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Offshore Wind Market Report: 2021 Edition

Disclaimer

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List of Acronyms

BNEF	Bloomberg New Energy Finance
BOEM	Bureau of Ocean Energy Management
BP	British Petroleum
CapEx	capital expenditures
COD	commercial operation date
COP	Construction and Operations Plan
CTV	crew transfer vessel
CVOW	Coastal Virginia Offshore Wind
DOE	U.S. Department of Energy
FERC	Federal Energy Regulatory Commission
ft	foot/feet
GW	gigawatt
HVAC	high-voltage alternating current
HVDC	high-voltage direct current
ISO-NE	Independent System Operator – New England
ITC	investment tax credit
kV	kilovolt
km	kilometer
LEEDCo	Lake Erie Energy Development Corporation
LCOE	levelized cost of energy
m	meter
MW	megawatt
MWh	megawatt-hour
NOWRDC	National Offshore Wind R&D Consortium
NREL	National Renewable Energy Laboratory
NYISO	New York Independent System Operator
NYSERDA	New York State Energy Research and Development Authority
OCS	Outer Continental Shelf
O&M	operation and maintenance
OEM	original equipment manufacturer
OpEx	operational expenditures
OREC	offshore renewable energy certificate
OWDB	offshore wind database

POI	point of interconnection
PPA	power purchase agreement
ROD	Record of Decision
s	second
SAP	site assessment plan
SOV	service operation vessel
TBD	to be determined
WEA	wind energy area
WTIV	wind turbine installation vessel

Executive Summary

Since 2015, maturing technology, rapidly evolving supply chains, increased competition, and experience from utility-scale installations have driven costs down and broadened the deployment of offshore wind energy across the globe. The "Offshore Wind Technologies Market Report: 2021 Edition" provides detailed information on the U.S. and global offshore wind energy industries to inform policymakers, researchers, and analysts about technology and market trends. The scope of the report covers the status of over 200 global operating offshore wind energy projects through December 31, 2020, and provides the status of, and analysis on, a broader global pipeline of projects in various stages of development. To provide the most up-to-date discussion of this evolving industry, this report also tracks the most significant domestic developments and events from January 1, 2020, through May 31, 2021.

U.S. Offshore Wind Energy Market

In 2020, the U.S. offshore wind energy project development and operational pipeline grew to a potential generating capacity of 35,324 megawatts (MW). Specifically, the pipeline experienced a 24% increase in 2020, up from 28,521 MW in 2019 (National Renewable Energy Laboratory [NREL] Offshore Wind Database 2020[1]). The 35,324 MW that make up the U.S. offshore wind energy project pipeline comprise two operating projects: the Block Island Wind Farm (30 MW) and the Coastal Virginia Offshore Wind (CVOW) pilot project (12 MW). Beyond this, one project—Vineyard Wind 1 [800 MW]—is fully approved, and has received all permits, an offtake contract to sell the power, and an interconnection agreement to deliver it to the grid. In addition, there are 15 projects in the pipeline that have reached the permitting phase, with either a Construction and Operations Plan[2] (COP) or an offtake mechanism for the sale of electricity, 16 commercial leases in federal waters that have gained exclusive site control, and seven wind energy areas that can be leased at the discretion of the federal government in the future. The Bureau of Ocean Energy Management (BOEM)— the government agency that regulates energy development in federal waters—has also designated nine Call Areas where future offshore wind energy development is being considered. The pipeline includes three projects located in state waters: the operating Block Island Wind Farm, the Aqua Ventus I floating-wind project in Maine, and the Lake Erie Energy Development Corporation Icebreaker Wind project. A map of the current pipeline activity is shown in Figure ES-1.

Further, the Biden Administration announced a 30-gigawatt (GW)-by-2030 national offshore wind energy goal and states continue to adopt their own offshore wind procurement mandates (White House 2021a). The federal target to install 30 GW of capacity by 2030 is the first U.S. national offshore wind energy goal. To make progress toward this goal, BOEM aims to evaluate at least 16 COPs by 2025 and work with the U.S. Department of Energy, U.S. Department of Commerce, and industry stakeholders to minimize environmental impacts and ensure the coexistence of offshore wind energy with other ocean users. Beyond the national level goal, states are aiming to procure at least 39,298 MW of offshore wind capacity by 2040. These

[1] All project data from this report come from NREL's internal offshore wind database, which contains information on more than 2,079 offshore wind energy projects located in 49 countries and totaling approximately 831,991 MW of announced project capacity (both active and dormant). For more information, see Section 1.1.1.

[2] A COP describes all the proposed activities and planned facilities that an offshore wind energy developer intends to construct and use for a project under a commercial lease. BOEM must approve the plan before construction can begin (BOEM 2020a).

federal and state deployment goals can help provide the U.S. offshore wind industry with more confidence that a sustained market will develop, increasing new investment in domestic manufacturing, vessels, and ports necessary for sustained, long-term deployment.

Additional progress made in the 2020/21 domestic offshore wind energy industry includes the following.

BOEM created five new wind energy areas (WEAs) in the New York Bight. Most of the growth in the pipeline during 2020/21 came from the addition of five new WEAs[3] in the New York Bight, positioning them for auction under the competitive leasing process (Figure ES-1).

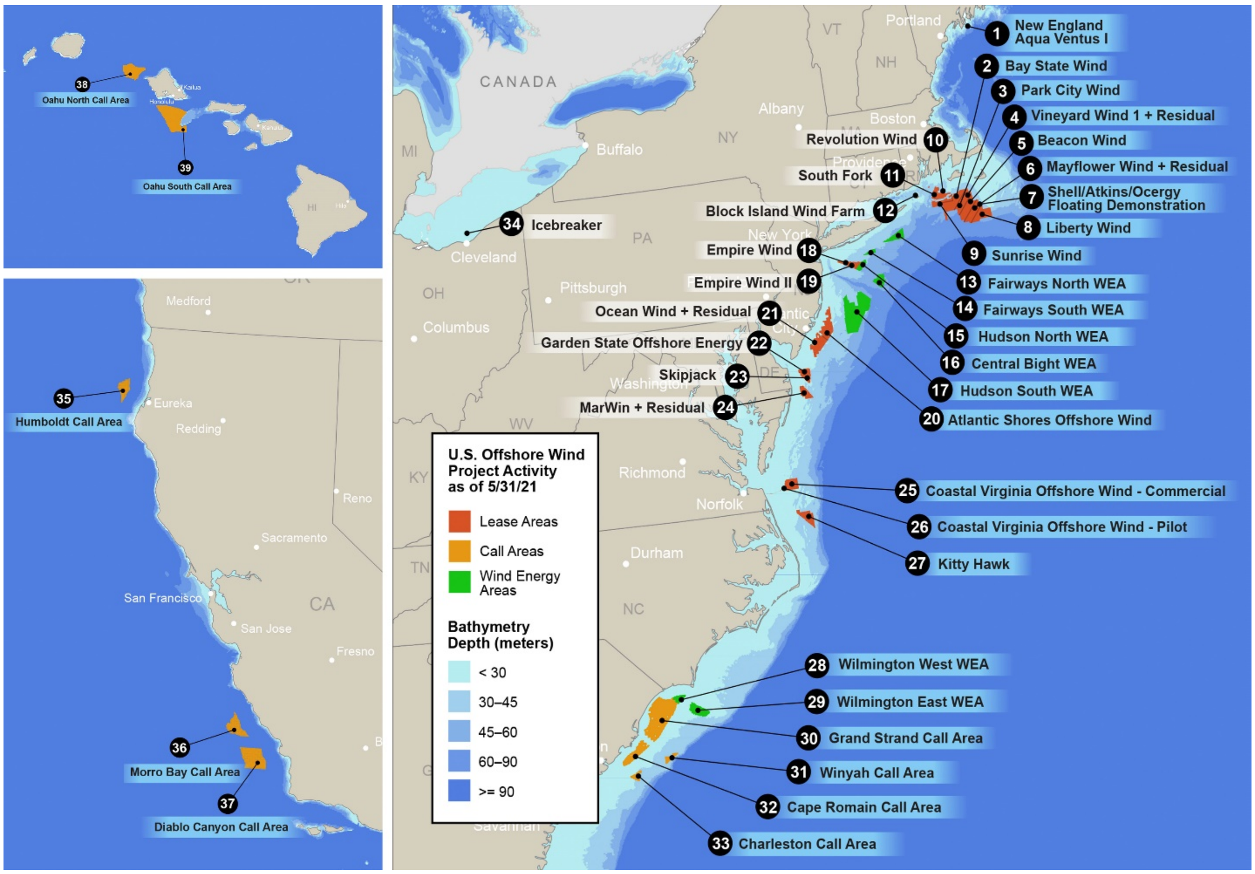

Figure ES-1. Locations of U.S. offshore wind pipeline activity and Call Areas as of May 31, 2021. ***Map created by NREL***

These new WEAs were part of the previously identified New York Bight Call Areas (BOEM 2021b). In aggregate, these yet-to-be-leased WEAs have the potential to hold about 9.8 GW of offshore wind capacity. In June 2021, BOEM issued a proposed sales notice that could potentially transform the Hudson North, Central Bight, and Hudson South WEAs into eight new wind energy lease areas. A final sales notice will be issued after a period of public comment.

[3] WEAs are ocean areas on the Atlantic Outer Continental Shelf that are not only the most suitable for commercial wind energy activities but may also present the fewest apparent environmental and user conflicts. BOEM has the authority to competitively lease WEAs to offshore wind energy developers.

CVOW pilot successfully connected to the grid. The 12-MW demonstration project (cover photo) was connected to the grid at Birdneck Substation near Camp Pendleton, Virginia, and started generating power in October 2020 and was fully commissioned in January 2021. The CVOW pilot was constructed by Ørsted using Jan De Nul's Vole-au-Vent wind turbine installation vessel. The project is owned by Dominion Energy and comprises two Siemens Gamesa 6-MW turbines mounted on EEW monopile substructures. It is the second U.S. offshore wind energy project to install commercial-scale wind turbines and the first project to be permitted and constructed in federal waters under the jurisdiction of BOEM.

Vineyard Wind 1 became the first fully approved commercial offshore wind energy project in the United States. After 3 years of review, Avangrid and Copenhagen Infrastructure Partners' 800-MW Vineyard Wind 1 project received a Record of Decision, indicating the approval of the project's COP in May 2021 (BOEM 2021b). The project had previously completed state and local permitting requirements in June 2019 and received an interconnect agreement from the Independent System Operator-New England in July 2020. With a revision to its COP in December 2020, Vineyard Wind reported it was switching from MHI-Vestas 9.5-MW wind turbines to GE 13-MW Haliade-X wind turbines. The project has reported plans to be fully connected to the grid by 2024.

Two U.S.-flagged offshore wind installation and support vessels were announced. Construction of the first U.S.-flagged wind turbine installation vessel, Charybdis, began at the Keppel AMFELS shipyard in Brownsville, Texas, in 2020 (Dominion Energy 2020b). The new vessel is 472 feet long and designed by GustoMSC. Lloyd's Register and Northeast Technical Services Co., Inc. also announced plans to construct a U.S.-flagged wind turbine installation vessel; however, as of May 31, 2021, construction has not yet started (Lloyd's Register 2020).

Global Offshore Wind Energy Market

Globally, the offshore wind energy industry installed 5,519 MW of capacity in 2020. Much of the added global generating capacity can be attributed to 2,174 MW of new deployments in the Chinese market, followed by 1,503 MW commissioned in the Netherlands, 714 MW in the United Kingdom, 706 MW in Belgium, 315 MW in Germany, and 107 MW divided among the rest of the world (NREL Offshore Wind Database 2020). By the end of 2020, cumulative global offshore wind installed capacity grew to 32,906 MW from 200 operating projects. Projections indicate that annual global capacity additions in 2021 and beyond will accelerate, with 23,415 MW of projects currently under construction. As of December 31, 2020, the global pipeline for offshore wind energy development capacity was assessed to be 307,815 MW.

Global Floating Offshore Wind Energy Market

The global pipeline for floating offshore wind energy more than tripled in 2020. Overall, the 2020 global floating offshore wind pipeline grew from 7,663 MW to 26,529 MW, representing 18,866 MW of growth since the "2019 Offshore Wind Technologies Data Update." This growth is attributed to several projects beginning their planning phase during 2020, especially in Asian markets.

No additions are made to the installed capacity for floating wind in 2020. Despite a surge of floating wind energy projects entering the early planning stages of the pipeline, the global market did not expand its installed capacity in 2020.

Offshore Wind Energy Technology Trends

The three leading wind turbine manufacturers have announced the development of larger offshore wind turbines ranging from 12- to 15-MW. The expected 12- to 15-MW offshore wind turbine class is now under full development, with Siemens Gamesa, Vestas, and GE all reporting their intention to have wind turbines at these nameplate ratings available for purchase by 2024 or sooner. U.S. orders indicate that most projects in the current pipeline will obtain wind turbines from one of these original equipment manufacturers.

Historic wind turbine size increases in Asia lag those in western markets while Asian projects also report lower capital costs. Prototype development data indicate that new Asian prototype wind turbine capacities are about 25% lower than their western counterparts, but upscaling in both markets is occurring at approximately the same rate. Based on developer reports, Asian offshore wind energy projects expect to achieve lower wind turbine and project costs, although cost data from Chinese markets are more difficult to verify and compare to project cost data from other parts of the world.

Offshore Wind Energy Cost and Price Trends

Globally, the average levelized cost of energy (LCOE)[4] of fixed-bottom offshore wind energy installations is now below $95/megawatt-hour (MWh). This cost level for projects that began commercial operations in 2020 represents a reduction of 16% on average, compared to NREL reporting in 2019. LCOE for wind projects that have a commercial operations date[5] in 2020 range between $78/MWh and $125/MWh. Offshore wind LCOE has declined by 28-51% between 2014 and 2020. (Wiser et al. 2021). By 2030, the surveyed experts predict LCOE levels of approximately $56/MWh, declining further to a range of $44/MWh to $72/MWh by 2050.

The levelized procurement price of U.S. offshore wind energy projects ranges between $96/MWh (Vineyard Wind 1) and $71/MWh (Mayflower Wind) for projects commencing commercial operations between 2022 and 2025. These prices from power purchase agreements and offshore renewable energy certificates are based on a total of 5.5 GW of signed agreements. Mayflower Wind's (all-inclusive) procurement price of $71/MWh is among the lowest-priced offshore wind energy projects announced globally. During 2020, the number of corporate power purchase agreement off-takers[6] also increased, indicating a new trend in diversifying offshore procurement options. In 2020 and early 2021, nearly 4 GW were procured with corporate off-takers in northern Europe.

[4] LCOE is the cost per unit of energy of generating electricity during an assumed project design life that allows for the recovery of all project expenses and meets investor return expectations (Wiser et al. 2016).
[5] The commercial operations date is the year the project is commissioned and begins producing full power
[6] A corporate offtaker is a commercial or industrial electricity user that purchases power directly from the wind project.

Floating offshore wind LCOE is predicted to decline from approximately $160/MWh in 2020 to $60–$105/MWh in 2030.[7] These estimated cost reductions are related to an expected floating deployment trajectory that spans from multiple wind turbine demonstration projects expected to come online through 2023 to medium- to full-scale commercial projects announced for commercial operation after 2023.

Future Outlook

Global offshore wind energy deployment is expected to accelerate in the future, with forecasts from 4C Offshore and Bloomberg New Energy Finance indicating a seven-fold increase in global cumulative offshore wind capacity—to 215 GW or more by 2030 (BNEF (2020a), 4C Offshore (2021)). As part of that predicted surge, the U.S. offshore wind energy market continues to expand, primarily driven by increasing state-level procurement targets in the Northeast and mid-Atlantic, an increased number of projects clearing major permitting milestones, as well as growing vessel, port, and infrastructure investments needed to keep pace with development. Moreover, a new national target of 30 GW of offshore wind energy by 2030, set in March 2021, could help illuminate the potential for future U.S. market growth. As the number of projects in the advanced permitting and approval phases now exceeds 11 GW, the first phase of U.S. development is well underway. However, despite the new national offshore wind energy deployment goal, fluctuating policy support, stakeholder concerns, constrained global supply chains, and land-based grid limitations pose challenges that could potentially temper the industry's progress.

Over the next few years, the frontiers for offshore wind energy development in the United States are likely to expand from the North Atlantic into other regions; each with their own challenges. In the near-term, new WEAs are likely to be identified in the Gulf of Maine where deeper waters require floating offshore wind technologies. In the Gulf of Mexico, wind speeds tend to be lower and hurricane risks need to be addressed, but regulatory activity has been initiated for possible leasing by the end of 2022. On the Pacific Coast and Hawaii, floating offshore wind energy Call Areas are advancing toward commercial leasing. Although markets in these regions may not reach their full stride for a decade, actions taken today could support future deployments. The Biden Administration's 30-GW-by-2030 goal could also set the industry on a trajectory to deploy 110 GW of offshore wind energy in the United States by 2050 (The White House 2021a). This level of offshore wind energy deployment would be a substantial part of a comprehensive decarbonization strategy to combat climate change.

[7] Research organizations making these predictions include NREL (2019, 2021), DNV GL (2020), ORE Catapult (2021), and over a hundred industry expert surveyed by Lawrence Berkeley National Laboratory (2021). For more information, see Section 6.2.

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1. Introduction

Offshore wind energy is a rapidly growing global industry that began commercial development in Europe over 20 years ago. In the United States, commercial-scale deployment is at a nascent stage. Policy commitments made in recent years combined with high commercial interest suggest strong growth in the coming years. This prospect is reinforced by renewed commitments from the Biden Administration, which recently established a first national deployment target of 30 gigawatts (GW) of offshore wind energy by 2030. Globally, offshore wind energy technology has evolved by combining experience from the land-based wind industry with logistical and supply chain solutions from the offshore oil and gas sector.

U.S. offshore wind energy adoption has been incentivized through state policies in the northeast and mid-Atlantic regions to help individual states meet renewable energy targets and promote economic growth. Offshore wind energy is valued in many of these states because large, utility-scale projects can be built offshore and adjacent to large, congested load centers while causing little interference to other ocean activities.

This "Offshore Wind Market Report: 2021 Edition" was researched and written by the National Renewable Energy Laboratory (NREL) for the U.S. Department of Energy (DOE) to provide offshore wind energy policymakers, regulators, developers, researchers, engineers, financiers, and supply chain participants with up-to-date quantitative information about the offshore wind energy market, technology, and cost trends in the United States and worldwide. This report includes detailed information on the domestic offshore wind energy industry, providing context to help navigate technical and market barriers and opportunities. It also covers the status of over 200 operating offshore wind power plants in the global fleet through December 31, 2020, and provides the details and analysis on a broader global pipeline of 838 projects at varying stages of development. In addition, this report provides a deeper assessment of domestic developments and events through May 31, 2021, for this evolving industry.

This report includes data obtained from a wide variety of sources about offshore wind energy projects that are both operating and under development to offer past, current, and forward-looking perspectives. These projects are also used as key inputs to the annual "Cost of Wind Energy Review" report, which provides an updated summary of the cost of land-based and offshore wind energy in the United States to support DOE's programmatic reporting on the cost of wind energy (Stehly et al. 2020). This report is also a companion to the "Land-Based Wind Market Report: 2021 Edition" and "Distributed Wind Market Report: 2021 Edition" funded by DOE and authored by the Lawrence Berkeley National Laboratory (Wiser et al. 2021) and the Pacific Northwest National Laboratory (Orrell et al. 2021), respectively. These companion reports cover the status of utility-scale and distributed, land-based wind energy located primarily in the United States and provide quantitative data and context for use by the wind industry and its stakeholders.

Global offshore wind energy deployment in 2020 held pace with 2019 deployment figures despite the potential for delays caused by the COVID-19 pandemic, with 5,519 megawatts [MW] of new installations. It is difficult to quantify the impact that COVID-19 might have had on the industry this past year, but long-term projections for future growth are clear-cut. These projections indicate accelerated growth both globally and nationally, with long-term projections of over 215 GW by 2030 and over 1,000 GW by 2050 (Bloomberg NEF [BNEF] 2020a; 4C Offshore 2021; International Renewable Energy Agency 2020).

During 2020 and early 2021, states, the federal government, and regulatory agencies made increasing policy commitments to offshore wind energy. Drivers behind this activity include an increased sense of urgency among policymakers and elected officials to decarbonize the energy sectors as well as continued lower costs in European and Asian offshore wind energy markets. The Biden Administration projects that meeting the 30 GW by 2030 target in the United States might generate $12 billion/year in project capital investments over the next 10 years (The White House 2021b, 2021c). Despite the new national offshore wind energy deployment goal and regulatory advancements, fluctuating policy support, constrained global supply chains, and onshore grid limitations could pose challenges that temper the industry's progress.

1.1 Approach and Method

1.1.1 NREL Offshore Database

The "Offshore Wind Market Report: 2021 Edition" uses NREL's internal offshore wind database (OWDB), which contains information on more than 2,079 offshore wind energy projects located in 49 countries and totaling 831,991 MW of announced project capacity (both active and dormant). The database includes both fully operational projects dating back to 1990 and anticipated future deployment that may or may not have announced their commercial operation date (COD).[8] The OWDB contains information on project characteristics (e.g., water depth, wind speed, distance to shore), economic attributes (e.g., project- and component-level costs and performance), and technical specifications (e.g., component sizes and weights). The database also contains information on installation and transportation vessels, as well as ports that support the construction and maintenance of offshore wind energy projects.

The OWDB is built from internal research using a wide variety of data sources including press releases, industry news reports, manufacturer specification sheets, subscription-based industry databases, global offshore wind energy project announcements, and peer-reviewed literature. Unless stated otherwise, the data analysis in this report—both global and domestic—is derived by NREL from the OWDB and reflects the best judgment of the authors and industry subject matter experts that were consulted. To ensure accuracy, NREL verified the OWDB against the following sources:

- 4C Offshore's Wind Database
- The Bureau of Ocean Energy Management (BOEM) on-line published data
- WindEurope's Annual Market Update
- BNEF's Renewable Energy Project Database.

Although the data were validated and harmonized with these other sources, minor differences in their definitions and methodology may cause the data in this report to vary from data in other published reports. For example, the method for counting annual capacity additions often varies

8 COD refers to the point in time at which an offshore wind energy project is fully installed, connected to the grid, and generating power.

among different sources, because of terms such as "installed" or "operational," and "first power" or "commercial operation date" are often defined differently. NREL considers a project to be commercially operational when all wind turbines are fully operational and transmitting power to a land-based electricity grid (see Table 1). Data may also vary in quality and are subject to high levels of uncertainty, especially data for future projects that are subject to change based on developer and regulatory requirements. Despite annual variability and potential future project-level uncertainty, trends reported elsewhere are consistent with long-term market trends in the OWDB.

Cost and pricing data in the OWDB span a lengthy period and are reported in different currencies. To analyze these data, we normalized all information in this report into 2020 U.S. dollars (USD) by:

- Converting costs and prices to USD, using the exchange rate for the year in which the latest data were reported (Bureau of the Fiscal Service 2019)
- Inflating the values, which are in nominal USD after the exchange rate conversion, to 2020 USD using the U.S. Consumer Price Index (U.S. Bureau of Labor Statistics 2019).

1.1.2 Classification of Project Status

The "pipeline" in this report is an offshore wind energy development and operating project tracking process that provides the ability to follow the status of a project from early-stage planning through decommissioning. We aligned the primary tracking method with the U.S. offshore wind regulatory process, but the methodology generally applies for tracking global projects as well. All offshore wind projects must navigate through the regulatory process that formally begins when a regulator initiates the leasing process to designate a wind energy area (WEA), which typically leads to a competitive lease auction.[9]

In parallel with the regulatory process are the developer's efforts to demonstrate the economic viability of the project and obtain financing. Regulatory and financing pathways often happen in parallel and have several interdependencies. Since financial negotiations are usually confidential, this report primarily tracks projects by their regulatory achievements. As a result, the "pipeline" is defined as the set of all offshore wind energy projects, including wind energy areas that are waiting to be auctioned, sites where developers hold offshore wind leases, operational projects, and decommissioned projects. If known, we report information on a project's offtake mechanisms and financial contracts as well.[10]

This year, NREL revised the method of calculating the U.S. offshore wind energy pipeline to adapt to changes in the processing of unsolicited lease requests under BOEM regulations. In general, BOEM pursues a competitive leasing process if competitive interest is found to exist in ocean areas proposed in unsolicited lease applications. Competitive interest is determined through the subsequent Calls for Nominations[11] when other developers can indicate if they are

[9] Applies to U.S. projects on the Outer Continental Shelf but varies internationally and in state waters.
[10] The "pipeline" is often measured by the quantity of policy commitments made by states. These figures are tracked separately in Section 2.4.2 and offer a good metric for comparison.
[11] A Call Area is a precursor to a defined WEA, but not all Call Areas become wind energy areas, and they are typically modified (e.g., reduced in size or augmented) to address stakeholder input.

interested in the proposed project sites of the original unsolicited applications. Through this process, BOEM determined that competitive interest did indeed exist at the proposed locations; therefore, the unsolicited lease applications are no longer being reviewed.

In our previous pipeline method, we included the generation capacity of these unsolicited projects, which totaled 2,350 MW in 2019, as part of the pipeline (all unsolicited projects proposed floating wind technologies in California or Hawaii). In 2020, these projects are no longer counted because they were superseded by Call Areas. The original unsolicited project applicants are eligible to participate in future auctions subject to BOEM rules. Because the Call Area boundaries may change, no portion of the Call Areas are counted in the pipeline totals.

In the early stages of a project, the exact project footprints and generating capacities are not always known, but NREL assumes that all lease areas will eventually be fully developed with an array power density of 3 MW/square kilometer (km^2). This assumption is common for calculating the potential capacity of a lease or Call Area but may represent a conservative estimate of eventual installed capacity (Musial et al. 2013, 2016). A conservative approach to estimating future potential capacity is used to allow for potential reductions to the developable area like navigation accommodations, geohazards, setbacks, and other easements (Musial et al. 2013), and that water depth and technology choices may limit where wind turbines are installed. (e.g., catenary mooring footprints increase needed area for floating wind energy projects in deep water) (Musial et al. 2013). Some developers may want higher array densities for their projects, or conversely, could decide or be required to leave areas undeveloped for various reasons. The pipeline capacity total is adjusted when those decisions are publicly announced.

Table 1 describes the classification criteria used in this report for tracking the development of offshore wind energy projects. These criteria have been used in past DOE-sponsored offshore wind energy market reports (Smith, Stehly, and Musial 2015; Musial et al. 2017, 2019b, 2020; Beiter et al. 2018). Note that the criteria used in Table 1 also apply to the global project classification, but some differences may not allow for direct comparisons, especially during the earlier stages of planning. This potential disconnect is mainly because some countries have different methods of establishing “site control.”[12]

[12] For example, in the United Kingdom, site control is established by a tender process, wherein winning bidders have the right to acquire seabed rights from the Crown Estate after receiving a consent agreement (The Crown Estate 2021). In Germany, the right for a project to take part in the Planfeststellung, which is the type of construction permit required for offshore wind generators, is granted to the successful bidder as part of a mandatory auction procedure under the Offshore Wind Energy Act (Windenergie-auf-See-Gesetz) (Hogan Lovells 2020).

Table 1. Offshore Wind Project Pipeline Classification Criteria

Step	Phase Name	Start Criteria	End Criteria
1	Planning	Starts when a developer or regulatory agency initiates the formal site control process	Ends when a developer obtains control of a site (e.g., through competitive auction or a determination of no competitive interest in an unsolicited lease area (United States only)
2	Site Control	Begins when a developer obtains site control (e.g., a lease or other contract)	Ends when the developer files major permit applications (e.g., a Construction and Operations Plan for projects in the United States)
3	Permitting = Site Control + Offtake Pathway	Starts when the developer files major permit applications (e.g., a Construction and Operations Plan and an offtake agreement for electricity production)	Ends when regulatory entities authorize the project to proceed with construction and certify its offtake agreement
4	Approved	Starts when a project receives regulatory approval for construction activities and its offtake agreement	Ends when sponsor announces a "financial investment decision" and has signed contracts for construction work packages
5	Financial Close	Begins when sponsor announces a financial investment decision and has signed contracts for major construction work packages	Ends when the project begins major construction work
6	Under Construction	Starts when construction is initiated[13]	Ends when all wind turbines have been installed and the project is connected to and generating power to a land-based electrical grid
7	Operating	Starts when all wind turbines are installed and transmitting power to the grid; COD marks the official transition from construction to operation	Ends when the project has begun a formal process to decommission and stops feeding power to the grid
8	Decommissioned	Starts when the project has begun the formal process to decommission and stops transmitting power to the grid	Ends when the site has been fully restored and lease payments are no longer being made
9	On Hold/Cancelled	Starts if a sponsor stops development activities, discontinues lease payments, or abandons a prospective site	Ends when a sponsor restarts project development activity

[13] Note that some developers may elect to start construction at an onshore landing area to secure certain subsidies or tax incentives.

1.2 Report Structure

The remainder of this report is divided into five sections:

Section 2 summarizes the status of the offshore wind energy industry in the United States, providing in-depth coverage on the project development pipeline, regulatory activity, offtake mechanisms, infrastructure and vessel trends, and regional developments.

Section 3 provides an overview of the global offshore wind energy market. Operational and proposed future projects are tracked by country, status, commercial operation date, and capacity. Developments on international floating offshore wind energy projects are also covered in detail.

Section 4 compiles information on the global floating offshore wind energy market. Progress from this nascent sector of the industry is detailed to enable more careful tracking of floating technologies.

Section 5 describes offshore wind energy siting and technology trends focusing on wind turbine technologies, turbine manufacturers, project performance, fixed-bottom substructures, electrical power, export systems, and floating technologies.

Section 6 provides insight into global and domestic offshore wind capital and operational costs, procurement prices, and financing trends for both fixed-bottom and floating technologies.

2. U.S. Offshore Wind Market Assessment

2.1 U.S. Offshore Wind Industry Overview

In 2020, the U.S. offshore wind energy pipeline grew to 35,324 MW—24% over the 28,521 MW reported in 2019. Following the 2020 U.S. presidential election, the Biden Administration set a national offshore wind deployment goal for 30 GW of capacity to be installed by 2030 (The White House 2021b). The 30-GW national deployment goal combined with a renewed 30% investment tax credit (ITC) (see Section 6) are likely to increase the industry's confidence in the future market and may catalyze investment in domestic manufacturing and supply chain capabilities, vessel and port construction, and grid infrastructure necessary for sustained, long-term growth. To support this goal, by 2025, BOEM aims to complete permitting for 16 offshore wind energy projects, of which most have already submitted Construction and Operations (COP) plans. BOEM's mandate includes a commitment to equitably settle use and environmental conflicts in federal waters, working closely with the U.S. Department of Energy, U.S. Department of Commerce, and industry stakeholders.[14]

A major factor driving offshore wind energy in the United States is individual state policy commitments. In 2020, three states made major increases in their offshore wind energy policy commitments. In April 2020, Governor Northam of Virginia signed the Virginia Clean Economy Act, which set a procurement goal of 5,200 MW by 2034 (Virginia 2020). In March 2021, Massachusetts Governor Baker approved "An Act Creating a Next Generation Roadmap for Massachusetts Climate Policy," which expanded the commonwealth's offshore wind energy deployment goal to 5,600 MW by 2035 (Mass.gov 2021). In June 2021, Governor Roy Cooper issued Executive Order 218, which created an offshore wind goal for North Carolina of 2,800 MW by 2030 and 8,000 MW by 2040. In aggregate, eight states have set offshore wind energy procurement goals that have grown from 23,698 MW by 2035 in 2019 to 39,298 MW by 2040 in 2020/2021.

New offshore wind energy deployment in 2020 was limited to the installation of the 12-MW Coastal Virginia Offshore Wind (CVOW) pilot project. CVOW's commissioning marked the first lease in federal waters to make it through the entire federal regulatory process led by BOEM. The CVOW pilot project is now connected to the grid at the Birdneck substation near Camp Pendleton, Virginia, and started generating power in October 2020 and was fully commissioned in January 2021. The project was constructed by Ørsted using the Vole-au-Vent wind turbine installation vessel, is owned by Dominion Energy, and comprises two Siemens 6-MW wind turbines mounted on EEW monopile substructures. Dominion plans to leverage the experience of constructing and operating this demonstration project to optimize and lower risk on their planned CVOW (commercial) 2,640-MW wind power plant that they expect will be online by 2026.

The Vineyard Wind 1 project, owned by Avangrid and Copenhagen Infrastructure Partners, received a final Record of Decision on May 10, 2021, and became the first fully approved commercial-scale project in the United States after 3 years of review (BOEM 2021b). The

[14] Industry stakeholders also include fishermen and other ocean users who may be impacted by offshore wind energy development.

project had completed state and local permitting requirements in June 2019 and received an interconnect agreement from the Independent System Operator-New England (ISO-NE) in July 2020. After a revision to its COP in December 2020, the project switched from MHI-Vestas 9.5-MW wind turbines to GE'S 13-MW Haliade-X wind turbines. The project plans to initiate onshore construction in 2021 and be fully connected to the grid and operational in 2024.

Lessons learned during Vineyard Wind 1's approval process by stakeholders, industry, and regulators can now help streamline the regulatory pathway for other potential projects. On January 14, 2021, the New York State Energy Research and Development Authority (NYSERDA) issued two new awards—Empire Wind 2 and Beacon Wind—to a joint team of Equinor and BP (NYSERDA 2021). Empire Wind 2 (1,260 MW) is in the New York lease area and is expected to start commercial operation in 2026. Beacon Wind (1,230 MW) is in one of the Massachusetts lease areas and scheduled to start commercial operations in 2028.

As the U.S. project pipeline grows, states and electric grid operators are increasingly concerned about integrating large capacities of offshore wind energy. In November 2020, the mid-Atlantic regional grid operator, PJM, opened a 120-day solicitation on behalf of the New Jersey Board of Public Utilities for qualified developers to submit potential transmission solutions that would help deliver offshore wind energy to the existing power grid (New Jersey Board of Public Utilities 2021). The competitive solicitation is the result of a request by the board to incorporate the state's 7,500-MW offshore wind public policy deployment goals into PJM's regional transmission planning process through a novel pathway known as the State Agreement Approach.[15] Other states are currently weighing options for a coordinated offshore wind transmission approach.

With several industry projects nearing their construction phase, there's an increased focus on infrastructure and supply chain investments. Examples of these investments (see Section 2.4) include:

- In 2020, the New Jersey Economic Development Authority announced that it would build the first offshore wind energy port in the United States (New Jersey 2021).
- During 2020, two U.S.-flagged offshore wind installation and support vessels were announced.
- On the supply chain side, Ørsted and Eversource announced a $24-million investment in a foundation manufacturing facility in Port of Providence, Rhode Island (Revolution Wind 2021). This will be the first Tier-1 U.S. manufacturing facility to enter the offshore wind supply chain.[16]
- In January 2021, Welcon and Marmen announced investing in a tower and transition-piece manufacturing facility in the Port of Albany, in conjunction with Equinor and NYSERDA (Marmen 2021).

[15] As part of its Federal Energy Regulatory Committee Order 1000 compliance filing, PJM created the State Agreement Approach, which considers transmission needs driven by public policy requirements and establishes procedures to identify transmission needs and evaluate solutions.
[16] Tier-1 products refer to major components that are essential to operating an offshore wind energy farm.

Industry is likely to increase the rate of major investments in port infrastructure, vessels, and manufacturing capacity as the first wave of offshore wind construction ramps up off the Atlantic Coast.

2.2 U.S. Offshore Wind Energy Market Potential and Project Pipeline Assessment

2.2.1 U.S. Offshore Wind Energy Pipeline

As of May 31, 2021, NREL estimates the U.S. offshore wind energy pipeline to have 35,324 MW of capacity, which is the sum of current installed projects, approved projects, projects in the permitting process, existing lease areas, and unleased WEAs. Table 2 shows the U.S. market divided into nine segments by capacity.

Table 2. U.S. Offshore Wind Energy Pipeline Capacity for Seven Categories

Status	Description	Total
Operating	The project is fully operational with all wind turbines generating power to the grid.	42 MW
Under Construction	All permitting processes are completed. Wind turbines, substructures, and cables are being installed. Onshore grid upgrades are underway.	0 MW
Financial Close	Begins when sponsor announces a financial investment decision and has signed contracts for major construction work packages.	0 MW
Approved	BOEM and other federal agencies have reviewed and approved a project's COP. The project has received all necessary state permits and has completed an interconnection agreement to inject power into the grid.	800 MW
Permitting	The developer has site control and has initiated permitting processes to construct the project and sell its power.	10,779 MW
Site Control	The developer has acquired the rights to a lease area. Capacity is estimated using a wind turbine density of 3 MW/km^2. Depending on market demand, developers may or may not incrementally build out projects to use a given lease area's entire size/potential.	11,652 MW
Unleased Wind Energy Areas	The rights to lease areas have yet to be auctioned to developers. Capacity is estimated using a 3 MW/km^2 wind turbine density function.	12,051 MW
		35,324 MW

We only use developer-specified project capacity values for the most advanced projects in the pipeline, which include operating projects (42 MW), projects under construction (0 MW), approved projects (800 MW), and projects that have advanced through the initial phases of the permitting process and are negotiating offtake agreements (10,779 MW). These projects have a clearer project plan, specified site boundary, and established design details.

In contrast, lease areas with site control and unleased WEAs have much less certainty about project capacity. Therefore, we use estimated capacities based on a uniform array density assumption of 3 MW/km^2. These estimated capacity values are likely to change as projects advance and their parameters are defined more precisely.

The biggest change to the total pipeline in 2020 resulted from transforming the four New York Bight[17] Call Areas into five new WEAs, adding up to 9,801 MW of potential capacity to the pipeline. Figure 1 compares the pipeline breakdown between 2019 and May 31, 2021. The pie charts show each of the pipeline classification categories as a percent of the total U.S. pipeline. In 2019, the pipeline was 25,821 MW, and by May 31, 2021, it grew to 35,324 MW.

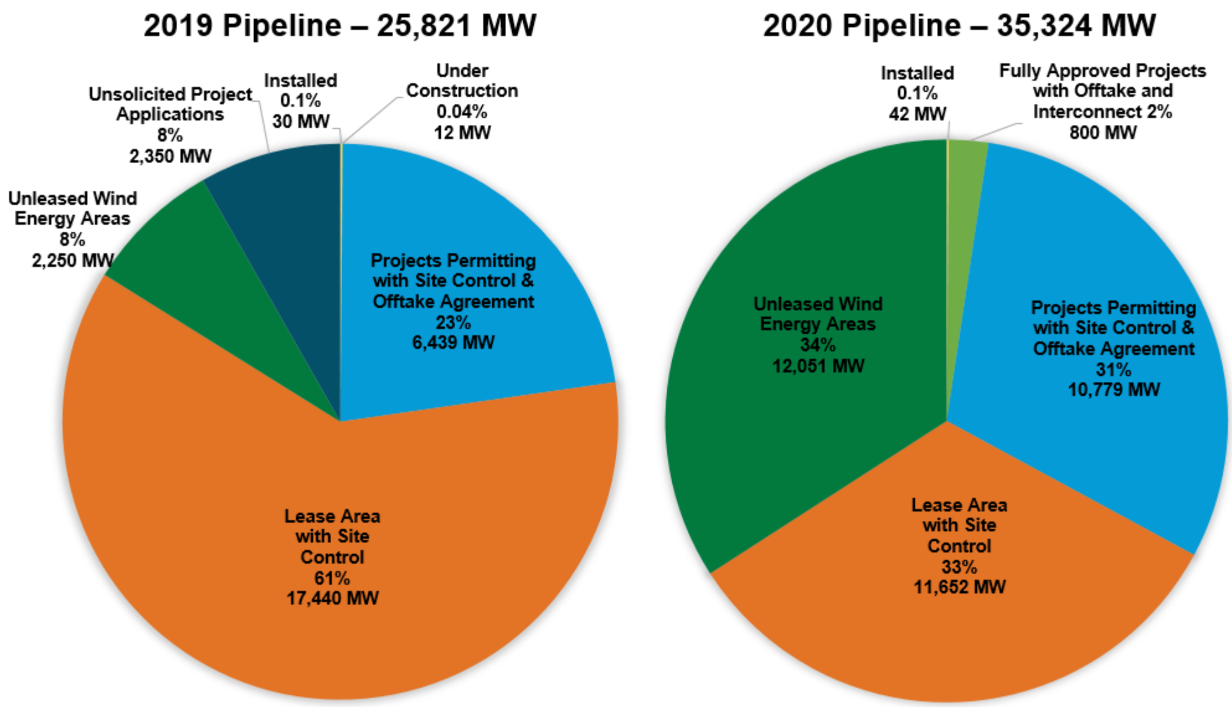

Figure 1. Percentages of U.S offshore wind energy pipeline for 2019 and 2020 (up through May 31, 2021) by classification category

Note that unsolicited project applications are not included in the 2020 pipeline pie chart.

Figure 2 shows the U.S. pipeline activity as of May 31, 2021, for all categories shown in Table 2 by state. The 2020 U.S. pipeline by project status includes two operating projects (42 MW); one fully approved project (Vineyard Wind 1, 800 MW); 15 projects (10,779 MW) that have site control, made major permitting progress, or secured a power offtake contract or have a viable pathway to obtaining one; 16 lease areas that developers have the rights to possibly develop (a technical potential of 11,652 MW); and seven unleased WEAs (with the potential to support 12,051 MW). Note that in Figure 2, we have zoomed in on the vertical scale to show the two U.S. operating projects at higher resolution. Projects progressing through offtake and permitting approval processes continue to be primarily located in the northeastern United States. The availability of new lease areas, the emergence of new Call Areas, and the presence or absence of state-level procurement policies currently drive project development. Recent regulatory activity outside the north Atlantic United States indicates the potential for increased geographic diversification for offshore wind. For example, there is increasing interest in developing floating

[17] The New York Bight is a geographic identification applied to a roughly triangular indentation along the Atlantic Coast of the United States that extends northeasterly from Cape May Inlet in New Jersey to Montauk Point on the eastern tip of Long Island.

offshore wind energy projects along the Pacific Coast, as described in Section 2.3.2 and Section 2.7.5.

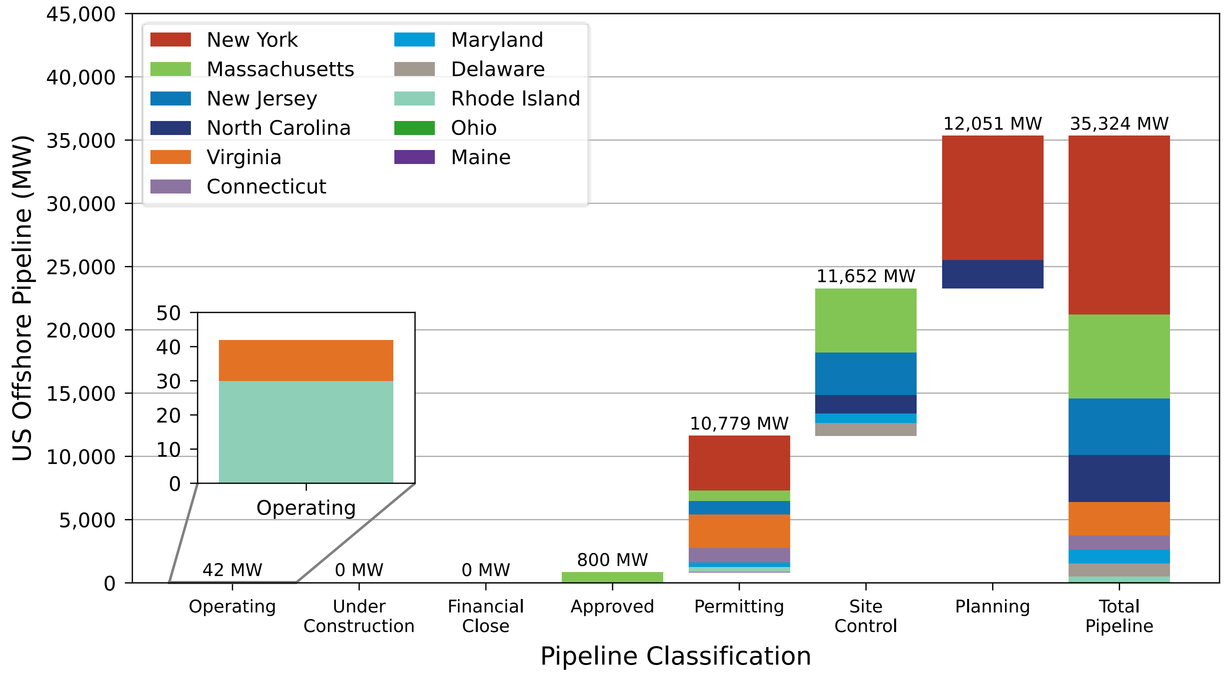

Figure 2. U.S. project pipeline classification by state[18]

Figure 3 shows the same pipeline data but sorted by state. Note that with the addition of the five new WEAs in the New York Bight, New York now has the highest pipeline potential, with over 14,000 MW; although, it is unlikely that all this generation potential will be delivered to New York (the state target is 9,000 MW by 2035). Also note that Massachusetts has the only commercial-scale project that is fully approved for development.

[18] The project location is defined by where the project's power is intended to be sold. If the project does not have an offtake agreement, the location listed is the physical location of the lease area. This clarification is needed where a project is in one state's lease area but sells power to a neighboring state market.

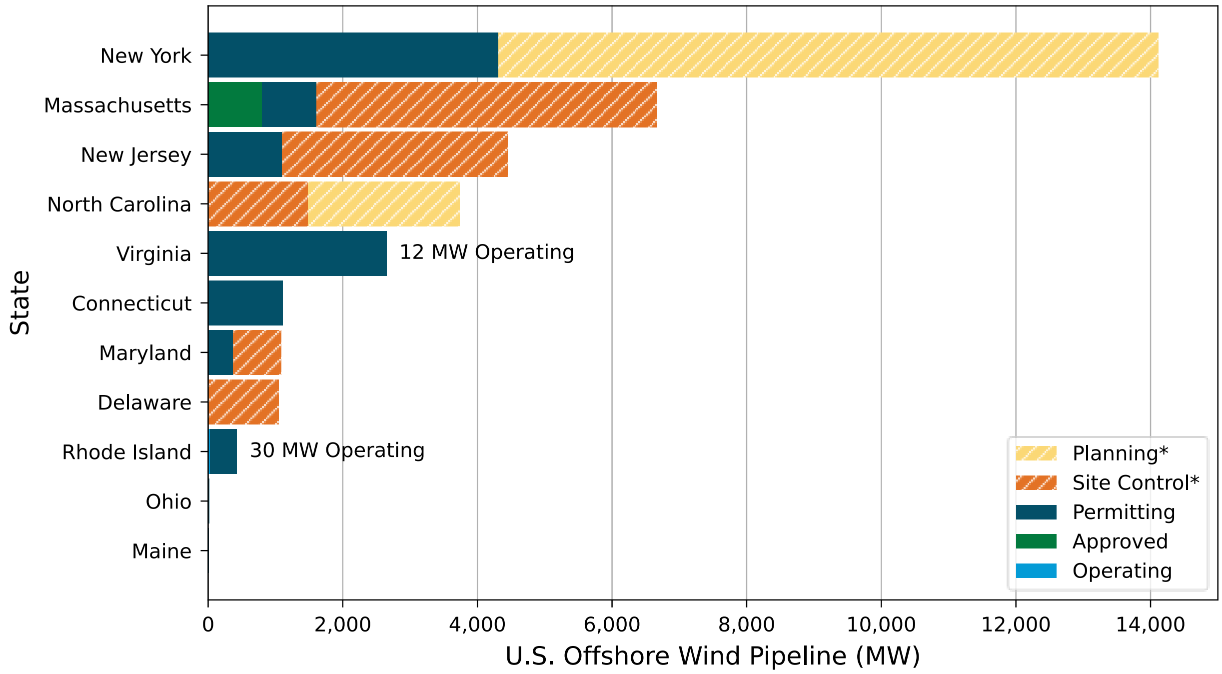

Figure 3. U.S. project pipeline by state[19]

All 35,324 MW that make up the U.S. offshore wind energy pipeline are itemized as an individual project or project opportunity in Table 3, and in the maps shown in Figure 4, Figure 5, and Figure 6, corresponding to the eastern Atlantic Coast (and Great Lakes), California Coast, and Hawaii, respectively. Note that the first column in Table 3 corresponds to the numbers on the maps.

[19] The project location is defined by where the project's power is sold to. If the project does not have an offtake agreement, the location is the project's physical location. This clarification is needed for projects located in a WEA adjacent to a state that may sell their power to a neighboring state's utility. Note that the asterisk for planning and site control denote where we used a turbine density of 3 MW/km^2 to estimate potential capacity.

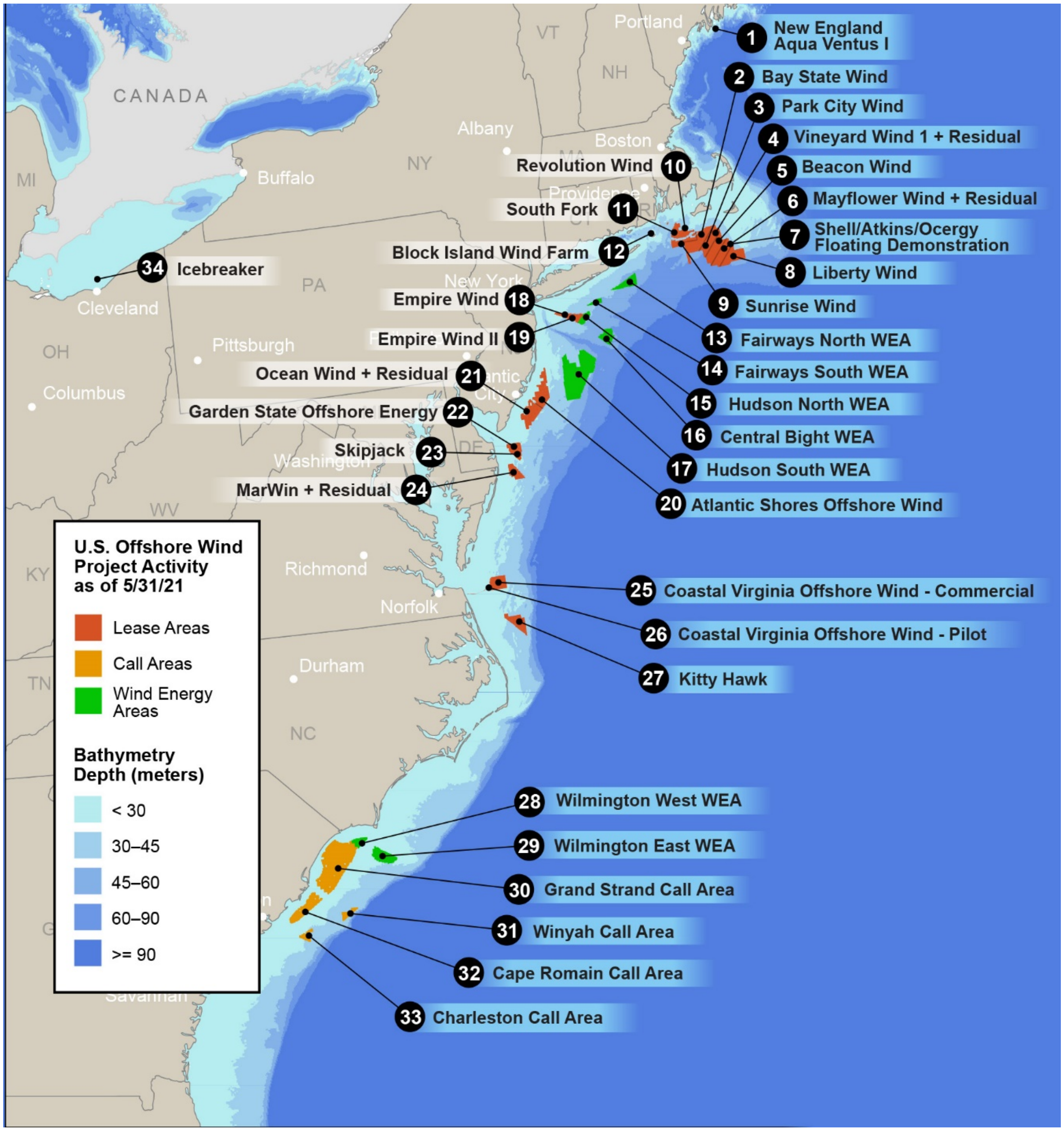

Figure 4. U.S. Atlantic Coast offshore wind energy pipeline and Call Areas as of May 31, 2021. *Map created by NREL*

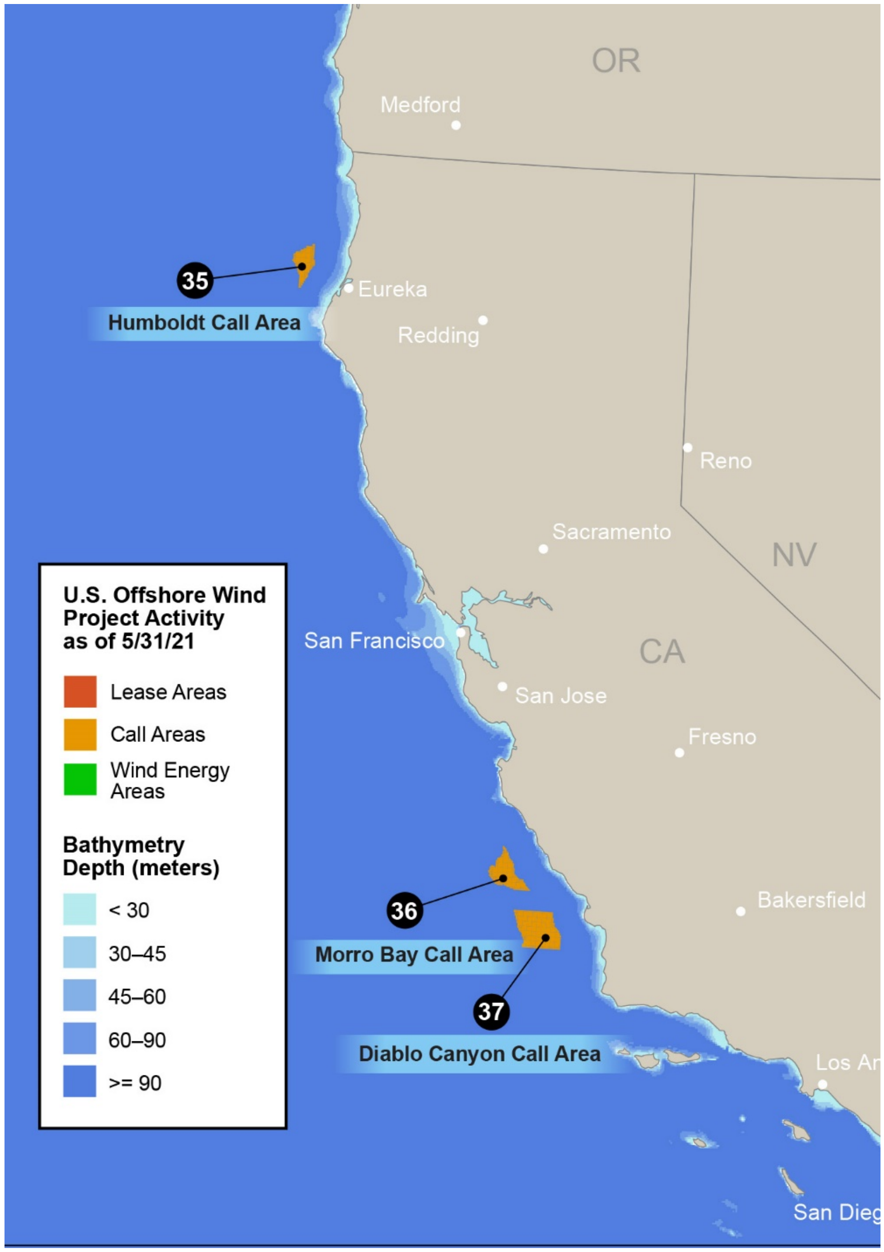

Figure 5. Locations of U.S. West Coast offshore wind Call Areas as of May 31, 2021. *Map created by NREL*

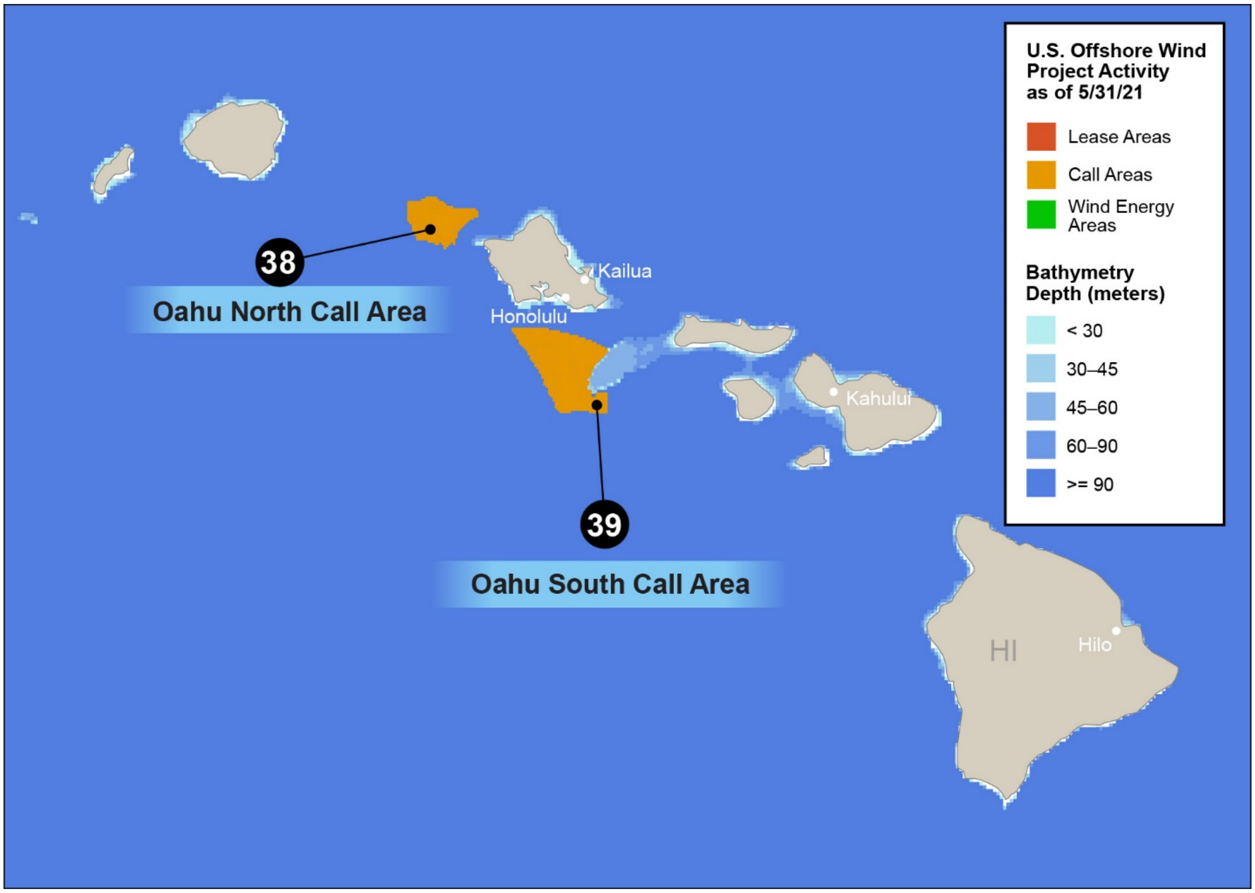

Figure 6. Hawaiian offshore wind Call Areas as of May 31, 2021. *Map created by NREL*

Table 3 includes nine Call Areas located in three regions, but the capacity of the Call Areas is not calculated or counted in the total pipeline capacity because these areas are considered preliminary and are likely to change in size and location. In total, there are 39 sites in the United States (as shown on the maps) where there is significant offshore wind energy development activity. Among this activity are three projects in state waters, including the operating Block Island Wind Farm in Rhode Island, New England Aqua Ventus I in Maine, and the Lake Erie Energy Development Corporation (LEEDCo) Icebreaker project located just north of Cleveland. Both Aqua Ventus and Icebreaker were originally funded under the DOE Advanced Technology Demonstration Project program, which began in 2012 (DOE 2021).

Table 3. U.S. Offshore Wind Pipeline

(In the table, N/A = not applicable; OCS = Outer Continental Shelf; OREC = offshore renewable energy certificate; PPA = power purchase agreement; ROD = Record of Decision; SAP = site assessment plan; and TBD = to be determined).

\	Lease/WEA /Call Area Location	Project Name	Developer	Status	Lease Area	Foundation Type	Wind Turbine	Permit Status	Offtake Agreement	Approved Interconnect Location	Estimated Commercial Operation Date	Operating (MW)	Approved (MW)	Permitting (MW)	Site Control (MW)	Planning (MW)
1	ME	New England Aqua Ventus I	Univ. of Maine/RWE/Mitsubishi	Permitting	State Lease	Floating	TBD	State Approved	PPA (ME)	TBD	2023			12		
2	MA	Bay State Wind	Ørsted/Eversource	Site Control	OCS-A 0500	Fixed Bottom	TBD	COP	TBD	Brayton Point	TBD				2,277	
3	MA	Park City Wind	Avangrid/Copenhagen Infrastructure Partners	Permitting	OCS-A 0501	Fixed Bottom	TBD	COP	PPA (CT)	TBD	2025			804		
4	MA	Vineyard Wind 1 + Residual	Avangrid/Copenhagen Infrastructure Partners	Approved	OCS-A 0501	Fixed Bottom	13-MW GE Haliade-X	ROD	PPA (MA)	Barnstable	2023		800		421	
5	MA	Beacon Wind	Equinor/BP	Permitting	OCS-A 0520	Fixed Bottom	TBD	SAP	OREC (NY)	TBD	2026			1,230		
6	MA	Mayflower Wind + Residual	Energias de Portugal Renováeis/Shell	Permitting	OCS-A 0521	Fixed Bottom	TBD	COP	PPA (MA)	TBD	2025			804	747	
7	MA	Shell/Atkins/Ocergy Floating Demonstration	Shell/Atkins/Ocergy	Permitting	OCS-A 0521	Floating	TBD	TBD	PPA (MA)	TBD	2025			10		
8	MA	Liberty Wind	Avangrid/Copenhagen Infrastructure Partners	Site Control	OCS-A 0522	Fixed Bottom	TBD	SAP	TBD	TBD	TBD				1,607	
9	MA	Sunrise Wind	Ørsted/Eversource	Permitting	OCS-A 0487/0500	Fixed Bottom	TBD	COP	OREC (NY)	TBD	2024			880		
10	RI	Revolution Wind	Ørsted/Eversource	Permitting	OCS-A 0486	Fixed Bottom	8-MW SG DD-167	COP	PPA (RI & CT)	TBD	2023			704		
11	RI	South Fork	Ørsted/Eversource	Permitting	OCS-A 0517	Fixed Bottom	TBD	COP	PPA (NY)	East Hampton	2023			130		
12	RI	Block Island Wind Farm	Ørsted/Eversource	Operating	State Lease	Fixed Bottom	6-MW GE Haliade 150 m	State Approved	PPA (RI)	Block Island	2016	30				
13	NY	Fairways North WEA	N/A	WEA	N/A	Fixed Bottom	TBD	N/A	N/A	N/A	N/A					1,071
14	NY	Fairways South WEA	N/A	WEA	N/A	Fixed Bottom	TBD	N/A	N/A	N/A	N/A					289
15	NY	Hudson North WEA	N/A	WEA	N/A	Fixed-Bottom	TBD	N/A	N/A	N/A	N/A					523
16	NY	Central Bight WEA	N/A	WEA	N/A	Fixed Bottom	TBD	N/A	N/A	N/A	N/A					1,028
17	NY	Hudson South WEA	N/A	WEA	N/A	Fixed Bottom	TBD	N/A	N/A	N/A	N/A					6,890
18	NY	Empire Wind	Equinor/BP	Permitting	OCS-A 0512	Fixed Bottom	TBD	COP	OREC (NY)	TBD	2024			816		
19	NY	Empire Wind II	Equinor/BP	Permitting	OCS-A 0512	Fixed Bottom	TBD	COP	OREC (NY)	TBD	2028			1,260		
20	NJ	Atlantic Shores Offshore Wind	EDF/Shell	Site Control	OCS-A 0499	Fixed Bottom	TBD	COP	OREC (NJ)	TBD	TBD				2,500	

\	Lease/WEA /Call Area Location	Project Name	Developer	Status	Lease Area	Foundation Type	Wind Turbine	Permit Status	Offtake Agreement	Approved Interconnect Location	Estimated Commercial Operation Date	Operating (MW)	Approved (MW)	Permitting (MW)	Site Control (MW)	Planning (MW)
21	NJ	Ocean Wind + Residual	Ørsted/PSEG	Permitting	OCS-A 0498	Fixed Bottom	13-MW GE Haliade-X	COP	OREC (NJ)	TBD	2024			1,100	847	
22	DE	Garden State Offshore Energy	Ørsted/PSEG	Site Control	OCS-A 0482	Fixed Bottom	TBD	SAP	TBD	TBD	TBD				1,050	
23	DE	Skipjack	Ørsted	Permitting	OCS-A 0519	Fixed Bottom	13-MW GE Haliade-X	COP	OREC (MD)	TBD	2026			120		
24	MD	MarWin + Residual	US Wind	Permitting	OCS-A 0490	Fixed Bottom	TBD	COP	OREC (MD)	Indian River	2023			248	718	
25	VA	Coastal Virginia Offshore Wind - Commercial	Dominion Energy	Permitting	OCS-A 0483	Fixed Bottom	14-MW SG 222 m	COP	Utility Owned	Fentress 500 kilovolts	2024			2,640		
26	VA	Coastal Virginia Offshore Wind - Pilot	Dominion Energy	Operating	OCS-A 0497	Fixed Bottom	6-MW SWT 164 m	State Approved	Utility Owned	Birdneck	2021	12				
27	NC	Kitty Hawk	Avangrid	Permitting	OCS-A 0508	Fixed Bottom	TBD	COP	TBD	TBD	2024				1,485	
28	NC	Wilmington West WEA	N/A	WE A	N/A	Fixed Bottom	N/A	N/A	N/A	N/A	N/A					627
29	NC	Wilmington East WEA	N/A	WEA	N/A	Fixed Bottom	N/A	N/A	N/A	N/A	N/A					1,623
30	SC	Grand Strand Call Area	N/A	Call Area	N/A	Fixed Bottom	N/A	N/A	N/A	N/A	N/A					N/A
31	SC	Winyah Call Area	N/A	Call Area	N/A	Fixed Bottom	N/A	N/A	N/A	N/A	N/A					N/A
32	SC	Cape Romain Call Area	N/A	Call Area	N/A	Fixed Bottom	N/A	N/A	N/A	N/A	N/A					N/A
33	SC	Charleston Call Area	N/A	Call Area	N/A	Fixed Bottom	N/A	N/A	N/A	N/A	N/A					N/A
34	OH	Ice Breaker	LEEDCo/Fred Olsen	Permitting	State Lease	Fixed Bottom	TBD	State Approved	PPA	TBD	2023			21		
35	CA	Humboldt Call Area	N/A	Call Area	N/A	Floating	N/A	N/A	N/A	N/A	N/A					N/A
36	CA	Morro Bay Call Area	N/A	Call Area	N/A	Floating	N/A	N/A	N/A	N/A	N/A					N/A
37	CA	Diablo Canyon Call Area	N/A	Call Area	N/A	Floating	N/A	N/A	N/A	N/A	N/A					N/A
38	HI	Oahu North Call Area	N/A	Call Area	N/A	Floating	N/A	N/A	N/A	N/A	N/A					N/A
39	HI	Oahu South Call Area	N/A	Call Area	N/A	Floating	N/A	N/A	N/A	N/A	N/A					N/A
												42	800	10,779	11,652	12,051
												Total Pipeline - 35,324 MW				

2.2.2 U.S. Offshore Wind Market Forecasts to 2030

Figure 7 shows two independent forecasts for offshore wind energy deployment in the United States through 2030. The chart illustrates the degree of expected market growth and the possible variability associated with the year, size, and location of future projects.

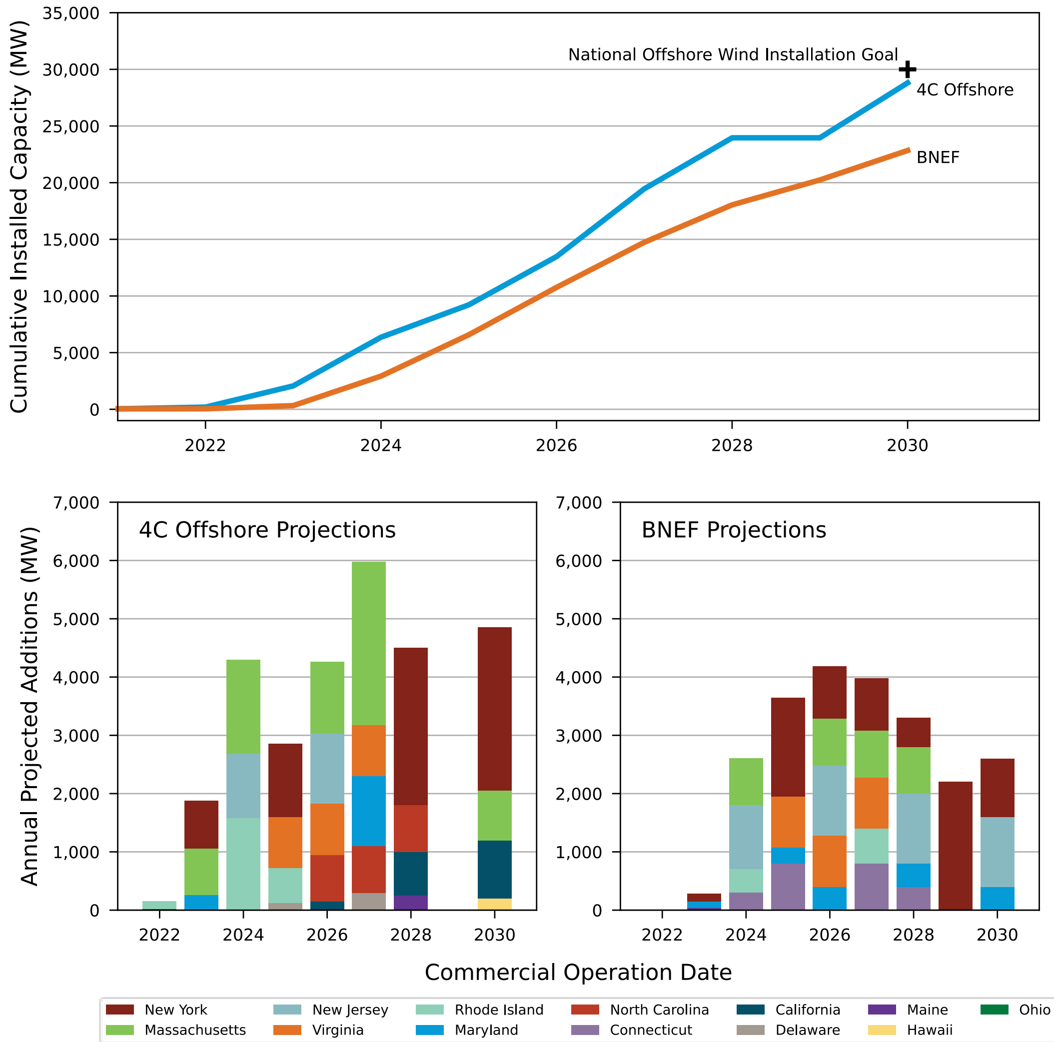

Figure 7. Industry forecasts for U.S. offshore wind energy deployment to 2030 including the national goal

The forecasts in Figure 7 were developed by BNEF (2020a) and 4C Offshore (2021), which estimate that offshore wind energy deployments in the U.S. market will cumulatively reach 22.8 and 28.8 GW by 2030, respectively. For reference, the newly adopted national deployment goal of 30 GW by 2030 is also shown in the figure. The two forecasts suggest that the U.S. market has the potential to reach 30 GW by 2030 considering that both BNEF and 4C Offshore estimates have continued to increase annually in past years. However, the size and speed of buildout are likely to depend on BOEM's ability to permit multiple projects in parallel, the availability of installation vessels and port infrastructure, onshore and offshore grid planning and upgrades, and evolving market demand.

The forecasts predict that most of the future offshore wind energy deployment out to 2030 will occur on the East Coast in states with currently existing or planned offshore wind energy procurement goals. Only 4C Offshore's forecast includes commercial-scale floating projects before 2030 in the United States, which are predicted to be deployed in California and Maine. Conservatively, the forecasts do not explicitly include the creation of new offshore wind lease areas, which are likely to be necessary to support existing state procurement targets.

2.2.3 Regulatory Activity

The United States experienced significant regulatory activity in 2020 and early 2021. BOEM received thirteen COPs to review, issued one Record of Decision (Vineyard Wind 1), and created five WEAs in the New York Bight, and removed unsolicited lease applications from their leasing review process (BOEM 2021c).

Federal permitting in the United States has several major steps after a lease area is acquired. BOEM first reviews and issues permits for site assessment. After those activities are complete, BOEM then reviews and issues permits subsequent to the approval of a project's COP. Table 4 describes the current federal permitting status for projects in each lease area in the order that the leases were issued.

Table 4. U.S Federal Offshore Permitting Status Summary

Geographic Location	Lease Number	Lease Issue Year	Project Name	Permitting Status
Delaware	OCS-A 0482	2012	Garden State Offshore Energy	Site Assessment Plan (SAP)
Virginia	OCS-A 0483	2013	Coastal Virginal Offshore Wind - Commercial	COP
Rhode Island/ Massachusetts	OCS-A0486	2013	Revolution Wind	COP
Rhode Island/ Massachusetts	OCS-A 0517	2013	South Fork Wind	COP
Rhode Island/ Massachusetts	OCS-A 0487	2013	Sunrise Wind	COP
Maryland	OCS-A 0490	2014	MarWin	COP
Massachusetts	OCS-A 0500	2015	Bay State Wind	COP
Massachusetts	OCS-A 0501	2015	Vineyard Wind 1	ROD
Delaware	OCS-A 0519	2018	Skipjack Offshore Energy	COP
New Jersey	OCS-A 0498	2016	Ocean Wind	COP
New Jersey	OCS-A 0499	2016	Atlantic Shores Offshore Wind	COP
North Carolina	OCS-A 0508	2017	Kitty Hawk	COP
New York	OCS-A 0512	2018	Empire Wind 1 Empire Wind 2	COP COP
Massachusetts	OCS-A 0520	2018	Beacon Wind	SAP
Massachusetts	OCS-A 0521	2018	Mayflower Wind Energy	COP
Massachusetts	OCS-A 0522	2018	Liberty Wind	SAP

2.2.4 Lease Activity

Acquiring exclusive rights to develop a lease area is required for building an offshore wind energy project in the United States. Although there were no new lease auctions in 2020, in early 2021, the five new WEAs in the New York Bight represent 9,802 MW of potential new lease area capacity. Table 5 describes each of these recently established New York Bight WEAs, which are also shown in Figure 8.

Table 5. New York Bight Wind Energy Area Characteristics

	Fairways North WEA	Fairways South WEA	Hudson North WEA	Central Bight WEA	Hudson South WEA	Total
Acres	88,246	23,841	43,056	84,688	567,552	807,383
Estimated Capacity (MW)[20]	1,072	289	523	1,028	6,890	9,802
Estimated Generation (megawatt-hour/year)[21]	3,754,037	1,014,210	1,831,628	3,602,678	24,143,998	34,346,551
Average Water Depth (meters)	49	42.5	43	56.5	45.5	47.3

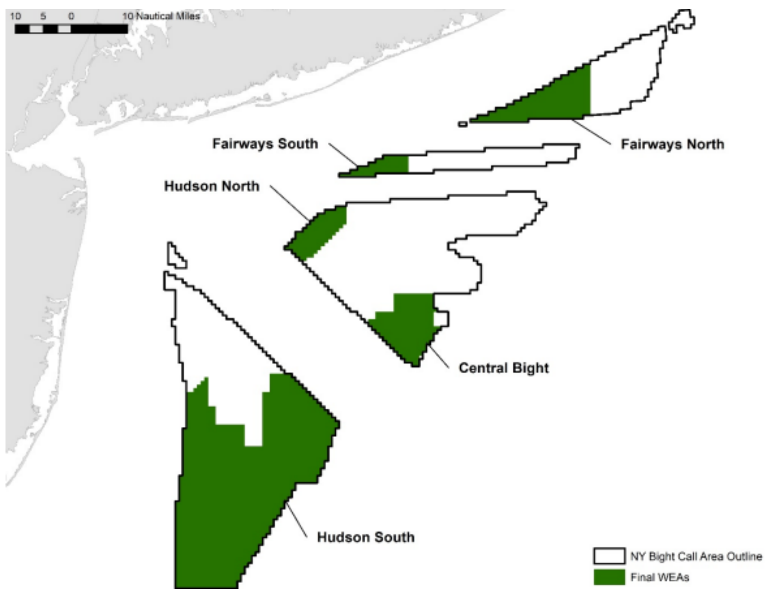

Figure 8. New York Bight WEAs

In June 2021, BOEM issued a proposed sales notice for the New York Bight WEAs (BOEM 2021d). The NY proposed sale notice would subdivide the Hudson North, Central Bight, and Hudson South WEAs into eight auctionable lease areas and implement updated bidder qualifications. After a 60-day period for public comment, BOEM has the option to make subsequent refinements and issue a final sales notice that sets the date for the competitive lease auction.

2.2.5 New Area Identification

BOEM periodically publishes Calls for Information and Nominations to assess commercial competitive interest for offshore wind energy development on specific parcels of ocean acreage in federal waters. The information gathered during these calls is used by BOEM in conjunction

[20] Capacity estimates assume a power density of 3 MW/km^2.
[21] Generation estimates assume a 40% net capacity factor. Net capacity factor is the actual amount of electricity delivered to the land-based grid divided by the energy it could have delivered if operating at full rated power over the course of the year without losses.

with other stakeholder input to identify future WEAs and subsequent lease area auctions. A Call Area is a precursor to a defined WEA, but not all Call Areas become wind energy areas, and they are typically modified (e.g., reduced in size or augmented) to address stakeholder input. In 2016, BOEM issued calls for four areas in federal waters off South Carolina and two areas off the Hawaiian island of Oahu. In 2019, BOEM created three Call Areas off California. In May 2021, BOEM, the White House, and the U.S. Department of Defense announced the Morro Bay Call Area boundaries were being expanded to 399 square miles and that potential conflicts with military training activities had been substantially mitigated (The White House 2021d). As of June 2021, there are nine active Call Areas for offshore wind energy in the United States (shown in Table 6). They can also be found on the maps in Figure 4, Figure 5, and Figure 6 and in Table 3.

Table 6. United States Offshore Wind Call Areas

State	Name	Year	Acreage	Substructure
South Carolina	Grand Strand Call Area	2016	628,003	Fixed bottom
South Carolina	Winyah Call Area	2016	34,871	Fixed bottom
South Carolina	Cape Romain Call Area	2016	155,498	Fixed bottom
South Carolina	Charleston Call Area	2016	35,583	Fixed bottom
Hawaii	Oahu North Call Area	2016	328,981	Floating
Hawaii	Oahu South Call Area	2016	154,670	Floating
California	Humboldt Call Area	2019	132,369	Floating
California	Diablo Canyon Call Area	2019	356,188	Floating
California	Morro Bay Call Area	2021	255,360	Floating

2.3 U.S. Offshore Wind Project Offtake

2.3.1 Project Offtake Agreements

In addition to obtaining site control and regulatory approval, negotiating an offtake agreement to sell the electricity and other clean power attributes (e.g., offshore renewable energy certificates [ORECs]) is one of the crucial steps to developing a bankable project. In the United States, each state has unique procurement targets and uses different mechanisms to procure an individual project's electrical generation from a developer. As of May 31, 2021, 17 offtake agreements have been signed for 12 U.S. projects, and three projects are in the process of negotiating terms with utilities, as shown in Table 7.[22] Figure 9 shows U.S. state procurement goals and awards between 2010 and 2040.

[22] Note, projects may sign more than one contract. For example, Vineyard Wind 1 signed two PPAs, and Revolution Wind has three PPAs with power sold into two different states.

Table 7. U.S. Offshore Wind Offtake Agreements as of May 31, 2021 (Listed in Chronological Order)

Project	Year Signed	Size (MW)	Duration (Years)	Offtake State	Contract Type	Regulator Approved	Levelized Nominal Price ($/megawatt-hour [MWh])	Power Delivery	Power Purchaser
Block Island Wind Farm	2010	30	20	RI	PPA	Yes	244	2016	National Grid
South Fork	2017	130	20	NY	PPA	Yes	163	2023	Long Island Power Authority
US Wind	2017	248	20	MD	MD OREC	Yes	131.93	2023	Exelon
Skipjack	2017	120	20	MD	MD OREC	Yes	131.93	2023	Exelon
Vineyard Wind 1	2018	400	20	MA	PPA	Yes	74	2023	National Grid, Eversource, Unitil
Vineyard Wind 1	2018	400	20	MA	PPA	Yes	65	2024	National Grid, Eversource, Unitil
Coastal Virginia Offshore Wind	2018	12	20	VA	PPA	Yes	780	2021	Dominion Energy
Revolution Wind	2018	400	20	RI	PPA	Yes	99.50	2023	Eversource, UIL
Revolution Wind	2018	200	20	CT	PPA	Yes	98.43	2023	Eversource, UIL
Revolution Wind	2019	104	20	CT	PPA	Yes	98.43	2023	National Grid
Ocean Wind	2019	1,100	20	NJ	NJ OREC	Yes	116.82	2024	Public Service Enterprise Group, Rockland Electric Cooperative, Jersey City Power & Light, Atlantic City Electric
Empire Wind 1	2019	816	25	NY	NY OREC	Yes	83.36	2024	New York Independent System Operator
Sunrise Wind	2019	880	25	NY	NY OREC	Yes	83.36	2024	New York Utilities
Aqua Ventus I	2019	12	20	ME	PPA	Yes	Undisclosed	2023	Central Maine Power
Mayflower Wind	2020	400	20	MA	PPA	Yes	58.47	2025	National Grid, Eversource, Unitil
Mayflower Wind	2020	404	20	MA	PPA	Yes	58.47	2025	National Grid, Eversource, Unitil
Icebreaker	2020	21	20	OH	PPA	Pending	Undisclosed	2023	Local Municipalities
Park City Wind	Negotiating	804	20	CT	PPA	Pending	N/A	2025	Eversource, UIL
Empire Wind 2	Negotiating	1,260	25	NY	NY OREC	Pending	N/A	2026	New York Utilities
Beacon Wind	Negotiating	1,230	25	NY	NY OREC	Pending	N/A	2026	New York Utilities

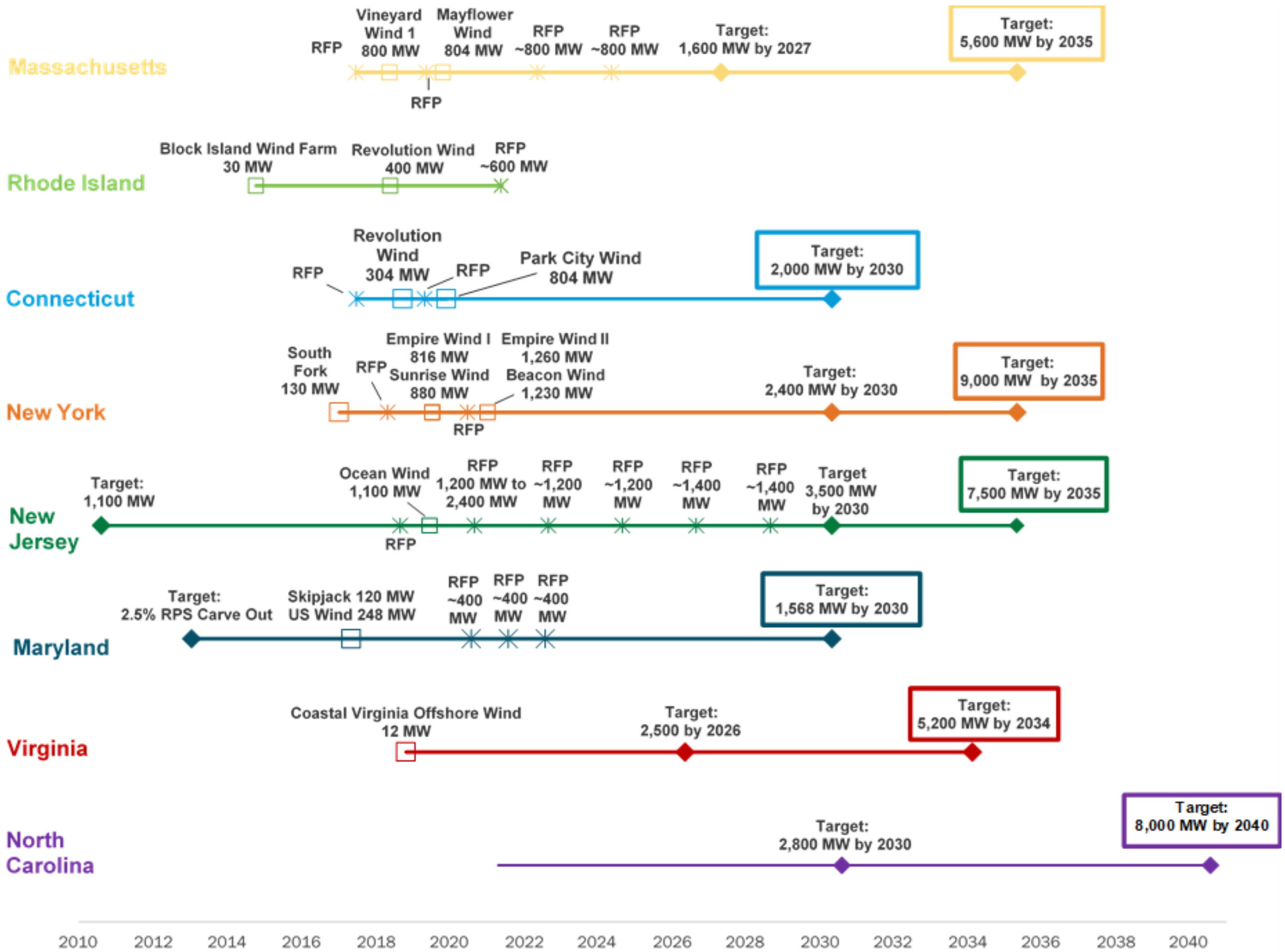

Figure 9. U.S. state procurement goal and award timelines[23]; *renewable portfolio standard (RPS)*

2.3.2 State Procurement Policies

The U.S. offshore wind energy market continues to be driven by an increasing amount of state-level offshore wind procurement activities and policies (Figure 9). In aggregate, these activities now call for deploying at least 39,298 MW of offshore wind capacity by 2040. These commitments are shown in Table 8. Virginia, Massachusetts, and North Carolina added new procurement policies in 2020 and the first part of 2021. The Virginia Clean Energy Economy Act set a 5,200-MW offshore wind energy goal by 2034. An Act Creating a Next Generation Roadmap for Massachusetts Climate Policy set a 5,600-MW goal by 2035. North Carolina Governor Roy Cooper's Executive Order 218 set a goal of 2,800 MW offshore wind by 2030 and 8,000 MW by 2040.

States that have adopted offshore wind energy policies listed in Table 8 do not necessarily use offshore wind resources in federal waters off their own state. For several projects (e.g., Revolution, Skipjack, South Fork), deployment is being planned in a WEA adjacent to the state that will receive the power. Projects consider the most favorable offtake options, generally in a

[23]Former Rhode Island Governor Gina Raimondo called for a roughly 600-MW offshore wind energy solicitation to be developed in 2021. Although that request is not codified, this table includes the possible solicitation to illustrate a comprehensive picture across the United States.

state where the anticipated value of offshore wind energy is highest and the most favorable power purchase agreements (PPAs) can be negotiated.

Table 8. Current U.S. Offshore Wind State Procurement Policies and Activity as of May 31, 2021

State	Total Capacity Commitment (MW)	Target Year	Amount Procured (MW)	Contract Type	Year Enacted	Authority
Massachusetts	5,600	2035	1,604	PPA	2016 2018 2021	An Act to Promote Energy Diversity An Act to Advance Clean Energy An Act Creating a Next Generation Roadmap for Massachusetts Climate Policy
Rhode Island[24]	430	-	430	PPA	-	-
New Jersey	7,500	2035	1,100	OREC	2010 2018 2019	Offshore Wind Economic Development Act Executive Order 8/Assembly Bill 3723 Executive Order 92
Maryland	1,568	2030	368	OREC	2013 2019	Maryland Offshore Wind Energy Act Clean Energy Jobs Act
New York	9,000	2035	6,816	OREC	2018 2019	Case 18-E0071 Climate Leadership & Community Protection Act
Connecticut	2,000	2030	1,104	PPA	2017	Public Act 17-44 House Bill 7156
Virginia	5,200	2034	12	Utility-Owned	2020	Virginia Clean Energy Economy Act
North Carolina	8,000	2040	0	TBD	2021	Executive Order 218
Total	**39,298**		**11,434**			

2.4 U.S. Infrastructure Trends

2.4.1 Vessels and Logistics

The Jones Act is a U.S. law that requires vessels that ship merchandise and passengers between two U.S. points to be U.S. built and registered (flagged), as well as owned and crewed by U.S. citizens or residents (U.S. Customs and Border Protection 2020). The act is a unique feature of the U.S. offshore wind energy market and a major driver in offshore wind construction and installation logistics. Currently, no Jones-Act-compliant wind turbine installation vessels (WTIVs) exist. A Tufts University analysis estimates WTIV demand in the United States could be as high as five vessels per year before 2030 (Bocklet et al. 2021). To avoid a supply chain bottleneck, developers must either commission the construction of new U.S.-flagged WTIVs or develop a Jones-Act-compliant installation strategy that integrates foreign-flagged WTIVs and U.S.-flagged feeder vessels. A potential strategy for combining foreign WTIVs with domestically flagged feeder barges is explained in this section.

[24] Note, Governor Raimondo signed Executive Order 20-01 that targeted Rhode Island being powered by 100% clean electricity by 2030, however it did not identify a specific offshore wind target.

Construction of the first-ever, Jones-Act-compliant WTIV began in 2020. Two additional Jones-Act-compliant WTIVs are scheduled to begin construction in the near future. Dominion Energy reported in May 2020 that it will lead a consortium to develop a vessel that is 472 feet (ft) long and 184 ft wide, with a draft[25] of 38 ft (Dominion Energy 2020a). The vessel, Charybdis, designed by GustoMSC, is being constructed in Brownsville, Texas, by Keppel AmFELS and is expected to cost $500 million (Dominion Energy 2020a). Dominion intends to base the vessel out of Hampton Roads, Virginia. It is designed to accommodate 119 crew members and lift 12-MW wind turbines or greater using a 426-ft, 2,200-ton crane supplied by Huisman. The keel laying for the Charybdis took place in December 2020, representing a milestone as construction started on the first U.S.-flagged WTIV (Dominion Energy 2020b). Dominion Energy reached another milestone in June 2021 when it announced that Ørsted and Eversource would charter the vessel to construct the Revolution Wind and Sunrise Wind projects (Shumkov 2021). In December 2020, Lloyd's Register stated that it signed an agreement to jointly develop designs for a Jones-Act-compliant wind turbine installation vessel with Northeast Technical Services Co., Inc. (Lloyd's Register 2020). Lloyd's Register states its design will be compatible with U.S. shipyards, and the physical parameters of the vessel will align with heavy lift requirements of the U.S. market. Another company, Eneti, announced it is in late-stage discussions with American shipbuilders about constructing a Jones-Act-compliant WTIV, but has not signed any binding agreements to date (Eneti 2021). The commissioning of these vessels is important, as the global pipeline of projects may mean increased demand and constrained availability of foreign-flagged WTIVs that can install wind turbines that are 12 MW or larger in the future.

Even with the availability of new Jones-Act-compliant WTIVs, many U.S. projects in the first phase of offshore wind energy deployment will rely on foreign-flagged installation vessels supported by U.S.-flagged feeder vessels. For example, Vineyard Wind 1 announced that FOSS Maritime Company LLC will transport turbines from the port of New Bedford to a jack-up installation vessel on-site provided by DEME Offshore US LLC (Vineyard Wind 2021). Additional investment in feeder vessels will still be required to support larger wind turbines and the expanded pipeline. In June 2020, 2nd Wind Marine and MiNO Marine LLC announced their intent to start building two Jones-Act-compliant offshore wind energy construction support vessels. These "superfeeder" vessels are capable of 10-knot cruising speeds fully loaded (2nd Wind Marine 2020; Moore 2020), and each one may cost over $150 million to construct (Von Ah et al. 2020). One potential advantage of the feeder installation strategy is that the more expensive WTIVs can spend more time installing components at the site and less time transporting components from port, which may shorten installation times and reduce total costs (Von Ah et al. 2020).

The challenges for procuring crew transfer vessels (CTVs), service operation vessels (SOVs), survey, and cable lay vessels for the construction and operation of U.S. offshore wind energy projects appear to be smaller because of greater availability and lower vessel construction costs. In the short term, existing vessels may be adapted or repurposed as Jones-Act-compliant CTVs and SOVs. Some custom-built vessels for the wind energy industry have already been supplied by U.S. shipyards and others have been announced (Von Ah et al. 2020). Edison Chouest Offshore announced in October 2020 that it would provide and operate the first Jones-Act-compliant SOV for operation and maintenance (O&M) at Ørsted's and Eversource's Revolution

[25] Draft refers to the vertical distance between the waterline and keel of the vessel.

Wind, Sunrise Wind, and South Fork Wind projects. The 260-ft vessel can support 60 crew members and meet U.S. Environmental Protection Agency Tier 4 emission standards (Edison Chouest Offshore 2020). In March 2021, Crowley announced it would partner with ESVAGT to construct Jones-Act-compliant SOVs to support offshore wind energy in the United States. (Crowley 2021). WindServe Marine, LLC delivered its first CTV, WindServe Odyssey, in October 2020 as part of a contract with Ørsted for the CVOW pilot and Revolution Wind projects (Shannon-Fuller 2020). In January 2021, Blount Boats delivered its second U.S.-flagged CTV, Atlantic Endeavor, to Atlantic Wind Transfers in support of the CVOW project. Atlantic Wind Transfers list the vessel as right-whale compliant, with a capacity for 24 passengers and 3–4 crew members (Blount Boats 2021; Atlantic Wind Transfers 2019).

Similarly, survey vessels, foundation installation vessels, and cable lay vessels can be obtained with relative ease (Von Ah et al. 2020). In December 2020, Great Lakes Dredge & Dock announced it would partner with Ulstein Design and Solutions B.V. to develop a Jones-Act-compliant subsea rock installation vessel for use in the U.S. offshore wind energy industry (Great Lakes Dredge & Dock Company 2020). Table 9 identifies the U.S.-flagged vessels that were announced in 2020 that will support the offshore wind energy industry.

Table 9. U.S.-Flagged Vessels Under Development To Support the Offshore Wind Industry

Vessel Category	Companies Backing	Project Contracts	Commissioning Date
Wind Turbine Installation Vessel	Dominion Energy, GustoMC, Keppel amFELS	Revolution Wind and Sunrise Wind	Expected 2023
Wind Turbine Installation Vessel	Lloyd's Register, Northeast Technical Services Co., Inc.	Not listed	Not listed
SuperFeeder	2nd Wind Marine, MiNO Marine LLC	Not listed	Not listed
Service Operations Vessel	Crowley, ESVAGT	Not listed	Not listed
Service Operations Vessel	Edison Chouest Offshore, Ørsted, and Eversource	Revolution Wind, South Fork Wind, Sunrise Wind	Not listed
Crew Transfer Vessel	Atlantic Wind Transfers, Blount Boats, Chartwell Marine	Coastal Virginia Offshore Wind	Second vessel delivered January 2021
Crew Transfer Vessel	WindServe Marine, Senesco	Coastal Virginia Offshore Wind, Revolution Wind	Vessel delivered in October 2020
Rock Installation	Great Lakes Dredge & Dock, Ulstein Design and Solutions B.V.	Not listed	Expected 2024

Several recent events clarified how Jones-Act provisions apply to specific facets of offshore wind energy development. Section 9503 of the National Defense Authorization Act for Fiscal Year 2021 affirms that the Jones Act applies to both fixed-bottom offshore wind energy development as well as other activities in which mooring lines and/or anchors touch the seabed on the Outer Continental Shelf (HR 6395).

An August 2020 U.S. Customs and Border Protection ruling suggests that foreign-flagged cable lay vessels are permitted to lay or remove cables from the seafloor, provided recovered cables are not unloaded at U.S. ports (Burley 2020). The ruling also states that cable burial via pressurized water jets that create cable trenches with high water pressure does not qualify as dredging and is therefore Jones-Act compliant. Also, crew members that are essential to the operation of the foreign cable lay vessel are not considered passengers.

A March 2021 U.S. Customs and Border Protection ruling clarified how foreign-flagged vessels may transport and position a first layer of scour protection material from U.S. ports under certain conditions (Burley 2021). Note that U.S. Customs and Border Protection recommends seeking official rulings or legal guidance given the Jones Act's complex and evolving interpretations.

2.4.2 Ports Investments

Even if sufficient vessels are available to support the U.S. deployment pipeline, the development and timing of port infrastructure could become a significant bottleneck for the industry. This delay may be especially true as wind turbines and project sizes continue to grow. Larger turbines and bigger projects push the limits of the existing infrastructure in terms of heavy-lift crane weight and height capacities, wharf access for increasingly larger ships, rising height clearances and channel draft requirements, and the growing need to expand physical laydown space (American Bureau of Shipping [ABS] 2021). Approximately five staging ports will be required to meet the needs of the first 10 GW of offshore wind energy projects on the Atlantic Coast alone (Lefevre-Marton et al. 2019). Floating wind will face additional challenges, as no U.S. ports currently exist that can support a commercial-scale floating wind project.

Developers and state bodies are making investments in port infrastructure to ensure there are sufficient cranes and laydown space required for large-scale commercial projects. There are several ports in the United States that will be able to support offshore wind energy deployment in various capacities, either as full-service wind hubs or smaller staging or service ports. These ports have begun to conduct upgrades or greenfield construction in anticipation of the first round of projects. A summary of major infrastructure investments that have taken place in recent years is provided in Table 10.

Table 10. Port Infrastructure Investments to Support Offshore Wind Energy

State	Port	Announced Date	Investment	Investors	Description
Massachusetts	**New Bedford Marine Commerce Terminal**	2/10/2020	$32.5 million from Vineyard Wind and Mayflower Wind $113 million in public money	State of Massachusetts (Massachusetts Clean Energy Center) Avangrid/Copenhagen Infrastructure Partners Energias de Portugal Renováeis/Shell	Vineyard Wind 1 signed an 18-month lease starting in December 2020. Developers also signed a subsequent lease to use the terminal for the Mayflower Wind project, which is expected to start construction in 2024. There are no height restrictions on-site or overhead restrictions from the terminal to open water. Twenty-one of the 29 acres are heavy-lift compatible.
	Brayton Point	5/13/2019	$650 million	Anbaric Partners	This project will convert a former coal power plant into an offshore wind energy development center. Investments include a 1,200-MW high-voltage direct-current converter, a 400-MW battery, additional laydown space, and a maintenance dock.
Rhode Island	**Port of Providence**	6/3/2020 4/14/2021	$40 million, of which $24 million is for a foundations center	Ørsted and Eversource	This project will support the construction of the Revolution Wind projects. The foundation assembly regional hub will supply the pieces to projects being developed by Ørsted and Eversource around the Northeast.
	Quonset Point		Shares the $40 million total listed above	Ørsted and Eversource	This project will support the construction of the Revolution Wind projects. Pier 2 is being upgraded to support offshore wind energy activities.
Connecticut	**New London State Pier**	2/12/2020	$157 million	Ørsted, Eversource, and the state of Connecticut	This project will create state-of-the-art heavy-lift facilities for an offshore wind energy assembly hub. It will also include increasing laydown space and the number and size of vessel berths, and the ability to lift and store heavy cargo. The redevelopment is expected to be complete by 2022. The pier will be used for wind turbine preassembly and project staging for Revolution Wind, South Fork, and Sunrise Wind projects.
	Bridgeport	10/11/2019	N/A	Avangrid	This project will redevelop a currently underutilized 18.3-acre waterfront to do critical-foundation, transition-piece steel fabrication and final outfitting. The port will also serve as an operation and maintenance hub for the Park City Wind project.
New York	**Port of Coeymans, South Brooklyn Marine Terminal, Port of Albany,** **Port Jefferson Harbor, Montauk Harbor**	2019–2021	$730 million	New York State (NYSERDA), Equinor, Ørsted, and Eversource	This project will include long-term port facility upgrades as well as long-term manufacturing investments for cutting-edge technologies, such as offshore wind tower manufacturing, staging and operations, gravity-base turbine foundations, and O&M.
New Jersey	**Port of Paulsboro**	12/22/2020	$250 million	Ørsted, Public Service Enterprise Group Inc. (PSEG), and EEW	Developers are building a state-of-the-art monopile manufacturing facility to support the Ocean Wind project and other projects in the U.S. pipeline. They plan to break ground in 2021, with monopile production slated for 2023.

State	Port	Announced Date	Investment	Investors	Description
	New Jersey Wind Port	6/16/2020	$300–$400 million, of which $200 million has been allocated	State of New Jersey (New Jersey Economic Development Authority)	This project will develop a port in Lower Alloways Creek Township to support offshore wind energy construction and operations. The initial phase will include 30 acres for marshalling and 25 acres for component manufacturing, with construction beginning in 2021. The second phase will add 150 acres for marshalling and manufacturing.
Maryland	Tradepoint Atlantic	7/23/2019	$13.2 million	Ørsted	Stage 1: Developers will create a lift-on/lift-off and roll-on/roll-off berth for wind turbine components, strengthening ground-bearing capacity for heavy-lift vessels. Stage 2: Developers will add 50 acres that will include laydown, storage, and an assembly area.
Virginia	Hampton Roads	9/14/2020	$529,788	State of Virginia (GO Virginia)	Dominion Energy plans to base its WTIV, Charybdis, at this port, which will also serve as the O&M base for CVOW. GO Virginia aims to attract supply chain investments.
	Portsmouth Marine Terminal	1/28/2020	$13–$33 million	Ørsted	Ørsted signed a $13-million lease for constructing the CVOW project. It may install an additional $20 million of cranes and other specialty improvements.

In 2020, the New Jersey Economic Development Authority announced that it would build the first purpose-built offshore wind energy port in the United States (New Jersey 2021). The port is expected to cost between $300 and $400 million and will be located on the Delaware River. The first phase will develop a 30-acre marshalling site and a 25-acre manufacturing site, and the second phase will add another 150 acres for further marshalling and manufacturing activities. Construction is expected to begin in 2021. In addition, the state of Connecticut reached a final agreement with Gateway Terminal, Ørsted, and Eversource for a public-private partnership worth $157 million to develop the State Pier in New London into an offshore wind energy center (Connecticut 2020). In April 2021, Ocean Wind (Ørsted and PSEG) announced that it, along with German steel manufacturer EEW, broke ground on a dedicated monopile manufacturing facility located at the Port of Paulsboro Marine Terminal in New Jersey. The quayside must be reinforced to bear the weight of 2,500-ton monopiles that will be manufactured on-site. Additional welding and painting facilities are also under construction, with a goal of producing the first monopiles at the facility by 2023 (Ocean Wind 2021).

In addition to the port infrastructure investments that have already been announced, the Biden Administration has announced several programs that call for investments in ports. Specifically, the U.S. Department of Transportation's Maritime Administration's Funding Opportunity Announcement via the Port Infrastructure Development Program makes $230 million available for port upgrades, including offshore-wind-energy-related efforts (MARAD 2021; The White House 2021b). The Administration's American Jobs Plan proposal calls for a $17-billion investment in coastal ports along with inland waterways, land ports of entry, and ferries, and includes a Healthy Ports program to reduce pollution impacts on adjacent neighborhoods, which are often communities of color (The White House 2021c). The proposed investments are in addition to up to $3 billion in existing guaranteed loans announced by DOE's Loan Programs Office to potentially support the innovative renewable energy technologies (The White House 2021b).

2.4.3 Electric Grid

Currently, each offshore wind power plant developer is responsible for planning and developing a grid connection to an onshore point of interconnection (POI) on a project-by-project basis. The default option is to use radial spur (generator lead line), in which each project brings its export cable directly to shore, independent of the other projects. Though it may be the simplest and cheapest approach for early developers in a region, existing POIs are limited. Several eastern states have initiated planning processes and studies to consider alternative options to the project-by-project interconnection approach.

In 2016, none of the proposed generation in the ISO-NE transmission queue was for offshore wind energy. By 2020, 11.6 GW of offshore wind energy was in the ISO-NE queue, accounting for 55% (Smith et al. 2021). As more offshore wind power plants connect to existing POIs, easy-access POIs will become increasingly scarce. This evolving scarcity could increase costs to future projects and delay the continued growth of the industry (Business Network for Offshore Wind 2020). A list of coastal POIs from Massachusetts to New Jersey, with recent queue data from ISO-NE, the New York Independent System Operator (NYISO), and PJM, is shown in Table 11 (Smith et al. 2021). All these POIs are within 10 miles of coastal waters, have a maximum voltage rating of at least 115 kilovolts (kV), or were identified in an active queue position as of mid-October 2020. The second column from the right indicates the estimated capacity of 28,500 MW of all POIs in aggregate based on the capacity of the nearby power plants that they serve. This analysis is an important first step, but further research is needed to determine with greater certainty what the POI capacity is needed for offshore wind energy, including factors such as whether other electric generating projects might compete for these POIs, whether some POIs might serve more than the existing nearby power plant, if there are any planned grid upgrades, and if all POIs are large enough for possible offshore wind interconnections.

Table 11. Independent System Operator Queue for Coastal Points of Interconnection From Massachusetts to New Jersey (Reproduced From Smith et al. 2021)

Regional Transmission Organization (RTO)	Coastal POIs	Power Plant Capacity Near POIs (MW)	Total Active Offshore Wind Queue Capacity (MW)
ISO-NE	18	13,010	16,372
NYISO	20	8,040	30,363
New Jersey in PJM	17	7,450	7,711
Total	**55**	**28,500**	**54,446**

The New Jersey Board of Public Utilities made New Jersey the first state to fully align its offshore wind transmission goals with its regional grid operator's planning process. New Jersey has a goal of 7,500 MW of offshore wind energy by 2035 and has requested the inclusion of this state public policy into the transmission planning process of PJM through a competitive solicitation process ("State Agreement Approach"), established by the Federal Energy Regulatory Commission's (FERC's) Order No. 1000. On April 15, 2021, PJM opened a competitive solicitation for transmission options for New Jersey's offshore wind energy goals. The solicitation closed on August 13, 2021.

A report by New York Power Authority (2019) involved studying European offshore wind energy and transmission by comparing project-by-project radial transmission to shared, networked transmission. Among other things, the report concluded that a radial transmission model is simpler to plan and implement, and that a networked grid can achieve economies of scale for offshore wind power plants. Further, a study of New York's power grid recommends that the state should consider creating the option to develop a meshed offshore power grid that could connect offshore wind power plants serving New York with each other and with plants meeting demand in New England and New Jersey (Pfeifenberger et al. 2021).

The New England States Committee on Electricity, a nonprofit organization that represents the collective perspective of the six New England governors in regional electricity matters, recommended in October 2020 that ISO-NE establish a thorough, long-term regional transmission planning process to meet the states' decarbonization policies. They also recommended ISO-NE analyze specific offshore wind energy scenarios for land-based system upgrades and the related systems that may be needed (New England States Committee on Electricity 2020).

The California Public Utilities Commission and the California Independent System Operator are developing sensitivity scenarios focused on potential offshore wind energy development in the California Call Areas to improve transmission assumptions and enhance future integrated resource planning (California Public Utilities Commission Energy Division 2020).

FERC is also interested in potential offshore wind transmission and interconnection solutions. On October 27, 2020, the commission convened a technical conference to discuss whether and how existing transmission planning, interconnection, and merchant transmission facility frameworks in regional transmission organizations/independent system operators can accommodate anticipated growth in offshore wind generation in an efficient and cost-effective manner that safeguards open-access transmission principles, or if new solutions are required (FERC 2020). In March 2021, FERC issued a notice for public comment focused on: 1) creating opportunities to improve the interconnection procedures for offshore wind energy generation, 2) incorporating state policies into regional transmission organization/independent system operators transmission planning and interconnection processes, 3) quantifying the potential benefits of planned transmission solutions for offshore wind integration, and 4) establishing dedicated transmission planning processes for offshore wind integration (FERC 2021).

2.5 U.S. Supply Chain Development

Achieving the Biden Administration's target of installing 30 GW by 2030 is expected to generate more than $12 billion per year in capital investment while creating tens of thousands of domestic jobs (The White House 2021b). This deployment opportunity is estimated to require an average of over 260 wind turbines to be installed per year. The corresponding demand for key commodities, length of electrical cable, and workforce is provided in Table 12 (Lantz et al. 2021). Sourcing all this demand domestically is currently not feasible, as the U.S. supply chain is in its infancy. As a result, the initial phase of offshore wind energy installed on the Atlantic Coast is expected to rely heavily on international supply chains for major components, installation vessels, and engineering design work. Although this reliance on the global supply chains will help accelerate U.S. offshore wind near term deployments it also demonstrates a significant need to expedite the development of a domestic supply chain. A mature U.S. supply chain will help lower project risk and costs, and provide local economic benefits to support the existing deployment pipeline (Business Network for Offshore Wind 2019); however, the timeline for developing these capabilities and infrastructure is not clear, which introduces uncertainty into the planning process for individual projects and may encourage developers to rely on international sources.

Despite this uncertainty, several key supply chain developments took place in 2020. The EEW monopile facility in the Port of Paulsboro is the largest industrial offshore wind manufacturing facility in the United States to date, and construction broke ground in April 2021 (Durakovic 2020b). In January 2021, Welcon and Marmen announced investing in a tower and transition-piece manufacturing facility in the Port of Albany, in conjunction with Equinor and NYSERDA (Marmen 2021). In May 2020, Siemens Gamesa announced that it is considering establishing a factory to assemble its new 14-MW offshore wind turbine in the United States, although no formal commitment to a specific site has been made (Stromsta 2020). Finally, in June 2020, Nexans was contracted to design, manufacture, and install three 65-kilometer (km)-long export cables for the Seagreen 1 wind farm in Scotland, which will be built in its manufacturing facility in Charleston, South Carolina (Offshore Magazine 2020). The Nexans announcement highlights the fact that facilities based in the United States may support not only the domestic pipeline, but also the broader, global demand for state-of-the-art offshore wind energy components.

Table 12. Projected Supply Chain Demands To Meet the Offshore Wind Target of 30 GW by 2030

(Adapted from Lantz et al. 2021)

Cumulative Deployment	30 GW at end year (yr)
Deployment Average	3.7 GW/yr
Offshore Wind Energy Generation	117 terawatt-hours/year at end year
Cumulative Capital Expenditure	$97billion at end year
Average Capital Expenditure	12.2 $billion/yr
Cumulative Wind Turbine Demand	2,110 units
Average Wind Turbine Demand	263 units/yr
Cumulative Steel Demand	7,093 thousand tons
Average Steel Demand	886 thousand tons/yr
Cumulative Permanent Magnets	81 thousand tons
Average Permanent Magnet Demand	10.1 thousand tons/yr
Cumulative Electric Cabling	9,240 miles
Average Electric Cabling	979 miles/yr
Wind Turbine Installation Vessels	4–6 minimum required per year
Cumulative Port Infrastructure Upgrades	$375–500 million
[Construction Period] Installation, Manufacturing, and Supply Chain Jobs	31.3 thousand full-time-equivalent jobs/yr
[Operating Period] O&M Technicians, Management, and Supply Chain Jobs	13.4 thousand full-time-equivalent jobs/yr

2.6 COVID-19 Impacts

The COVID-19 pandemic shocked global economies in 2020. However, the impact of potential delays on the global offshore wind energy industry was relatively limited, because most countries categorize the energy sector as an essential service and allowed ongoing construction activities to continue despite lockdowns in other areas of the economy (International Energy Agency 2020a, 2020b). Furthermore, a number of countries enacted policy changes to enable flexibility in qualifying for key incentive programs; for example, the United States extended the Continuity Safe Harbor for projects that began construction in 2016 or 2017 (Internal Revenue Service 2020) and then subsequently passed a COVID-19 tax relief package that allows offshore wind energy projects that begin construction before 2026 to qualify for a 30% investment tax credit (U.S. Congress 2020b). As a result, there was no significant reduction in the amount of offshore wind capacity installed in 2020 relative to pre-COVID forecasts (International Energy Agency 2020a).

It remains possible that the COVID-19 pandemic may still adversely impact the construction timelines of planned offshore wind energy projects going forward, as some predevelopment activities such as permitting and environmental surveying have been delayed (International

Energy Agency 2020a). Effects on U.S. projects include Ørsted's announcement that delays in the Revolution Wind, Ocean Wind, Skipjack, and Sunrise Wind projects can be attributed (in part) to the impacts of COVID-19 (Durakovic 2020c). The full effects of the ongoing COVID pandemic are not yet certain.

2.7 Other Regional Developments

Over the course of 2020 and early 2021, a number of other offshore-wind-energy-relevant developments occurred:

2.7.1 North Atlantic

Maine. The University of Maine's New England Aqua Ventus I entered into a joint venture with Diamond Offshore Wind (Mitsubishi Corporation) and RWE Renewables to deploy a single 10- to 12-MW wind turbine mounted on a floating, concrete semisubmersible foundation in 2023 (University of Maine 2020). Additionally, Governor Mills announced a plan to develop the nation's first floating research array in the Gulf of Maine to support commercial-scale floating offshore wind energy development (Maine 2020).

Rhode Island. Governor Raimondo issued Executive Order 20-01 in January 2020, which aims to meet 100% of Rhode Island's electricity demand from renewable energy by 2030. As part of that effort, National Grid will issue a 600-MW offshore wind energy solicitation in 2021 (Rhode Island 2020).

New Hampshire. The state senate passed SB 151-FN, which directs the state's utilities to hold a competitive solicitation to procure up to 800 MW of offshore wind capacity by 2028 (New Hampshire 2021).

2.7.2 South Atlantic

North Carolina. Avangrid submitted a COP for an initial 800-MW phase of its Kitty Hawk project. It is unclear what entity will procure the power and if the project will inject that power into the North Carolina grid or a neighboring state.

2.7.3 Gulf of Mexico

Louisiana. Governor Edwards announced plans to work with BOEM to develop an intergovernmental taskforce for offshore renewable energy (BOEM 2020b). The Gulf of Mexico has the potential to generate a significant fraction of the region's electricity, especially in western Louisiana and Texas (Musial and Greco 2020).

2.7.4 Great Lakes

New York Great Lakes Feasibility Study. The New York Department of Public Service issued Order 15-01168, directing NYSERDA to complete a feasibility study for offshore wind energy to be deployed in the Great Lakes (Lake Erie and Lake Ontario) by the end of 2021 (NYSERDA 2020).

2.7.5 Pacific

California. State representative Chiu introduced AB 525, which would direct the California Public Utilities Commission and other agencies to evaluate and quantify the maximum feasible capacity of offshore wind energy to achieve reliability, ratepayer, employment, and decarbonization benefits and to establish offshore wind energy planning goals for 2030 and 2045 (California 2021). Besides the proposed legislation, the California Public Utilities Commission is also looking for ways to update its offshore wind assumption used in integrated resource planning processes. As part of this effort, NREL developed detailed wind resource and technology cost assessments for floating offshore wind turbines potentially deployed in California between 2019 and 2032 (Beiter et al. 2020b; Optis et al. 2020). The Schatz Energy Research Center also completed a comprehensive analysis of potential floating offshore wind options in northern California (Severy et al. 2020).

Oregon. State representative David Brock Smith introduced HB 3375, which aims to establish 3 GW of commercial-scale floating offshore wind energy projects within federal waters off the coast of Oregon by 2030 (Oregon 2021).

2.8 Environmental and Fisheries Research and Monitoring

Resource monitoring before and after construction will help address data gaps and reduce environmental and ecological uncertainty and risk associated with the development of offshore wind energy. Monitoring efforts are not just important at the project or state level, but also provide value on a larger regional scale. Regional efforts such as the Responsible Offshore Science Alliance and the Regional Wildlife Science Entity will help address the need for a more comprehensive resource monitoring approach. In addition, states such as New York and New Jersey now require developers they have selected to support regional monitoring of wildlife and key commercial fish stocks through a contribution of $10,000/MW. These activities aim to ensure that development of offshore wind energy is occurring in an environmentally responsible manner while reducing risks and leading to more cost-effective projects.

3. Global Offshore Wind Energy Development

Following the record 2019 deployment of more than 5,618 MW, 5,519 MW of new offshore wind energy was commissioned globally in 2020, as shown in Figure 10.

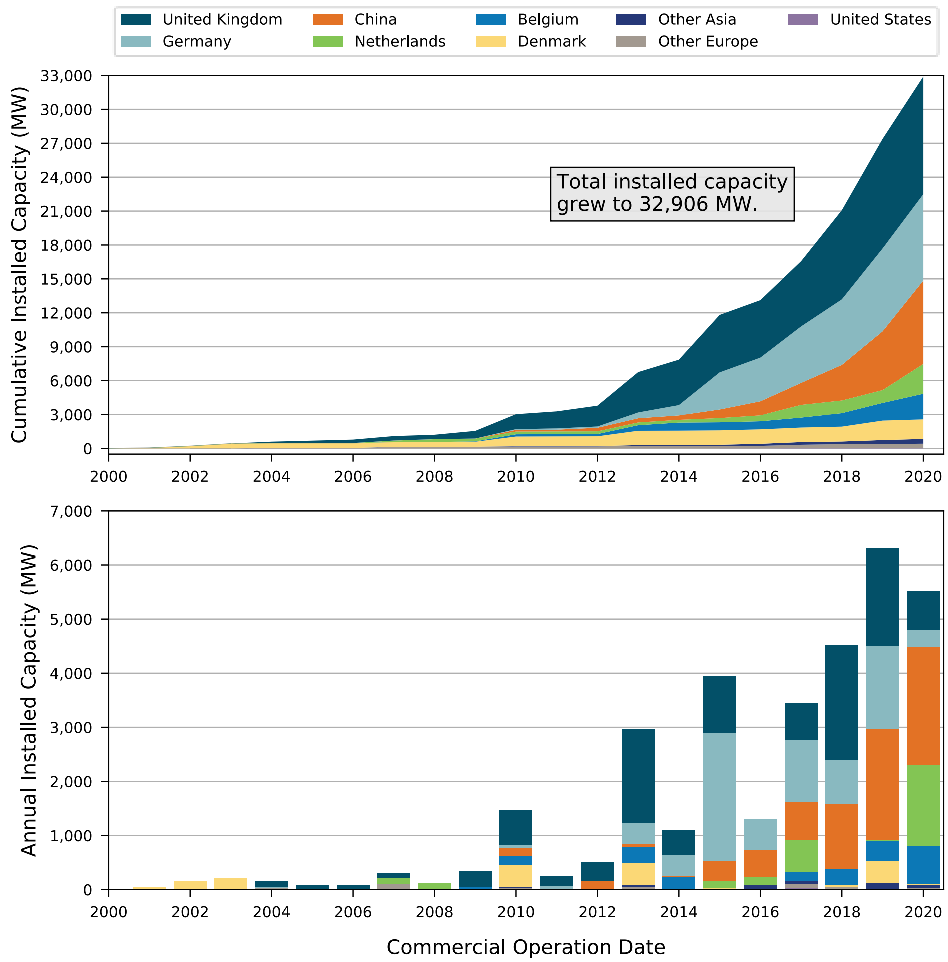

Figure 10. Global cumulative offshore wind energy deployment (top) and annual capacity additions (bottom) through 2020

The growth in global capacity can be attributed to a strong increase in deployment in the Chinese market, with 2,174 MW of new Chinese offshore wind capacity reaching commercial operation, followed by 1,502 MW commissioned in the Netherlands, 714 MW in the United Kingdom (U.K.), 706 MW in Belgium, 315 MW in Germany, 60 MW in South Korea, 25 MW in Portugal, and 12 MW in the United States. By the end of 2020, the capacity grew to 32,906 MW from 200 operating projects. Projections for 2021 indicate greater amounts of new global capacity based on over 23 GW of projects currently under construction.

The global offshore wind market is still centered in Europe, with approximately 25,073 MW of installed cumulative capacity. Asia is the second-largest regional market, with 7,791 MW, and North America is the third-largest market, with only 42 MW of capacity installed today. The OWDB indicates that future year-on-year market growth will increase in both the Asian and U.S.

markets. Europe's large regional offshore wind energy market is sustained, in part, because it has the most transparent national offshore wind procurement schedules that provide market certainty, regionally-based original equipment manufacturers (OEMs) and installers, mature logistical and manufacturing supply chains, and strong research and development networks to support its development. The Asian offshore wind energy market may soon surpass the European market in terms of annual capacity additions, driven primarily by China's demand for renewable energy and motivation to advance the country's domestic manufacturing capabilities. As shown in Figure 11, the top three countries contributing to offshore wind capacity growth in 2020 were China, the Netherlands, and the United Kingdom.

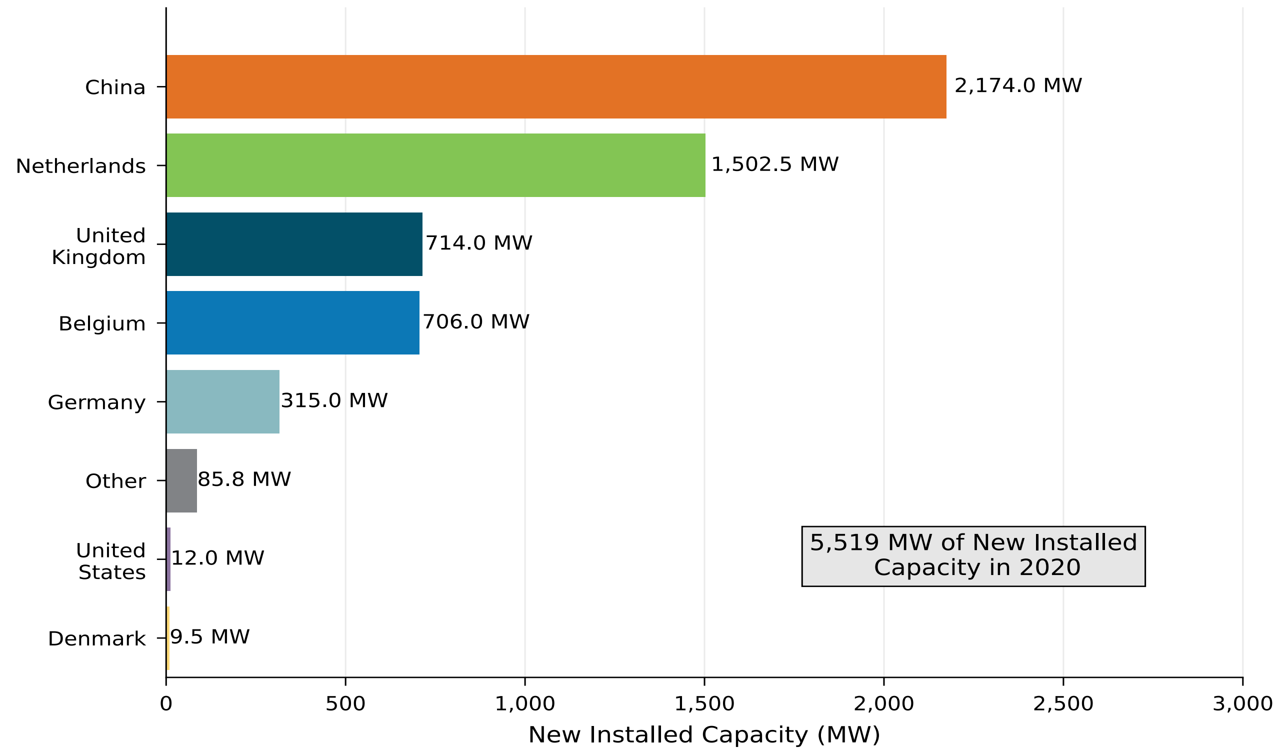

Figure 11. Global offshore wind installations in 2020

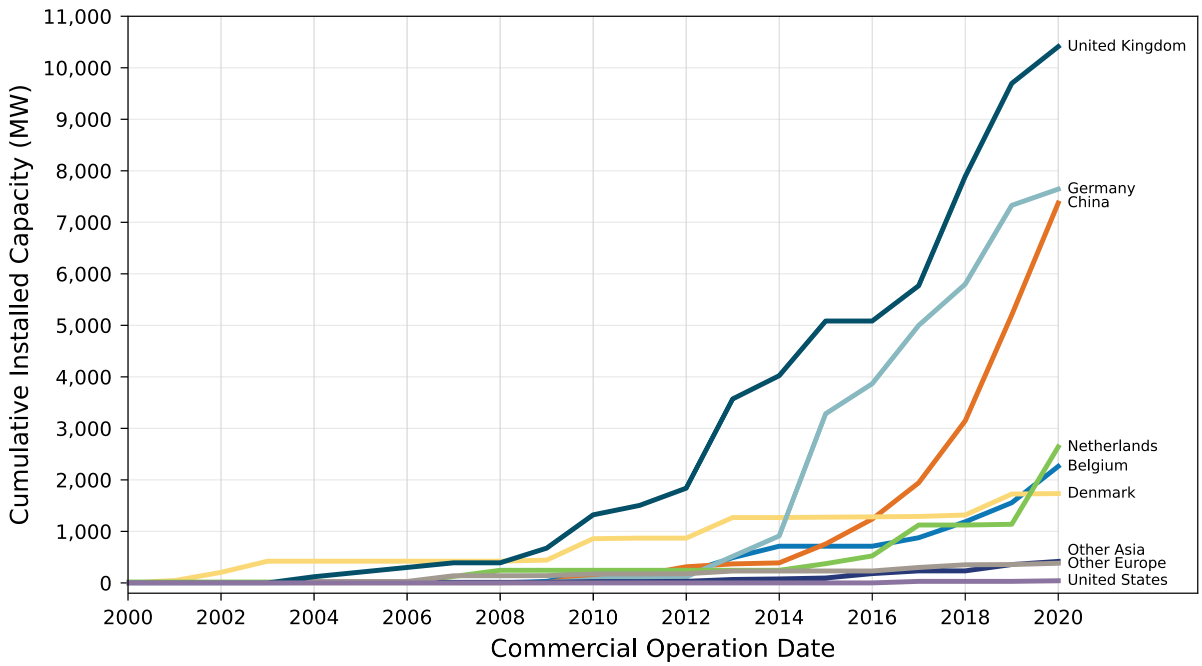

Figure 12. Global cumulative offshore wind installation by country

Of the 32,906 MW of cumulative offshore wind energy deployment recorded by the end of 2020, Figure 12 also shows how that capacity is distributed among all countries. The United Kingdom continues to lead the world in terms of total deployment, with 32%, followed by Germany (23%), China (22%), the Netherlands (8%), Belgium (7%), and Denmark (5%). By 2010, the United Kingdom gained a larger share of total deployment. Germany began its transition to offshore wind energy around 2010 and has sustained deployment. Figure 12 also shows the sharp acceleration of the Chinese market, especially in the past 3 years—a trend that is likely to continue.

3.1 Market Projections

This report contains both near-term (2026) and medium-term (2030) projections for the global offshore wind energy market. Near-term trends are based on NREL's OWDB and medium-term trends are based on a collection of outside sources, but primarily BNEF and 4C Offshore forecasts. These projections can help illuminate broad market trends, identify different national and regional deployment trajectories, and approximate the level of uncertainty in future deployment estimates.

3.1.1 Project Pipeline Through 2026

The near-term project projection is based on data obtained for NREL's OWDB and represents our best understanding of the global offshore wind energy market. Note that market dynamics, policies, and future technological innovations are always subject to change and could impact these projections. Near-term projections are based on industry data reporting their status in the pipeline and the developers' expected commercial operation dates. Projects that have made it past financial close have a much higher probability of being completed and a much lower uncertainty about when they will be completed. Figure 13 shows the 23,415 MW of new offshore wind energy under construction globally, broken down by country.

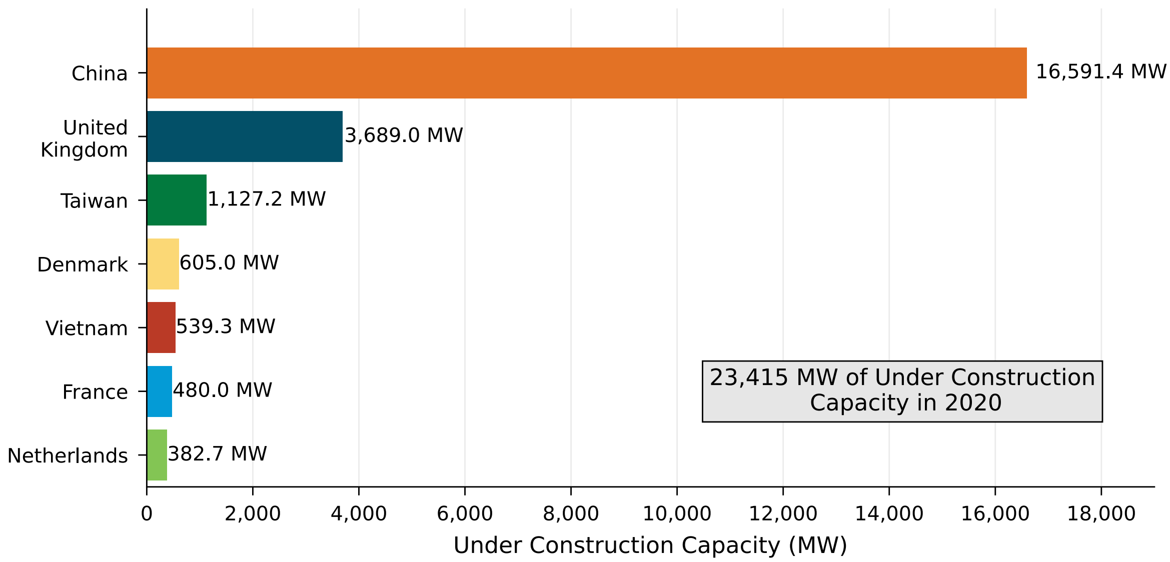

Figure 13. Offshore wind capacity under construction by country as of 2020

By the end of 2020, 73 projects in Asia were under construction, representing 18,258 MW of new capacity. Most construction (60 projects [16,591 MW]) is occurring in China, followed by Vietnam (10 projects [539 MW]), and Taiwan (3 projects [1,127 MW]). The large amount of construction in Asian offshore wind energy markets is expected to continually grow in the coming years. In Europe, eight projects, with a combined capacity of 5,157 MW, are currently under construction. Of the projects under construction, five are in the United Kingdom (3,689 MW), one in Denmark (605 MW), one in France (480 MW), and one in the Netherlands (383 MW).

In 2020, roughly 11 GW of projects reached financial close. In Europe, 16 projects, representing 7,244 MW of capacity, reached financial close. In the Asian market, 21 projects, representing 3,746 MW of capacity, reached financial close. In total, excluding operating projects, there are about 34 GW of projects that have reached financial close or are under construction as of 2020.

Figure 14 provides a yearly estimate of new deployment based solely on the developers' estimation of when they expect their project to be commissioned. Although a project developer may not always be at liberty to disclose detailed updates or information related to its exact deployment schedule, the developer COD data are a rough proxy for near-term deployment. Between 2021 and 2023, annual capacity additions are expected to be dominated by China and the United Kingdom. After 2024, developments in other Asian markets, the United States, and other European countries such as Germany and Poland may diversify the market. Based on only the projects reporting COD dates in Figure 14, these new additions would result in approximately 123 GW of new capacity from 2021 through 2026.[26] As shown in Figure 15, the cumulative offshore wind energy deployment by 2026 could reach approximately 145 GW.

[26] NREL uses a 5-year look ahead because project development further into the future is inherently uncertain.

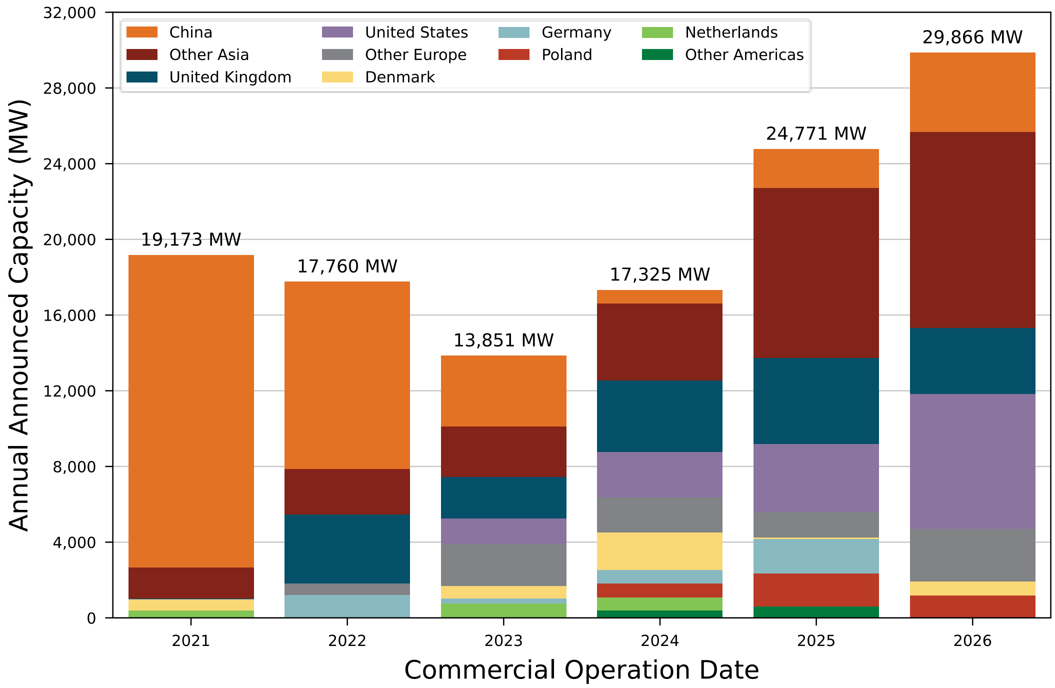

Figure 14. Developer-announced offshore wind capacity through 2026 for projects with financial closure

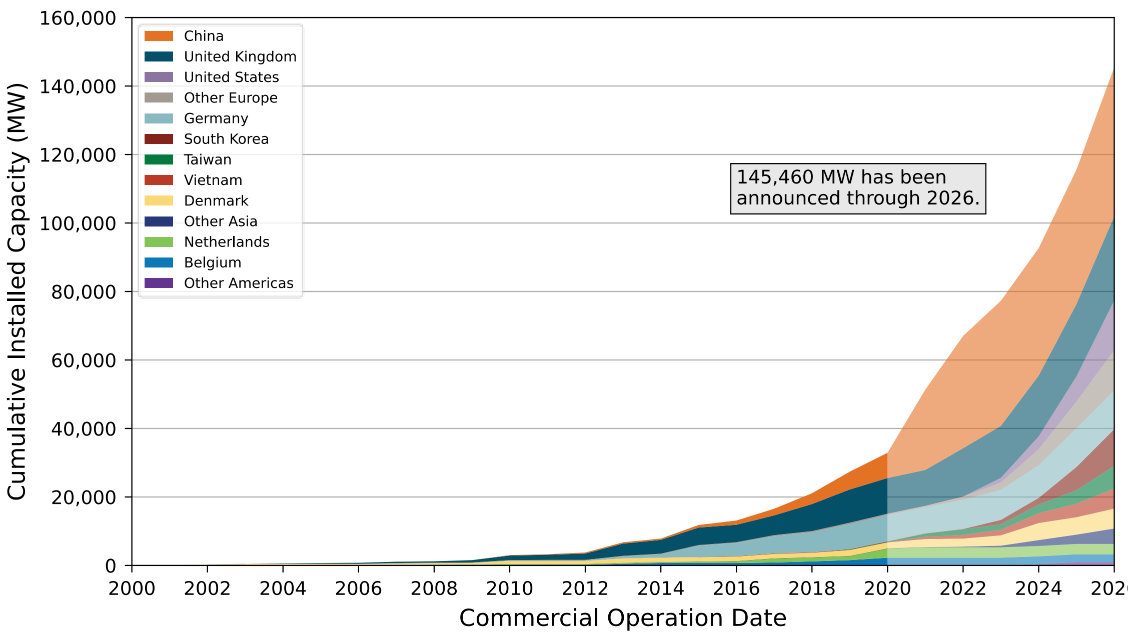

Figure 15. Estimated cumulative offshore wind capacity by country based on a developer-announced CODs (shaded areas represent forecasted deployments)

3.1.2 Total Global Pipeline

Figure 16 shows the global capacity of the operating and announced development pipeline for all offshore wind energy projects by region in 2020 to be 308 GW, compared to approximately 230 GW that was reported in 2019. The uptick is primarily attributed to more Asian projects entering the planning phase. This figure does not provide information about the likely timing or probability of developments within the long-term pipeline but provides overall announced capacity for all active projects recorded in the NREL OWDB. Generally, projects that are more advanced within the pipeline are likely to reach COD and be installed sooner than those at an earlier stage; however, international differences in regulatory structure can result in a wide range of development timelines. The global project pipeline illustrates that most of the world's installed projects and those under advanced development are in Europe, but the majority of the world's potential future capacity is in Asia. Looking at project status, there are approximately 52 GW of approved projects in the global pipeline—almost equal to the amount of capacity currently installed and under construction combined. If all the approved capacity is constructed, the dramatic expansion of the global market will require the further expansion of global supply chains and manufacturing capabilities, and a larger, more robust installation and support vessel fleet.

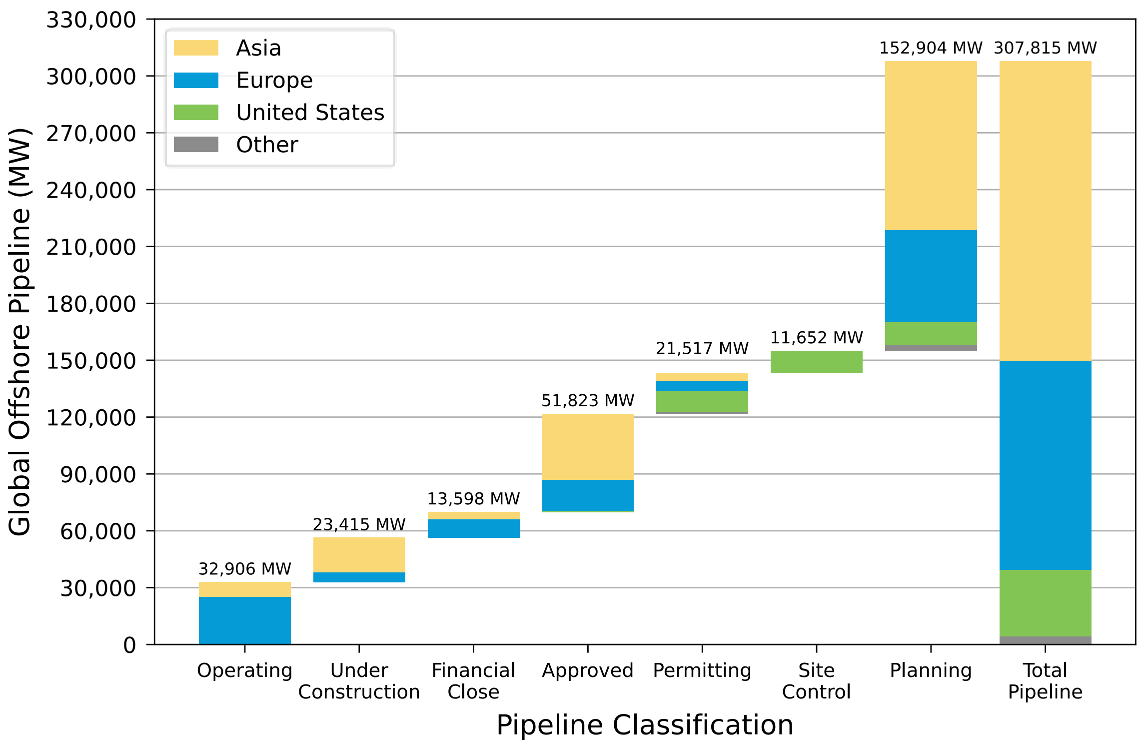

Figure 16. Total global pipeline by status

3.1.3 Projections to 2030

In Figure 17, two forecasts are shown: one by BNEF (2020a) and one by 4C Offshore (2021), which estimate the future growth of the global offshore wind energy industry. BNEF forecasts offshore wind energy will reach 203 GW by 2030, whereas 4C Offshore estimates a projected deployment level of 215 GW by 2030. Both forecasts are provided to illustrate the variability associated with longer-range deployment estimates.

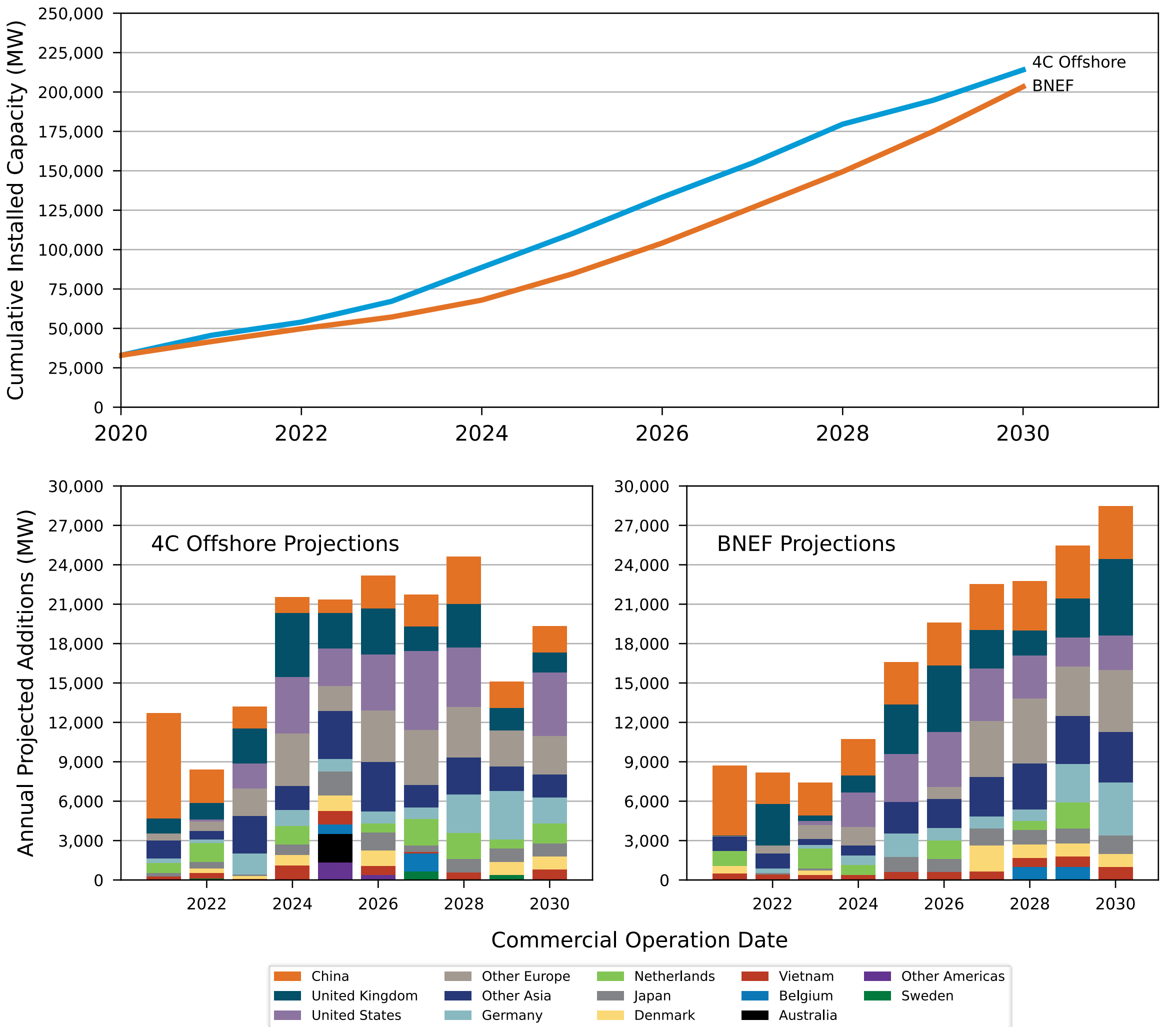

Figure 17. Industry forecasts for global offshore wind energy deployment to 2030

Like the near-term forecast to 2024, the most striking shift in offshore wind market dynamics in the 2030 forecast scenarios is the estimated growth of the Chinese market. Both forecasts expect China will cumulatively deploy between 45 and 52 GW by 2030. Forecasts also predict European developers will continue to incrementally build projects at a similar rate relative to today, with Europe holding roughly 45% of the total installed global offshore wind capacity by 2030. China itself is expected to represent 22% of the total 2030 installed capacity, with the remaining other Asian countries (e.g., Taiwan, Korea, Japan, and Vietnam) accounting for 9%. Depending on the forecast scenario (4C Offshore or BNEF), the U.S. proportion of installed capacity could range from 10% to about 12% of the global total by 2030.

3.2 Country-Specific Offshore Wind Energy Markets

Future offshore wind energy development will be driven by changes that occur at the country level, especially by implementing national offshore wind capacity or procurement targets and developing and publishing offshore wind lease schedules. National offshore wind capacity targets define the size of the future demand and leasing schedules can help determine how fast the supply will grow to meet that demand.

Table 13 shows 28 auctions scheduled over the next 4 years for over 69 GW of new offshore wind capacity. In 2020 alone, four recently completed or ongoing auctions cover at least 20,000 MW of potential new capacity. Sections 3.3.1 and Sections 3.3.2 provide country-specific offshore wind energy market developments.

Table 13. Global Offshore Wind Tender Dates and Sizes[27]

Country	2020	2021	2022	2023	Total (MW)
United Kingdom	ScotWind–10,000 MW Round 4–8,000 MW			Round 5–8,500 MW ScotWind 2	26,500
Poland		OWA Phase 1–5,900 MW			5,900
Norway		Utsira Nord/Sørlige Nordsjø II–4,500 MW			4,500
Japan		Japan–1,000–1,500 MW	Japan–1,000–1,500 MW	Japan–1,000–1,500 MW	4,500
Netherlands		Hollande Kust West–1,400 MW	Ten noorden van de Waddeneilanden–700 MW	Ijmuiden Ver I&II–2,000 MW	4,100
France	Normandy–1,000 MW	Brittany–250 MW Oléron–1,000 MW	Mediterranean– 500 MW	South Atlantic–1,000 MW	3,750
Ireland		Renewable Electricity Support Scheme–1,000 MW	Renewable Electricity Support Scheme 3–1,000 MW	Renewable Electricity Support Scheme 4–1,000 MW	3,000
Germany		Sites N-3.7, 3.8, 0-1.3–958 MW	N-7.2–930 MW	N-3.5, 3.6.–900 MW	2,788
Denmark	Thor–800 MW to 1,000 MW	Hesselø–1,200 MW			2,200
Taiwan			Taiwan–2,000 MW		2,000
Belgium				Princess Elizabeth Zone–1,700 MW	1,700
Total (MW)	**20,000**	**25,708**	**6,730**	**16,600**	**69,038**

3.2.1 European Market Activities

Poland

The Ministry of Energy strategy for 2040 calls for 5,900 MW of offshore wind energy by 2030 and between 8,000 and 11,000 MW by 2040 (IHS Markit. 2021). The Offshore Wind Act of 2021 provides up to 5,900 MW allocated by a contract for difference[28] in 2021 and 2,500 MW of

[27] Note: This table does not include all potential future offshore wind auctions held at the international level, only those that have been made publicly available. For example, there is a high probability China will hold multiple auctions over this time period but does not have a published schedule.

[28] A contract for difference is a long-term contract between an electricity generator and an offtaker. The contract enables the generator to stabilize its revenues at a level agreed upon earlier (the strike price) for the duration of the contract. Under the contract for difference, payments can flow from the offtaker to the generator, and vice versa. Further, when the market price for electricity generated by a generator (the reference price) is below the strike price set out in the contract, payments are made by the offtaker to the generator to make up the difference. However, when the reference price is above the strike price, the generator pays the offtaker the difference.

capacity procured through contract-for-difference auctions in 2025 and 2027 (WindEurope 2021). Projects must be operational within 7 years of award, meaning 10,900 MW of generating capacity by 2034.

Denmark

Denmark has approximately 1,700 MW of installed offshore wind capacity, 600 MW under construction, and the 344-MW Vesterhav Nord/Syd project approved by regulators with a 2023 COD. The 2018 Energy Agreement gave the Danish government the authority to procure 2,400 MW of offshore wind capacity through three additional tenders, with projects required to come online between 2027 and 2030 (Danish Energy Agency 2018). The first tender called Thor was initiated in 2020 and aimed to procure between 800 and 1,000 MW. The second tender called Hesselø will open in 2021 and be sized between 800 and 1,200 MW. The 2020 June Climate Agreement set a goal of creating two energy islands by the early 2030s that could act as hubs to collect electricity from the surrounding offshore wind farms and distribute the electricity between countries via electricity grid connections (Danish Energy Agency 2020). The islands would be located in Bornholm (2 GW) and the North Sea (3,000–10,000 MW). The offshore wind farms connected to the energy island in the North Sea will be tendered out at a later date. The islands will be considered critical infrastructure, and the state will have a majority ownership in collaboration with one or more private actors.

Germany

Germany has 7,600 MW of operational offshore wind capacity, and roughly 3,100 MW of new capacity approved through tenders held in 2017 and 2018. An amendment to the Offshore Wind Energy Act (WindSeeG) raised the country's offshore ambitions from 15,000 MW to 20,000 MW by 2030 and added a 40-GW-by-2040 goal (Federal Ministry for Economic and Energy Affairs 2020). Two offshore areas called "N-3.7" and "N-3.8" in the North Sea will be auctioned off in 2021, with projects coming online in 2026 (BSH 2020).

Netherlands

The Netherlands has roughly 2,600 MW installed, with 383 MW under construction and 1,470 MW reaching financial close at the end of 2020. The country's coalition and climate agreements committed to 11,000 MW of offshore wind energy by 2030 (Government of the Netherlands 2019). The Netherlands plans to have tenders for the two Hollande Kust West lease areas (1,400 MW) in 2021, the 10 noorden van de Waddeneilanden site (700 MW) in 2022, and the IJmuiden Ver cluster (4,000 MW) between 2023 and 2025. Those tenders will see projects come online between 2025 and 2029. Further, the Dutch government commissioned the North Sea Outlook to assess potential energy pathways between 2030 and 2050 and found the country could benefit from deploying between 38,000 MW and 72,000 MW of offshore wind capacity (Government of the Netherlands 2020).

North Sea Wind Power Hub Consortium

Given multiple countries' goals to develop offshore wind energy in the North Sea, three regional transmission system operators, Energienet, Gasunie, and TenneT, developed a consortium to imagine the future of shared infrastructure investments to optimize not only the flow of electricity from offshore wind farms but also potential energy mediums produced via energy conversion processes (e.g. hydrogen or power-to-x) that are critical for achieving the European Union's ambitious climate goals (North Sea Wind Power Hub 2021).

Belgium

Belgium has 2,200 MW of installed capacity, with 706 MW of new capacity installed in 2020. No new installations are expected until the government identifies specific lease areas and announces tender for the roughly 4,500-GW Princess Elisabeth Zone in the Belgian North Sea.

France

France awarded 2,500 MW of fixed-bottom offshore wind capacity in 2012 and 2014, with commissioning now expected in 2022. Approximately 100 MW of floating offshore wind capacity will be operational by 2021/2022. Awards for 600 MW of fixed-bottom offshore wind energy projects were made in 2019 as part of the Round 3 Dunkirk tender (€44/megawatt-hour [MWh]). A further 3,750 MW of fixed-bottom and floating capacity will be tendered from 2020 to 2023, with an operational goal of 5,200–6,200 MW by 2028. About 1,000 MW per year will be tendered from 2024 to 2028.

United Kingdom

The United Kingdom is the world leader of offshore wind energy deployment, with 10,400 MW of capacity installed, 3,700 MW under construction, 3,500 MW at financial close, and an additional 10,500 MW of capacity approved for further development. The U.K. offshore wind energy market is being driven by a national net-zero 2050 target that could require 75,000 MW of offshore wind (Durakovic 2019). Prime Minister Johnson has called for at least 40,000 MW by 2030 (BBC 2020). Potential bottlenecks that could delay deployment include grid coordination and competition for global supply chains. Beyond the traditional power market, the United Kingdom also has a growing demand for corporate renewable procurement and clean electricity for hydrogen production.

Ireland

Currently, Ireland has 25 MW of installed capacity, but Ireland's National Energy and Climate Plan 2021–2030 increased the nation's offshore wind goal from 3,500 MW by 2030 to 5,000 MW by 2030 (Department of the Environment, Climate and Communications 2020). Ireland's first offshore-wind-energy-specific auction called Renewable Electricity Support Scheme 2 is scheduled to open for qualification in 2021.

3.2.2 Asian Market Activities

China

With over 7,000 MW installed by the end of 2020, China achieved its 5-GW-by-2020 offshore wind deployment target set by the 13th Energy Five Year Plan (International Energy Agency 2021). The 14th Energy Five Year Plan announced in 2021 will likely increase China's national offshore wind energy commitment. Currently, provincial level goals that total over 150,000 MW are a bigger driver than national goals. Despite the announcement that subsidies are scheduled to phase out after 2021, 4C Offshore expects the Chinese offshore wind energy market to continue to expand, with a maximum of 52,000 MW under development by 2030 and 78,000 MW by 2035 (4C Offshore 2021). Only Guangdong and Zhejiang provinces plan to retain local subsidy plans.

Japan

By the end of 2020, Japan had 86 MW of offshore wind capacity installed. In December 2020, the Japanese government announced it wants to procure 10,000 MW by 2030 and 45,000 MW by 2040 as part of its net-zero emission goals by 2050 (Japan Times 2020). These targets may be codified in the forthcoming 6th Strategic Energy Plan. Japan started soliciting offshore wind energy projects in 2020 via authority granted in Act No. 89 of 2018. The Ministry of Economy, Trade, and Industry and the Ministry of Land, Infrastructure, Transport and Tourism are auctioning four offshore wind energy zones: three that are located off Akita Prefecture and one located off of Choshi City (Durakovic 2020d). The agencies have also begun accepting submissions from local prefectures interested in becoming “Promotion Areas” as part of future auction processes.

Korea

Korea has 100 MW of offshore wind capacity installed and roughly another 3,000 MW undergoing permitting. This capacity will be used to support the Ministry of Trade, Industry and Energy’s goal of 12,000 MW of offshore wind capacity by 2030 (Norton Rose Fulbright 2020). As part of this effort, South Korea announced it will develop the world’s largest and most expensive offshore wind farm, with 8,200 MW (estimated $43 billion) off Sinan (Hyonhee Shin 2021). Korea also developed regional targets (including for floating wind technologies) that account for approximately13,000 MW.

Taiwan

By the end of 2020, Taiwan had 128 MW of installed capacity, with over 1,100 MW under construction and roughly 1,500 MW that reached financial close. The Taiwanese government also boosted their offshore wind energy ambitions by raising the target of 5,500 MW by 2035 to 15,500 MW by 2035 (Ferry 2021). The government’s increased ambitions could be challenging, especially considering the cancellation of the 350-MW Guanyin project in early January 2021. Taiwan is expected to hold another solicitation for approximately 2,000 MW in 2022.

Vietnam

Vietnam has 99 MW installed, 539 MW under construction, roughly 1,300 MW approved, and 1,200 MW undergoing permitting. The Vietnamese government is working with the World Bank, Danish Energy Agency, and the Global Wind Energy Council to determine its long-term wind energy goals. A Global Wind Energy Council study recommended a 10,000-MW build-out by 2030 and 25,000 MW by 2035, moving up to 40,000 MW by 2040, at which point offshore wind energy could supply 17% of Vietnam’s electricity (Global Wind Energy Council 2020).

4. Global Floating Offshore Wind Energy

The floating offshore wind energy market is still driven by the prospect of accessing a much larger ocean area with high-quality wind resources, but in water depths that are too deep (nominally greater than 60 meters [m]) for conventional fixed-bottom technologies. In the United States, more than 58% of the total technical offshore wind resource is located in water depths greater than 60 m, and in Europe that number grows to 80% (Musial et al. 2016; WindEurope 2018). Globally, the development of a floating offshore wind energy market continues to emerge as experience and knowledge are gained from pilot projects in Europe, Asia, and North America. This pilot- and demonstration-focused phase, which should see most projects enter operation by 2023–2024, is expected to inform the development of cost-effective, commercial-scale projects that may be installed as early as 2025.

4.1 Floating Offshore Wind Energy Pipeline

There are currently 11 floating offshore wind energy projects installed around the world representing 79 MW of capacity. Five projects (59 MW) are installed in Europe and six (20 MW) are in Asia. There are an additional 15 projects representing approximately 293 MW that are currently under construction or have achieved either financial close or regulatory approval. Four projects (79 MW) have advanced to the permitting phase, and another 87 are in the early planning stages (26,078 MW). Overall, the 2020 global floating offshore wind energy pipeline represents approximately 26,529 MW of capacity, growing by 18,866 MW relative to the "2019 Offshore Wind Technology Data Update," as shown in Figure 18.[29] Note the y-axis has two scales to help identify the advanced early-stage projects.

[29] Note: Potential floating offshore wind energy development along the Pacific Coast in the United States is not included in Figure18 because sites have not been identified as wind energy areas by BOEM. The May 2021 White House announcement increases the probability that existing Call Areas may eventually be suitable for potential commercial development and will be included in future market reports if or when specific WEAs are identified.

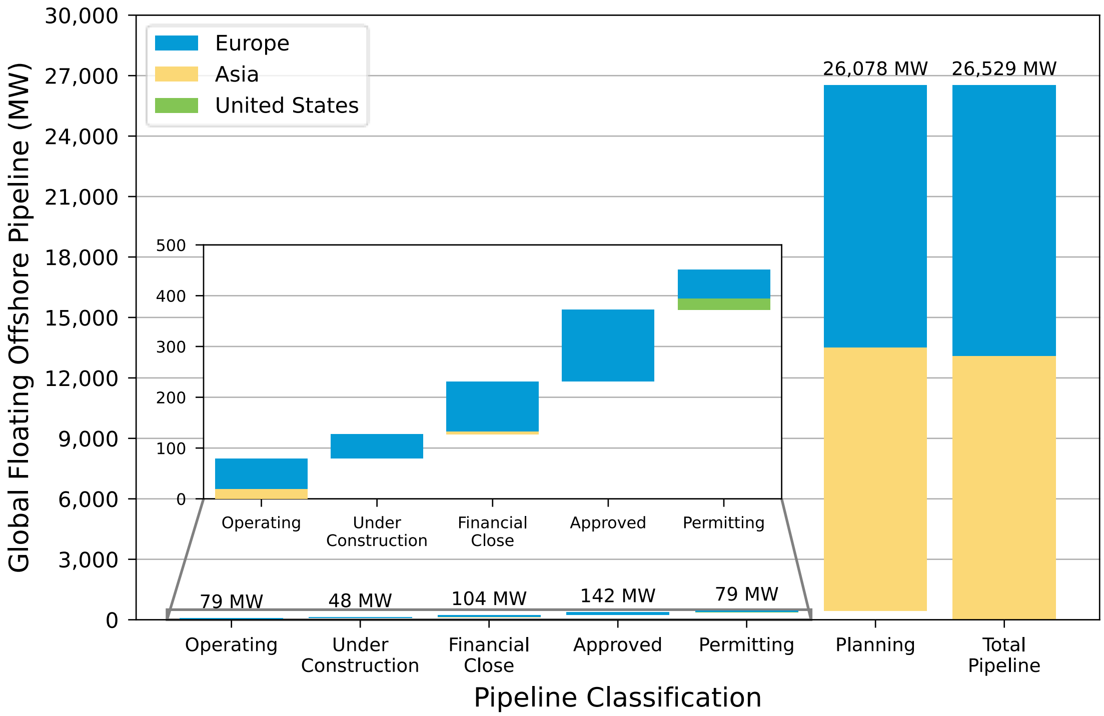

Figure 18. Total global floating offshore wind energy pipeline

Table 14 includes the total global offshore wind energy floating pipeline and breaks it down by country. Two changes to note from the 2019 Offshore Wind Technology Update:

1. Some projects (1,348 MW) have moved back in the pipeline from the permitting stage to planning. This change was confirmed according to the 4C Offshore Database and reflects the uncertainty and transparency of project development and planning processes in nascent markets.

2. The total installed floating capacity decreased by 5 MW as a result of the decommissioning of early pilot projects.

Table 14. Global Floating Offshore Wind Energy Pipeline

Country	Operating (MW)	Under Construction (MW)	Financial Close (MW)	Approved (MW)	Permitting (MW)	Planning (MW)	Grand Total (MW)
China			5.5			68	73.5
France	2			113.7		517	632.7
Germany			2.3			8	10.3
Ireland						2,926	2,926
Italy						3,747	3,747
Japan	19.006					1,028	1,047.006
Norway	2.3		91.6			3,507	3,600.9
Portugal	25					125	150
Saudi Arabia						500	500
South Korea	0.75					9,457	9,457.75
Spain			2.225	8	25	1,036	1,071.225
Sweden	0.03			10			10.03
Taiwan						2,000	2,000
United Kingdom	30	48	2	10	32	1,159	1,281
United States					22		22
Total	**79.086**	**48**	**103.625**	**141.7**	**79**	**26,078**	**26,529.41**

Figure 19 illustrates the current floating offshore wind energy market pipeline in terms of time, depth, project size, and country for projects out to 2026 that report water depth. The figure reveals how the floating offshore wind energy market has evolved from small-scale, single-wind-turbine prototypes (2009–2015) to multiturbine demonstration projects (2016–2022). Post-2022, the first commercial-scale floating offshore wind projects are expected to be installed, with a significant jump in project size. Water depths also increase as the project sizes get larger. Each of the projects shown in Table 15 are plotted in Figure 19 if the project has an announced COD of 2026 or earlier and its water depth has been disclosed.

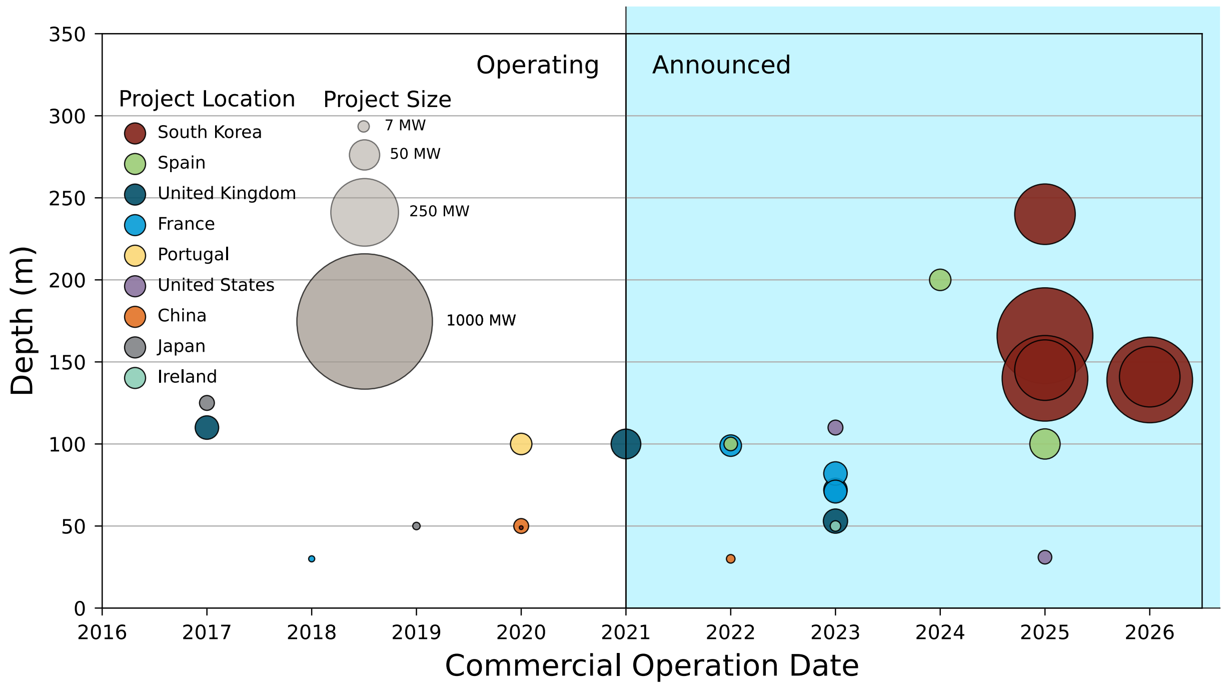

Figure 19. Global floating offshore wind energy projects by depth, country, and project size

Table 15. Floating Projects by Country, Status, Capacity, and COD

Project Name	Country	Status	Capacity (MW)	Estimated COD
CTGNE Yangjiang Shapa - phase III - floating demo	China	Financial Close	5.5	2021
V-type Floating Demonstration Project	China	Planning	12	2020
Longyuan Nanri Island Floating Project	China	Planning	4	2022
Nezzy	China	Planning	15	2022
Shanghai Far & Deep-Sea Floating Demo	China	Planning	25	2022
Floatgen Project	France	Operating	2	2018
Les éoliennes flottantes de Provence Grand Large	France	Approved	25.2	2022
EolMed	France	Approved	30	2023
Les éoliennes flottantes de Groix & Belle-Île	France	Approved	28.5	2023
Les éoliennes flottantes du Golfe du Lion	France	Approved	30	2023
EOLINK 5 MW Demonstrator	France	Planning	5	2022
EOLINK - EOLIENNE FLOTTANTE 12MW	France	Planning	12	2023
GICON Schwimmendes Offshore Fundament (SOF) Pilot	Germany	Financial Close	2.3	2022
AFLOWT (Accelerating market uptake of Floating Offshore Wind Technology)	Ireland	Planning	6	2023
Fukushima Floating OffshoRe Wind FARm Demonstration Project (Forward) Phase 1	Japan	Operating	2	2013

Project Name	Country	Status	Capacity (MW)	Estimated COD
Fukushima Floating OffshoRe Wind FARm Demonstration Project (Forward) Phase 2	Japan	Operating	12	2017
Kitakyushu - NEDO next-generation floating wind turbine system - demonstration	Japan	Approved	3	2021
Kyushu University Wind Lens Project - phase 1	Japan	Operating	0.006	2012
Sakiyama 2-MW floating wind turbine	Japan	Operating	2	2016
Goto Sakiyama Oki Huangdao - Pilot	Japan	Planning	22	2022
UNITECH Zefyros by Hywind Technology	Norway	Operating	2.3	2009
TetraSpar Demonstrator - Metcentre	Norway	Financial Close	3.6	2021
Hywind Tampen	Norway	Financial Close	88	2022
SeaTwirl S2	Norway	Planning	1	2022
WindFloat Atlantic (WFA)	Portugal	Operating	25	2020
Plambeck Emirates (Floating)	Saudi Arabia	Planning	500	2024
Ulsan 750-kilowatt floating demonstrator	South Korea	Operating	0.75	2020
Ulsan 5MW Floating Prototype	South Korea	Planning	5	2022
Donghae 1	South Korea	Planning	200	2025
Donghae – White Heron – East 1	South Korea	Planning	400	2025
Donghae – MOTIE and Ulsan Metropolitan City Consortium Phase 1	South Korea	Planning	200	2025
Donghae – Gray Whale – Phase 1	South Korea	Planning	500	2025
Donghae – White Heron – East 2	South Korea	Planning	400	2026
Donghae – TwinWind – Phase 1	South Korea	Planning	200	2026
Jindo	South Korea	Planning	420	2026
PivotBuoy - PLOCAN	Spain	Financial Close	0.225	2021
DemoSATH - BIMEP	Spain	Financial Close	2	2022
Floating Power Plant - PLOCAN	Spain	Approved	8	2023
FLOCAN 5	Spain	Permitting	25	2024
MULTIPLAT2	Spain	Planning	10	2022
FLOTANT – PLOCAN	Spain	Planning	10	2022
Cardon	Spain	Planning	50	2025
Dunas	Spain	Planning	50	2025
GOFIO	Spain	Planning	50	2025
Guanche	Spain	Planning	50	2025

Project Name	Country	Status	Capacity (MW)	Estimated COD
MOJO	Spain	Planning	50	2025
CanArray	Spain	Planning	60	2026
SeaTwirl S1	Sweden	Operating	0.03	2015
Hywind Scotland Pilot Park	United Kingdom	Operating	30	2017
Kincardine - DOLPHYN – 2-MW demo	United Kingdom	Financial Close	2	2024
Kincardine - Phase 2	United Kingdom	Under Construction	48	2021
Wave Hub	United Kingdom	Permitting	32	2023
Maine Aqua Ventus I	United States	Permitting	12	2023
Mayflower Wind Floating Demonstration	United States	Permitting	10	2025
Total			**3,688 MW**	

Figure 20 plots the project data in Table 15 to show estimated cumulative deployment of floating offshore wind energy projects by country. Of the 3,688 MW of floating offshore wind capacity through 2026,[30] the majority is estimated to be in South Korea (2,300 MW), Spain (365 MW), Saudi Arabia (500 MW), and France (132 MW). Most other deployments will be evenly spread throughout multiple countries in Europe. However, because most of these large commercial projects are still in the planning phase, there is a high degree of uncertainty about their economic viability.

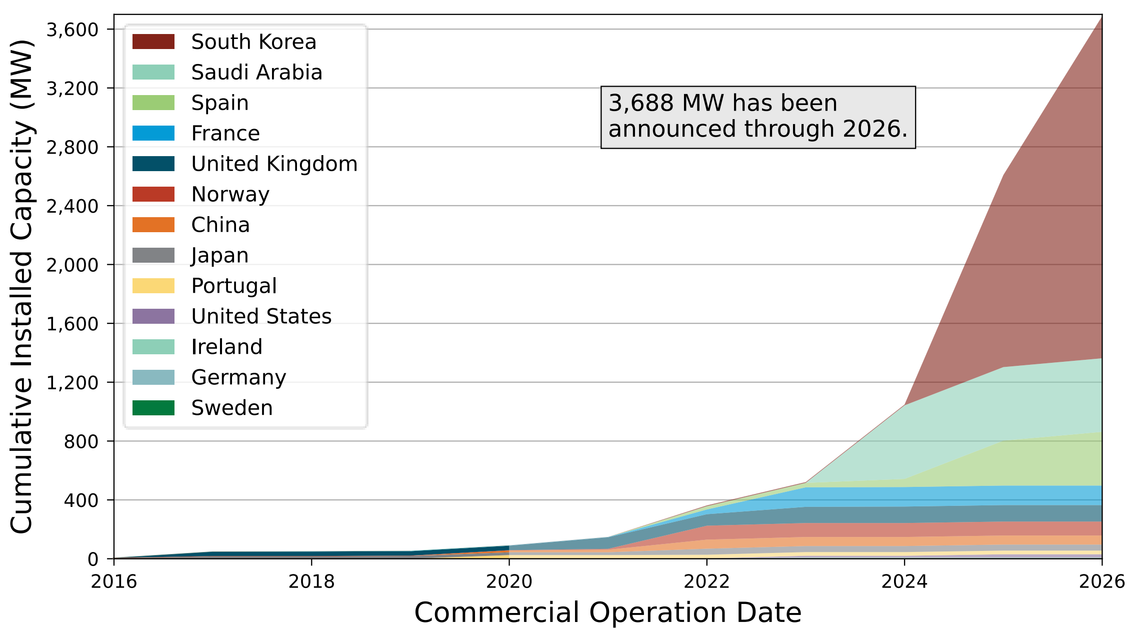

Figure 20. Cumulative floating offshore wind capacity by country based on announced COD through 2026

[30] Note almost all announced projects with COD dates are before 2026.

5. Offshore Wind Energy Technology Trends

Offshore wind energy technology is maturing rapidly in Europe and Asia, but further cost reductions can be realized through continued advancements. Larger wind turbines, advanced controls, supply chain optimization, increased competition, and systemwide design approaches have contributed to much of the recent offshore wind energy cost declines over the past few years, which in some cases have enabled zero-subsidy project bids in recent European auctions. New technology, such as floating offshore wind, is also enabling new markets to evolve. Recent cost reductions have allowed fixed-bottom offshore wind systems to compete with existing generation technologies in some energy markets. Overlapping supply chains and shared components mean that some of the same cost reduction drivers translate directly to the floating offshore wind market. As a result, floating wind energy may soon be commercially feasible in several new offshore wind regions.

An important new trend we are tracking is accelerated growth in Asian offshore wind energy markets, especially China. Over the next few years, China is expected to lead globally in total offshore wind energy deployment (4C Offshore 2021). This market report separates some of the technology and cost trends for these Asian markets, because technology used in the United States will rely mostly on European technology and to some extent European vessels. In the near-term, Asian wind turbines are not expected to be deployed in U.S. or European markets. However, because of their increasing global market share, Asian offshore wind deployment is beginning to impact global market averages. New Chinese and Korean wind turbines that are being deployed in Asian countries have smaller nameplate capacities than their European counterparts. In many cases, Asian projects are closer to shore and in shallower waters. Using NREL's OWDB described in Section 1, we rely substantially on empirical data for planned projects advancing through the pipeline to provide insight into global technology siting trends through 2024. The OWDB also provides insight regarding offshore wind turbine capacities, substructures, electric infrastructure, and logistical approaches for construction and maintenance activities. Much of the discussion is focused on fixed-bottom technologies, although floating offshore wind technologies are also included.

5.1 Global Offshore Wind Siting Trends

Figure 21 summarizes offshore wind energy project deployment trends for four parameters—depth, distance, project status, and project size—and shows these trends for global offshore wind energy projects that have advanced to at least the site-control phase.

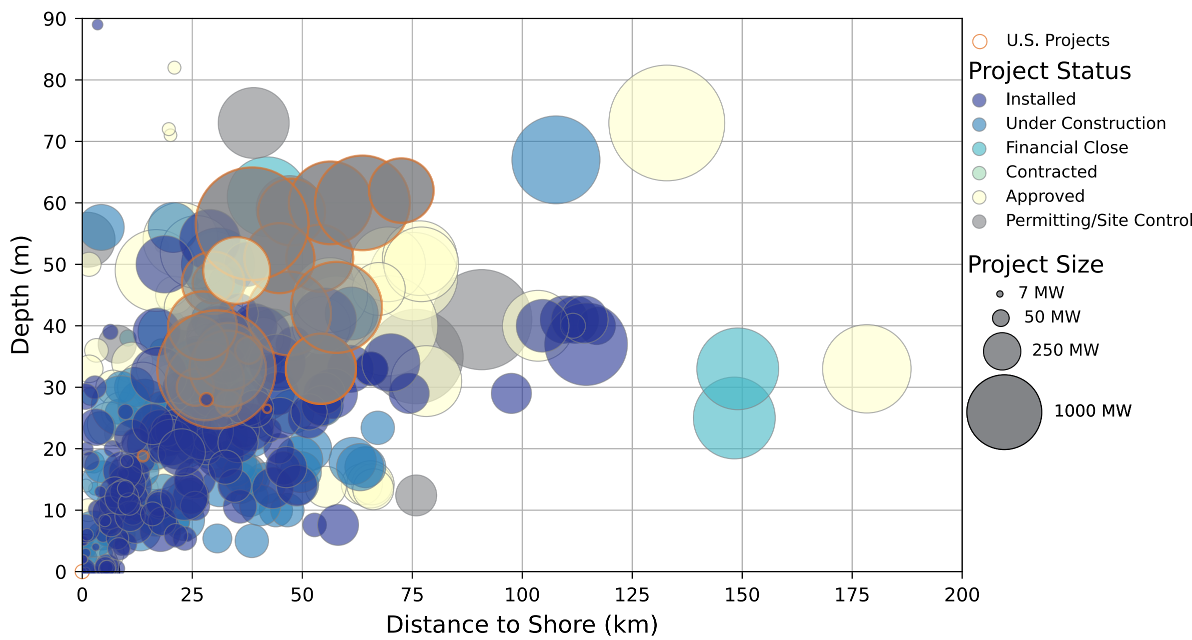

Figure 21. Global fixed-bottom offshore wind energy project depths and distances to shore

In Figure 21, global projects are color-coded by the project phase they have advanced to in the pipeline. The 16 U.S. projects that have advanced to the permitting phase in the regulatory process are also included. The figure indicates that generally, newer projects tend to be larger, further from shore, and located in deeper water. Larger project size has been shown to lower projects cost (Beiter et al. 2020b). The trends toward increased distance from shore and water depth can be attributed to incremental technology improvements in support structures, a better understanding of project risks, and near-shore site scarcity caused by increasing demand. More remote siting has also been enabled by technology advancements in electrical grid infrastructure, such as high-voltage direct current (HVDC) technology, which avoids the higher losses of a long-distance alternating-current transmission system.

The previously mentioned trends may not be fully apparent from the plot shown in Figure 21 because the large quantity of project data may obscure these trends to some degree. Figure 22 and Figure 23 show distance to shore and water depth by COD from the global project data to clarify historical and projected trends. Asian projects are depicted with an X to assist in identifying and separating regional trends.

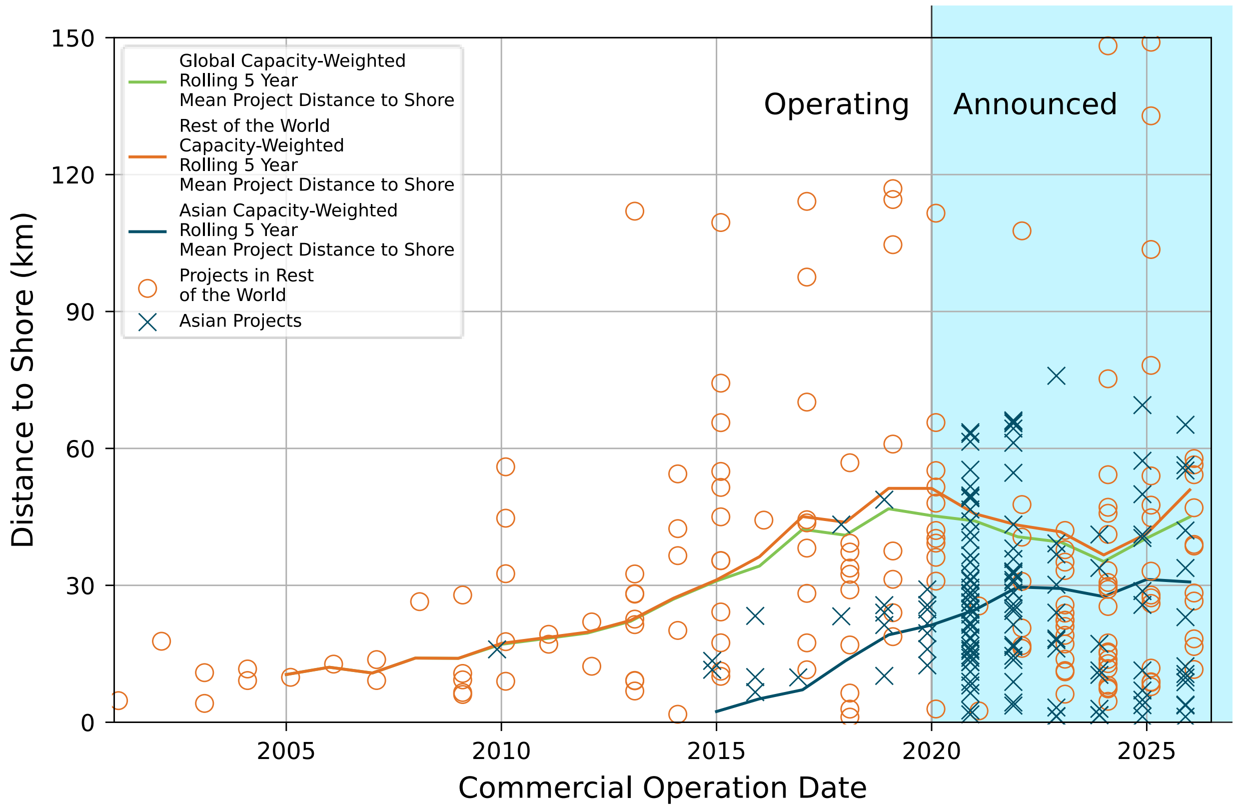

Figure 22. Distance from shore for global operating and future offshore wind energy projects

In Figure 22, average distance to shore increases over time but appears to peak around 2018 and is projected to decrease through 2024. This counterintuitive trend can be partially explained by the rapid expansion of offshore wind energy into new Asian markets, and China in particular, where different regulatory environments and social concerns have enabled projects to be built closer to shore than in Europe. Although there is less certainty about projects further into the future, the data indicate that the decrease in the global curve shown in Figure 22 may be temporary, and that projects in both Asia and the rest of the world will eventually move farther from shore after 2024.

The average water depth over time for global offshore wind projects is presented in Figure 23. The historic trend of increasing water depth levels off slightly in 2020, but by 2024 the data indicate the trend toward deeper-water projects will continue. As in the case of distance to shore, the relatively flat trajectory for water depth is attributed to the large quantity of early Asian projects that are located closer to the shore in shallower waters. The data indicate that after 2025 the Asian and global trends will converge.

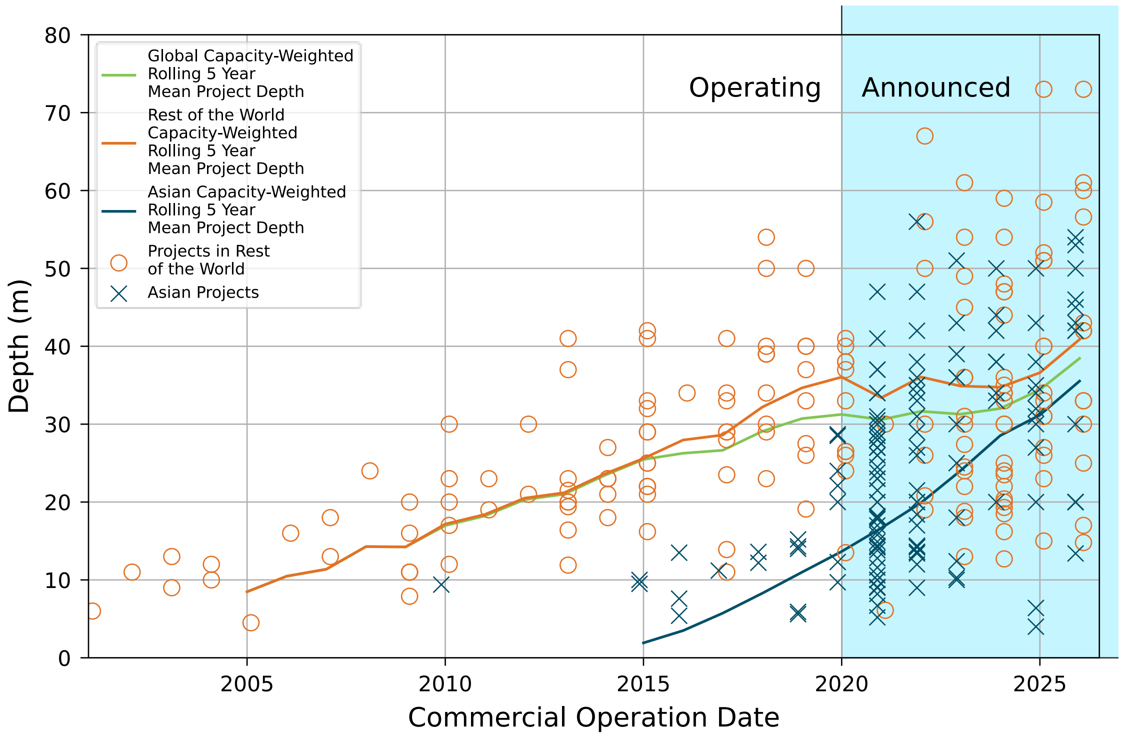

Figure 23. Water depth for global operating and future projects

5.2 Offshore Wind Energy Substructures

Nearly all operating offshore wind energy projects have used fixed-bottom foundations. Figure 24 shows the current substructure technology mix for offshore wind energy projects operating at the end of 2020, totaling 32,906 MW. Monopiles remain the dominant foundation type, representing 74.8% of the total offshore wind foundation market for installed projects. Jacket substructures are the next most common foundation type, with 10.8% of the existing market.

Figure 25 indicates that developers plan to increase the use of jacket foundations by over fourfold in future projects relative to existing projects, representing 21.5% of the announced market. Further, the share of monopiles drops to 51.6% of the announced market. This change comes as projects are being planned in both new and existing markets with deeper waters and manufacturing options for jackets increase. However, industrialization of the production of monopiles and the demonstrated ability of the industry to adapt the foundations to deeper waters while maintaining low cost may allow monopiles to remain the dominant substructure type for some time. Based on announced projects, gravity-base foundations are likely to increase their market penetration in future projects. Also, they might be more suitable in rocky soils where pile driving may be difficult or underwater noise may impact marine mammals.

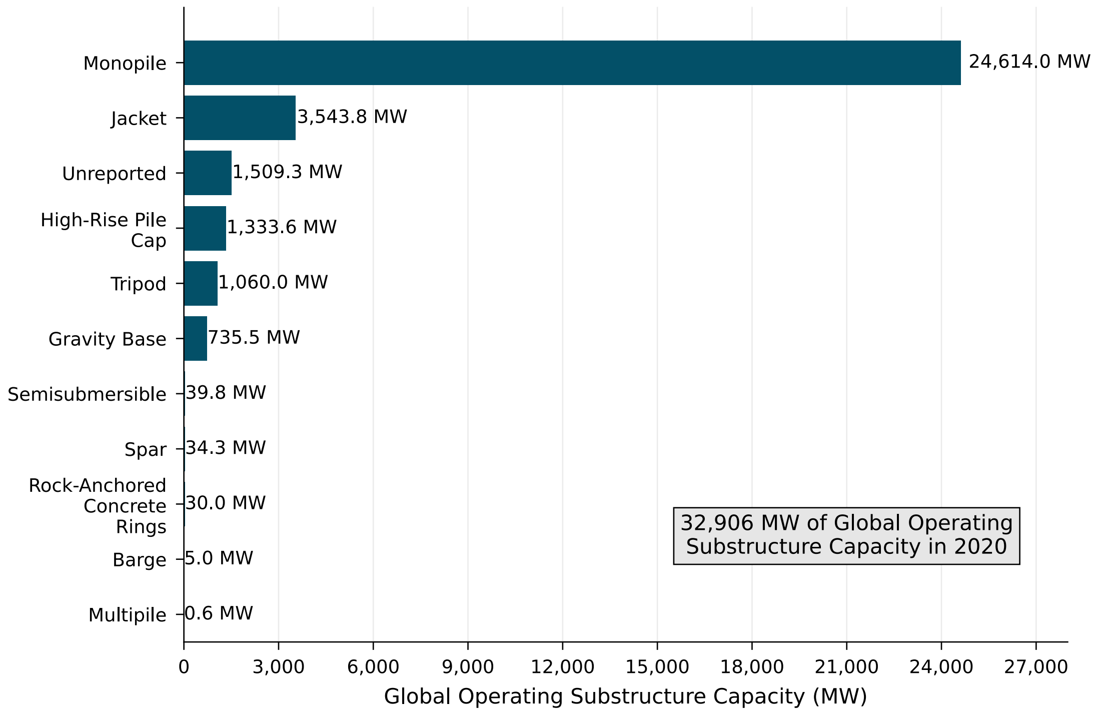

Figure 24. Offshore wind substructure technology used in operating projects

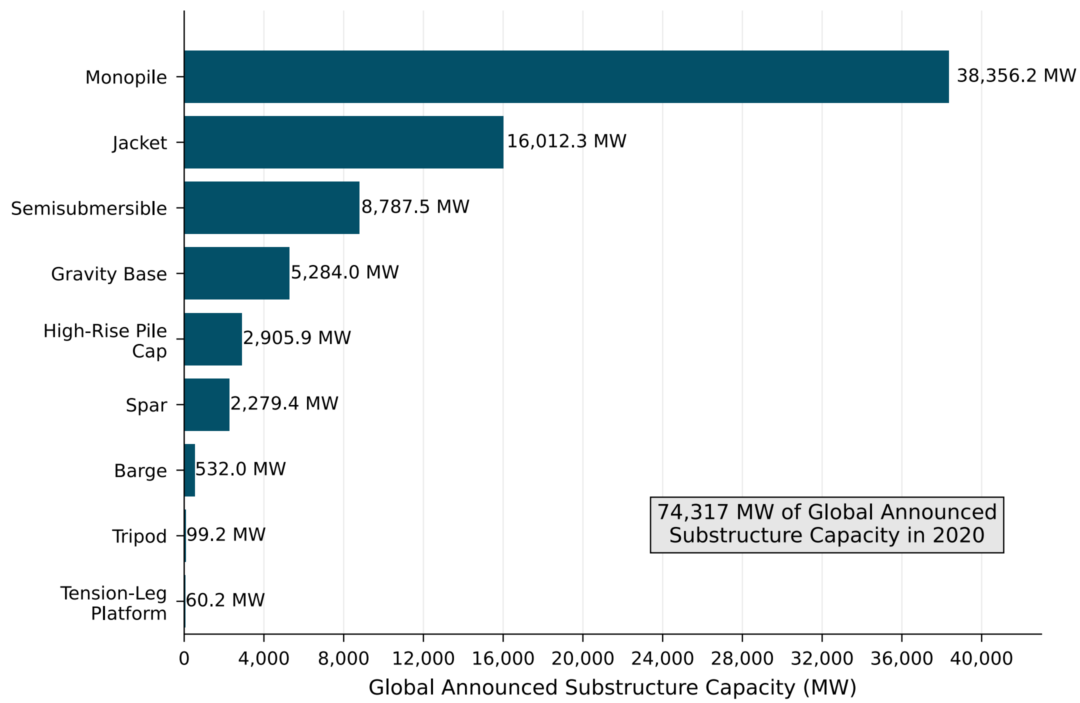

Figure 25. Announced offshore wind substructure technology for future projects

As the industry deploys the next generation of floating offshore wind substructures, improvements to existing technology and new hybrid floating platform designs are being introduced that have the potential to lower system costs. In 2021, the Salamander floating offshore wind project in Scotland signed a memorandum of understanding with Ocergy to study the possibility of using its substructure technology. The Ocergy semisubmersible technology is designed for faster assembly, reduced steel, and lower draft to access more ports (Durakovic 2021b). In 2018, Stiesdal Offshore Technologies partnered with Innogy and Shell to introduce the TetraSpar concept, which has a shallow draft like a semisubmersible to allow for inshore assembly but can deploy a ballast weight at sea for stability (Stiesdal Offshore Technologies 2018). The demonstration project is expected to install a 3.6-MW Siemens Gamesa wind turbine and be towed to a test site near Stavanger, Norway, in 2021 (Stiesdal Offshore Technologies 2021). In November 2016, SBM Offshore won a contract to deliver three floating platforms for the 24-MW Provence Grand Large pilot wind energy project in the French Mediterranean. The SBM tension-leg platform substructure design is unique because it is stable before attaching the mooring lines—an uncommon characteristic and one of the major drawbacks of conventional tension-leg platforms (SBM Offshore 2019).

Figure 26 breaks down installed and announced floating substructure capacity by technology. Most floating projects in the pipeline (75.2%) plan to use semisubmersible substructures. The preference for these types of substructures is attributed to their relatively shallow draft and hydrodynamic stability after wind turbine installation. These attributes allow them to be assembled, installed, and commissioned at quayside, and towed out to site without the use of heavy-lift installation vessels. Innovations like rapid disconnect cables may help facilitate tow-to-port O&M strategies.

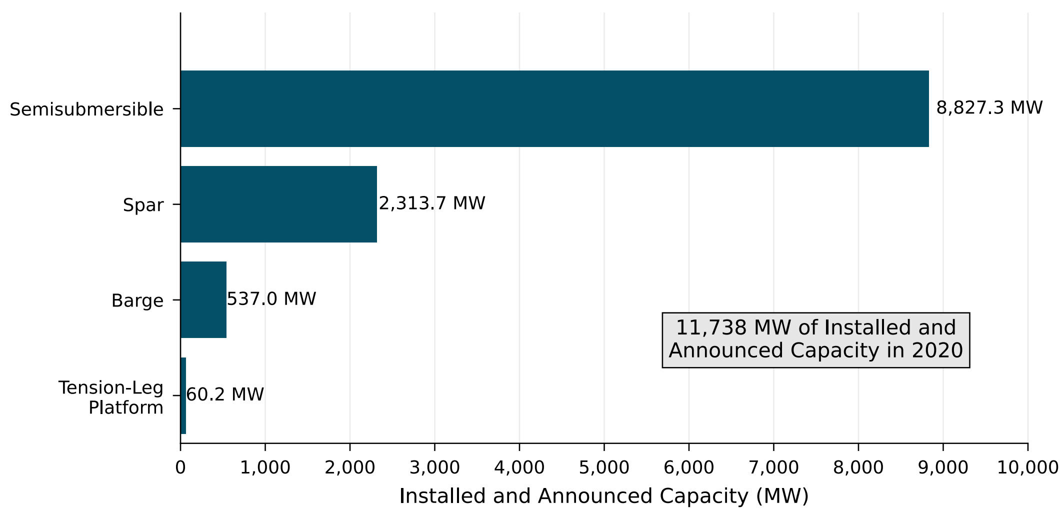

Figure 26. Global floating substructure market share

The floating offshore wind industry has been gaining commercial interest over the past few years. Since 2019, the project pipeline expanded by nearly fourfold, mostly because of new projects entering the planning phase. To realize a robust project pipeline, floating offshore wind technology needs to mature. Further, continued experience and engineering refinements are needed in systems optimization, infrastructure development, mooring systems, and dynamic cables (Barter et al. 2020). However, one of the primary barriers to cost reduction is that the market volume is not yet large enough for investors and developers to reap the benefits of large-scale production or establish an organized supply chain (Umoh and Lemon 2020). The National Offshore Wind R&D Consortium (NOWRDC) recommends increased investments in the domestic supply chain as well as floating system industrialization to stimulate deployment (NOWRDC 2021).

5.3 Offshore Wind Turbines

Increased wind turbine nameplate capacity is one of the main drivers behind lower offshore wind energy costs. Developers prefer to use the largest wind turbine available for a given project because fewer are needed for the same plant capacity, which reduces balance-of-system costs on a per-kilowatt basis (Shields et al. 2021). Because offshore wind turbines do not face the same transportation constraints as land-based turbines, they can be larger (Bilgili, Yasar, and Simsek 2011).

The major offshore wind turbine OEMs are competing to increase turbine size in response to market demand. Siemens Gamesa Renewable Energy, Vestas, and General Electric (GE) have all announced next-generation wind turbines in the 12- to 15-MW range. These wind turbines are slated for commercial availability between 2022 and 2024 (Siemens Gamesa 2020; Vestas 2021a; GE 2018).

Most recently, Vestas (formerly MHI-Vestas), announced the development of the V236-15.0 MW. This wind turbine is scheduled to have a prototype in operation by 2022, which will have the largest swept area of any machine on the market with 115.5-m blades and a 236-m rotor diameter (Vestas 2021a). Serial production is scheduled for 2024.

Figure 27 shows the historical trend of offshore wind turbine upsizing. The figure presents data for the global-weighted average offshore wind turbine capacities, hub heights, and rotor diameters over time, with the values for 2020 indicated in the gray box in the plot area.

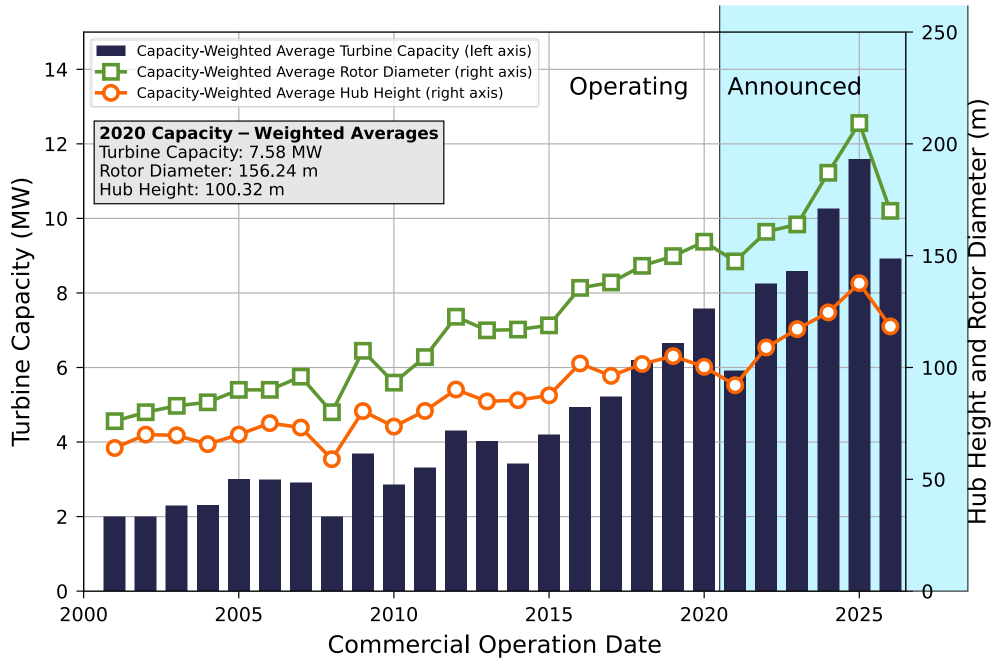

Figure 27. Global average offshore wind turbine capacity, hub heights, and rotor diameters

Composite manufacturing, design, and material innovations, as well as load reducing advancements in wind turbine controls, have facilitated the upscaling of wind turbine rotors. This trend of increasing rotor diameters can be observed in Figure 27. Wind turbine hub heights tend to increase directly with rotor diameter to maintain a 25–30 m clearance between the blade tip and water surface. This increase in hub height as wind turbines scale to larger sizes also results in incremental performance improvements resulting from vertical wind shear,[31] but those improvements are site-specific and offset to some degree by increased tower costs. Note the relatively large drop in wind turbine capacity in Figure 27 for 2026 is an artifact of two projects that are driving the mean value down. Specifically, this decrease in 2026 can be attributed to a 1,100-MW Irish project using 5-MW wind turbines and a 100-MW Chinese project using 3-MW turbines. This data anomaly is not likely to persist over time as more projects announce their COD.

Figure 28 shows the same data as Figure 27 for the global-weighted average offshore wind turbine capacities (black bars) but is plotted against the trends in new turbine prototypes in the year they were first installed. As expected, there is a lag of several years between the time those prototypes were released and when they were fully adopted by the commercial market.

As the Asian market advances, it is beginning to have a stronger influence on the global wind turbine growth trends shown Figure 28. The Chinese-manufactured wind turbines are identified by a separate trend line that shows smaller turbines in early Asian projects.

For example, the NREL database shows that 648 MW of Chinese projects with 4-MW wind turbines are expected to come online in 2021, along with 610 MW of other Asian projects with 5.2-MW to 5.5-MW wind turbines. However, some European projects also use smaller turbines;

[31] Vertical wind shear is the change in wind speed as function of height.

for example, a 383-MW project in the Netherlands is installing 4.3-MW wind turbines in 2021 on an inland lake where vessel size is limited by locks. Projections increase through 2025 because of commercial availability of next-generation turbines.

Figure 28 overlays the dates of operational wind turbine prototypes with the annual installed capacities to provide data that help forecast the future size of offshore wind turbines and to show competition among OEMs in the future. Data points representing Chinese wind turbine prototypes are outlined in black to distinguish regional trends, and exponential curve fits of historical prototypes show that growth in wind turbine capacity is likely accelerating among both Asian and European/U.S. (western) OEMs.

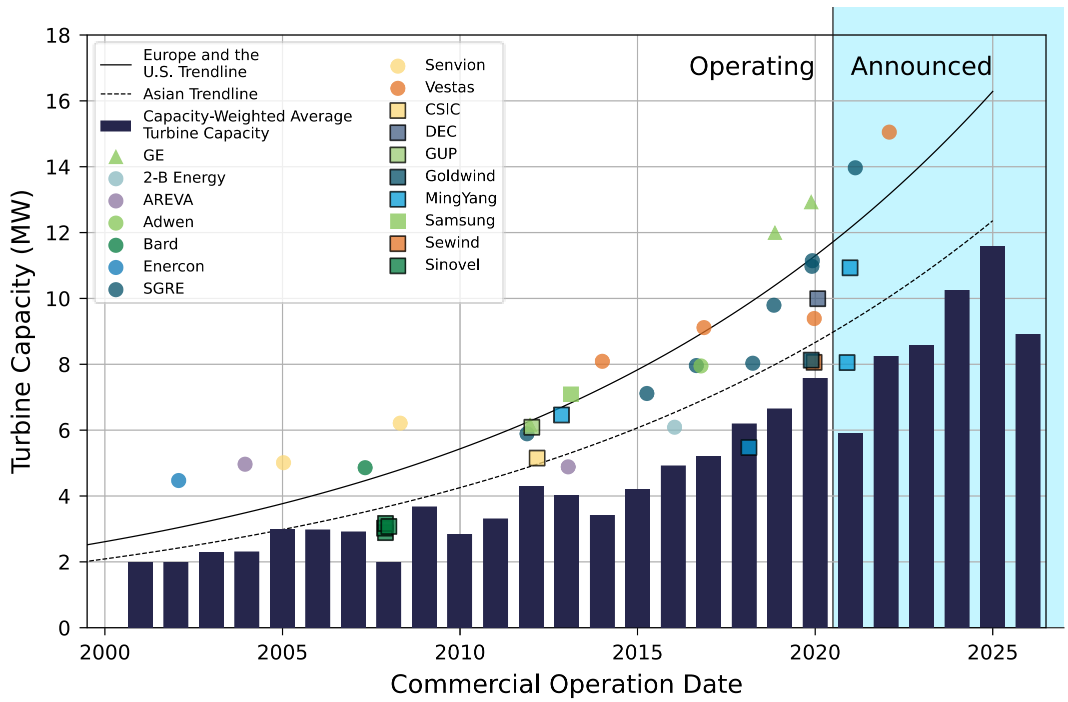

Figure 28. Comparison of offshore wind turbine prototypes with commercial offshore turbine growth

Siemens Gamesa Renewable Energy and Vestas are pursuing aggressive development timelines of less than 2 years between the announcements of their 14- to 15-MW wind turbines and the planned date of operational prototypes (Siemens Gamesa 2020; Vestas 2021a). This development timeline is on par with GE's Haliade-X 12-MW prototype in Rotterdam, which was installed less than 2 years after the announcement (GE 2018, 2019). Historically, it has taken OEMs longer than two years to achieve an operating prototype after it is announced.

Figure 28 indicates a lag of approximately 6 to 8 years between installing a prototype and the year in which the global market average reflects the adoption of these turbines. However, the future OEM timelines in both Asia and the West are more optimistic than historical trends would indicate because they have announced that new turbines models will be available on the market in less than 4 years following the installation of their respective prototypes.

The difference between the wind turbine prototype trendline for western turbines and the trendline for Asian turbines indicates that Asian prototypes are approximately 20%–25% lower in capacity than their western counterparts in 2020. While both western and Asian trendlines are increasing at about the same rate, the upscaling of Asian turbines lags western prototypes by about 4 years. Examples of some recent Chinese prototype turbines include Sewind (Shanghai Electric), MingYang, and Goldwind, which have all announced or successfully installed prototypes in the 8- to 11-MW range in 2020 and 2021 (Yahoo! Finance 2020; Buljan 2020a; reNEWS 2020). It is not apparent if either the western or Chinese OEMs will continue upscaling.

The largest wind turbine currently operating in the world is the GE Haliade-X prototype in Rotterdam, which has been uprated to 13 MW by increasing the generator and drivetrain capacity (GE 2020). The practice of uprating an existing turbine nameplate rating with the same rotor has become more commonplace among OEMs in the offshore wind markets and has been a strategy to increase wind turbine rating on the same platform without retooling blade production. This practice of increasing generator rating allows the wind turbine to generate more energy and helps the economics of the wind power plant, but the developers must carefully consider the potential for increased fatigue loading and decreased design life. Figure 29 and Figure 30 illustrate wind turbine OEM market share for operating projects and announced projects, respectively.

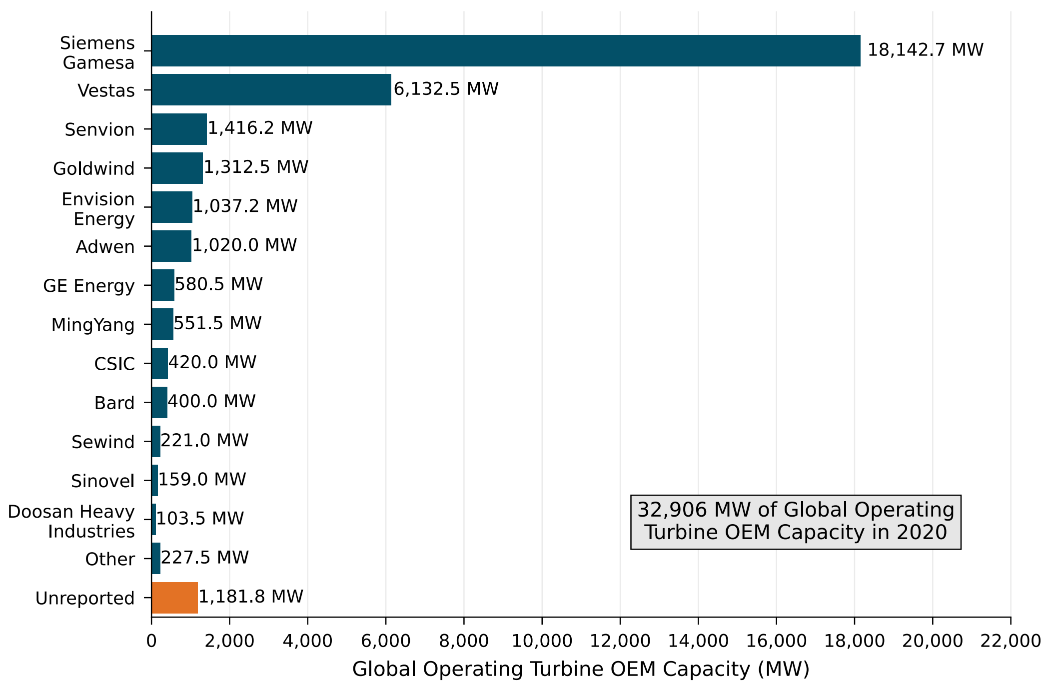

Figure 29. Offshore wind turbine manufacturer market share in operating projects

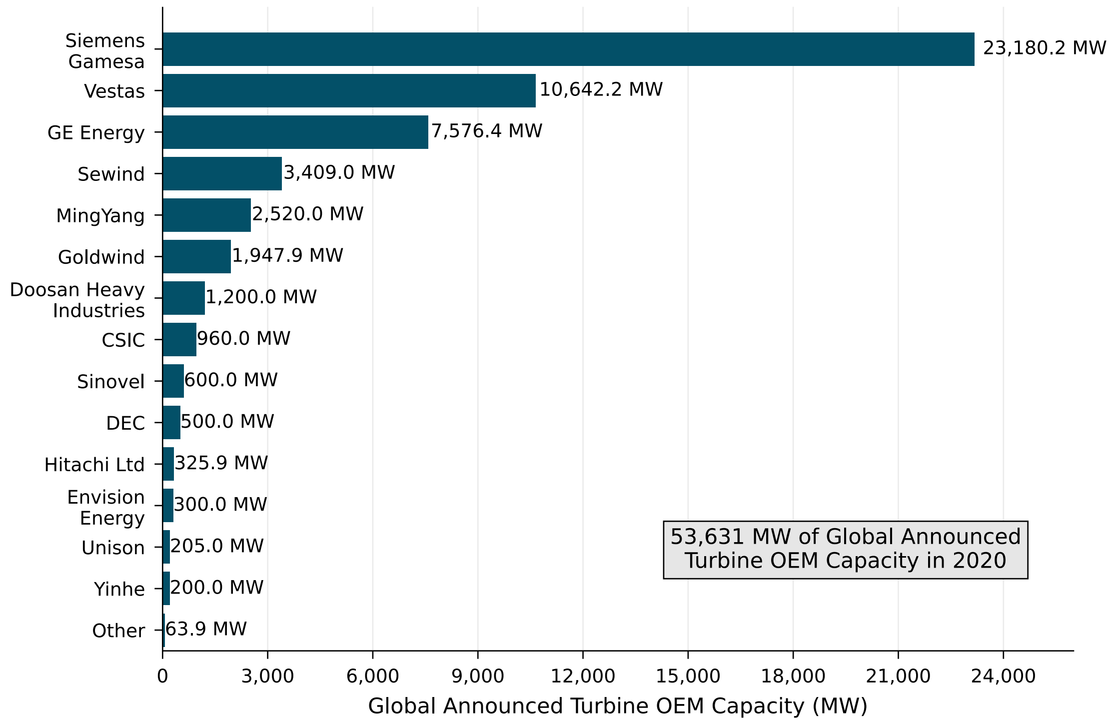

Figure 30. Offshore wind turbine manufacturer market share for announced projects

Siemens Gamesa continues to be the dominant offshore wind turbine manufacturer, with 55% market share, but the data show its market share in future projects will decrease to 43% as Vestas, GE, and Chinese OEMs gain market share.

Vestas is the second-largest OEM in terms of market share of existing capacity. MHI-Vestas was established in 2013 to help Vestas expand its position in the capital-intensive offshore wind market. However, in October 2020, Vestas announced they were acquiring the Mitsubishi Heavy Industries’ share of the joint venture (Vestas 2020).

GE Energy, which was largely focused on the land-based market until its acquisition of Alstom in 2015, was the first of the major OEMs to scale up. GE advanced from the 6-MW Haliade wind turbine to the 12-MW Haliade-X turbine announced in 2018 and has seen its projected market share, based on announced projects, increase to nearly 15 times its current installed offshore operating capacity.

In China, Sewind (Shanghai Electric), MingYang, and Goldwind appear to be the dominant players based on announced project commitments.

Like fixed-bottom offshore wind developers, floating offshore wind developers want to use the largest commercial offshore turbines available on the market to lower costs. To date, no OEMs have announced plans to develop floating-specific offshore wind turbines, although some adaptive features may be needed, such as stiffer towers and advanced controls, to mitigate tower motion. It is likely that OEMs will wait until there is a larger and more advanced pipeline of floating offshore wind energy projects before committing to investments in floating-specific wind turbines. Until then, floating offshore wind energy projects will use the existing fleet of fixed-bottom offshore turbines with smaller adaptations of the control system and towers. For example, Equinor's Hywind Tampen project plans to use 11 Siemens Gamesa 8.0-167DD turbines on spar floating substructures and the Kincardine project in Scotland intends to install five Vestas V164-9.5 MW turbines on semisubmersible substructures (Equinor 2021; Grupo Cobra 2019).

5.4 Wind Turbine Blade Recycling

The offshore wind energy industry is beginning to address sustainability considerations for decommissioning wind power plants. Although steel towers and substructures and other metallic or plastic components can be recycled using conventional methods, composite blades are more difficult to recycle. As a result, offshore wind OEMs and developers are attempting to increase wind turbine blade recycling, with the announcement in January 2021 of DecomBlades, a new consortium that includes major manufacturers Siemens Gamesa, Vestas, and GE through its subsidiary LM Wind Power (Siemens Gamesa 2021). In January 2020, Vestas announced a goal of producing zero-waste wind turbines by 2040 (Ekstrand 2020) and established an academic/industrial partnership called Circular Economy for Thermoset Epoxy Composites in May 2021 (Vestas 2021b). Ørsted is a member of DecomBlades and has committed to reusing, recycling, or recovering all decommissioned blades from its wind power plants (Ørsted 2021).

5.5 Offshore Wind Electrical Infrastructure

About 20% of the cost of an offshore wind power plant is in the electrical infrastructure, which comprises the wind turbine transformers and connections, export cables, array cables, offshore substations, and the land-based substation and interconnect (Stehly et al. 2020).

5.5.1 Subsea Cables

Growth of offshore wind energy globally is driving an increase in demand for subsea power cables. The market is divided into export cables that connect an offshore substation to a land-based grid, and array cables that connect neighboring wind turbines and transmit electricity to the offshore substation. A handful of companies dominate the global subsea cable market, and only one, Nexans, has a subsea, high-voltage cable manufacturing plant in the United States.

NKT, a leading high-voltage cable supplier, estimates that U.S. demand for subsea cables will be 691 km/year (430 miles/year) to 1,113 km/year (692 miles/year) by 2030 and European demand for offshore cables will be 1,800 to 2,000 km/year (Musial et al. 2020). In addition, the industry is trending toward 66 kV for array cable voltage capacity, up from 33 kV previously (Yang 2020), as shown in Figure 31. Upscaling cable voltage capacity from 33 to 66 kV has allowed developers to connect the same number of wind turbines on an array string while the turbines increase in capacity. As turbine capacity continues to grow, industry experts also expect the trend toward higher cable voltages to continue (Yang 2020).

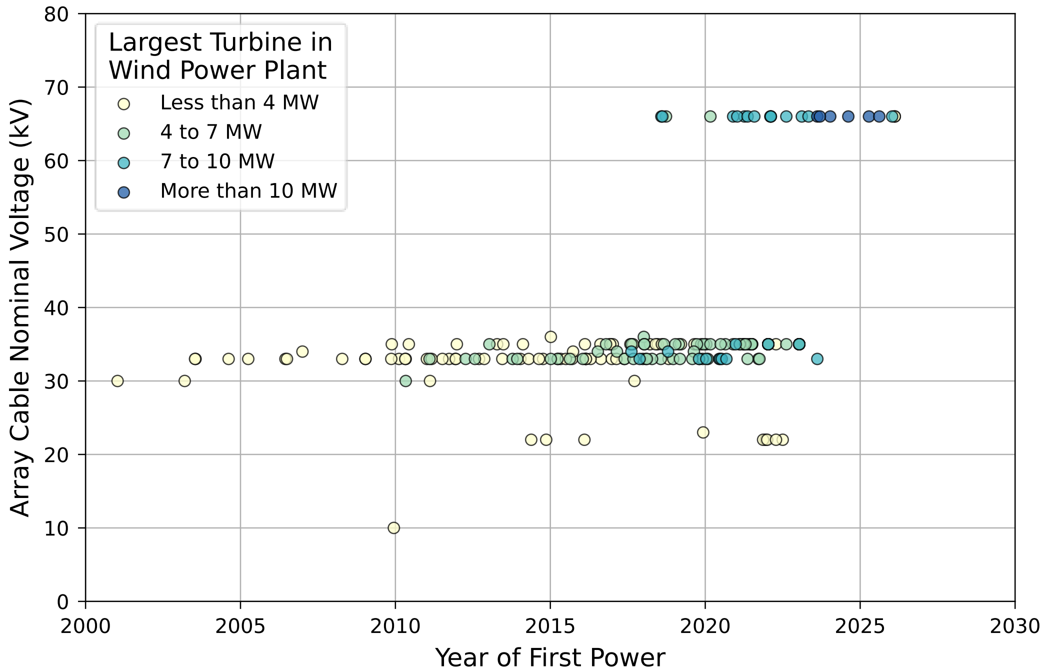

Figure 31. Distribution voltage of array cable versus year of first power

Figure 32 shows the distribution of export cable lengths for installed and proposed projects in the database as a proxy indicating the project's distance to shore broken down by region. The chart shows that the longest cables (the most distant projects) are in Europe.

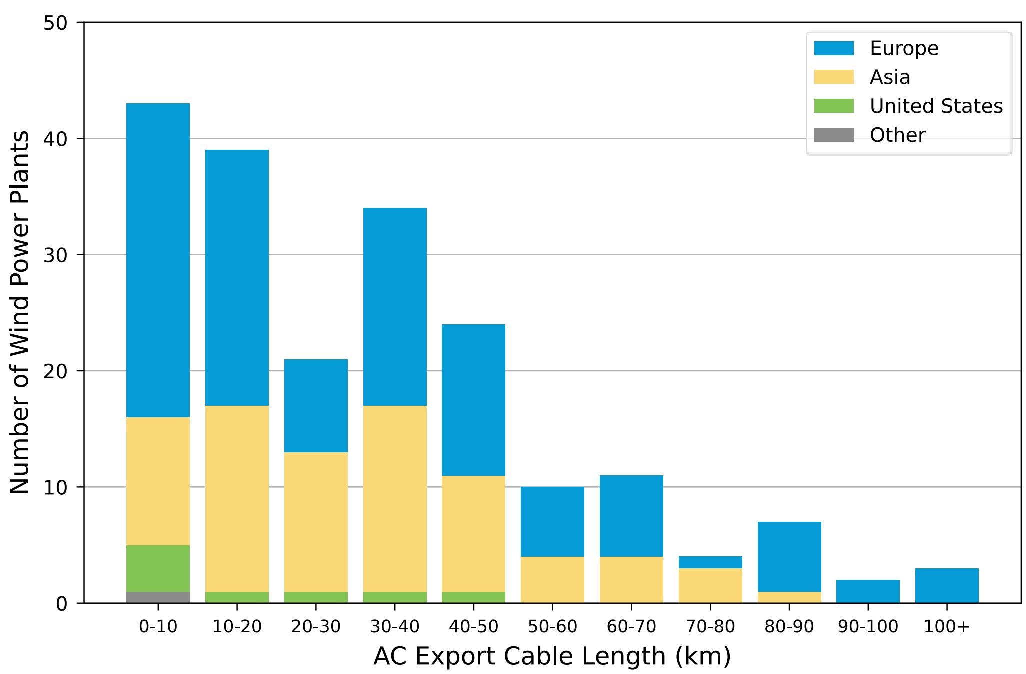

Figure 32. Number of wind farms versus length of alternating current (AC) export cable length

5.6 Grid Integration and Transmission Trends

The United Kingdom, Denmark, and the Netherlands all have radial grid connections. Germany is the only European country to have adopted a truly networked grid model. However, with 10 GW of offshore wind energy already installed, onshore POIs in the United Kingdom are having to be found further inland, which leads to higher costs and more disruption for coastal communities. The U.K.'s Office of Gas and Electricity Markets, the government regulator for the electricity and natural gas markets, is considering an integrated offshore wind transmission network that could substantially reduce transmission costs. In 2020, the U.K. National Grid Electricity System Operator reported that compared to the status-quo radial approach, shifting to an integrated transmission network with shared transmission infrastructure would likely save ratepayers up to 18% (£6 billion~–$8 billion) in capital and operating costs by 2050 (See Figure 33). Savings would be largest where significant offshore wind energy needs to connect to the land-based network that is already near operational limits and where offshore wind would be far from shore. An integrated transmission network would reduce impacts to the environment and coastal communities because the number of onshore and offshore transmission assets, cables, and on-shore landing points could be significantly lowered. If the United Kingdom transitions to a shared transmission network by 2025, costs can be reduced by 18%, total transmission assets by 70%, and landing points by 72% by 2050. Delaying that transition to 2030 significantly reduces benefits to: cost reductions of only 8%, total assets of only 40%, and landing points of only 38%.

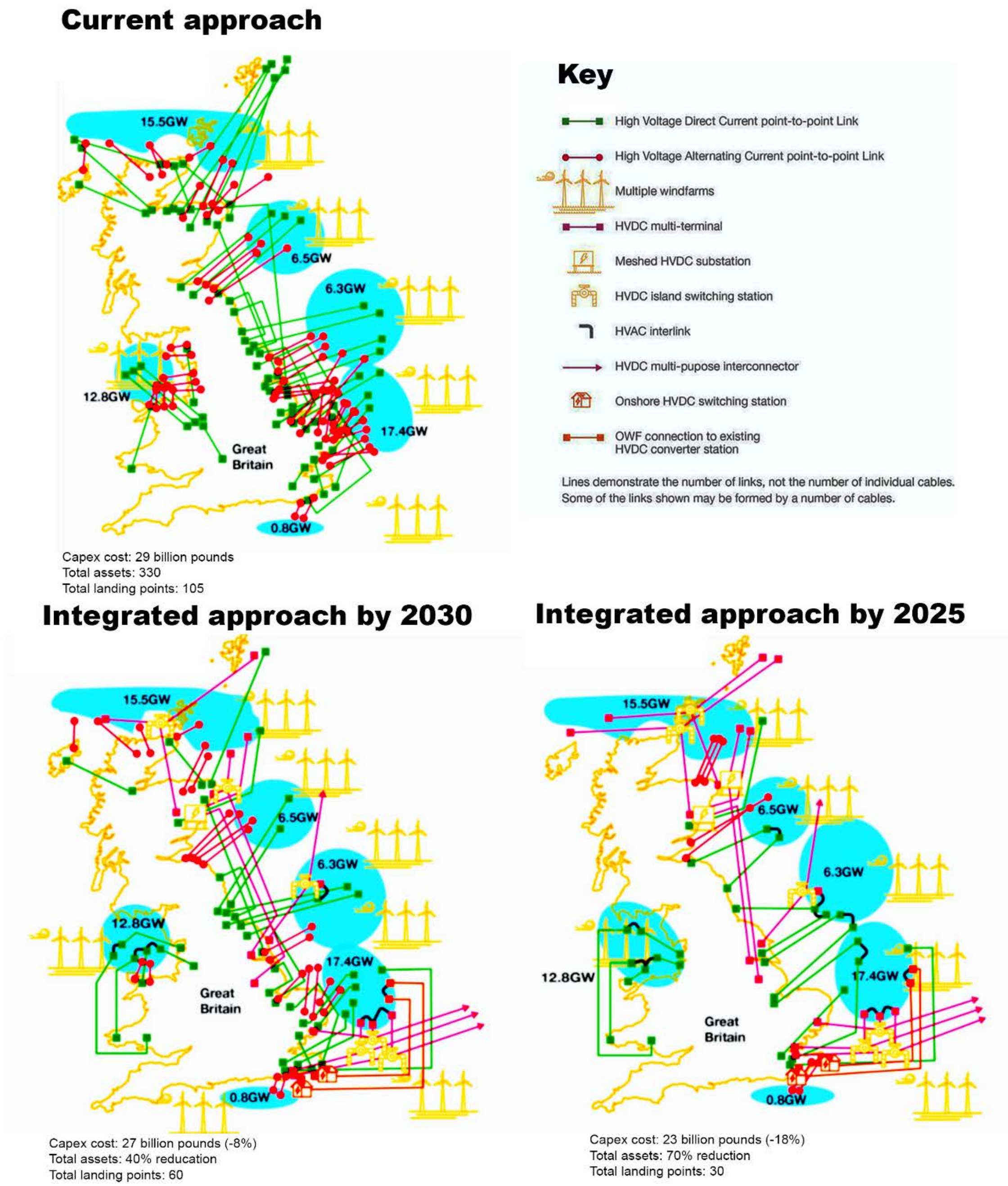

Figure 33. Status quo (upper left) and integrated (lower left and lower right) U.K. network designs.
Image from National Grid Electricity System Operator, Offshore Coordination Project

The lower left figure illustrates the network and benefits if a switch to an integrated approach occurs by 2030. The lower right figure illustrates the network and benefits if a switch to an integrated approach occurs by 2025. Green lines are the HVDC point-to-point link. Red lines with circles on the ends are the HVAC point-to-point link. Red lines with squares on the ends are the HVDC multiterminal. Red arrows are the HVDC multipurpose interconnectors. Black elbow bends are the HVAC interlinks. Lines demonstrate the number of links, not the number of cables. Some of the links shown may be formed by a number of cables.

Furthermore, most of the technology needed to accomplish the integrated transmission design is available or will be by 2030. The exception being HVDC circuit breakers, which have been used in three projects in China but not in Europe at transmission levels. HVDC lines are cost-effective for transmitting power across long distances because they lose less power than HVAC lines. HVDC circuit breakers may be available for use in two sites in Scotland. If HVDC circuit breakers do not become available in time, an integrated transmission network could be designed for these projects but at an expected higher cost and increased likelihood of network faults.

5.7 Green Hydrogen Production

Governments, energy companies, and end users (chemical companies, steel producers, and so on) are increasingly looking at offshore wind as a power source to produce green hydrogen that can be used in other sectors of the economy (e.g., transportation, heating, industry, grid storage) as a zero-emission fuel. Several global projects have either been proposed or are in early stages of development including:

Shell, RWE, Gasunie, Gascade, Equinor, Ørsted, and Boskalis. These developers plan to use 10 GW of offshore wind energy to produce hydrogen and pipe it to Europe as part of the AquaVentus/AquaDuctus project. The goal of these efforts is to produce up to 1 million tonnes of hydrogen from 2035 onward (RWE 2020).

Ørsted and POSCO form South Korean Hydrogen Pact. POSCO, one of South Korea's largest industrial and steel conglomerates, plans to use 1.6 GW of Ørsted's offshore wind capacity off the coast of Incheon to power its hydrogen production requirements.

Neptune Energy's PosHydon. This project will integrate offshore wind, offshore gas, and offshore hydrogen for Dutch utilities Eneco, Gasunie, Noordgastransport, and Northern Offshore Gas Transfer (Burgess 2021).

Ørsted's H2RES. The 2-MW wind-to-hydrogen project will use the company's two 3.6-MW offshore wind turbines at Avedøre Holme to produce 1,000 kilograms of hydrogen per day and power zero-emission road transport in the greater Copenhagen area (Buljan 2021).

5.8 Global Wind Turbine Installation Vessel Fleet

Offshore wind energy developers are starting to respond to the lack of WTIVs capable of installing offshore wind turbines of 12 MW and greater, but there is still uncertainty regarding the ability of the global fleet to handle planned installations of offshore wind capacity by the mid-2020s (Hartkopf-Mikkelsen 2020; Rystad Energy 2020). A Tufts University analysis of global supply chain impacts on the emerging U.S. offshore wind energy market indicates that the current global WTIV fleet is unprepared to install wind turbines of 12 MW and larger (Bocklet et al. 2021). The figure compares the lifting capabilities of 12 WTIVs relative to the requirements for installing GE Haliade-X wind turbines in water depths of 50 m (depth representative of near-term U.S. East Coast projects). The 12 existing and future vessels were considered based on available public data[32] for crane-lifting capacities and their potential involvement in U.S. offshore wind energy projects.

[32] Assessment reflects available data and should not be considered comprehensive.

The figure compares the vessels' crane hook heights above the waterline with the assumed 150-m hub height of the Haliade-X (indicated by the dashed red lines). Vessels are assumed capable of installation if the hook height is above the hub height. According to the figure, only 3 of 8 existing vessels can currently install wind turbines of 12 MW or greater. The figure underscores the role physical vessel parameters, such as deck height, play in offshore wind turbine installation.

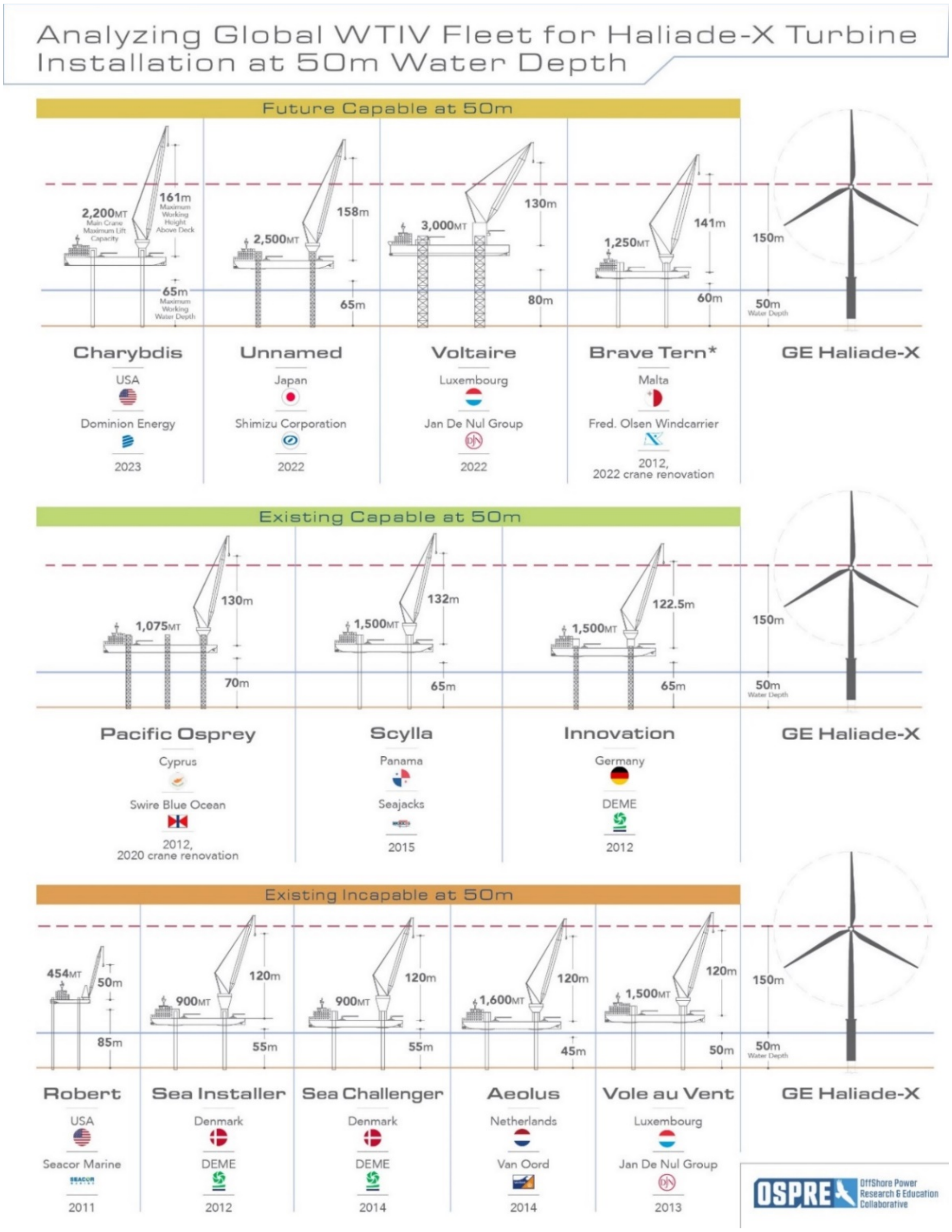

Figure 34. Analysis of global WTIV installation capabilities. ***Image from Bocklet et al. (2021)***

Notes: dashed red line indicates the 150-m hub height. Crane-lifting capacities, maximum operational water depth, and crane hook heights above deck are called out for each vessel. The * indicates values for Brave Tern after pending crane upgrades.

With many offshore wind energy projects in the global pipeline and developers opting for ever-larger wind turbines, The figure suggests the need for more WTIVs capable of installing the next generation of offshore wind turbines or alternative installation strategies that reduce the need for custom-made installation vessels. A shortage of WTIVs could lead to increased wind energy costs via higher vessel charter rates or project delays.

There are several new WTIVs already under construction as companies scramble to meet demand for installing larger wind turbines. Jan De Nul began constructing its “mega jack-up” vessel, Voltaire, and floating installation vessel, Les Alizes, at drydocks in China (Durakovic 2020a; Jan De Nul 2020). Voltaire is a purpose-built, dynamic-positioning-system[33] WTIV that can operate in 80-m water depths and has a main crane capacity of over 3,000 tonnes. The vessel is scheduled to be completed in 2022 and has already been contracted to install GE Haliade-X wind turbines at the Dogger Bank project. Les Alizes will have a main crane capacity of over 5,000 tonnes, but does not have a jack-up system, as it is designed with a dynamic thruster system to keep the vessel stationary in deeper water. Les Alizes is expected to be operating in 2022. Additionally, Shimizu Corporation in Japan announced in August 2020 that it contracted Gusto MSC to design a jack-up WTIV (SC-14000XL) by 2022 that can lift 1,250 tonnes above 161 m (Snyder 2020).

Although only a handful of new WTIVs were under construction in 2020, several companies announced agreements to construct new vessels in a rush to meet demand. In August 2020, Triumph Subsea Services announced a letter of intent for two GustoMSC NG-1400XL WTIVs for delivery in 2023 (Allen 2020). Knud E. Hansen of Norway announced a new design for its ATLAS C-Class of jack-up vessels for installing wind turbines that are 20 MW or greater (Buljan 2020b). The ATLAS vessels will have a 3,000-tonne crane. Scorpio Bulkers changed their name to Eneti and began exiting the dry goods shipping business to focus on transporting, installing, and servicing offshore wind energy systems (Scorpio Bulkers 2020; Eneti 2021). In May 2021, Eneti announced they had signed a binding contract with Daewoo Shipbuilding and Marine Engineering for $330 million to build a WTIV capable of installing wind turbines 185 m above sea level by 2023, with an option to buy a second vessel at the same price. OIM Wind announced the BT-220IU jack-up vessel, which can install wind turbines with hub heights above 130 m with a Huisman crane and will be ready in 2022 (Durakovic 2021a). Another group of Norwegian companies—Ocean Installer and Vard—have agreed to develop a WTIV capable of installing wind turbine components greater than 1,000 tonnes over 150 m high (Skopljak 2020). AqualisBraemar announced it will supervise construction of two WTIVs by Dayang Offshore Equipment Co., Ltd. (OuYang 003 and OuYang 004) for the Chinese market (AqualisBraemar 2020). Both vessels should be capable of installing 10-MW wind turbines with cranes capable of lifting 600 tonnes to heights of 140 m.

5.9 Offshore Wind Technology Summary

The trend toward wind turbine upsizing in the offshore wind industry pervades most other technology trends in 2020 because it has been demonstrated to have one of the most significant impacts on cost reduction (Beiter et al. 2020b). As such, turbine upscaling is also a major focal point in trends related to substructures and infrastructure such as ports and vessels. All three of

[33] A dynamic positioning system is a technology solution to automatically maintain a vessel's position and heading by using its own propellers and thrusters.

the major turbine OEMs are working on developing high-power capacity wind turbines ranging from 12 to 15 MW and with rotor diameters spanning up to 236 m. These turbines, which are among the largest machines ever built, embody dozens of new technical innovations ranging from advanced control systems, sensors, and materials to lightweight direct-drive generators. As these enormous wind turbines promise to emerge as a commercial option between 2022 and 2024, the associated support structures, installation vessels, fabrication facilities, and operational strategies are also being upsized. The average offshore wind turbine capacity installed in 2020 was 7.6 MW, up from 6.3 MW in 2019. The average rotor diameter in 2020 was 156 m, with an average tower height of 100 m.

Monopile substructures remain the dominant foundation type, especially in Europe. However, future project announcements show that the market share for monopiles will drop from 75% in installed projects to about 52% in announced projects, yielding some share to jackets, gravity base, and floating substructures.

Floating offshore wind technology is still maturing but the industry is pushing toward large-scale commercialization using lessons learned from upscaling fixed-bottom technology. The industry is motivated to accelerate commercialization of floating technology with the expectation that increased market commitments and industrialization of floating systems will lower costs and inspire investors to further accelerate large-scale production.

Electrical grid upgrades are increasingly required in many parts of the world to integrate large quantities of renewable energy, including offshore wind. Interest is growing in establishing a more coordinated approach to adapt the current electrical grid to receive this power. Similarly, ports and vessel developments are accelerating to keep pace with the high volume of deployments that are coming, as well as the increased wind turbine size.

6. Cost and Price Trends

Offshore wind energy continued to exhibit rapid cost declines in 2020, with further reductions estimated for the decades ahead. This section presents cost trends from empirical project data and estimates from leading research organizations, both for fixed-bottom and floating offshore wind technologies. It also includes price data from recent competitive procurements for U.S. and European fixed-bottom projects. Both cost and price data are presented in this section. Costs are often derived from bottom-up modeling or project reporting; price data are often made available as part of public tenders. Prices and costs are conceptually different but considered together (or over time), as they provide a perspective on the economic offering from offshore wind energy. The project sample size varies across the metrics that are shown in this section.

6.1 Fixed Bottom

6.1.1 Levelized Cost of Energy Trends

The average levelized cost of energy (LCOE)[34] for projects commissioned in 2020 has declined to levels of just below $95/MWh, with a range of $78/MWh to $125/MWh globally (Figure 35). This decline represents a reduction of 16% on average compared to 2019 (Musial et al. 2020). Offshore wind energy has been on a clear cost reduction trend since 2014, with LCOE declining by 28%–51% compared to 2020 (Wiser et al. 2021; Jansen et al. 2020; Lazard 2020). For their midcase scenario, leading research entities and consultancies estimate that LCOE will be $56/MWh on average by 2030 and range[35] between $38 and $48/MWh by 2050.[36]

Variation in the estimated LCOE within any given year is caused by many factors, including:

- Differences in site characteristics (e.g., wind speed)
- Regulatory and market environment
- Calculation methods
- Assumptions about financing
- Technology and market maturity.

[34] LCOE is the cost per unit of energy of generating electricity during an assumed project design life that allows for the recovery of all project expenses and meets investor return expectations (Wiser et al. 2016).
[35] The range of minimum and maximum LCOE is reported here for 2050.
[36] The period 2035–2050 is not shown in Figure 35 but was derived from the same sources.

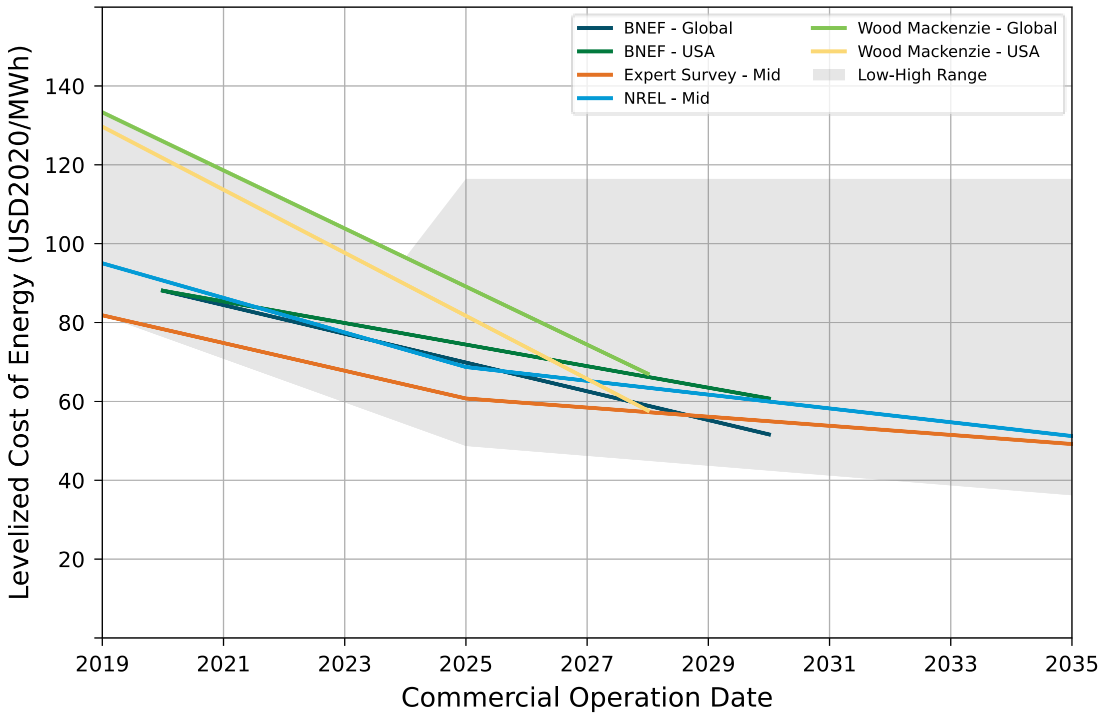

Figure 35. Global LCOE estimates for fixed-bottom offshore wind

Sources: BNEF 2020b; Wiser et al. 2021 (Expert Survey); NREL 2020a; Wood Mackenzie 2019; Low-High Range also includes DNV GL (2020), International Renewable Energy Agency (2020); International Energy Agency (2020c); U.S. Energy Information Administration (2020).[37]

The sources used in Figure 35 report LCOE data on a regular basis and are a reference point for many industry and research stakeholders. Among the included data sources is a recent survey of more than 140 global wind energy experts (Wiser et al. 2021). The expert "mid" scenario for global fixed-bottom applications aligns with the general cost reduction trend and shows a considerably lower LCOE in 2019 compared to the other displayed estimates. In this expert elicitation, LCOE levels in North America were projected to be approximately a third higher than in Europe between 2019 and 2035. The analysis of experts' expectations from Wiser et al. (2021) also emphasizes that the extent and rate of offshore cost reductions have been underpredicted between 2014 and 2020.

Cost projections adopting a learning-curve approach can offer a complementary method for forecasting future cost reductions (Wiser et al. 2016). For each doubling of capacity, a learning curve indicates a rate at which LCOE declines based on empirical project data. Learning rate estimates of offshore wind energy vary considerably, from 14% to 33% (Junginger and Louwen 2019; Wiser et al. 2021). Global offshore wind energy is projected to grow to approximately 220 GW by 2030 (Section 3.2.3), nearly sevenfold the currently installed capacity of 33 GW. Assuming these deployment levels, an average learning rate of 14% (the lower end of the range

[37] Reference scenario shown for the U.S. Energy Information Administration (2020).

mentioned earlier) and an LCOE of $95/MWh in 2019 yields a possible LCOE of $62/MWh by 2030, which is at the higher end of the literature estimates shown in Figure 35.

6.1.2 Capital Expenditure Trends

Capital expenditures (CapEx) are the single largest contributor to the life cycle costs of offshore wind power plants and include all expenditures incurred prior to the start of commercial operation.

Figure 36 shows the reported CapEx over time for operational projects as well as for those in various stages of the near-term project pipeline globally. After a period of increasing CapEx[38] until 2014–2015 (Musial et al. 2017), CapEx has since decreased, with the capacity-weighted average CapEx reaching approximately $3,750/kW in 2020 (COD) globally.[39] In 2020, CapEx in Europe and the United States was higher on average than in Asia. However, CapEx seems to be converging since 2015, with Europe and the United States reaching similar levels on average to those in Asia by 2027. WindEurope reported a CapEx of $4,000/kW in 2020 for European projects, a considerable markup over the lowest-ever CapEx of $2,900/kW in 2018 (Brindley and Fraile 2021). This increase in Europe is reportedly driven by a series of higher-than-average cost projects in France, which are the first commercial offshore wind power plants to reach their financial investment date and are constructed under strict local content requirements (Saint Nazaire, Saint Breuc, and Fecamp), and the United Kingdom (Neart na Gaoithe and Dogger Bank).

Reported global project data suggest a decline of the weighted average CapEx globally from $4,000 in 2020 to $3,000/kW by the mid-2020s. The underlying data for Figure 36 include considerable variation of CapEx within a given year. For projects with a COD in 2020, CapEx falls into a range of approximately $2,050/kW (Borssele 3&4, Netherlands [732 MW]) to $4,530/kW (Trianel Windpark Borkum II [203 MW]) among projects with capacities greater than 100 MW. Several factors may possibly explain the variation in CapEx within a given year and over time (Smith, Stehly, and Musial 2015), including:

- Varying spatial conditions (e.g., water depth, distance to port, point of interconnection, and wave height of sites that affect technical requirements of installing and operating a wind farm)
- Project size
- Different levels of supply chain shortages (e.g., components, vessels, and skilled labor)
- Changing prices for commodities and energy
- Macroeconomic trends, such as fluctuating exchange rates
- A change in the appreciation of the costs and risks associated with offshore wind energy project implementation.

[38] Capacity-weighted average
[39] Only for those projects with a project capacity of greater than 100 MW.

CapEx has been reported for 120,141 MW of global offshore wind energy projects. Figure 36 shows the announced costs for 119 installed projects (29,042 MW), with 67 projects (18,581 MW) that have started construction, 21 projects (7,377 MW) that have secured financial close, 60 projects (30,690 MW) that have received regulatory approval, 18 projects (9,481 MW) in the permitting process, and 39 projects (23,484 MW) that are still in the planning phase. The uncertainty related to these CapEx data varies between projects and over time (Appendix).

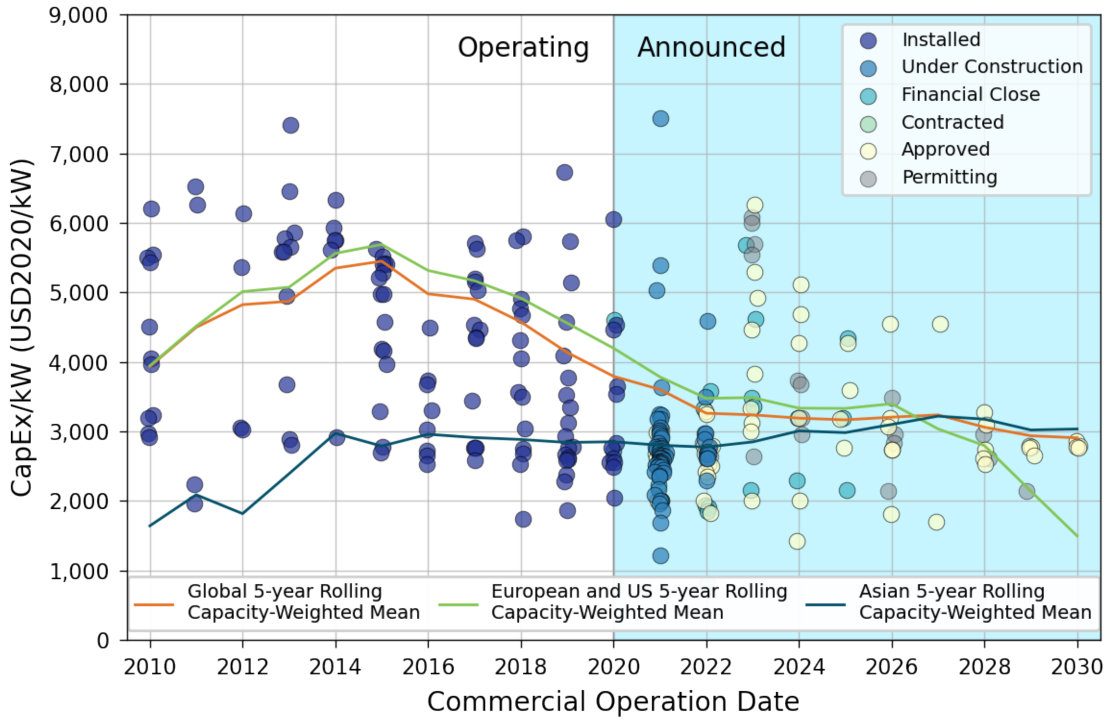

Figure 36. Capital expenditures for global offshore wind energy projects

Offshore wind turbine costs are estimated to be between 25% and 45% of the total CapEx (Stehly, Beiter, and Duffy 2020). Typically, turbine price data are derived from turbine supply agreements negotiated for individual projects, but because of their proprietary nature, access to these data is limited (Appendix). In 2020, available turbine price data ranged from $1,000/kW to $1,400/kW (Table 16). The global wind turbine prices derived from company financial statements (first row of Table 16) do not differentiate between markets and order volumes.[40] It is also not clear from company financial statements as to which COD years the order intake refers to. Hence, they might not reflect U.S. wind turbine pricing accurately but can still serve as a reference point. The financial statement data show that wind turbine pricing has stayed within approximately $1,400/kW and $1,700/kW between 2018 and 2020. The data from BNEF feature a considerably lower wind turbine pricing of $1,000/kW, projected to decrease further to $850/kW by 2030.

[40] Wind turbine prices could be inferred from Siemens Gamesa (2020). Price data from the financial statements of other turbine manufacturers could not be identified.

Table 16. Available Offshore Wind Turbine Prices

	2018	2019	2020	2030	Source
Turbine Price – Financial Statements ($/kW)	1,500	1,690	1,400	N/A	Siemens Gamesa (2020)
Turbine Price – Estimate ($/kW)	N/A	N/A	1,000	850	BNEF (2020)

Note: For the data from Siemens/Gamesa (2020), the reported order intake value ($) was divided by the capacity order intake (MW) from the company's financial statement.

Wind turbine upsizing (Section 5.3) is often identified as a primary cost driver (Wiser et al. 2021). Using higher-rated turbines for a given project size reduces the number that need to be installed and serviced. The tendency of project developers to opt for the highest-rated turbine model that is available in commercial markets supports the assumption that there are economic incentives associated with higher-rated wind turbines. Turbine manufacturers seem to be able to provide a turbine price offering, which generates savings in the balance-of-station ($/kW) and O&M ($/kW/year) expenditures that outweigh the additional costs of a higher-rated turbine ($/kW). This reduction in the total system costs from turbine scaling is enabled by continued innovations, such as the use of lightweight materials, advanced manufacturing methods, systemwide load control, and economies of scale in production and delivery.

6.1.3 Operational Expenditures

Operational expenditures (OpEx) are higher for offshore wind energy than land-based wind generation, with annual OpEx in the range of $70–$80/kW for offshore and $30–$40/kW for onshore (Lazard 2020). Access by maintenance personnel to offshore sites is an important component of this difference in costs. Wind and wave conditions can limit access to these sites, leading to increased downtime or required investments in specialized vessels or helicopters for personnel transfer that can operate in challenging sea states.

Industry analysts project that OpEx will decrease 7%–16% from 2020 values by 2025 and 14%–29% by 2030 (Figure 37). Technology advancements that may contribute to future cost decreases include:

Increasing wind turbine capacity. Costs for many O&M tasks depend on the number of wind turbines rather than their capacity. For a given wind power plant capacity, OpEx tends to be lower for fewer, larger turbines than for more, smaller turbines because of the reduction in the number of service operations. Ørsted reported a 33% reduction in OpEx/MW for 6- to 8-MW turbines compared with 3- to 4-MW turbines (Ørsted 2018).

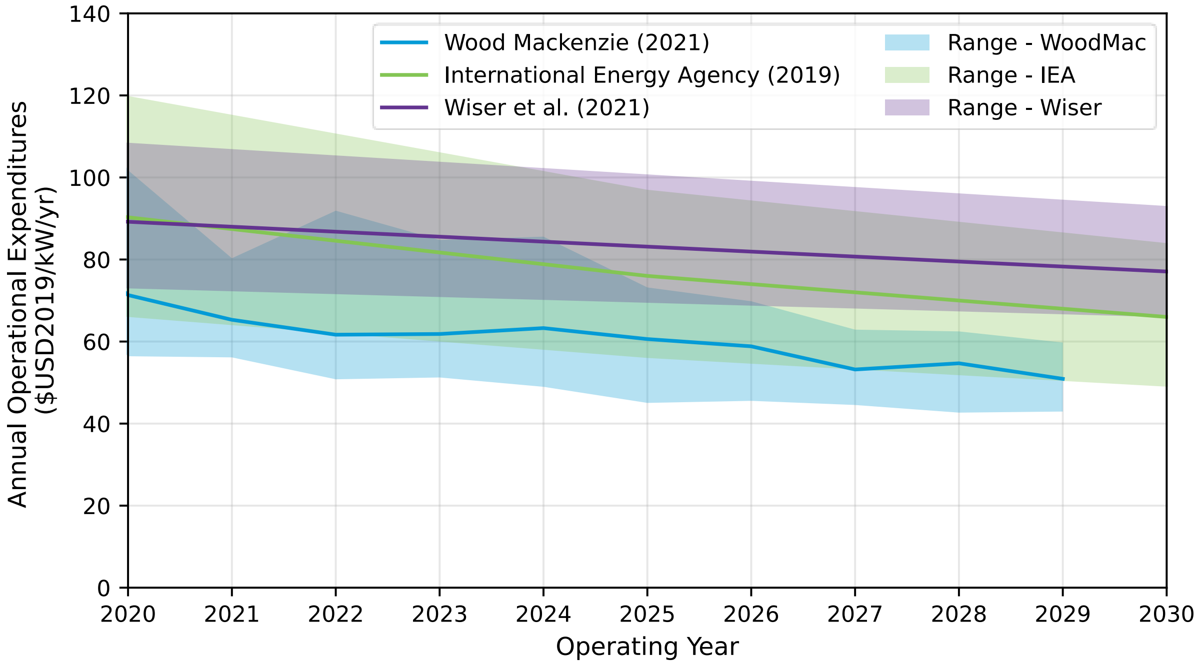

Figure 37. Global offshore wind power plant operational expenditures

Increasing reliability. Unscheduled or corrective maintenance and replacement parts are responsible for 58% of annual OpEx (Liu and Garcia da Fonseca 2020). Reducing the number of repairs required and improving the ability to plan maintenance in advance (allowing for schedule optimization) can lower costs.

Remote maintenance. A wide range of strategies are being adopted, including remote monitoring to enable earlier detection of problems and facilitate preventive maintenance; and airborne, subsea, or blade-crawling devices for inspection and repair of hard-to-access components.

Access. Improvements in offshore access capabilities[41] increase safety, decrease transfer times from the vessel to the wind turbine, and allow maintenance to take place more often during the year.

A factor that could increase O&M cost is the trend toward siting offshore wind power plants farther from shore (Figure 22), which leads to longer transit times that can reduce turbine availability. Possible strategies to mitigate the effects of greater distances to shore include the use of service operation vessels that provide crew accommodations for longer periods at sea (~1 month) and can operate in higher sea states than typical crew transfer vessels, as well as clustering maintenance operations across groups of wind power plants to optimize logistics and vessel utilization.

[41] Examples of improved access capabilities include platforms that are fixed to the tower above the splash zone with fender posts to absorb vessel impact, flexible gangways extended from the vessel and held in the lee of the tower base, installation of friction posts against which the vessel maintains a forward thrust during transfer, a facility for winching the vessel out of the water during harsh sea conditions, and winch/netting for personnel and equipment.

6.1.4 Price Trends

Prices from the competitive procurement of offshore wind energy provide insight into the economic offering of offshore wind. The prices are often revealed as part of publicly held auctions or PPA awards. Prices are influenced by a variety of factors, including costs, competition, and the awarded support and contract regime (e.g., a contract for difference or PPA). Price data can be used as indicators to costs (Junginger and Louwen 2019; Beiter et al. 2021a), after making adjustments to enable direct comparison (Beiter et al. 2021b). The projects depicted in Figure 38 represent the strike prices after adjusting for contract length, export cable expenses, the monetized value of tax incentives and currency year. They represent all-in prices (e.g., export cable costs are included). Between 2020 and 2025 (COD), the average procurement prices decrease from approximately $120/MWh to $93/MWh, or nearly 22%. In the United States, the levelized PPA and OREC prices range between $96/MWh (Vineyard Wind 1,400 MW) and $71/MWh (Mayflower Wind, 804 MW) between 2022 and 2025 (COD), based on a total of nearly 5.5 GW of signed agreements. The Skipjack and US Wind[42] projects have a considerably higher price of $141/MWh than the other U.S. projects, perhaps because of their smaller project sizes of 120 MW and 248 MW, respectively. With an adjusted levelized PPA price of $71/MWh, the Mayflower Wind project is among the lowest-priced announced offshore wind projects globally.

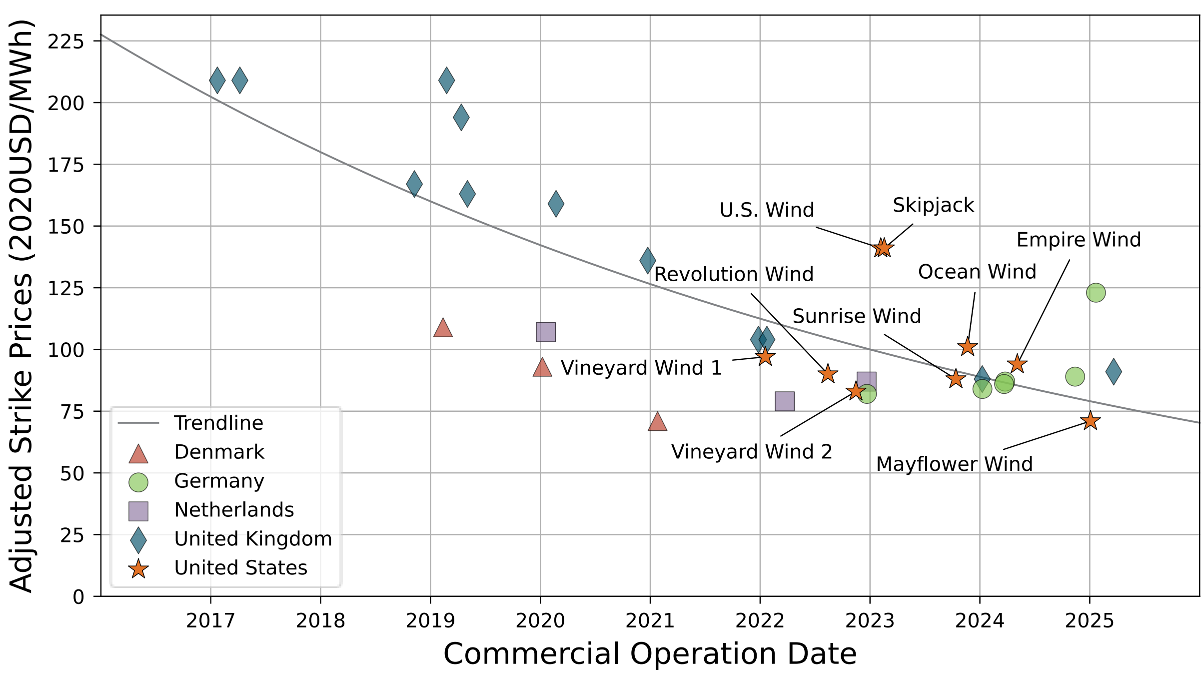

Figure 38. Adjusted strike prices from U.S. and European offshore wind procurements. *From Beiter et al. (2021a) for U.S. projects*

[42] The US Wind project in Maryland has been named MarWin.

During 2020, an increased number of corporate PPA offtake agreements further solidified a relatively new trend in offshore wind procurement. The entry of corporate offtakers[43] offers an additional procurement pathway for offshore wind energy projects, in addition to the conventional utility offtakers that have dominated offshore wind procurements until 2018. In 2020 and early 2021,[44] nearly 4 GW were procured with corporate offtakers (Table 17) in Northern Europe. Corporate procurement volumes, often in fulfillment of sustainability goals, range from PPA contract volumes between 27 MW and 960 MW during 2020 and the first part of 2021. The PPA contract period ranges between 10 and 15 years.

Table 17. Corporate PPA Offtake for Global Offshore Wind Energy Projects

Contract Signed	Project	Offtaker	Seller	Duration (Years)	Capacity (MW)
2019	Borkum Riffgrund 3	Covestro	Ørsted	10	100
2019	Borssele 3&4	Microsoft	Eneco	15	90
2020	Borkum Riffgrund 3	Amazon	Ørsted	10	250
2020	Seagreen	Statkraft	SSE Renewables/Total	N/A	538
2020	Humber Gateway	E.ON	RWE Renewables	13	219
2021	Dogger Bank A & B	Ørsted	SSE Renewables/ Equinor	15	960
2021	Dogger Bank A & B	Shell Energy Europe	SSE Renewables/ Equinor	15	480
2021	Dogger Bank A & B	Danske Commodities (Equinor)	SSE Renewables/ Equinor	15	480
2021	Dogger Bank A & B	Danske Commodities (SSE Energy Supply)	SSE Renewables/ Equinor	15	480
2021	Horns Rev 2	Danfoss	Ørsted	10	27
2021	Hollandse Kust Noord	Amazon	Shell/Eneco	N/A	380
Total					**4,004**

Sources: Segal (2020); Shumkov (2021); World Oil (2020); Renewable Energy World (2021)

[43] An offtaker is the counterparty to a renewable energy contract who is buying the product from a generator (Beiter et al. 2020a).
[44] Data only considered until May 31, 2021.

6.2 Floating Offshore Wind Energy Cost Trends

Floating offshore wind LCOE is estimated to decline from approximately $160/MWh (2020) to $60–$105/MWh (2030) by various research organizations. These estimates, depicted in Figure 39, assume commercial-scale floating wind power plants and learning-curve benefits commensurate with a mature industry. The cost of floating offshore wind technology is currently based on a small set of data from the first phase of demonstration projects. Generally, the potential for floating offshore wind cost reduction is high (Wiser et al. 2021) because early-stage technology advances usually result in significant cost reductions. In addition, technological and commercial developments from fixed-bottom offshore wind systems might translate to floating offshore wind systems. Cost estimates from technology-specific cost reduction potential come from a range of factors, including (but not limited to) the ability of floating offshore wind systems to:

- Leverage cost reductions, innovations, and experience from fixed-bottom systems
- Use existing supply chains
- Optimize floating structures using lighter components and increased modularity
- Reduce the number and complexity of construction steps at sea (e.g., by assembling the wind turbine and substructure at quayside)
- Automate production and fabrication of the floating platforms
- Access higher wind speeds sufficient to outweigh the higher O&M and installation costs associated with greater distances to shore and harsher meteorological conditions.

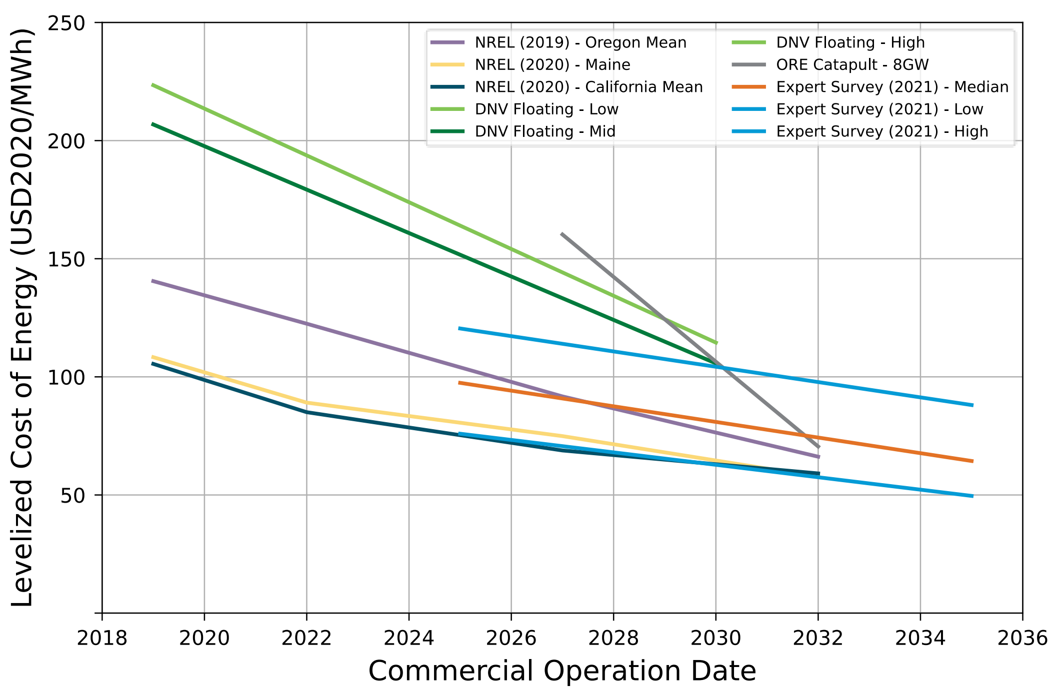

Figure 39. Global LCOE estimates for floating technology

Sources: Musial et al. 2019a (NREL 2019 - Oregon); Musial, Beiter, and Nunemaker 2020 (NREL 2020 - Maine); Beiter et al. 2020b (NREL 2020 - California); DNV GL 2020 (DNV Floating); ORE Catapult 2021 (ORE Catapult); and Wiser et al. 2021 (Expert Survey 2021)

6.3 Financing Trends

In contrast to fossil-fueled power plants (e.g., natural gas or coal), variable costs of offshore wind power plants are relatively small, and most lifetime costs are incurred up-front through CapEx for the development and construction of a project. These upfront expenditures generally require investment volumes of more than $1 billion for utility-scale projects.[45] The financing rate of a project, commonly expressed in terms of the weighted-average cost of capital,[46] has considerable impact on lifetime project costs (i.e., LCOE) because it determines the annual debt service and equity repayment for the initial (CapEx) investment.

During 2020, offshore wind energy projects in Europe and Asia continued to access low-cost capital, which is consistent with a broader trend of declining equity and debt rates and a growing share of debt compared to equity for renewable energy asset financing. Approximately $30 billion was invested in new European offshore wind capacity (7.1 GW) during 2020. This constitutes a record investment volume, up from $11 and $7.5 billion in the two preceding years (Brindley and Fraile 2021). In Europe, project finance dominated offshore wind energy investment transactions during 2018 with a share of 82%. Table 18 depicts financing conditions typical for European and U.S. offshore wind energy projects between 2006 and 2020. The debt share for these projects has consistently been at or above 70% since 2012.

Table 18. Typical Financing Conditions for U.S. and European Offshore Wind Energy Projects

Year	Coverage	Debt/Sponsor Equity/Tax Equity (%)	Pricing[47] (Basis Points)	Source
2006–2007	Europe	60/40/0	150–200	Guillet (2018)
2009–2011	Europe	65/35/0	300–350	Guillet (2018)
2012–2013	Europe	70/30/0	200–250	Guillet (2018)
2014–2015	Europe	70/30/0	200–250	Guillet (2018)
2016–2017	Europe	75/25/0	150–225	Guillet (2018)
2018	Europe	70/30/0	120–175	Guillet (2018)
2019	United States	50/20/30	150-175	Norton Rose (2019)
2020	United States	80/20 (combined)[48]	170	Martin (2020b)

Note: Year 2008 not available from sources.

[45] For instance, the 800-MW Vineyard Wind 1 project has a reported investment volume of approximately $2 billion (Renewables Now 2018).
[46] The weighted-average cost of capital is the average cost of all sources of capital based on the percentage contribution to the total capital structure.
[47] Basis points are indicated as being above the London Interbank Offer Rate. One basis point is equal to 1/100 of a percent and 100 basis points equals 1%.
[48] The split between sponsor and tax equity is not clear from the source (Martin 2020b) and is reported here as an aggregate.

6.4 Tax Credits

On December 27, 2020, the Consolidated Appropriations Act, 2021 (H.R. 133) was signed into law (U.S. Congress 2020b). The act includes a 30% investment tax credit (ITC) for offshore wind energy. This constitutes the first ITC that is specific to offshore wind investments. The ITC level of 30% is considerably higher than the tax incentives (phase-down) schedule of the Tax Extender Act of 2019 (Tax Extender Act of 2019) that was in effect prior to the Consolidated Appropriations Act of 2021. The 30% ITC rate applies to any project for which construction starts after 2016 through the end of 2025. If met, the 5% Safe Harbor Rule[49] effectively permits projects to take advantage of the ITC as long as they place the qualifying facility into service within 10 calendar years after the calendar year during which construction of the project began, yielding a latest-possible COD date of 2035 (i.e., with construction start in 2025).[50] The change introduced by the Consolidated Appropriations Act is retroactive.[51] The U.S. Treasury is considering whether to extend this provision to 7 or 10 years (Martin 2020a). The production tax credit is no longer an option (as an alternative to ITC election) for any projects that start construction after 2021.

[49] The 5% Safe Harbor Rule stipulates that a project must incur at least 5% of the total cost of the facility to satisfy the “begin construction” requirement of the investment tax credit/production tax credit and prove a “continuous program of construction” or “continuous efforts to advance towards completion of the facility” (Internal Revenue Service [IRS] 2013).

[50] A facility meets the Safe Harbor Rule if it is placed in service 10 calendar years from the calendar year during which construction began (IRS 2021). Also note that on May 27, 2020, the IRS issued Notice 2020-41, providing a 1-year extension to the Continuity Safe Harbor for projects that began construction in 2016 or 2017 (IRS 2020).

[51] This rate can be claimed only on the tax basis that is built up after 2016 if the tax basis has already been incurred before that point.

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Appendix. Uncertainty of Capital Expenditure Estimates

All levelized cost of energy components are subject to considerable uncertainty and variation. In this section, we discuss some of the primary reasons for the uncertainty that we have encountered in analyzing capital expenditures and wind turbine prices.

Capital Expenditures

Capital expenditures (CapEx) are uncertain for a variety of reasons: 1) the CapEx data are normally self-reported by developers and difficult to verify independently, 2) there is limited transparency into the financial impact of cost overruns, and 3) it is often unclear whether the reported CapEx fully captures the total cost of installing the wind energy project and connecting it to the grid. Generally, greater confidence can be placed in cost estimates that are in more mature stages of the project life cycle (e.g., costs for projects that have reached the financial investment decision are typically more accurate than for a project that has not yet received permits). Only limited CapEx data are available for any given year after 2025. As a result of this relatively small sample, and the projects' early planning stages in which firm contracts for capital equipment have yet to be executed, the level of confidence is relatively low. When considered together, though, these data can provide insight into the long-term cost trends.

Wind Turbine Prices

Wind turbine prices may vary considerably among specific projects. Some of the factors in turbine pricing include delivery costs to the staging port, warranty period (typically 5 years), availability guarantees, project order size, turbine attributes (e.g., turbine rating and drivetrain topology), market competition, timing, and specific strategic market behavior (e.g., first-mover advantages, customer retention). Wind turbine CapEx has declined rapidly over the last few years, which has led to a considerable spread in price estimates found in publicly available literature sources.

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Cover details: Dominion Energy's Coastal Virginia Offshore Wind 12-MW pilot project located 27 miles off the coast of Virginia Beach, Virginia. Photo courtesy of Lyfted Media for Dominion Energy.