This upwelling amount can be verified by tracking the depth of standard oceanographic features of water temperature (isotherms), salinity (isohalines) or, most appropriately, density (isopycnals).

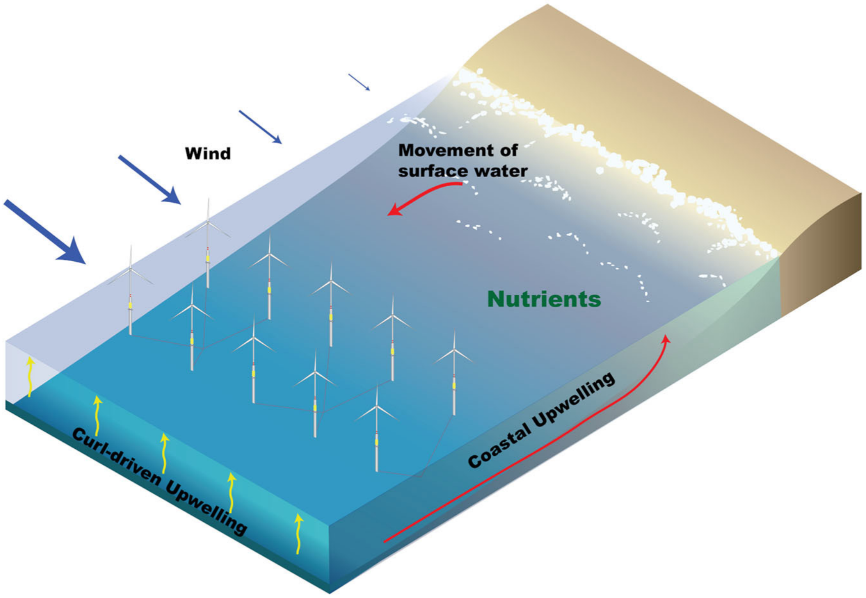

Figure 11. Schematic of upwelling processes near an eastern ocean boundary. Coastal upwelling occurs in a 10–20 km coastal band and curl-driven upwelling over a larger offshore area (from Raghukumar et al. 2022).

Two- to five-day periods of upwelling winds are separated by weak winds (wind relaxations) or even northward downwelling winds during summer (downwelling-favorable winds force surface water downward). The upwelling supplies nutrients from depths of the ocean without sunlight to the sunlit surface waters, fueling the growth of photosynthetic phytoplankton and a productive food web that includes zooplankton (krill), small fishes (forage fish), larger fishes (e.g., rockfish [*Sebastes* spp.], hake [*Mercluccius productus*], salmon [*Salmo* spp. and *Oncorhynchus* spp.]), seabirds, marine mammals, and humans.

The southward, upwelling-favorable winds off the Oregon coast vary from north to south. Off the northern and central Oregon coast, southward summer winds averaged over all upwelling, relaxation, and downwelling events are relatively weak, with an average alongshore wind speed of about 6.4 knots (3.3 m s^{-1}; stress of 0.02 N m^{-2}). To the south and offshore of Cape Blanco in southern Oregon, both the average and individual wind events increase alongshore wind speeds, reaching average values of 12.8 knots (6.6 m s^{-1}; stress of 0.08 N m^{-2}) (Samelson et al. 2002). Orographic intensification—a process in which an atmospheric flow near the surface is compressed by tall mountains and hence accelerates —of the winds near Cape Blanco may be responsible for this variation. Winds of more than 30 knots near Cape Blanco during summer are not uncommon, and generated interest in offshore generation of electricity from wind.

Another form of upwelling, curl-driven upwelling, occurs at the edges of these strong winds off Cape Blanco. Curl-driven upwelling refers to a process in which horizontal differences in wind speed drive horizontal differences in the amount of surface Ekman transport and hence upwelling and downwelling to conserve mass. Curl-driven upwelling here can be of the same magnitude as direct, coastal upwelling farther south in the California Current (Pickett and Paduan 2003), for example near the offshore wind array areas off Humboldt and Morro Bay, California. The wind curl near Cape Blanco contributes to the separation of the southward coastal upwelling jet in this region (Barth et al. 2000, Castelao and Barth 2006), a process that fluxes nutrient- and species-rich coastal waters offshore and south, contributing to the productivity in the northern California Current.

In the region of Heceta Bank off the Oregon coast, where the width of the continental shelf doubles from about 30 km (18.6 mi.) to over 60 km (37.3 mi.), there is another contribution to upwelling that is not directly due to the wind (Barth et al. 2005). A strong (0.5–1 m s^{-1}) southward coastal upwelling jet sweeps around the contours of Heceta Bank in a counterclockwise half-circle. This strong curving of the flow introduces a centrifugal force that is balanced by additional upwelling. The additional upwelling makes the waters over Heceta Bank colder, saltier, more nutrient rich, and consequently more productive than the continental shelf waters to the north and south (Barth et al. 2005).

Some have questioned the ramifications for upwelling off Oregon if offshore wind development extracts energy from the southward, upwelling-favorable winds. Models projected that wind speeds will decrease by about 10 percent, or 1 m s^{-1}, in a typical 10 m s^{-1} (20 knots) upwelling event given energy extraction by a wind array of about 150–500 turbines, each designed to extract 10 MW of power and spaced 1.8 km (1 nautical mi.) apart (Raghukumar et al. 2023). Such an array would yield 1.5–5 GW of wind energy capacity; the lower end of this range is comparable to the approximately 1 to 2 GW estimates for the Oregon lease areas. The decrease in winds can extend up to 150 km (81 nautical mi.) downwind of the wind energy areas (Raghukumar et al. 2023). Because upwelling is balanced by offshore surface Ekman transport, this 1 m s^{-1} decrease results in a decrease in upwelling speeds of about 1.6 m day^{-1}, a reduction of about 18 percent. For a 5 m s^{-1} (10 knot) wind, the corresponding decrease in upwelling speed is 0.4 m day^{-1}, again about 18 percent. These simple estimates agree with the model outputs (Raghuhumar et al. 2023).

Research on the potential upwelling effects of floating offshore wind to date has included only models of physical circulation (Raghukumar et al. 2023). These models suggested that the region of reduced wind speeds in the lee of a wind array leads to about a 10 percent reduction in the total amount of coastal upwelling when summed across the wind array region. Furthermore, the wind array induces a curl-driven downwelling on the inshore side of the wind array and equally sized, curl-driven upwelling on the offshore side of the wind array. Evaluation of the effects of modified upwelling circulation on nutrient delivery and lower trophic level responses in the California Current is ongoing. Separately, modeling and observations of the effects of the wind turbine structures on upper-ocean circulation, for example wake effects and mixing, are also needed.

Wind energy extraction by fixed-bottom foundations has been well-studied in the North Sea (Broström 2008, Daewel et al. 2022), and formation of upwelling and downwelling regions in the lee (downwind) of a wind array has been documented (Floeter et al. 2022). However, these results are not applicable to potential offshore wind arrays on the west coast of the United States because these latter arrays likely will be floating and attached to the sea floor by mooring lines and anchors, not fixed-bottom foundations (steel piles or lattice structures fixed to the sea floor).

Any long-term changes in upwelling due to wind energy extraction will be complicated and potentially difficult to detect. A useful metric for assessing wind-driven upwelling is the sum of the upwelling and downwelling at a particular location over the entire upwelling season, called cumulative upwelling (Barth et al. 2007). The result is effectively the strength of the marine growing season, and is expressed in wind stress days, or N m^{-2} days. As an example, cumulative upwelling off central Oregon, estimated from winds measured at NOAA's Newport, Oregon, Coastal-Marine Automated Network station (NWP03) (Large and Pond 1981), averaged 3.0 wind stress (N m^{-2}) days, with annual variability of 1–3 wind stress (N m^{-2}) days and a standard deviation of 0.8 wind stress (N m^{-2}) day (Barth et al. 2024). The annual variability results from differences in the timing and strength of the atmospheric North Pacific high pressure system and adjacent continental low pressure system. The southward, upwelling-favorable summer wind flows between these two pressure systems (Huyer 1983). The annual variability exceeds the estimated 18 percent decrease in cumulative wind stress (N m^{-2}) days due to offshore wind energy extraction, which will complicate detection of any changes in wind-driven upwelling due to offshore wind energy extraction. Long-term studies that are initiated before offshore wind array operations begin and are sustained for multiple years during operations will be necessary to document any such changes.

In the Cape Blanco region and off the southern Oregon coast, the strong, southward, upwelling-favorable winds during summer often exceed 10 m s^{-1}, the maximum wind speed for the most efficient extraction of wind energy (Song et al. 2020). Therefore, the approximately ten percent reduction in wind speed due to offshore wind energy extraction can be offset by winds that exceed 11 m s^{-1}. Furthermore, wind in excess of 11 m s^{-1} will continue to contribute to wind-driven upwelling and will not be reduced through extraction of energy by turbines.

Any decrease in upwelling due to offshore wind energy extraction also may be offset by an increase in alongshore, upwelling-favorable winds that is projected as climate changes (Bakun 1990). In theory, the difference in temperature between the land and the sea will increase because the ocean will warm less than the adjacent land. The resulting increase in the onshore-offshore atmospheric pressure gradient will result in an increase in southward, upwelling-favorable winds. In some places in the northern California Current, trends in direct wind measurements are consistent with this hypothesis (e.g., García-Reyes and Largier 2010). For example, there is a significant increasing trend in cumulative summer upwelling off Newport (Barth et al. 2024). The number of days on which the maximum temperature at Portland International Airport (Station OR6751, mesonet.agron.iastate.edu) exceeded 90°F increased over the last 25 years at a rate of 0.18±0.06 days per year (Barth et al. 2024). As land temperatures increase, so does the onshore-offshore atmospheric pressure gradient. The cumulative upwelling is also increasing at a rate of 0.03±0.02 N m^{-2} days per year. At these rates, it would take 10–20 years to offset a 10–20 percent reduction by offshore wind energy extraction.

Underwater Sound

Kaustubha Raghukumar

Underwater sound from offshore wind turbines can occur during all phases of development (construction, operations, and decommissioning), and can encompass both continuous and impulsive sound (Figure 12).

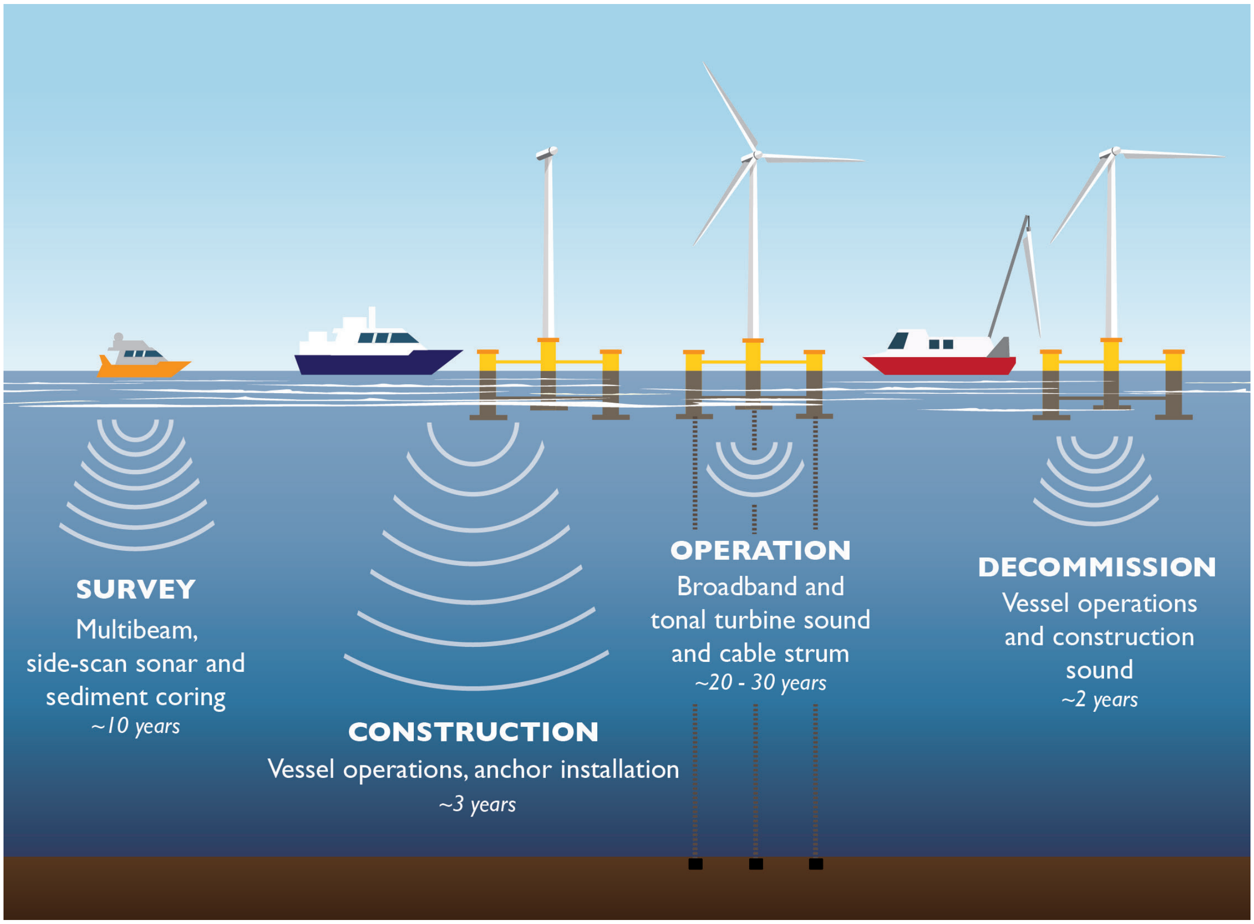

Figure 12. Acoustic life of an offshore wind array. Development phases include site surveys, construction, operation, and decommission. Graphic by Allison Walkingshaw, adapted from Mooney et al. 2020.

Underwater sound and its transmission, or acoustics, during offshore wind array construction can be generated by vessel activity in support of construction (continuous sound) and by impulsive or vibratory pile driving during installation of monopiles or jacketed foundations (for fixed-bottom foundations) or anchors for installation of tension leg platforms. Operational sound from offshore wind arrays is typically associated with the vibration of the superstructure (blades, tower, and platform) and resulting radiation of underwater sound. Decommissioning of offshore wind arrays can result in generation of underwater sound by the removal of foundations and vessel activity.

Marine mammals experience sound as pressure; fishes and invertebrates sense particle acceleration associated with the propagation of an acoustic wave, whereas benthic animals can sense seabed vibrations. Although percussive pile-driving in shallow water (fixed foundations) can generate high levels of sound that can cause behavioral responses in marine animals, analogous effects of floating offshore wind installations have not been observed or measured. Pile driving for floating offshore wind platforms will be related to anchor installation for tension leg platforms. However, unlike fixed-bottom foundations, these piles will not span the water column and are more likely to use a deep-water vibratory hammer for installation into the seabed, resulting in lower sound levels than impulsive pile-driving.

Effects of loud, impulsive sound on marine mammals can include temporary and permanent threshold shifts (hearing loss), masking (e.g., interference with communication, navigation, or detection of predators and prey), and behavioral changes (Madsen et al. 2001, Thompson et al.

2010, NMFS 2018, NRC 2003). Radiated sound from impulsive and vibratory pile-driving during installation of fixed bottom wind turbines is the best-understood source of sound from these structures. Some measurements have been made of operational sound from fixed platforms. Underwater sound from floating offshore installations is among the least studied of all sources of sound from offshore operations.

Sound levels associated with floating installations may be lower than those associated with fixed-bottom turbines. Pile-driving of water-column spanning piles will not occur in deep water, and is likely to be limited to installation of anchors for tension lines. Quieter alternative installation methods, such as suction buckets or gravity installations, likely will be mature by the time the first offshore wind arrays on the U.S. West Coast are installed. In suction bucket foundations, giant upside-down steel buckets are sunk directly onto the seabed. A suction pump then removes the water and air from inside the bucket, creating negative pressure inside the bucket and driving the foundation down into the seabed. Gravity foundations are concrete and filled with water and sand, sinking the base so it sits firmly on a layer of gravel that has been prepared on the seabed.

Operational sound from floating offshore wind arrays is likely to be different than that from fixed-bottom foundations. The presence of multiple mooring lines associated with each turbine structure can result in mooring sound via cable strum, which is absent in fixed-bottom turbines. A study of two Scottish wind arrays (Risch et al. 2023) found that, unlike in fixed structures, the occurrence of impulsive mooring-related sound scaled with wind speeds for floating turbine structures. Whether mooring sound levels from U.S. West Coast installations will exceed regulatory thresholds for temporary threshold shifts is uncertain.

The acoustic output from offshore wind arrays can be ameliorated to minimize impacts on marine animals and the surrounding environment. Bubble curtains or sound abatement systems sometimes are employed to reduce the sound generated during the construction phase. Single or double bubble curtains create a wall of rising bubbles around the construction site. The impedance mismatch between the bubbles and surrounding water dampens underwater sound exposure levels by up to 20 dB (Bellmann et al. 2020). Other sound abatement systems include in-pipe acoustic dampening devices or cofferdams (typically limited to shallow water pile installation), which are enclosures built around the pile-driving area that reduce the sound that is transmitted into the surrounding water. It is recognized that depending on the acoustic output, specific deep water acoustic mitigation measures may need to be developed or appropriately adapted from shallow water techniques. Additionally, during construction phases, passive acoustic monitoring or visual monitoring is used to detect marine mammals near construction sites. If mammals are detected, construction activities may be delayed or halted temporarily to avoid causing harm. Construction activities may be scheduled outside of breeding or migratory periods to reduce potential impacts on taxonomic groups such as whales or dolphins. If necessary, operational noise from cable strum could be reduced by use of jacketed cables.

Once operational, offshore wind turbines generate lower levels of sound than during construction. Operational sounds primarily are produced by the rotation of blades and internal machinery, and from cable strum due to the presence of water-column spanning tension lines. Mitigation strategies for operational sound may include designing turbines with quieter gears and bearings and use of jacketed tension lines. Some sound also is expected from decommissioning activities such as vessel activity and anchor removal. This sound could be similar to those generated during the construction phase, but without pile driving.

Secondary Entanglement Hazards

Greyson Adams, Erica Escajeda, Arne Jacobson, Sharon Kramer, and Mark Severy

Entanglement in fishing gear and other debris is a well-documented cause of injury and mortality of marine mammals, sea turtles, and other marine animals. Entanglement is characterized as primary, secondary, or tertiary. Direct entanglement with mooring lines and cables associated with marine energy infrastructure, including offshore wind systems, is known as primary entanglement. Secondary entanglement occurs when an animal becomes entangled in floating debris caught on the mooring lines and cables associated with a floating offshore wind (FOSW) system. Tertiary entanglement occurs when an animal that is already entangled in gear or debris becomes ensnared on undersea cables and lines. Because floating offshore wind systems are a relatively new technology with few deployments, the risk of entanglement with floating offshore wind platforms, mooring lines, or anchors is not yet fully understood. No cases of entanglement have been documented in relation to FOSW.

Offshore wind facilities on the U.S. West Coast are expected to operate in deeper waters than conventional fixed-bottom offshore wind arrays along the U.S. East Coast and in Europe. Wind turbines on the U.S. West Coast will be in water with depths ranging from about 550 m (1804 ft.) to 1300 m (4265 ft.) necessitating the use of floating platforms and robust mooring systems to maintain their position while operating. Each wind turbine platform will be anchored to the sea floor by mooring lines, and platforms will be connected to each other by electric power cables suspended in the water column. Although these mooring lines and electrical cables themselves are not expected to create a significant entanglement risk for most species (Benjamins et al. 2014), there is concern that derelict fishing gear and other debris may wrap around the lines and cables, creating a secondary entanglement hazard.

Many types of marine debris can entangle marine life, including lost fishing gear. Modern fishing gear is often made of durable synthetic materials that do not biodegrade (Macfadyen et al. 2009), and therefore can remain a hazard for years after they are lost or discarded. A global analysis of 5,440 documented instances of entanglement in lost fishing gear by marine mammals, sea turtles, sharks, and rays indicated that 55 percent of the entanglements were with fishing nets, 35 percent with monofilament lines, and about 10 percent with lines associated with traps and pots, rope of unknown origin, and other sources (Stelfox et al. 2016).

Some marine animals are more susceptible to entanglement than others. Seventy percent of documented entanglement events affected marine mammals, 27 percent affected sea turtles, and 2 percent affected sharks and rays (Stelfox et al. 2016). Juveniles of all species are at higher risk of entanglement than adults due to their inexperience and curiosity and, in the case of sea turtles, their inability to avoid obstacles (Benjamins et al. 2014, Duncan et al. 2017). Body size, flexibility while swimming, behavior, and ability to detect objects in the water affect the degree of risk (Benjamins et al. 2014). Among marine mammals, baleen whales are considered to be the most susceptible to entanglement due to their foraging and feeding behavior, limited ability to detect obstacles immediately in front of them, and large body size (Benjamins et al. 2014, Maxwell et al. 2022). In contrast, porpoises, dolphins, and toothed whales have smaller body sizes and can use echolocation (reflection of sound waves) to detect objects in their path, which helps them avoid entanglement. That said, toothed whales can still become entangled given that some hazards are difficult to detect, especially when an animal is distracted (e.g., while foraging; Benjamins et al. 2014). Sea lions and seals may be somewhat more vulnerable to entanglement than toothed whales because of their smaller body size and their interest in unfamiliar objects (Cawthorn 1985, Yoshida and Baba 1985).

Floating offshore wind infrastructure on the U.S. West Coast will create novel vertical structure in deep waters. Mooring lines, electrical cables, floating platforms, and other FOSW system elements are likely to support communities of invertebrates, such as barnacles, mussels, anemones, and corals. These invertebrates will attract fishes, which may then attract marine mammals and other larger-bodied species. If lost fishing gear or other debris becomes entangled in the cables and lines, animals foraging around the infrastructure may be at higher risk of entanglement.

Although no FOSW facilities currently are installed on the U.S. West Coast, research is underway to identify potential strategies for reducing the risk of secondary entanglement. A California Energy Commission-funded study led by researchers at the Schatz Energy Research Center at California State Polytechnic University, Humboldt, working with partners from Pacific Northwest National Laboratory, MARE Group, H. T. Harvey & Associates, and others, is exploring systems for detecting secondary entanglement hazards on offshore wind mooring lines with a combination of vibration sensors and underwater remotely operated vehicles. Early detection would enable removal of the hazards before animals become entangled.

Additional ongoing research, funded by the Bureau of Ocean Energy Management and led by Desray Reeb, is developing a three-dimensional entanglement simulation model to assess entanglement risk for two whale and one sea turtle species on the basis of animal movements, behavior, and types of ocean debris (BOEM 2023). Such assessments can contribute to evaluation of potential risks of different mooring designs and make improvements that minimize hazards to marine life.

Electromagnetic Fields

Sarah Henkel, Kyle Newton, and Taylor Chapple

Ambient, natural electric and magnetic fields in the ocean come from three sources: Earth's geomagnetic field, electric fields induced by the movement of charged objects (e.g., currents, waves, organisms) through a magnetic field, and bioelectric fields produced by the exchange of ions across the gills and the movements of marine organisms during respiration (Normandeau et al. 2011, Bedore and Kajiura 2013, Gill et al. 2014). Marine organisms that are responsive to electric or magnetic fields include elasmobranchs (sharks, rays, and skates; Figure 13); some bony fishes, such as salmon, tuna, and sturgeon; crustaceans (e.g., crabs, shrimp, lobsters, and barnacles); and sea turtles (Normandeau et al. 2011, Putman 2018).

Offshore renewable installations harness the kinetic energy of offshore wind, waves, tides, or currents and convert the energy into electricity that is transported back to shore through high voltage cables (HVCs). The direct electrical signal from these cables is shielded by cable coatings or conduits and is often further reduced by burying the cable. However, as electricity is conducted through the HVCs, magnetic field artifacts of 0.05–150 μT are emitted radially from the cables. The strength of a magnetic field (or B-field) is measured as the magnetic flux density and is expressed in tesla units (T). At their maximum, the magnitudes of these magnetic fields may be up to three times that of the local geomagnetic field. The emitted magnetic fields induce electric field artifacts as currents, waves, or organisms move through them. The electric field artifacts (1–700 μVm^{-1} or microvolts per meter) can be detected at distances of tens of meters (Gill and Desender 2020). The intensity and characteristics of these fields depend on whether the current is alternating (AC) or direct (DC), the amount of power transmitted, and the cable characteristics. The relative detectability or influence of the emitted magnetic fields and the induced electric fields depends on the local geomagnetic field and other environmental factors.

In the United States, ecological studies have been conducted on the 69 kV cable that connects the San Juan Islands, Washington, to the mainland; the 200 kV DC Trans Bay Cable that runs from the East Bay to under San Francisco Bay; the Acoustic Thermometry of Ocean Climate/ Pioneer Seamount submarine cable (operational 1995–2002) that runs 95 km (59 mi.) from Pioneer Seamount to the Pillar Point Air Force Station in Half Moon Bay, California; the 10 kV DC Monterey Accelerated Research System power and data cable that follows a 52-km (32-mi.) arc across Monterey Bay to the Monterey Accelerated Research System observatory site; and 35 kV AC cables that cross the Santa Barbara Channel to power oil platforms Harmony and Heritage. In Oregon, the cables for Oregon State University's wave energy device test site (PacWave) are 36kV AC and have burial depths up to 1 m. Other offshore renewable energy installations may use DC cables, particularly to connect offshore wind facilities to shore. Below we highlight measured laboratory and field responses to different types of electromagnetic fields (described above) in taxonomic groups relevant to Oregon.

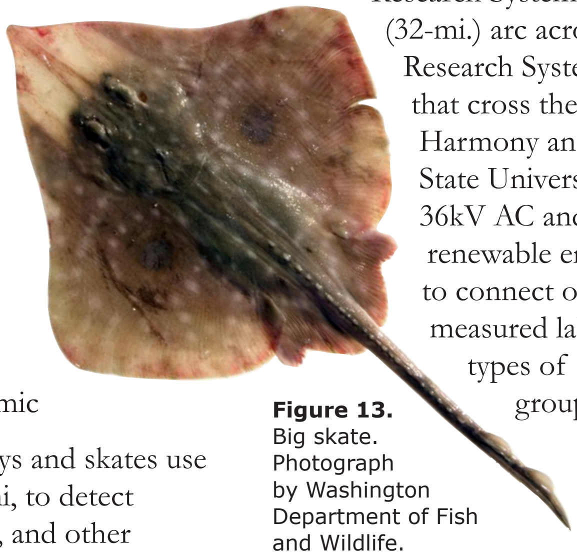

Figure 13. Big skate. Photograph by Washington Department of Fish and Wildlife.

Elasmobranchs. Sharks, rays and skates use their electroreceptors, or the ampullae of Lorenzini, to detect the bioelectric fields produced by prey, predators, and other individuals of their own species (Murray 1960, Dijkgraaf and Kalmijn 1962). These electroreceptors are best able to detect weak (about 20 nV/cm), low frequency (0.5–10 Hz), sinusoidal (AC) electric fields (reviewed in Newton et al. 2019) with behavioral thresholds at <1 nV/cm (Jordan et al. 2009, 2011). Elasmobranchs may also use their electroreceptors to detect the geomagnetic field as orientation and navigational cues during migration (Kalmijn 1982, Paulin 1995, Anderson et al. 2017, Newton and Kajiura 2017, Keller et al. 2021).

Laboratory experiments demonstrated that spotted catsharks (*Scyliorhinus canicula*), which occur in the northeastern Atlantic Ocean and Mediterranean Sea, were neither attracted to nor avoided electromagnetic fields. However, during DC trials they spent 20 percent less time moving among areas than during AC trials or control conditions, and their swimming speed increased (Hermans et al. 2024). In other laboratory experiments, juvenile thornback rays (*Raja clavata*) and New Zealand carpet sharks (*Cephaloscyllium isabellum*) were attracted to DC but not AC cables (Orr 2016, Albert et al. 2022). Two species native to the U.S. West Coast, big skates (*Beringraja binoculata*) (Figure 13) and longnose skates (*Caliraja rhina*), detected and responded to experimentally altered magnetic field conditions (41.0–54.6 μT constant) and the activation of a cable running either AC (±500 μT max) or DC (500 μT constant), but did not show measurable aversion to the cable. The average swimming velocity of big skates slightly increased during initial AC exposure and decreased during initial DC exposure, but after 10 minutes of electromagnetic field exposure, velocities became similar to those without such exposure. The generally less active longnose skates maintained decreased swimming velocity under both electromagnetic field conditions (Newton et al. unpublished data).

In the field, electroreceptive little skates (*Leucoraja erinacea*) spent significantly more time in the vicinity of HVCs emitting electromagnetic fields than in control areas (Hutchinson et al. 2020a). Within the zone of strong electromagnetic fields, the skates also traveled further and made large turns more often. There was no difference in the skates' average speed or height above the seabed.

Bony Fishes. Numerous species of teleosts (bony fishes) have electroreceptive capabilities (Kramer 1996, Bullock 1999). Salmonids and scombrids (e.g., tuna) have a magnetite receptor system and respond to magnetic fields in the 10–12 µT range (Normandeau et al. 2011). Geomagnetic field-based navigation behavior has been documented in salmon species (Putman et al. 2014, Minkoff et al. 2020, Naisbett-Jones et al. 2020).

In the laboratory, magnetic fields had no effects on embryonic or larval mortality, growth, or hatching success of Atlantic halibut (*Hippoglossus hippoglossus*), California flounder (*Paralichthys californicus*), northern pike (*Esox lucius*), or rainbow trout (*Oncorhynchus mykiss*), although magnetic fields shortened the time to hatching in northern pike embryos (Woodruff et al. 2013, Fey et al. 2019, 2020). The direction of swimming by naïve juvenile salmon exposed to magnetic field intensity and inclination angles similar to those at the northern and southern extremes of their ocean distribution changed, indicating that salmon can detect and respond to both of those environmental attributes (Putman et al. 2014).

Figure 14. Green sturgeon. Photograph by Mike Healy, California Department of Fish and Wildlife.

Field studies on teleost fishes revealed no evidence that magnetic fields act as permanent barriers to long-distance migrations of Chinook salmon (*Oncorhynchus tshawytscha*), green sturgeon (*Acipenser medirostris*) (Figure 14), or European eel (*Anguilla anguilla*) (Ohman et al. 2007, Westerberg and Lagenfeldt 2008, Wyman et al. 2018, 2023, Klimley et al. 2021). However, juvenile Chinook salmon and green sturgeon moved more slowly in an area in San Francisco Bay with an energized DC cable (Wyman et al. 2018, 2023). Similarly, juvenile lake sturgeon (*Acipenser fulvescens*) spent more time near AC cables (Bevelhimer et al. 2013).

Crustaceans. Western Atlantic spiny lobster (*Panulirus argus*) sense Earth's magnetic field, which aids in orientation and navigation (Lohmann et al. 1995, Lohmann and Ernst 2014, Boles and Lohman 2003). Some West Coast crab fishermen have suggested that Dungeness crab (*Metacarcinus magister*) are deterred by electrical charges emitted by corrosion of the metals used in crab pots.

In the laboratory, spinycheek crayfish (*Orconectes limosu*) preferred shelter with artificial magnetic fields over those without charge (Tanski 2005). During experimental exposure to relatively large increases in magnetic field strength, from ~0.05 mT background to 1.0–1.2 mT from direct current (DC), Dungeness crabs were slightly more attracted to zones with stronger electromagnetic fields and slightly more active in areas with weaker fields (Woodruff et al. 2013). The physiological and behavioral response of brown crabs (*Cancer pagurus*) in the United Kingdom to 250 μT was limited, but the crabs clearly were attracted to shelters exposed to 500 and 1000 μT (Scott et al. 2021) and 2.8 mT (Scott et al. 2018), with a significant reduction in time spent roaming. At 500 and 1000 μT, the crabs' circadian rhythm was disrupted. The animals had higher d-Glucose concentrations and total haemocyte (blood cell) count after four or eight hours of exposure than with no exposure, but d-Glucose and blood cell count returned to baseline after 24 hours of exposure to the elevated electromagnetic field. The positions within a tank of Dungeness crab and red rock crab (*Cancer productus*) exposed to geomagnetic field displacement (41.0–54.6 μT constant), AC (±500 μT max), and DC (500 μT constant) changed, indicating that both crab species could detect and respond to the stimuli. Dungeness crabs were more evenly distributed in the tanks in electromagnetic field treatments, whereas red rock crabs appeared to be attracted to cable; DC slowed Dungeness crabs, whereas both AC and DC slowed red rock crabs (Newton et al. unpublished data).

In the field, abundances of crustaceans near the Acoustic Thermometry of Ocean Climate /Pioneer Seamount submarine cable off Half Moon Bay, California, were higher than in control areas (Kogan et al. 2006). Crustacean abundance also increased following installation of the Monterey Accelerated Research System cable (Kuhnz et al. 2015). Abundances of yellow rock (*Metacarcinus anthonyi*) and red rock crabs along an energized cable in the Santa Barbara Channel were higher than along an exposed pipe or in natural habitat, indicating that attraction to the cable was not limited to its structure (Love et al. 2017a, b). Similarly, American lobsters (*Homarus americanus*) spent more time in the vicinity of HVCs emitting electromagnetic fields than in control areas (Hutchison et al. 2020a). Despite these apparently attractive properties of cables, the positions of red rock and Dungeness crabs in arenas placed next to energized (0.046–0.08 mT) or unenergized submarine power cables did not differ (Love et al. 2015). Pursuit of bait by red rock or Dungeness crabs did not change when they had to walk over or away from energized cables (Love et al. 2017a, b; Williams et al. 2023).

Sea Turtles. Leatherback (*Dermochelys coriacea*), loggerhead (*Caretta caretta*), and green (*Chelonia mydas*) turtles may be capable of detecting magnetic fields as low as 0.005 to 29 μT (Normandeau et al. 2011) and may use magnetic fields for migration (Putman et al. 2011). However, loggerhead turtles did not differentiate magnetic displacements in laboratory experiments (Fuxjager et al. 2014).

These field and laboratory studies indicate that many marine species respond to electromagnetic fields from underwater cables or magnetic fields applied directly. In some cases, they are attracted to the fields. However, there is no evidence of harm associated with proximity to electromagnetic fields at the wide range of intensities that have been tested. Furthermore, marine species have been documented crossing high voltage subsea cables to continue on migratory pathways and pursue bait. At their present densities, high voltage subsea cables do not appear to hinder migration or feeding of marine species. As increasing numbers of cables are installed for offshore energy projects, migratory species of concern should be monitored for potential impacts due to repeated encounters.

Effects on Fishes

Scott Heppell and Selina Heppell

Effects of floating offshore wind (FOSW) development on fishes are poorly studied. Therefore, potential effects are largely inferred from studies on fishes' responses to other physical structures in their environment, including offshore oil platforms, fixed wind structures, and artificial reefs. FOSW structures will likely affect fish habitat and will themselves become habitat for some species and their prey, so the location of the site affects biological responses (Maxwell et al. 2022). Transient effects associated with FOSW installation, including placement of anchors and moorings, and laying and trenching of cables for power to reach shore-based facilities, can have negative impacts on fishes and their habitats through alteration of the physical and biological environment, sound, and pollution. Permanent effects associated with maintenance and operation of an FOSW site include the physical presence of structures, associated changes in oceanographic features and species' habitats, sound, and biofouling mitigation (Miller et al. 2013). Some transient effects could be long-lasting, especially if laying of cables or placement of anchors interacts with Essential Fish Habitat or Habitat Areas of Particular Concern as defined by the Pacific Fishery Management Council (PFMC 2021).

Many fishes are attracted to structures in the ocean; this is the fundamental basis for the placement of fish aggregation devices for fisheries and artificial reefs. Some fishes are attracted to offshore energy structures, including oil platforms (Snodgrass et al. 2020) and fixed wind energy structures (Miller et al. 2013). Depending on the location of the FOSW site, the fishes that are most likely to be attracted to turbine platforms and counterweights are water column (pelagic) species, such as small schooling fishes and their predators, and the pelagic juveniles of fishes that are associated with the ocean floor, such as rockfishes. Anchors and cables may create structure on the seafloor that can be attractive to fishes that are associated with rocks and reefs, including rockfishes and lingcod (*Ophiodon elongatus*) (Figure 15).

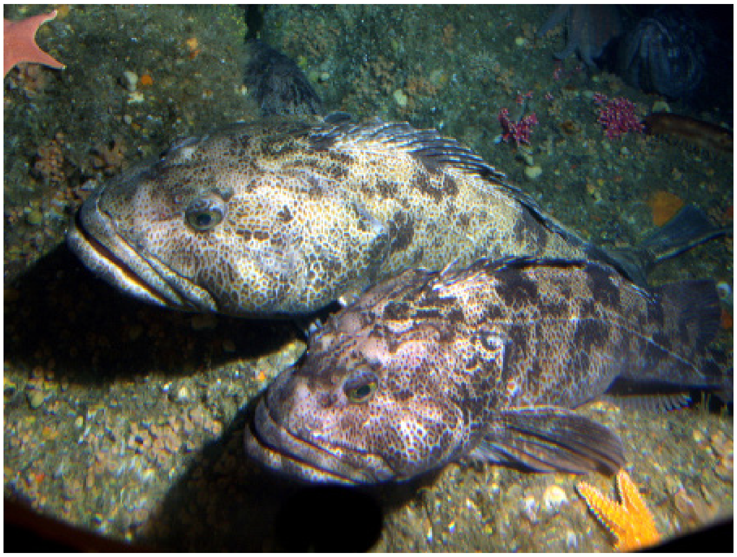

Figure 15. Lingcod. Photograph from Alaska Department of Fish and Game.

Installation processes, including placement of anchors for the moored device and routing of cables to onshore power transfer locations, may cause both transient and permanent habitat disturbance. Placement of anchors in Essential Fish Habitat or Habitat Areas of Particular Concern will likely affect species that rely on those areas. The Pacific Fishery Management Council warned the Bureau of Ocean Energy Management about these impacts in letters written under the authority of the Magnuson-Stevens Fisheries Conservation and Management Reauthorization Act (Pettinger 2024).

The renewable power from the FOSW arrays must come onshore at some location. This means interactions with nearshore environments that are also potential Essential Fish Habitat or Habitat Areas of Particular Concern and are designated as key habitats in the Oregon Nearshore Strategy (kelp, rocky reef) (ODFW 2016). Scouring of the seafloor by altered hydrodynamic flow and the physical movement of cables laid for power transmission and anchoring has been noted in some installations (Copping et al. 2021). In 2024, the Pacific Fisheries Management Council addressed concerns about transmission line and infrastructure interactions with Essential Fish Habitat and Habitat Areas of Particular Concern in a letter to the U.S. Department of Energy.

Three-dimensional hard structures placed in an otherwise open environment create both the potential for vertical habitat throughout the water column and a potential point of aggregation. Hard structures allow for the settlement of encrusting algae and invertebrates, which in turn attract mobile invertebrates and fishes. This artificial reef effect can either increase or decrease growth rates of fish populations (Claisse et al. 2014, Fortune et al. 2024). Proximity to natural habitats may affect fish concentrations around the offshore wind structures and anchors, and the animals' natural tendency to aggregate around structures could have negative effects if the site is in an area of poor quality, such as a site in which hypoxia is frequent (Yu et al. 2023). FOSW placement in areas with good circulation and nutrient flow could increase the chances of creating new fish habitat that increases rather than decreases regional population size (Smith et al. 2016, Paxton et al. 2022). Similarly, including fine-grained structure that provides shelter for juvenile fishes could reduce predation and increase the quantity of habitat for some species or life stages of fishes. However, industry mitigation for biofouling (anti-fouling paint, cleaning) could reduce the potentially beneficial growth of algae and invertebrates that provide food and shelter for fishes on the structures. Furthermore, the potential for fishing restrictions near FOSW structures could enhance the role of the structures in increasing population size.

Underwater sounds created by FOSW during construction, maintenance, and operation will affect some fishes, particularly those that are sensitive to vibration (Popper et al. 2022). Sound produced by FOSW platforms at frequencies to which fishes are sensitive can affect fishes in a variety of ways (see *Underwater Sound*, this chapter). Some fishes produce a considerable amount of sound to communicate with one another. The calls of fishes near FOSW structures may be masked, or if the physiological capacity exists, fishes may shift the sonic frequency at which they call. The behavior of acoustically sensitive species may change as they either avoid or are attracted to the sound-producing device. Sound does not attenuate quickly in water, and low-frequency sounds produced by FOSW could affect fishes over a large area surrounding the site.

As detailed above, some fishes are sensitive to electromagnetic fields over short distances. However, electromagnetic fields attenuate quickly in water, so their effects are likely to be localized, and most studies have shown minimal effects on fish behavior (Hutchison et al. 2020b).

FOSW sites have the potential to negatively or positively impact fish habitat, and the effects vary by species, facility design, and spatial extent. Evaluating potential effects of FOSW on fishes will require detailed monitoring with a statistically rigorous design, such as before-after-control-impact (Bailey et al. 2014). Peer-reviewed data on observed effects are limited, and many of the impacts are speculative. Effects on fish presence, behavior, and life history functions must be measured locally, but also considered with respect to their potential impacts on local and regional populations.

Submerged Cultural and Archaeological Resources off the Oregon Coast

Loren G. Davis

During the Pleistocene epoch, global sea levels were about 130 m (425 ft.) lower than at present because ice sheets covered much of the Northern Hemisphere. As a result, Oregon's coastline extended about 56 km (35 mi.) beyond its current boundaries. Offshore development is required to avoid disturbing archaeological sites that are now submerged.

Following the Pleistocene, rising sea levels undoubtedly caused ancestral coastal peoples to relocate repeatedly. The archaeological record of Oregon's coastal tribes is known from recorded sites that demonstrate ancestral settlements along shorelines that approximated the modern coastline. Archaeologists expect that additional evidence of Oregon's coastal tribes may be held in archaeological sites that are now submerged on Oregon's continental shelf.

Evaluating these submerged cultural resources is essential for understanding the region's complete human history and occupation. Submerged archaeological sites may provide evidence of early human habitation, migration routes, and adaptation strategies that are not captured in the terrestrial archaeological record. Federal law mandates the protection of archaeological resources on federal lands, including submerged sites. Oregon state law protects archaeological sites on public lands, which include the state waters of Oregon's continental shelf. Geophysical surveys of the seabed surface and below are used to identify potential archaeological features or ancient landforms. Marine coring then extracts sediment samples and can reveal evidence of ancestral human occupation on the now-submerged landforms.

Preservation of submerged archaeological and cultural heritage sites during development of offshore renewable energy facilities most effectively can be achieved by focusing construction and other disruptive activities within non-archaeological deposits, such as sediment layers that accumulated after the Pleistocene, and avoiding disturbance of older, deeper layers in which significant archaeological sites are more likely. Implementing such measures not only complies with legal protections, such as those mandated by Section 106 of the National Historic Preservation Act of 1966, but also ensures the preservation of archeological and tribal cultural resources and submerged heritage.

Societal Responses to Offshore Wind Infrastructure

Shawn Hazboun and Hilary Boudet

Floating offshore wind infrastructure, including floating turbines, cable landings, substations, and port facilities, may affect coastal Oregon communities and ocean user groups. To ensure that planning and deployment bring the least harm to these people and places, several considerations are paramount, including prioritizing energy justice, ensuring adequate public engagement on siting, and implementing fair and inclusive community benefit plans.

In this section, we review public perceptions of offshore wind energy technologies and examine social concerns about potential impacts from floating offshore wind infrastructure in Oregon. We then examine floating offshore wind development through the lens of energy and environmental justice and offer points for thought, including the relevance and challenges of community benefit plans in mediating adverse impacts and distributing benefits.

Public Perceptions of Floating Offshore Wind Development

Public support for floating offshore wind development off Oregon's coast is necessary for it to succeed as an energy technology and mode of decarbonization. Across the United States, there is broad public support for renewable energy technologies, such as onshore wind and solar photovoltaics (Ansolabehere and Koninsky 2014, Bergquist et al. 2020, Hazboun and Boudet 2020). However, the public has limited familiarity with marine renewable energies (Stelmach et al. 2023), including floating offshore wind, because their deployment is new. This is especially true on the West Coast, where no offshore wind facilities have been deployed. Despite public support for renewable energy, decades of public opinion research have revealed a social gap in renewable energy siting (Bell et al. 2005, 2013), or a mismatch between the high level of support for renewable energy in public opinion polls and the local opposition that can arise as a project begins siting. It may be tempting to frame the opposition as NIMBYism (not in my backyard), which is usually meant to represent local opponents as selfish, shortsighted, or not committed to decarbonization (Dear 1992, Schively

2007). However, scholars have discouraged use of the NIMBY label and encouraged developers and policymakers to instead validate and address local concerns (Devine-Wright 2005, 2011; Rand and Hoen 2017). The reasons why host communities may be concerned about or opposed to nearby renewable energy development include but are not limited to potential impacts on their environment, traditional economic drivers, culture, community character, or places that hold special value. Furthermore, scholars have recognized that local communities are often left out of planning processes for renewable energy siting, or are provided minimal opportunity to engage, which can shape how much they trust the developer and planning officials (Dwyer and Bidwell 2019).

An early motivation for developing offshore wind energy technology was the perception that it would not be opposed locally because the turbines were at sea and not in close physical proximity to communities (Haggett 2011). This assumption has proven incorrect. As with many cases of onshore wind energy development, offshore wind energy development can encounter both public support and public opposition (Firestone and Kempton 2007, Haggett 2011, Wiersma and Devine-Wright 2014, de Groot and Bailey 2016, Firestone et al. 2020, Fleming et al. 2022). Public concern or opposition stems from perceived potential adverse effects on coastal communities and ocean users, fishing and tourist economies, the visual landscape, and recreational and cultural resources (Haggett et al. 2020, Russell et al. 2020, Ferguson et al. 2021). Additional public concerns include the relative cost of offshore wind compared with other energy sources, perceptions of risks given the newness of the technology, the fact that wind energy developers are often outsiders and in many cases large corporations, the transmission of generated electricity to distant cities, and the belief that the resources needed to build and deploy a floating offshore wind array will cause more harm than benefit to the environment (Bidwell et al. 2022, Nytte et al. 2024).

The amount, timing, and quality of engagement with communities and the broader public before a facility is sited greatly affect public perception of the project, its developers, and regulators (Firestone and Kempton 2007, Haggett 2011, Dwyer and Bidwell 2019, Firestone et al. 2020). Early, meaningful, frequent, and two-way engagement with the public and impacted communities is central to whether the regulatory process is perceived as transparent and fair, or closed and partial. The main forms of public participation in that process, public comment periods and hearings, collect sentiments but do not require a change of action or even a direct response (Brown and Eckold 2020, De'Arman 2020). In analyzing the process surrounding the development of Block Island, the United States's first offshore wind array, and the high level of local support for the project, Dwyer and Bidwell (2019) suggested that regulatory process leaders built trust with affected and interested parties through diverse informal actions and by meeting their expectations for two-way engagement. Other studies also suggest that two-way deliberation is essential to successful public engagement for energy development, including offshore wind (McAdam and Boudet 2012, Klain et al. 2017).

Defining the public and the community impacted by floating offshore wind infrastructure is complex, perhaps even more so than for onshore development. One community might be closest to the coastal turbines, another might accommodate the cable landing, and a different district might host port infrastructure or turbine manufacturing. Additionally, many Oregonians may view the Oregon coast and marine environment as special places and therefore be concerned about what they perceive as the industrialization of the ocean for energy generation (Perry et al. 2014, Stelmach et al. 2023). Ocean economies, such as fisheries and whale watching, often use large areas of the ocean. Moreover, several tribal nations have direct interests in and rights to Oregon's coastal areas. With so many affected parties and such new technology, attending to community, tribal, and public concerns will be paramount to the future of floating offshore wind development in Oregon.

Environmental and Energy Justice

Despite its environmental benefits, the social impacts and equity considerations of renewable energy siting and deployment are often similar to those of traditional energy development (Ottinger et al. 2014, Dunlap 2018, Bacchiocchi et al. 2022, Walker et al. 2023). Development of floating offshore wind in Oregon and along the West Coast offers an opportunity for regulators, developers, and communities to learn from the past and work toward an inclusive, collaborative, and equitable development outcome. This goal of more-equitable development of new energy facilities is increasingly important to communities and at various levels of government.

The framework of energy justice has risen to prominence in academic, policy, and activist agendas on energy (Sovacool et al. 2017). Energy justice uses principles of justice to understand how energy production, energy policy, and energy consumption create unequal benefits and burdens for different members of society and leave out or ignore some groups (Jenkins et al. 2016).

The Biden administration had a central focus on energy justice. Promoting environmental justice was a key part of the Inflation Reduction Act, and Biden's Justice40 Initiative set a target for 40 percent of federal investments in clean energy and climate change to reach disadvantaged communities (DOE n.d.). Furthermore, Biden appointed an energy justice advocate and former professor, Shalanda Baker, as Director of the Office of Energy Justice and Equity at the U.S. Department of Energy. Under Biden, this office and the department had an exacting focus on energy justice.

Oregon and other state governments also designed and implemented policies that focus on a so-called clean energy transition for all, where all includes diverse racial, ethnic, geographic, and economic statuses— policies that foster a so-called just transition (Baker 2020). In Oregon, House Bill 2021, passed in 2021, not only set the ambitious goal of 100 percent clean electricity for Oregon's largest utilities by 2040 but placed a high priority on benefiting communities of color and rural, coastal, and low-income towns and workers.

Justice and equity are important considerations throughout the energy development process, and there are multiple dimensions of justice. Recognition justice acknowledges host communities and other affected groups and focuses on ensuring that no group is excluded from the process or misrepresented (Schlosberg 2007, Jenkins et al. 2016). Procedural justice refers to a fair and transparent process in which affected parties are participants; it is invoked most commonly during public engagement exercises but also in siting decisions, permitting, and negotiation of community benefits (Bell and Carrick 2017). Distributive justice relates to the equitable distribution of the benefits and harms of an energy facility and how the adverse impacts are mitigated.

Each dimension of justice may be most relevant at different points in the offshore wind energy development timeline. The timeline begins prior to project conception with a basic assumption that every person has human rights. Recognitional justice can be considered when envisioning the project by including and valuing divergent perspectives and recognizing intersectionality (compounding disadvantage from multiple marginalized identities). Existing meaningful areas, such as marine protected areas and cultural areas, must also be considered at this stage. Formal environmental assessments provide an opportunity for (and usually require) public participation. Procedural justice is most critical during the planning and siting process and must include engagement and meaningful participation by affected publics. Distributive justice is salient during implementation, and developers must negotiate with communities to understand what types of benefits, such as economic development, energy access, or education, are perceived as most important.

An additional two dimensions of justice, capability justice and future justice, are relevant to the operation and decommissioning process despite the long lag time before those stages. The capability approach to justice (Nussbaum and Sen 1993) suggests that the impact of an operating offshore wind array should be evaluated in terms of how it affects everyone's ability to live a safe, fulfilling, and dignified life. This evaluation includes factors such as economic impacts on fishers, effects of the supply chain on the workforce, and pricing implications for consumers (especially those living with lower incomes). Future justice refers to how offshore wind infrastructure might impact future generations that will be responsible for decommissioning. Future justice also includes consideration of wind energy development in the context of global climate change.

These concepts provide a framework for thinking about how development of floating offshore wind in Oregon can be equitable in its recognition of host communities and other impacted groups, fair and transparent in its decision-making processes, and just in the distribution of benefits and burdens. An emerging policy option with the potential to advance energy justice is the implementation of community benefit plans, which typically are negotiated between the developer and impacted communities and sometimes are overseen by regulators.

Community Benefit Plans

Negotiation of community benefit plans is increasingly common in offshore wind development. Community benefit plans are also required in some policy contexts. For example, the U.S. Department of Energy requires community benefit plans as part of all Bipartisan Infrastructure Law and Inflation Reduction Act funding opportunity announcements. Community benefit plans are not a new concept: they have been used during construction of some onshore renewable energy facilities and stadiums, and in development of European offshore wind energy. Other models of benefit-sharing from these types of development include community ownership. Here, we focus on community benefit plans because of their increasing use in the offshore wind energy sector in the United States.

Community benefit plans can help empower communities to negotiate terms of development and can lead to greater public acceptance of a project. For example, community benefits of the Block Island wind array were collaboratively negotiated by the island community and the developer, Deepwater Wind (Klain et al. 2017), and were vital for the project's success. The negotiated benefits were mainly non-monetary and included provision of an electrical grid connection from the mainland to the island (which previously had to transport diesel for generators), inclusion of fiber optic cables in the underwater cable bundle to increase the community's internet speed, several infrastructure improvements on the island, and local jobs (Klain et al. 2017).

Community benefit plans may be voluntary, legally binding Community Benefit Agreements (or Host Community Agreements or Good Neighbor Agreements) and may include Community Workforce or Project Labor Agreements. The negotiated suite of benefits may include direct payment to the community, tax incentives, restoration of public space, educational partnerships, infrastructure improvement, and other types of indirect benefits (Bedsworth and Hoff 2024).

In its California offshore wind leases of 2023, the Bureau of Ocean Energy Management offered a five percent bidding credit to developers if they demonstrated a commitment to entering into a General Community Benefit Agreement, and another five percent for committing to a Lease Area Use Community Benefit Agreement. The same provision was offered in the Oregon auction in 2024 (Federal Register 2024).

Because every community has different needs, and not all impacted groups are within the community closest to the infrastructure, there is no single model of community benefits for offshore wind development. Rudolph et al. (2018) proposed that negotiation of community benefits begin with a mutually agreed-on definition of the community, a collective understanding of who should benefit, agreement on the types of benefits that will be provided, and shared understanding of how the parties perceive the impacts of the project.

Although community benefit plans may lead to recognitional, procedural, and distributive equity in offshore wind development, they have challenges and pitfalls. For example, community benefit plans can be perceived by host communities as bribes offered by the developer to buy social acceptance. Additionally, a community's capacity to negotiate on its own behalf is often limited by staffing and funding; in some cases, the developer may agree to pay consultant or legal fees. Ensuring that all impacted parties participate in the negotiation can be a challenge, and there may be disagreement on who should be represented. Opinions on who should be represented depend partly on the definition of community and also on the actors' level of commitment to recognitional justice.

Floating offshore wind development in Oregon bears promise as a decarbonization technology, but it is not intrinsically different from traditional energy development in its potential to disproportionately burden communities and ocean user groups. Furthermore, a substantial proportion of Oregon coastal communities are rural, low-income, include Indigenous peoples and tribal governments, and are classified as disadvantaged communities (CEQ 2024). As development proceeds, regulators, developers and community leaders must ensure justice, gauge public perceptions of development, and manage expectations if trust and support for offshore wind are to grow and ultimately lead to more successful and accepted outcomes. If these factors are not addressed, development proposals are likely to stall and fail due to public mistrust and resistance.

Adaptive Management Principles

Andrea Copping and Hayley Farr

Adaptive management is a systematic process intended to improve policies and practices by learning from the outcomes of management decisions and reducing scientific uncertainty. The concept of adaptive management originated to address the extent to which scientific uncertainty complicates natural resource management and development (Holling 1978, Walters and Hilborn 1978, Walters 1986). Recognizing the limitations of numerical modeling to represent complex natural systems and to predict outcomes of perturbations, early proponents of adaptive management proposed linking experiments with hypothesis testing and systems assessments and recommended that affected and interested parties participate in the process (Holling and Meffe 1996). In contemporary Oregon, adaptive management begins with the participation of tribal nations, coastal communities, and other interested and affected parties.

Adaptive management is often referred to as learning by doing, leading to iteration of management actions on the basis of new information (Walters and Holling 1990, Williams and Brown 2012). In the United States, adaptive management has been adopted by the Department of the Interior (Williams et al. 2009).

Adaptive management is most effective when the objectives of management are clear and measurable, there is an opportunity to learn, uncertainty impedes a decision or hinders the effectiveness of management, real choices among alternatives exist, institutions are committed to and capable of measuring outcomes and acting in response to that information, and there is a mandate to act despite uncertainty. The development of floating offshore wind (FOSW) allows for learning that is intrinsic to adaptive management. However, if development may threaten legally protected species or other resources, it may be necessary to follow the more-conservative mitigation hierarchy: avoid, minimize, rectify, reduce, offset (Copping et al. 2019). If it becomes apparent at any step in the mitigation hierarchy that uncertainty is inhibiting actions or effectiveness, adaptive management can be implemented again.

Adaptive management has been used to facilitate permitting of land-based wind energy infrastructure (Köppel et al. 2014, May et al. 2017, Copping et al. 2019). The most common applications of adaptive management to land-based wind include curtailing energy production to avoid harm to protected species and consulting with groups of affected and relevant parties that examine monitoring data periodically to gauge whether changes in operations may be needed (Copping et al. 2019).

Many of the land-based mechanisms for avoiding conflicts between renewable energy development and protected species are not fit for offshore wind energy development. Adaptive management has been favored for marine energy permitting in the United Kingdom (Savidge et al. 2014) and United States (Oram and Marriott 2010, Jansujwicz et al. 2015, Marafino et al. 2023). As fixed-bottom offshore wind development has become a reality on the U.S. Atlantic Coast, adaptive management processes are being considered as viable given scientific uncertainty and the need to involve interested and affected parties in decision-making and management processes (Williams et al. 2009).

Adaptive management has not yet been applied to FOSW in the United States or other countries despite substantial uncertainty and limited evidence about the potential effects of the technology. We suggest that consideration of adaptive management for FOSW include four components. The first is determination of the level of uncertainty about potential effects and whether the proposed wind array is located away from areas with protected species or other resources. This determination is most useful at the start of planning for siting a wind array. Second, before installation, assess whether it is feasible to establish a robust, site-specific monitoring program. Third, before development permits are approved, evaluate the potential for convening an adaptive management team that is active for the life of the project. The team should include those with an immediate need for information about the project, such as the developers, regulatory agency staff, owners of the shore-based landing, and perhaps representatives of major user groups. The members of the team must be able to commit to meeting periodically, perhaps twice per year in the early stages of operation and annually thereafter, to review monitoring data and make informed recommendations for adjusting data collection and analysis. Fourth, during scoping of potential effects before permitting, ensure that other strategies, such as the mitigation hierarchy (Dempsey et al. 2023) and marine spatial planning (Douvere 2008, NCOOS n.d.), complement adaptive management.

Conclusion

Bryson Robertson and Karina Nielsen

The West Coast states of Oregon, Washington, and California have 2050 goals for economy-wide decarbonization and 100 percent clean electricity. Meeting these economy-wide and electricity-focused goals is imperative to mitigate the worst impacts of climate change. In 2022, more than 85 percent of carbon dioxide emissions in the United States were a result of energy generation, storage, transportation and combustion.

To meet these goals, each state will be grappling with the tripartite challenge of concurrently retiring significant fossil fuel-fired electricity generation capacity, meeting increasing electrical load or demand, and developing and managing a new suite of clean renewable energy generation, all while maintaining reliability and affordability for consumers. In assessing the possible pathways and actions that can be taken to achieve these goals, each state is examining its renewable energy resources and opportunities. Land-based wind and solar power will play a major role in the future electricity system, but they are insufficient to meet the triple challenge alone.

The offshore winds on the U.S. West Coast represent one of the most energetic and consistent renewable energy resources in the nation, and a possibly viable technological pathway to mitigate climate change and meet decarbonization goals. The technology to harness offshore winds is in a period of rapid global research, development, and deployment.

The lease areas in California and the proposed lease areas in Oregon are in far deeper ocean waters than previously attempted for offshore wind, which leads to uncertainty for many government, community, tribal, and industry parties. The development of floating offshore wind energy along the West Coast also has significant technological and supply chain uncertainty due to a limited trained workforce, aging electrical transmission, and a lack of the port infrastructure necessary to support deployments and delivery. However, the regulatory and permitting process is long, data intensive, and requires considerable public input. There is potential that this slow process will allow for clarification of many technological and economic concerns prior to deployment. Any deployments in Oregon will benefit from many years of experience, data collection, and knowledge of development from California and other regions worldwide.

Acknowledging Oregon's diverse and valued natural environment, existing ocean users, tribes, and Oregonians' attachment to the state's coast, any potential development is far more likely to succeed with authentic, collaborative, and capacity-generating engagement among a wide range of tribes, community groups, commercial operations, and the public.

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