The Demand for a Domestic Offshore Wind Energy Supply Chain

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1 National Renewable Energy Laboratory
2 DNV
3 The Business Network for Offshore Wind

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NOTICE

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Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

Errata

This report, originally published in March 2022, has been revised in June 2022 to make several minor updates to data included in this report based on feedback from industry experts:

- We corrected the investment cost of the Prysmian cable facility to $200 million in Table 1. It was previously listed as $900 million, which is the value of the awarded cable contracts for the factory.
- We updated the specifications for the New Jersey Wind Port in Table 9 with new input from the port designers. This change indicates that wind turbine installation vessels will be capable of accessing the port, which is also reflected in Table 10.
- We updated the channel depth for the Port of Seattle in Table 11 to above 30 meters, indicating that there are no navigation channel depth limitations for floating wind installation out of this port.
- We consolidated several types of support vessels in Table 17 and provided a rough estimate of the number of vessels that may be required per project. We also reclassified CTVs, heavy lift vessels, and anchor handling tug supply vessels from a low risk to a moderate risk to the 30 GW target.

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List of Acronyms

AHTS	anchor-handling tug supply
BOEM	Bureau of Ocean Energy Management
CLV	cable-laying vessel
COD	commercial operation date
CTV	crew transfer vessel
DOE	U.S. Department of Energy
FTE	full-time equivalent
GBF	gravity-based foundation
GW	gigawatt
HVAC	high-voltage alternating current
HVDC	high-voltage direct current
HLV	heavy-lift vessel
I-O	input-output
JEDI	Jobs and Economic Development Impact
km	kilometer
m	meter
MW	megawatt
NREL	National Renewable Energy Laboratory
O&M	operation and maintenance
OEM	original equipment manufacturer
SCC	Supply Chain Connect
SOV	service operation vessel
t	tonnes
WISDEM	Wind-Plant Integrated System Design and Engineering Model
WTIV	wind turbine installation vessel

Executive Summary

In March of 2021, the Biden administration established a national offshore wind energy target to install 30 gigawatts (GW) by 2030. This ambitious goal was intended to not only help reduce dependency on fossil fuels, but also establish a new and sustainable renewable energy industry in the United States. The announcement referenced the potential benefits of establishing a domestic supply chain, including providing existing suppliers with the ability to produce thousands of components while creating tens of thousands of U.S. jobs over the course of the decade.

The administration's vision aligns with the perspective of the offshore wind energy industry. At a Leadership 100 event hosted by the Business Network for Offshore Wind in 2019, offshore wind energy developers and manufacturers identified the need for a road map outlining a pathway to a domestic supply chain as the top priority facing the industry. Building up domestic manufacturing capabilities will not only energize local industries but can possibly de-risk individual projects by reducing reliance on importing resources from European or Asian markets. Although establishing a domestic supply chain will require significant investment, it has the potential to benefit the entire industry and, by extension, help meet the country's decarbonization goals.

In this report, we characterize the challenges and opportunities facing the domestic supply chain industry and evaluate its potential benefits. This report is the first of a two-part series, describing the full supply chain road map and its associated benefits. The first report focuses on the high-level deployment, workforce, and component requirements that need to be met to achieve the national offshore wind energy target. We present:

- A deployment pipeline that demonstrates the pathway to 30 GW and anticipated deployment rates after 2030, the associated demand for major fixed-bottom and floating offshore wind components (e.g., wind turbines, foundations, cables, substations), and the vessel and port requirements to support those installation activities.
- A series of sensitivity analyses showing how the demand for components, ports, and vessels changes for different technology pathways and availability of the global supply chain.
- An estimate of the total number of jobs that would be required to support the deployment scenarios under varying levels of assumed domestic content.
- A detailed list of the Tier 1, 2, and 3 components (e.g., finished components, subassemblies, and subcomponents, respectively) required to construct fixed-bottom and floating offshore wind energy projects.
- A discussion of critical path components that represent a significant challenge, bottleneck, or risk for a future domestic supply chain.

The follow-on report, scheduled for publication in 2022, will build on those results to characterize the need for critical Tier 2 and 3 components and how effectively existing supply chain capabilities can be used to meet the component demand. The readiness level of existing suppliers will be used to define potential domestic supply chain scenarios that leverage the strengths of the current system. We will evaluate the range of outcomes that are associated with those different scenarios, including regional jobs and economic benefits, impact on project cost and logistics, and the potential effects on disadvantaged communities or populations.

In this report, we focus on the high-level demand for resources that will inform the next stage of analysis. We begin by establishing a deployment pipeline that conveys the scheduling of how existing offshore wind lease areas can be developed. This pipeline considers evolving technologies over the course of the decade, such as increasing wind turbine ratings and the types of vessels required to install projects, along with sensitivities to bottlenecks in the global supply chain and different market penetrations of fixed-bottom foundations. We use the deployment rates of the pipeline along with technology assumptions to consider the demand for ports and vessels and provide a high-level assessment of how effectively these resources can support the planned offshore wind energy buildout. The number of components manufactured annually feeds into an economic input/output model to evaluate the number of jobs and the magnitude of economic benefits that could be created under varying levels of domestic content. We break down these overall job numbers to identify the types of components that have the potential to provide the highest impact on a domestic workforce. Finally, we provide a detailed explanation of the types of Tier 1, 2, and 3 components that will be needed as part of offshore wind energy deployment and identify critical path items that may present a challenge for a domestic supply chain.

The following are the key findings of the different sections we investigated in the first phase of the study:

The United States Project Pipeline

- The awarded and soon-to-be-awarded lease areas (including the California and New York Bight wind energy areas[1]) have sufficient capacity to deploy 30.1 GW by the end of 2030, making it possible to achieve the national offshore wind energy target. Developing a domestic supply chain that produces components dedicated to the U.S. market is a potential solution to de-risking the deployment target against supply chain delays.
- Additional leasing will be required to maintain a consistent deployment rate after 2030, which will be vital for developing a sustainable domestic supply chain with a predictable demand for components. The Bureau of Ocean Energy Management (BOEM) has announced plans to hold new lease area auctions between 2022 and 2025 that will likely support the demand for steady deployment after 2030.
- The deployment pipeline of awarded, soon-to-be-awarded, and anticipated lease areas (from BOEM's planned auctions) is shown in Figure ES1. If all projects progress with realistic deployment and permitting schedules without significant disruptions, deployment will rise to just over 6 GW in 2028. Deployment after 2030 assumes that the anticipated lease areas that will be awarded by BOEM in the 2020s will contribute sufficient capacity to maintain a consistent deployment of at least 4–6 GW per year, which is required to reach a cumulative capacity of nearly 60 GW by 2035 and at least 110 GW by 2050. This pipeline is not a forecast of offshore wind energy deployment but is defined as a realistic scenario that can be used to evaluate the demands that will be placed on the supply chain.

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[1] The New York Bight wind energy areas were converted to lease areas and auctioned in February, 2022, as this report was in the publication process.

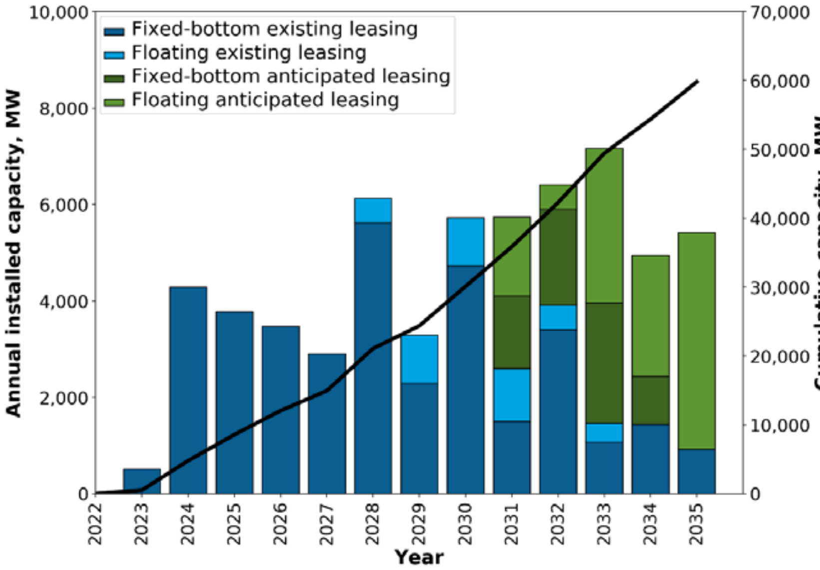

Figure ES1. Annual and cumulative installed capacity for existing and anticipated lease areas. With no supply chain constraints, 30.1 GW are expected to be installed by the end of 2030. The Bureau of Ocean Energy Management's anticipated leasing of new areas from 2022 to 2025 will be required to maintain a consistent deployment rate after 2030 (MW = megawatts).

- The annual demand for major components, shown in Figure ES2, follows the trends of the deployment pipeline. Achieving the national offshore wind energy target will require over 2,100 wind turbines (mostly with a 15-megawatt rating), along with at least 2,100 foundations (monopiles, jackets, gravity-based foundations, and semisubmersible platforms), over 11,000 kilometers (km) of cables, 5 wind turbine installation vessels, 10 feeder barges, 58 crew transfer vessels, and 4 cable lay vessels.
- Most components in the early 2020s will be sourced from European suppliers while domestic manufacturing facilities are being planned and constructed. However, it is unlikely that international suppliers will have sufficient throughput to support the construction of both European and U.S. offshore wind energy projects. If a domestic supply chain is not developed in time, bottlenecks in the global supply chain will present a significant risk to achieving the national offshore wind energy target.

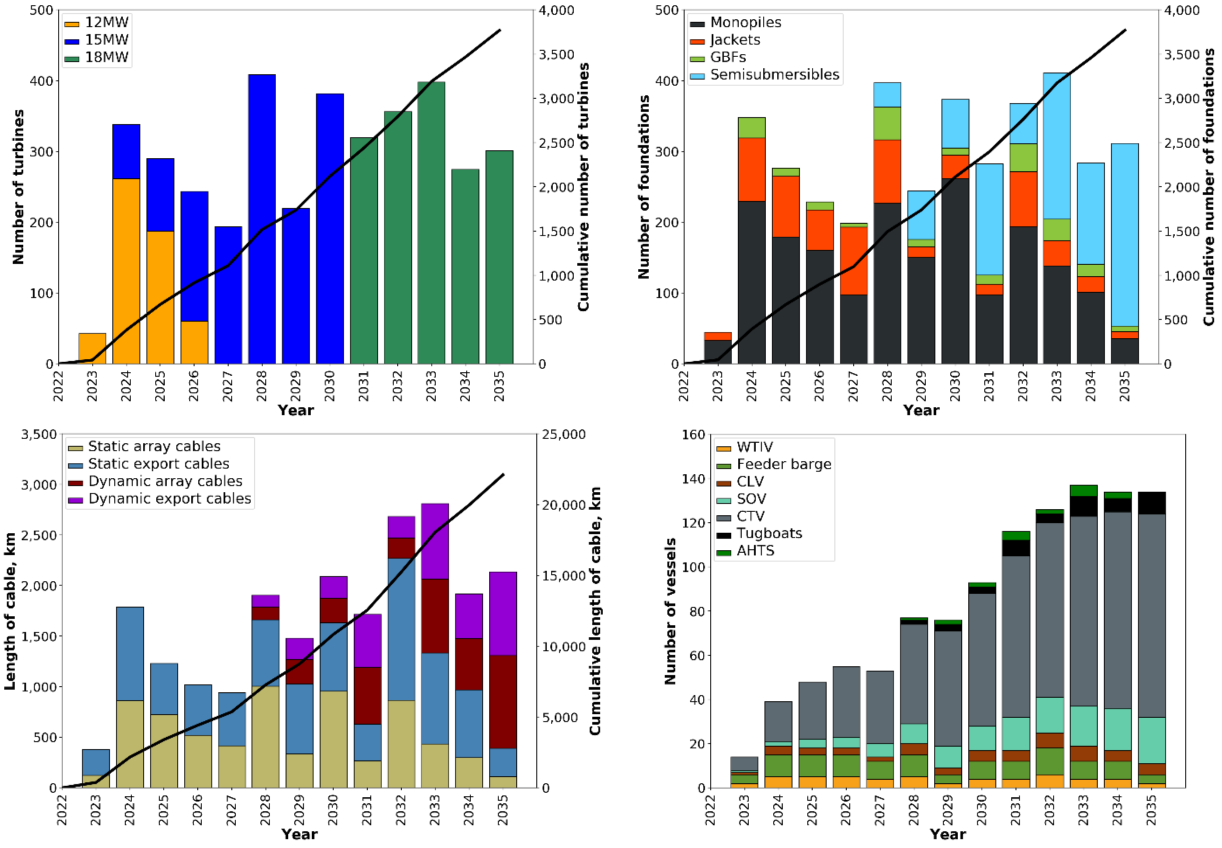

Figure ES2. Annual and cumulative component demand for (clockwise from top left) wind turbines, foundations, vessels, and cables. A wind turbine includes three rotor blades, one nacelle, and one tower.

GBF = gravity-based foundation; WTIV = wind turbine installation vessel; CLV = cable lay vessel; SOV = service operation vessel; CTV = crew transfer vessel; AHTS = anchor handling tug supply

United States Ports and Vessel Assessment

- Few existing East or West Coast ports have sufficient capabilities to fully support offshore wind energy activities, although a number of ports are actively investing in infrastructure upgrades.
- Table ES1 provides a high-level screening of the readiness level of 22 East Coast ports for fixed-bottom offshore wind marshalling activities. Only one port (Portsmouth Marine Terminal in Virginia) has the existing capabilities to support loadout of wind turbine installation vessels, although these vessels should also be able to dock at the planned New Jersey Wind Port. Draft limitations in the navigation channels and at quayside may require projects to use a feeder barge strategy to install projects even if Jones-Act-compliant wind turbine installation vessels (WTIVs) are available.

Table ES1. Summary of East Coast Ports Marshalling Capabilities and Assessments

Port Name	State	Laydown Area (acres)	Quayside Length (meters [m])	Number of Berths	Berth Depth (m)	Channel Depth (m)	Bearing Capacity (tonnes [t]/square meter [m^2])	Air Draft Limit (m)	Readiness Level (WTIV)	Readiness Level (Feeders)
New Bedford	MA	29	366	3	9.1	9.1	20 t/m^2	None	🟥 Berth/channel depth, and quayside length	🟩 Quayside length
New London State Pier	CT	30	1,244	4	12.2	10	Assume > 15	None	🟨 Channel depth	🟩
South Brooklyn Marine Terminal	NY	88	417	2	10.7	12.2	30	60	🟥 Berth depth, quayside length, and air draft	🟨 Quayside length
New Jersey Wind Port	NJ	70	854	4	11.5	9.88	29.8	None	🟩	🟩
Tradepoint Atlantic	MD	3,300	1,021	2	10.97	10.97		None	🟥 Berth/channel depth, bearing capacity	🟨 Bearing capacity
Portsmouth Marine Terminal	VA	287	1,079	3	13.11	13.11	Assume >15 t/m^2	None	🟩	🟩
Other ports (1)	-	-	-	-	-	-	-	-	🟨	🟨
Other ports (4)	-	-	-	-	-	-	-	-	🟥	🟨
Other ports (9)	-	-	-	-	-	-	-	-	🟥	🟥

- Table ES2 provides high-level screening of the readiness level of 13 West Coast ports for floating offshore wind marshalling activities. West Coast ports typically do not have the available infrastructure or are too congested with shipping activities to support offshore wind energy, although ports such as Coos Bay, Oregon, and Humboldt, California, are actively planning upgrades.

Table ES2. Selected West Coast Ports Marshalling Capabilities and Assessment

Port Name	State	Laydown Area (acres)	Quayside Length (m)	Number of Berths	Berth Depth (m)	Channel Depth (m)	Bearing Capacity (t/m^2)	Air-Draft Limit (m)	Readiness Level (Floating Substructure)
Port of Seattle	WA	1,541.9	2,400	20	23.2	>30		None	High congestion and bearing capacity
Port at Coos Bay	OR	1,335	80	7	11.28	11.28		Select areas limited	Bearing capacity and quayside length
Humboldt Marine Terminal	CA	150	703	2	11.6	10.67	Assume > 15	None	Channel depth
Morro Bay	CA		80	1	5.5	5.5		None	Laydown area, quayside length, berth/channel depth, and bearing capacity
San Francisco	CA		870		15.2	15		67	Laydown area, bearing capacity, and air draft
Oakland	CA	1,300	7,800	185	15	15		67	Bearing capacity and air draft
Hueneme	CA	120	800	5	10.5	11		None	Berth depth
Los Angeles	CA	7,500	3,650	25	12	12		Select areas limited	High congestion
Long Beach	CA	525	4,750	10	25	25		Select areas limited	High congestion
San Diego	CA	96	750	8	12.8	12.8		None	High congestion

- New vessels are required to alleviate risks of missing the national offshore wind energy target, with wind turbine installation vessels posing the biggest risk followed by feeder barges, cable lay vessels, service operation vessels, crew transfer vessels, scour protection vessels, heavy lift vessels, and anchor handling tug supply vessels. Table ES3 identifies the highest risk vessels and the estimated costs, lead times, and demand for these vessels to deploy 30 GW of offshore wind energy by 2030.
- Although wind turbine installation vessels do not necessarily need to be Jones-Act compliant if a feeder barge installation strategy is used, building those vessels domestically may make it more likely that they are dedicated to projects in the United States.

Table ES3. Vessels That Pose a High or Moderate Risk To Achieving the National Offshore Wind Energy Target

Vessel Type	Estimated Cost	Estimated Construction Time	# Existing	Estimated Peak Demand to 2030	Risk to 30-GW Target
U.S.-dedicated wind turbine installation vessel	$250–$500 million	3 years	0 (1 under construction)	5	🟥
Cable lay vessel	$250 million	3 years	0	4	🟨
Feeder barge/vessel	$150–$200 million new, $10–$20 million retrofit	Depends on design	20 jack-ups, 44 barges	10	🟨
Service operation vessel	$50–$100 million new, $10–$50 million retrofit	2-3 years	0 (2 under construction, multiple oil and gas vessels which could be adapted)	13+	🟨
Crew transfer vessel	$5–$10 million	1- 2 years	3	58	🟨
Scour protection vessel	$200 million	3 years	0 (1 under construction)	2	🟨
Heavy lift vessel	Depends on design		18	Depends on installation strategy	🟨
Anchor handling tug supply vessel	$100 - $200 million	2 years	Limited supply	2	🟨

Jobs and Economic Sensitivities for a Domestic Supply Chain

- Workforce estimates for varying levels of domestic content show that the average number of annual jobs varies between 12,300 and 49,000 full-time equivalents (FTEs)[2], as shown in Figure ES3, depending on the annual deployment rate. Through 2030, the peak demand occurs in 2028, with a requirement of between 15,500 FTEs (if 25% of components are produced domestically) and 62,000 FTEs (if 100% of components are produced domestically). This maximum job demand is an indication of the highest workforce level that the United States may need to have trained/hired depending on domestic content each year. In all likelihood, the actual number of jobs would fall within this range as the domestic supply chain grows to support the offshore wind energy project pipeline.

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[2] We report the average of the 25% and 100% domestic content scenarios over time. The average number of jobs begins at 12,300 full-time equivalents (FTEs) in 2023 and grows to a peak of 49,000 FTEs in 2028. We then report the separate peak demands from the 25% and 100% domestic content scenarios (15,500 FTEs and 62,000 FTEs in 2028, respectively).

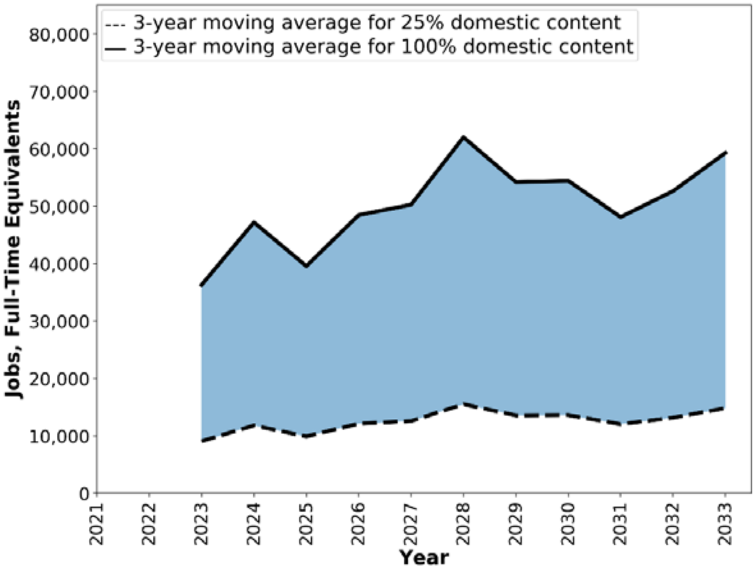

Figure ES3. Baseline scenario - number of jobs (FTEs) for all component demand based on scaling domestic content for the entire supply chain

- The number of jobs attributed to manufacturing specific components is provided in Table ES4. These figures include direct jobs (which fabricate or assemble final components at a manufacturing plant) and indirect jobs (which produce parts or materials for a major component). Nacelle production (including fabrication and assembly of subcomponents) has the potential to create the highest demand for jobs, particularly through the fabrication and assembly of subcomponents, such as generators, gearboxes, and power converters. Fabrication of monopiles, towers, and rotor blades provide the next highest opportunity for job creation.

Table ES4. Average and Maximum Number of Direct and Indirect Jobs Produced per Component for Varying Levels of Domestic Content

Component	Average Number of Jobs Through 2030		Maximum Job Demand Through 2030	
	25% Domestic Content	100% Domestic Content	25% Domestic Content	100% Domestic Content
Fixed-bottom projects				
Nacelle	4,600	18,600	5,300	21,200
Rotor blade	900	3,500	1,100	4,300
Towers	1,200	4,700	1,500	5,900
Monopile	1,300	5,400	1,600	6,600
Transition piece	800	3,100	1,000	3,800
Jacket	500	2,000	700	2,900
Gravity-based foundation	400	1,500	500	2,000
Substation topside	30	100	30	100
Array cable	300	1,100	300	1,300
Export cable	600	2,300	700	2,900
Floating projects				
Nacelle	1,100	4,600	1,900	7,700
Rotor blade	200	800	300	1,300
Towers	300	1,100	400	1,800
Floating (semisubmersible) structure	2,200	8,700	3,600	14,700
Substation topside	3	15	15	60
Dynamic array cable	100	400	200	700
Dynamic export cable	200	800	300	1,400

- There are typically more indirect jobs than direct jobs for Tier 1 components. This breakdown of job types indicates that a more comprehensive domestic supply chain that provides parts and materials to Tier 1 facilities will significantly increase the local economic benefits that can be realized from the supply chain.
- The ramp up in jobs in the first half of the 2020s demonstrates that there is an immediate need for workforce development, as planned domestic manufacturing facilities come online and begin to fabricate and assemble components for initial offshore wind energy projects. Plant-level workers (such as trades workers and assemblers) will likely provide the largest contribution to this workforce growth. Educational institutions, unions, original equipment manufacturers, and developers could work together to ensure workers are adequately trained and ready to hire as U.S. manufacturing begins production.

- The effects of the expanded labor pool from a domestic supply chain could inject an average of $1,600–$6,200 million per year of value-added gross domestic product (GDP) into the nation's economy. Value-added GDP does not represent the full magnitude of investment in offshore wind energy but characterizes the benefits returned to the local economy and workforce throughout the component production process. This amount of GDP growth depends on the level of domestic content, with further expansion of the supply chain leading to greater impacts on the economy.

The Required Components in an Offshore Wind Energy Supply Chain

- Original equipment manufacturers and project developers have announced plans to build at least 11 new manufacturing facilities in the United States, including those focused on major components, such as wind turbine blades, foundations, towers, and cables. At this time, only one major facility is operational. Additional facilities will be required to achieve a fully domestic offshore wind supply chain.
- The wide range of Tier 2 and Tier 3 components required for offshore wind energy projects represents an opportunity for existing businesses to leverage their capabilities to support the growing offshore wind energy market. Those specialized components would likely require additional investment or certification to develop the capabilities to manufacture them domestically.
- We provide a detailed breakdown of the Tier 1, 2, and 3 components for fixed-bottom and floating offshore wind energy projects and identify critical path items that represent a particular challenge to establishing a domestic supply chain. Some of these components include:
    - Permanent magnets for wind turbine generators, which require rare-earth metals that are not mined domestically and specialized processing techniques that are not available in the United States
    - Yaw bearings and pitch bearings, which are not produced domestically at the sizes required for offshore wind turbines (4-meter [m] and 6-m diameters, respectively)
    - Flanges, which are used to connect tower and monopile sections but are also not manufactured domestically at the scale required for offshore wind turbines (10-m diameters)
    - The large steel plates that are rolled into the circular monopile or tower sections are not widely produced domestically at the size or type of steel required; steel automation capabilities are less advanced domestically than they are globally
    - Hub castings are not produced in the United States at the size needed for offshore wind turbines; the foundries required to manufacture these castings may not be developed because of their significant environmental impact
    - The length of offshore wind turbine blades (over 100 m) makes it unlikely that existing blade facilities for land-based wind turbines will be repurposed; instead, new facilities will be required
    - Array and export cables are converted from raw materials to finished products in single factories; some of the materials, such as specific lead alloys and plastics used for insulation, need to be imported as they are not currently produced in the United States

  - Assembly of offshore substations at United States shipyards is more likely to take place if critical subtier components, such as power transformers, switchgear, and power compensation devices are produced locally; gas-insulated switchgear and shunt reactors that are certified for offshore operations are not currently made in the United States. Developing domestic manufacturing capabilities for these components presents a relatively challenging business case as there is a smaller demand for offshore substations (1 – 2 substations per project as opposed around 100 wind turbines)
  - The volume and type of mooring chain that will likely be used for floating offshore wind energy projects is not manufactured domestically; furthermore, the entire global supply chain may have difficulty keeping pace with the demands of commercial-scale floating wind energy projects.

The key findings of this report suggest that the national offshore wind energy target of 30 GW by 2030 represents a significant and achievable opportunity to develop a new domestic industry that can deliver clean energy, manufacturing capabilities, and job growth. Reaching this goal will likely require substantial advances in the U.S. supply chain along with development in complementary sectors, such as offshore permitting and grid transmission. Major investments in manufacturing facilities, ports, vessels, and workforce training initiatives will be necessary to jump-start the domestic offshore wind supply chain and design it in such a way to be flexible enough to adapt to new technologies and larger wind turbines.

Those initiatives play a supporting role to the primary goal of decarbonizing the U.S. grid by expanding the renewable energy portfolio; however, investing in domestic content is not just a mechanism for creating local economic growth, but a pathway toward reducing the risk of achieving offshore wind energy deployment targets. Developing local infrastructure and workforce capabilities will create resources and jobs that are dedicated to the domestic market and are less sensitive to global supply chain bottlenecks. Furthermore, those upfront investments will not only strengthen the chances of meeting the national offshore wind energy target but will also position the industry for continued expansion beyond 2030 by leveraging sustainable, cost-effective, and local resources. The road map presented in this two-part series of reports will outline potential pathways to strategically developing a supply chain to collectively increase the benefits for both deployment targets and local stakeholders.

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1 Introduction

1.1 Background and Motivation

The offshore wind energy industry in the United States is on the brink of transitioning from an unfulfilled vision to a robust source of renewable energy, jobs, and economic benefits for the foreseeable future. The pipeline of domestic projects being planned or permitted has grown to over 35,000 megawatts (MW) in 2021 from just over 15,000 MW in 2015 (Musial et al. 2021; Smith et al. 2015). The pathway to realizing the full potential of the U.S. market has been catalyzed by the national offshore wind energy target of 30 gigawatts (GW) of installed capacity by 2030 established by the Biden administration; this announcement not only identifies a deployment target for offshore wind energy but also strives to create a sustainable local industry with good-paying union jobs and a strong domestic supply chain (White House 2021). Shortly after this announcement, Vineyard Wind became the first commercial-scale offshore wind project in the United States to achieve financial close and anticipates beginning offshore construction work in 2022 prior to delivering first power to the grid in 2023 (Vineyard Wind 2021). The growing momentum of the offshore wind energy industry has created a need to solve the logistical problem of how to ramp up infrastructure capabilities quickly enough to deploy the domestic pipeline instead of acting as a bottleneck. The need for an industry road map to address major market barriers, characterize existing strengths and gaps, and provide insight into supply chain solutions was identified by industry stakeholders as the top priority needed to advance the U.S. offshore wind energy industry (Business Network for Offshore Wind 2019).

The vital need for supply chain capabilities, including manufacturing facilities, offshore wind ports, and installation vessels, has led to a series of announced investments in recent years despite the uncertainty around the size and schedules of the deployment pipeline. Table 1 shows the list of major supply chain announcements made by project developers and original equipment manufacturers (OEMs). Additional investments have been planned or made for the development or expansion of 12 ports, a wind turbine installation vessel (WTIV), feeder barges, service operations vessels (SOVs), crew transfer vessels (CTVs), and scour protection installation vessels (Musial et al. 2021).

Table 1. Major Supply Chain Announcements in the United States

Component	Location	Investors	Investment ($ million)	Status
Blades	Portsmouth Marine Terminal (Virginia)	Siemens Gamesa	200	Announced
Nacelles (final assembly only)	New Jersey Wind Port (New Jersey)	Vestas, Atlantic Shores	Not announced	Announced
	New Jersey Wind Port (New Jersey)	GE, Ørsted	Not announced	Announced
Towers	Port of Albany (New York)	Marmen Welcon, Equinor	350	Announced
Monopiles	Paulsboro Marine Terminal (New Jersey)	EEW, Ørsted	250	Under construction
	Sparrows Point (Maryland)	US Wind	150	Announced
Foundation platforms	Port of Providence (Rhode Island)	Eversource, Ørsted	40	Announced
Secondary steel	Port of Coeymans (New York)	Eversource, Ørsted	86	Announced
Transition pieces	Port of Albany (New York)	Marmen Welcon, Smulders	Not announced	Announced
Array and export cables	Nexans high-voltage cable facility (South Carolina)	Nexans	200	Operational
	Kerite (Connecticut)	Kerite, Marmon Group, Vineyard Wind	4	Operational
	Tradepoint Atlantic (Maryland)	Eversource, Ørsted	150	Announced
	Brayton Point (Massachusetts)	Prysmian, Avangrid	200	Announced
Offshore substations	Ingleside (Texas)	Kiewit, Eversource, Ørsted	Not announced	Operational

The announced facilities listed in Table 1 demonstrate the demand for a wide range of offshore wind energy components and the willingness of project developers to invest in local factories that can dedicate their throughput to projects in the United States. As the announced construction costs for those new facilities range between $40 and $350 million, they represent a significant financial commitment for the investors. Investing in those facilities can be partially attributed to the local content requirements imposed by individual states, which compel project developers to fund local infrastructure growth and workforce development as part of their contract to sell electricity from an offshore wind project to a power utility; however, it also reflects the perceived risk of sourcing major components from international suppliers. Although more robust offshore wind supply chains exist in Europe and Asia, those regions have their own ambitious deployment targets and may not have the throughput to fully supply the U.S. pipeline. As a result, developing a domestic supply chain has the potential to benefit the offshore wind energy industry by reducing risk and logistical complexities associated with sourcing components internationally while creating local jobs and economic benefits.

Despite the potential advantages to a variety of stakeholders, the pathway to a self-sufficient domestic supply chain involves significant obstacles, including:

- Uncertainty around the deployment pipeline makes it challenging to develop new supply chain facilities as the return on investment is unclear. This lack of clarity is exacerbated by the substantial cost and long lead times required to develop or upgrade new manufacturing facilities, ports, or vessels.
- Local content requirements are not designed to incentivize collaborative solutions that involve multiple states, leading to compartmentalized and suboptimal development of the supply chain.
- The readiness level of existing domestic suppliers to pivot to the offshore wind energy industry is not well understood. Furthermore, the ability to manufacture a number of critical components is not currently available in the United States.
- Developers could choose to source major components from supply chains in Europe or Asia instead of a domestic supply chain, although this might introduce additional risk associated with the reliability of component delivery, the ability to qualify for U.S. tax benefits or other incentives, and competition with international projects for orders.

This report is the first of a two-part study funded by the National Offshore Wind Research and Development Consortium that comprehensively evaluates how a domestic supply chain that leverages existing capabilities could be developed to support the deployment pipeline required to reach the national offshore wind target of 30 GW by 2030.

1.2 Previous Offshore Wind Supply Chain Analyses in the United States

There have been a number of previous studies that evaluate the demand placed on the offshore wind energy supply chain in the United States. The first comprehensive evaluation was conducted by Navigant Consulting, Inc. on behalf of the U.S. Department of Energy (DOE) (Hamilton et al. 2013). The report projected supply chain and workforce demand under varying deployment scenarios and discussed challenges and opportunities related to market entry in the United States for component suppliers. Hamilton et al. (2013) identified several key themes that remain relevant today, including the need for a stable deployment pipeline and streamlined regulatory environment to incentivize investment in new manufacturing facilities; the difficulties in manufacturing large-scale, offshore wind-specific components; the need for new ports, vessels, and transmission infrastructure; and the anticipated competition with Europe and Asia to access global supply chains.

McClellan (2019) looked at the potential capital investment required to deploy 18.6 GW of offshore wind energy on the Atlantic Coast by 2030 and estimated that nearly $70 billion in revenue could be available to businesses manufacturing primary components for the offshore wind supply chain. The report was updated by the Special Initiative on Offshore Wind (2021) to include development and operational expenditures and to reflect an updated deployment pipeline, resulting in an increase to almost $109 billion in available revenue to the supply chain. Those reports also project annual forecasts of major component demand and associated capital expenditures.

A supply chain analysis of the national offshore wind energy target was conducted by Lantz et al. (2021) to provide information to DOE on the impacts of the 30-GW target. The authors used a capacity expansion model to evaluate deployment scenarios through 2030 and 2050 under a range of power sector conditions, and then characterized the capital expenditures, quantities of key materials, number of WTIVs, magnitude of port upgrades, number of new manufacturing facilities, and number of new jobs that would be required to support those buildout scenarios. This analysis was independent of the Biden administration's work to establish the 2030 and 2050 offshore wind energy targets of 30 GW and 110 GW, respectively, and considered the potential implications of achieving the goals. Additional analyses of the national offshore wind energy target have been conducted, often highlighting how the limitations of the existing supply chain may constrain the ability of the offshore wind industry to reach 30 GW of deployment (IHS Markit 2021).

In addition to national-level supply chain analyses, several detailed state-level analyses have been conducted to assess the role that an individual state can play in the domestic offshore wind energy supply chain. North Carolina, Virginia, Massachusetts, New York, and Rhode Island have released individual or cooperative studies that demonstrate their individual manufacturing, infrastructure, or policy advantages and make recommendations for how each state can increase their presence in the offshore wind industry (Grace et al. 2017; BVG Associates 2018; Blanch et al; 2021). In some cases, supply chain assessments focus on more specific county-level impacts, such as the value of developing a floating wind port in San Luis Obispo county (Hamilton et al. 2021). Recommendations typically include supporting existing suppliers as they transition to the offshore wind energy industry, encouraging regional collaborations with other states, providing clarity around the deployment pipeline, strengthening port assets, and expanding workforce development opportunities.

1.3 Study Scope

In this two-part study, we combine the approaches of bottom-up, state-level, supply chain evaluations with national-level deployment analyses to comprehensively evaluate how a new domestic supply chain can build on the strengths of existing suppliers and manufacturers. We use an up-to-date and peer-reviewed deployment pipeline that reflects a realistic component demand schedule for finished components as well as the underlying subassemblies and subcomponents. By comparing this component demand with the current capabilities of today's manufacturers, we will evaluate the readiness level of the existing supply chain to develop scenarios for a future, entirely domestic supply chain.

This report characterizes the high-level deployment, workforce, and component requirements that need to be achieved by a domestic supply chain to reach the national offshore wind energy target of 30 GW by 2030. Our analysis focuses on the manufacturing capabilities and associated installation infrastructure (e.g., ports and vessels) required to reach the goal, and does not consider related aspects of the supply chain, such as sourcing raw materials or service and operation activities, in great detail. We also do not consider other factors that will impact the United States' ability to achieve the 30-GW target, such as uncertainty surrounding the permitting process and the lack of available transmission infrastructure. Those areas will require further study to understand their impact on achieving the national offshore wind energy target. Furthermore, we expand on previous supply chain analyses to consider not only the finished components for an offshore wind energy project but also the tiers of subassemblies and subcomponents. For this study, we define the following tiers of offshore wind components:

- **Tier 1: Finished components**. Finished components are the major products that are purchased by an offshore wind energy project developer, such as the wind turbine, foundation, or cables. Tier 1 suppliers contract directly with the project developer.
- **Tier 2: Subassemblies**. Subassemblies are the systems that have a specific function for a Tier 1 component, which may include subassemblies of a number of smaller parts, such as a pitch system for blades. Tier 2 manufacturers contract with Tier 1 suppliers as a subcontractor or vendor.
- **Tier 3: Subcomponents**. Subcomponents are commonly available items that are combined into Tier 2 subassemblies, such as motors, bolts, and gears. Tier 3 manufacturers are typically vendors that provide components to Tier 2 suppliers.
- **Tier 4: Raw materials**. Raw materials, such as steel, copper, carbon fiber, concrete, or rare-earth metals, are directly processed into Tier 2 or 3 components. In this study, we do not focus on Tier 4 materials except for select components that require critical commodities or materials that are particularly challenging for the supply chain.

In this report, we present:

- A deployment pipeline that demonstrates the pathway to 30 GW, the associated demand for major fixed-bottom and floating offshore wind components (e.g., wind turbines, foundations, cables, substations), and the vessel and port requirements to support those installation activities.
- A series of sensitivity analyses showing how the demand for components, ports, and vessels changes for different technology pathways and availability of the global supply chain.
- An estimate of the total number of jobs that would be required to support the deployment scenarios under varying levels of assumed domestic content.
- A detailed list of the Tier 1, 2, and 3 components (i.e., finished components, subassemblies, and subcomponents) required to construct fixed-bottom and floating offshore wind energy projects.
- A discussion of critical path components that represent a significant challenge, bottleneck, or risk for a future domestic supply chain.

The study results provide a basis for a follow-on report, scheduled for publication in 2022, which will convey a bottom-up assessment of the readiness level of the existing supplier network and how a domestic supply chain could be developed to take advantage of their capabilities. Although this supply chain road map will identify challenges and risks facing the development of a domestic supply chain, our primary goal is to highlight the opportunity for domestic manufacturers, communicate pathways for suppliers to get involved in the offshore wind energy industry, and determine the collective benefits that can be realized if a domestic supply chain is achieved.

2 The U.S. Project Pipeline

2.1 Objective and Scope

Evaluating the supply chain demand needed to meet the national offshore wind energy target of 30 GW by 2030 first requires establishing a realistic estimate of the project deployment pipeline and evaluating the sensitivity of this pipeline to potential bottlenecks. This pipeline incorporates both the overall project installation schedule and the annual installed capacity. This section focuses specifically on how effectively the current project pipeline meets the 30-GW target and highlights potential supply constraints the domestic offshore wind energy industry is facing. We demonstrate how bottlenecks in the European supply chain may impact the installation rate of U.S. projects, which may limit the ability of the industry to install 30 GW by 2030. In this section, we will:

- Detail the U.S. offshore wind energy project development timelines, including existing and anticipated lease areas throughout the Atlantic, Pacific, and Gulf of Mexico coasts
- Qualitatively identify and model the impact of potential supply constraints on the U.S. project pipeline

2.2 Approach and Method

The goal of our approach is to estimate how currently announced lease areas and wind energy areas (WEAs) will be developed into operational projects. As part of this, we characterize a hypothetical, but likely, deployment rate after 2030 that includes additional capacity that will be made available through the Bureau of Ocean Energy Management's (BOEM's) anticipated leasing of the Gulf of Mexico, Central Atlantic, California (beyond the already-announced Morro Bay and Humboldt WEAs), Oregon, Hawai`i, and Gulf of Maine regions between 2022 and 2025 (BOEM 2021). To evaluate the U.S. deployment pipeline, we:

- Collected publicly available data on offshore wind lease areas and WEAs awarded by BOEM and supplemented this with information on state-level offshore wind policies and objectives along with proprietary information provided directly by project developers
- Developed technology assumptions about wind turbine rating, project characteristics, vessel spreads, and supply ports between 2022 and 2035 and assigned those assumptions to each project in the pipeline
- Identified the most likely commercial operation date (COD) for each project based on the current permitting status and defined the time frame for manufacturing, transporting, and installing major components; this time frame assumes that most major components are sourced from European supply chains as limited manufacturing capacity exists in the United States
- Aggregated all projects to provide a cumulative deployment pipeline showing the annual deployment of offshore wind energy, including the demand for Tier 1 components, vessels, and port infrastructure
- Reviewed the assumptions, methodology, and results with key regulatory agencies and stakeholders, and updated the approach to reflect comments from those groups.

2.3 Overview of Planned U.S. Projects

The deployment pipeline used in this study is based on the list of project characteristics defined by Musial et al. (2021), with some modifications to individual CODs or capacities based on proprietary information provided by project developers. The development pipeline includes installed projects, projects under construction, projects engaged in permitting, all other leased areas, and WEAs that BOEM has announced will be leased for offshore wind energy development in the near future. The pipeline also includes the WEAs comprising the New York Bight (excluding Fairways North and South), which will be auctioned in February 2022.[3] We only included the Wilmington East WEA from the Carolina coast as all other WEAs and Call Areas in the region are on hold, subject to executive withdrawal from leasing between 2022 and 2032 (shown in Figure 1). Wilmington East is expected to be leased in 2022 (BOEM 2021).

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[3] The New York Bight wind energy areas were converted to lease areas and auctioned in February, 2022, as this report was in the publication process.

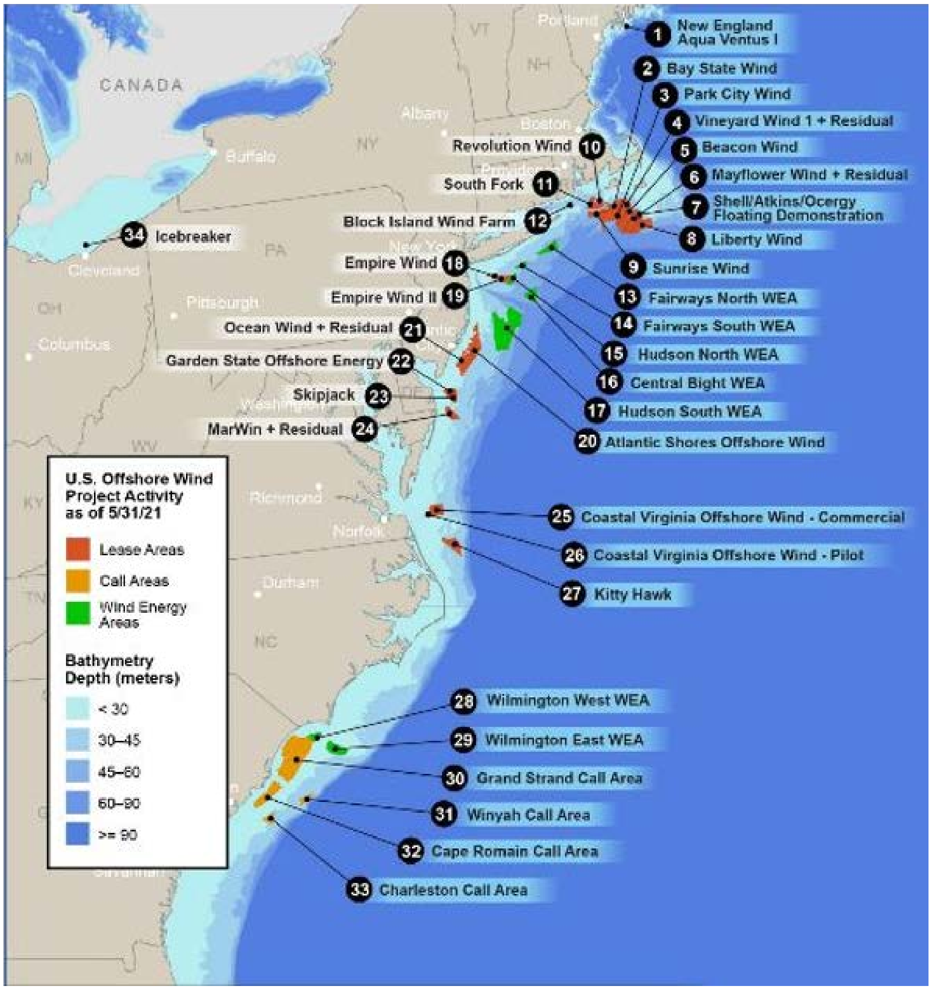

Figure 1. U.S. Atlantic Coast offshore wind pipeline and WEAs included in this study. *From Musial et al. (2021)*. Fairways North, Fairways South, Hudson North, Central Bight, and Hudson South comprise the New York Bight areas. Wilmington West, Grand Strand, Winyah, Cape Romain, and Charleston are not considered as existing WEAs in this study as they are on hold, subject to executive withdrawl from leasing between 2022 and 2032.

BOEM has also announced its intention to move forward with the Morro Bay and Humboldt WEAs (376 and 207 square miles, respectively). The Morro Bay WEA removed the East Extension from the original Call Area when it was created in November of 2021 (BOEM 2021b). Those areas are expected to bring at least 3.0 GW of electricity to the grid. BOEM anticipates leasing both areas in late 2022 (BOEM 2021a). Additional proposed leasing by BOEM in the Gulf of Mexico, Central Atlantic, Oregon, and Gulf of Maine regions is included in the pipeline after 2030. Finally, we include additional leasing in the Carolina Long Bay, Hawai`i, and California regions after 2030. Although these areas have not yet been announced by BOEM, they have all been the focus of offshore wind planning activities and have the potential to be developed in the 2030s.

Figure 2. U.S. West Coast Call Areas. ***From Musial et al. (2021)*****. The Morro Bay Call Area (including the West Extension) was converted to a WEA in November 2021 (BOEM 2021b).**

Other possible areas for offshore wind energy development, including the Great Lakes and the South Atlantic, have not been included in this study. Offshore wind development remains in a very early stage in those regions and therefore, its influence on the outcomes of the demand analysis would likely have little impact on the 30-GW-by-2030 goal.

Overall, the results of our assessment indicate that the total capacity of U.S. offshore wind energy projects will increase from 42 MW in 2021 to 30.1 GW by 2030 and 59.8 GW by 2035.[4] This assessment assumes that 2.0 GW of the New York Bight lease area would achieve COD by 2030, with the remaining 4.1 GW achieving COD between 2030 and 2035. That assumption may be conservative, and it is certainly possible that development of the New York Bight could be accelerated, offering an alternative path to reaching 30 GW by 2030. Those deployment numbers do not consider potential delays that may be caused by constrained supply chains, infrastructure limitations, or regulatory challenges, which could create significant roadblocks that prevent the industry from reaching the national offshore wind energy target. One of the goals of this study

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[4] The 2035 deployment figure includes anticipated capacity from BOEM's proposed leasing schedule.

(and the follow-on report) is to identify ways to reduce those risks and improve the likelihood of realizing the full potential of the available lease areas.

2.3.1 Project Assumptions and Boundaries

Given the limited information available on the construction and operation methodology for the offshore wind developments being investigated, we made a number of assumptions to define the boundaries and limitations of this study, including:

General Offshore Wind Energy Development

- Our analysis focuses on the 2030 time horizon, but in many cases we report results through 2035 to include the buildout of all projects in the pipeline.
- All existing projects and awarded lease areas in U.S. waters are included in this study. We do not report the capacities or CODs of these projects as our estimates draw from proprietary data from project developers.
- The New York Bight and Wilmington East WEAs on the East Coast, and the Humboldt and Morro Bay WEAs on the California coast, are included in this analysis, given BOEM has announced plans to auction leases in these areas in 2022 (BOEM 2021a).
- Several developers that have obtained site control of lease areas have announced projects that do not fill the entire lease area. As a result, we assume that 65% of any remaining acreage not currently in use for the primary development would be available for project expansion; unless more specific information was available.
- Anticipated deployment beyond 2030 includes BOEM’s proposed leasing of the Gulf of Mexico, Central Atlantic, Oregon, and Gulf of Maine regions (BOEM 2021a), as well as deployment in regions of interest such as Carolina Long Bay, Hawai`i, and additional California areas. At the time of this writing, BOEM has not identified the size (and, therefore, the available capacity) in those regions. We have developed top-level assumptions about the capacities, CODs, and substructure topologies of the different regions (see Table 2). It is important to note that this anticipated deployment scenario is only one possible future for the offshore wind energy industry in the United States. The industry could evolve in many different directions which would impact the demand on the supply chain; however, despite this uncertainty, we still define one potential scenario to identify the requirements for a domestic supply chain.

Table 2. Anticipated Leasing Deployment Assumptions

Location	COD	Fixed-bottom or floating?	Project capacity, MW
Gulf of Mexico	2031	Fixed-bottom	1,500
	2032	Fixed-bottom	1,000
	2035	Floating	1,500
Central Atlantic	2033	Fixed-bottom	1,500
	2034	Fixed-bottom	1,000
	2034	Floating	1,000
Oregon	2034	Floating	1,500
Gulf of Maine	2031	Floating	144
	2033	Floating	1,200
Carolina Long Bay	2032	Fixed-bottom	1,000
	2033	Fixed-bottom	1,000
Hawai`i	2032	Floating	500
California	2033	Floating	1,000
	2033	Floating	1,000
	2035	Floating	1,000
	2035	Floating	1,000
	2035	Floating	1,000

Technology Assumptions

- We assume average wind turbine power ratings of 12 MW for projects with CODs through 2025, 15 MW for projects with CODs from 2026 to 2030, and 18 MW for projects with CODs beyond 2030. Table 3 provides basic wind turbine parameters for the generic models. Parameters such as blade length, tower height, and nacelle and tower mass are important when evaluating which installation vessels can be used. We assume a nominal spacing of 1 nautical mile between adjacent wind turbines within the lease area boundary.
- We consider three types of foundations for fixed-bottom projects: monopile, jacket, and gravity-based (gravity-based foundation, or GBF). We assign those foundations to individual projects in the pipeline based on site conditions and announced supply chain investments; for example, we assign monopiles to projects with average water depths less than 40 meters (m) and use GBFs for selected projects in the New York Bight as there has been some interest in developing GBF facilities in the area. We assume that all floating projects installed by 2035 will use a semisubmersible platform.
- We assume that projects require one offshore substation per 800 MW of capacity, and that projects located over 100 kilometers (km) from shore use high-voltage direct current (HVDC) export systems (projects closer to shore use high-voltage alternating current [HVAC]).

- The length of static array cable length is the sum of the distance between wind turbines plus twice the water depth, with an overall 10% margin added. We also assume dynamic array cables are suspended 250 to 300 m below the surface to avoid interference with vessels.
- We assume one export cable route per substation with a length equal to the distance between the offshore substation and landing location (if known) or closest point at shore.
- The simple technology assumptions that we use in this report may differ from actual technology pathways. This difference could be due to faster than expected adoption of new innovations (for example, 18-MW turbines becoming available before 2030) or constraints in the supply chain driving alternate technology choices (for example, commercialization of superconducting generators which would eliminate the need for rare earth metals [Veers et al. 2020]).

Table 3. Wind Turbine Technology Assumptions

COD	Rated Power (MW)	Rotor Diameter (m)	Blade Length (m)	Nacelle Mass (tonnes)	Tower Height (m)	Tower mass (tonnes)
Through 2025	12	215	107	600	127	700
2026 to 2030	15	238	116	677	136	800
After 2030	18	260	127	812	147	939

Installation Logistics

- Fixed-bottom foundations are installed with either a heavy-lift vessel (HLV) or a WTIV, except in the case of gravity-based foundations, which can be floated and towed to the site.
- On the East Coast, the “construction window” (when construction will be allowed/feasible) is assumed to be limited to 8 months of the year (67%) based on a combination of weather restrictions and protected wildlife activity.
- For California, the construction window is limited to 9 months of the year (75%).
- We assume that any vessel with a U.S. flag complies with the Jones Act, meaning that it can transport components between a U.S. port and an offshore wind energy project site. No Jones Act-compliant WTIVs currently exist, although one is under construction.
- We assume that U.S. projects along the East Coast will use feeder barges to deliver components to WTIVs that remain on-site, eliminating the need for WTIVs to travel to/from the staging port. This strategy both allows the use of non-Jones-Act-compliant WTIVs and reduces costs, because WTIVs are considerably more expensive than feeder barges; however, it does present a challenge as it requires potentially risky ship-to-ship operations at sea.
- Vessel parameters (Table 4) are based on a database maintained by DNV that tracks base port, Jones Act compliance, payload, length, and other capabilities for WTIVs, feeder barges, HLVs, service operation vessels (SOVs), crew transfer vessels (CTVs), cable lay vessels (CLVs), and anchor handling tug supply vessels (AHTSs). Those capabilities dictate how many vessels are required to meet the annual pipeline demand.

Table 4. Vessel Parameters

Parameter	Value
WTIV per turbine (only)	36 hours (hr)
WTIV per foundation (only)	36 hr
HLV per offshore substation	240 hr
Feeder barge minimum size	90 m
Feeder barge transit time	12 hr
Feeder barge time on-site	108 hr
Wind turbine sets per barge	3
Barge mobilization time	36 hr
CTVs, construction year	2 units
CTVs, year 1	2 units
CTVs, years 2–25	1 unit
CLV speed	4 km/day
CLV mobilization/demobilization time	20 days

2.3.2 Demand Scenarios

We considered five demand scenarios, as described in Table 5, which focus on Tier 1 supply chain components. The baseline scenario is the direct output of the modeled total demand, including offshore wind energy development on both the East and West Coasts, without adjustment. It assumes every project is constructed per the developers' schedules, with no limitation on turbine supply or vessel availability. The baseline scenario includes awarded and soon-to-be-awarded lease areas as well as anticipated leasing from BOEM's proposed leasing schedule. Deployment associated with the latter lease areas is clearly delineated on the deployment plots to identify the more uncertain results from unannounced lease areas. The moderate and significant supply constraints scenarios model various levels of limitation specific to wind turbine supply for East Coast projects, in which the availability of components from the European supply chain is constrained to 4 GW and 2 GW per year, respectively. The uniform foundation market share scenario explores the impact of altering the mix of foundation types to 33% GBF, 33% monopile, and 33% jacket, again for the East Coast only. The monopile-only scenario assumes that 100% of the foundations on the East Coast are monopiles.

Table 5. Pipeline Scenarios

Scenario	Description	Foundation Type
Baseline	Represents the component demand compiled from all project data, leases, and WEAs included in the study. Development timelines were based on project data or estimated based on best-available information.	Fixed and Floating
Moderate supply constraints	Assumes the supply of wind turbines from Europe is sufficient to largely meet the U.S. demand, with exports up to 4 GW to the United States annually. In the event limits are reached, unmet demand is shifted to future year(s). This constraint does not impact the floating pipeline.	Fixed
Significant supply constraints	Assumes the ability of the European supply chain to meet the U.S. demand is constrained to 2 GW per year, further shifting demand to future years. This constraint does not impact the floating pipeline.	Fixed
Uniform foundation market share	Same as the baseline scenario, but assumes that 33% of foundations are GBF, 33% monopile, and 33% jacket.	Fixed
Monopile-only	Same as the baseline scenario but assumes that 100% of foundations are monopiles.	Fixed

2.4 Project Pipeline Scenarios

We aggregated project details by year to show the Tier 1 component demand over time, during three development phases: (1) procurement and manufacturing, (2) transport and storage, and (3) installation and commissioning (COD). Figures showing only the COD phase for each scenario are discussed in Sections 2.4.1 through 2.4.3.

2.4.1 Baseline Scenario

The baseline scenario is based on pipeline projections without any consideration of supply chain or vessel limitations. The annual installed capacity is shown in Figure 3, with colored bars showing the relative fixed-bottom and floating deployment and a line graph displaying the cumulative installed total. We include on the plot the awarded and soon-to-be-awarded lease areas (including the New York Bight, Carolina Long Bay, and California) as well as hypothetical capacity that could be introduced by additional BOEM leasing between 2022 and 2025 (BOEM 2021a). Although the capacities of these anticipated lease areas have not yet been announced by BOEM, we assume that they are sufficient to set the U.S. offshore wind energy industry on a pace to reach or exceed the 2050 deployment target of 110 GW. Table 2 lists our assumptions for the deployed fixed-bottom and floating capacity in these regions. We will use this deployment pipeline that includes BOEM's existing and anticipated lease areas as the baseline scenario for the remainder of this report. Again, this scenario is not a forecast of offshore wind energy deployment in the U.S. but is one possible pathway along which the industry could evolve.

Under this scenario, 30.1 GW of offshore wind energy can be installed by 2030, which would successfully fulfill the national offshore wind energy target. Meeting this target would require developing the New York Bight and California WEAs by 2030 even though these areas are not expected to be leased until 2022 (BOEM 2021a). The baseline scenario includes a total of 27.6 GW of fixed-bottom projects installed on the East Coast and 2.5 GW of floating projects installed on the West Coast by 2030. Installing 2.5 GW of floating wind energy off the coast of California by 2030 is a relatively ambitious timeline given that the technology is less developed than fixed-bottom offshore wind and that leasing will not occur until the end of 2022 (BOEM 2021a); however, the state of California has passed legislation to support the growth of offshore wind energy and aspires to be a global leader in the field (California 2021). As such, we assume that it is possible to launch commercial-scale offshore wind energy in California before the end of the decade although it would require significant work in developing the technology, supply chain, and regulatory and permitting processes. The total deployment rises to 59.8 GW by 2035.

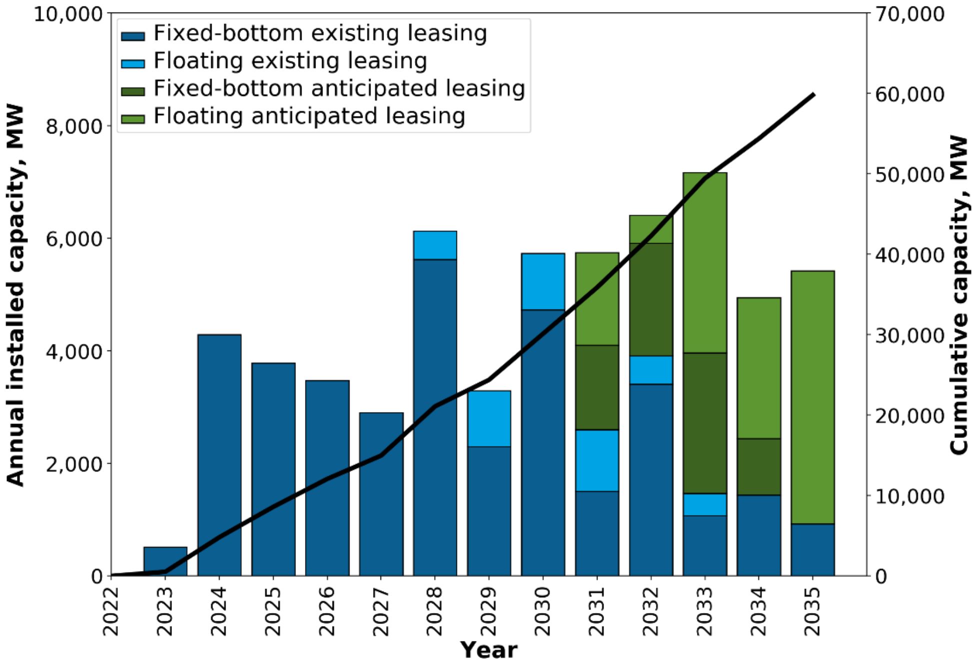

Figure 3. Annual and cumulative installed capacity for existing and anticipated lease areas. With no supply chain constraints, 30.1 GW are expected to be installed by the end of 2030. The Bureau of Ocean Energy Management's anticipated leasing of new areas from 2022 to 2025 will be required to maintain a consistent deployment rate after 2030.

The pipeline shows demand reaching peaks of 6.1 GW in 2028 and 5.7 GW in 2030, after which the pipeline shows a relatively consistent annual deployment of between 4.9 and 7.1 GW. A consistent deployment rate would be beneficial for developing a domestic supply chain as the key components of the supply chain (i.e., manufacturing facilities, ports, vessels, and workforce) could be sized for a predictable demand. Achieving a sustainable demand and supply chain would require BOEM's planned leasing to establish this consistent deployment rate throughout the 2030s, which would make it easier to invest in new supply chain assets with a reliable return on investment. Without the anticipated leasing to expand deployment after 2030, annual installed capacity would drop to 1.2 GW in 2031 and remain low in the 2030s, presenting a significant challenge to building new supply chain facilities in the United States. We will present further analysis on the demand for Tier 1 manufacturing facilities in the next phase of this study.

Figure 4 shows the annual demand for major components, including wind turbines, foundations, cables, and vessels. The demand is based on the deployment in the baseline scenario, including the anticipated deployment after 2030; we do not differentiate between awarded and anticipated component demand for simplicity in the figures. The annual demand for those components generally follows the trends of the overall installation pipeline, although the components will be manufactured 1–2 years prior to project installation. Reaching the 30-GW national offshore wind energy target would require over 2,100 wind turbines to be installed along the East and West coasts, primarily comprising around 1,500 15-MW wind turbines. The same number of foundations are required, with monopiles achieving the dominant market share with nearly 1,300 installed by 2030. Over 6,200 km of array cables need to be installed along with over 5,200 km of export cables (both static and dynamic). Finally, at least 5 WTIVs could be required annually to install foundations and wind turbines along with a maximum of 10 feeder barges, 58 CTVs, 11 SOVs, and 4 CLVs. Although most vessels are focused on the installation phase of a project, the demand for CTVs grows over time as they service the increasing number of operating projects. We assume that feeder barges are readily available, although no Jones-Act-compliant WTIVs currently exist and only 2 WTIVs exist that can meet the size requirements for installing 15-MW turbines. This global supply of vessels will barely meet the U.S. demand even if they exclusively supported the U.S. market (whereas realistically they will be employed for international projects as well).

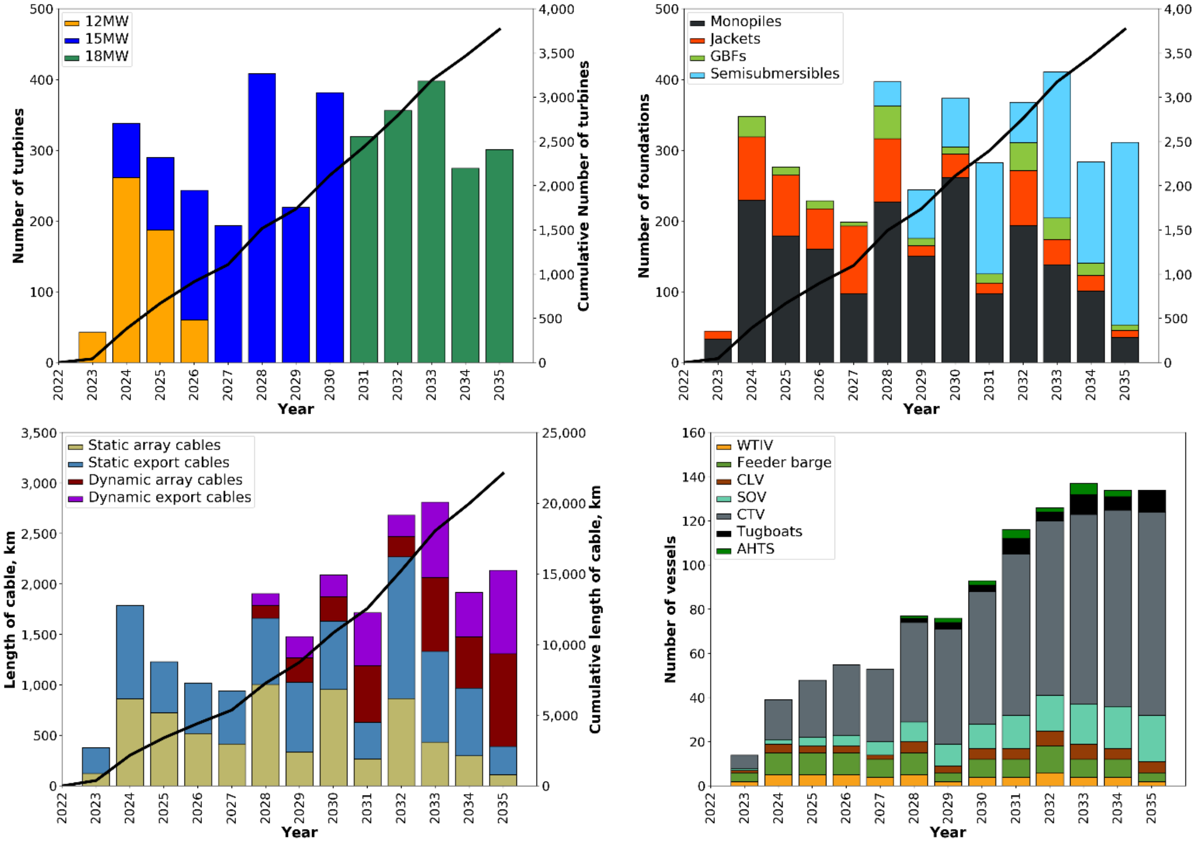

Figure 4. Annual and cumulative component demand for (clockwise from top left) wind turbines, foundations, vessels, and cables for the baseline scenario, including existing and anticipated lease areas. A wind turbine includes three rotor blades, one nacelle, and one tower.

The results in Figure 4 present the required demand to achieve the national offshore wind energy target but do not specify if the components come from European or domestic supply chains. Projects installed in the early part of the decade will necessarily rely on international supply chains as domestic Tier 1 manufacturing capabilities do not exist. As announced manufacturing facilities (see Table 1) begin to come online, more production will shift to the U.S.; however, these facilities will likely not have sufficient capacity to support the full component demand outlined in Figure 4. The second phase of the supply chain road map study will provide further analysis into the number of required Tier 1 facilities to support the deployment pipeline and will characterize how the amount of domestic content is expected to grow over time.

2.4.2 Constrained Supply Chain Scenarios

At the writing of this report, the United States does not have the ability to supply, transport, or install the majority of components required to build out the offshore wind infrastructure needed to achieve 30 GW by 2030. Until a domestic supply chain is developed, the country will need to rely largely on European manufacturers to supply projects along the East Coast, where the first U.S. offshore wind projects are being installed. For the West Coast floating projects, components will likely be sourced from Asia. In this section, we consider the impact of reduced European supply under the assumption that no domestic manufacturing capabilities are developed to provide a worst-case estimate of how overall deployment figures could be impacted by bottlenecks in European supply.

Although Europe has advanced offshore wind supply chains, it also plans to greatly increase offshore wind energy deployment in the 2020s; as a result, European facilities may not be able to support the demand of U.S. projects over the same time frame. An offshore wind construction forecast in Europe has been developed by WindEurope and is shown in Table 6. Europe has 25 GW of offshore wind energy installed as of the end of 2020, but to reach its target of climate neutrality by 2050, the country needs to increase its net capacity by a factor of 12, to 300 GW. By the end of this decade, the volume of offshore wind energy in Europe is targeted to rise to over 112 GW. By 2026, European projected annual demand for offshore wind installations will more than triple to nearly 12 GW annually. We provide a more in-depth discussion of major European suppliers and their potential role in supporting the U.S. deployment pipeline in Appendix C.

Table 6. Offshore Wind Outlook in Europe From 2021 to 2030 (Source: WindEurope July 2021)

Year	European Union (EU) Cumulative Capacity (GW)	EU Planned Capacity (MW)	EU Planned Installations (# of Wind Turbines
2020	25	0	0
2021	28.7	3,650	468
2022	33.8	5,106	560
2023	38.0	4,204	432
2024	43.7	5,788	508
2025	53.5	9,719	845
2026	65.3	11,795	873
2027	77.1	11,795	873
2028	88.9	11,795	873
2029	100.6	11,795	873
2030	112.4	11,795	873

A complete assessment of the demands that the European pipeline will place on existing supply chain facilities is outside the scope of this study; however, the perspectives we have gathered from industry practitioners suggest that the capability of European suppliers to support projects in both the United States and Europe without creating major delays poses a significant risk to the national offshore wind energy target. We consider the impact of this potential bottleneck from European manufacturers on U.S. deployment pipeline in two scenarios representing moderate and significant supply constraints. Again, this assumes that no domestic manufacturing exists to pick up the slack in the supply chain. The supply constraints in both scenarios are applied to awarded and soon-to-be-awarded East Coast lease areas as these are the projects that are most likely to rely on European suppliers if domestic solutions are not available. The baseline deployment rate is used for floating projects on the West Coast and projects from BOEM's anticipated leasing schedule. If similar bottlenecks materialize in Asian supply chains, these West Coast projects could also be impacted and total deployment would be reduced.

The moderately constrained scenario assumes that the European wind turbine OEMs only have sufficient production capacity to export up to 4 GW of wind turbines per year to the United States. The significantly constrained scenario assumes that only 2 GW of wind turbines can be imported annually to the United States. Both scenarios assume that when a new turbine model is introduced, it can take up to 2 years to ramp up full-scale production of that model. The results of these deployment constraints are shown in Figure 5.

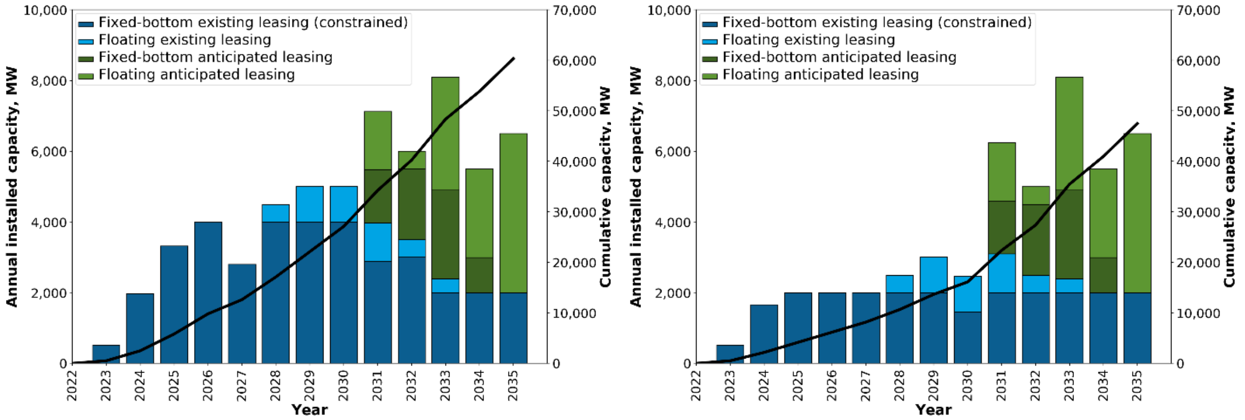

Figure 5. Annual and cumulative installed capacity for moderately (left) and significantly (right) constrained European supply scenarios. The constraints on the supply chain reduce the installed capacity in 2030 to 27.1 GW and 16.1 GW, respectively.

Reduced supply from Europe limits the annual installed capacity in the United States and delays projects that are unable to receive wind turbines on time. As a result, the deployment pipeline gets pushed, with more projects being built in the 2030s. Both scenarios miss meeting the national offshore wind energy target, with the moderately and highly constrained scenarios achieving 27.1 GW and 16.1 GW by 2030, respectively.

The annual demand for major components for both scenarios is plotted in Figure 6. The trajectory of individual component demand follows the overall pipeline, although those components would be manufactured 1–2 years in advance of the installation dates.

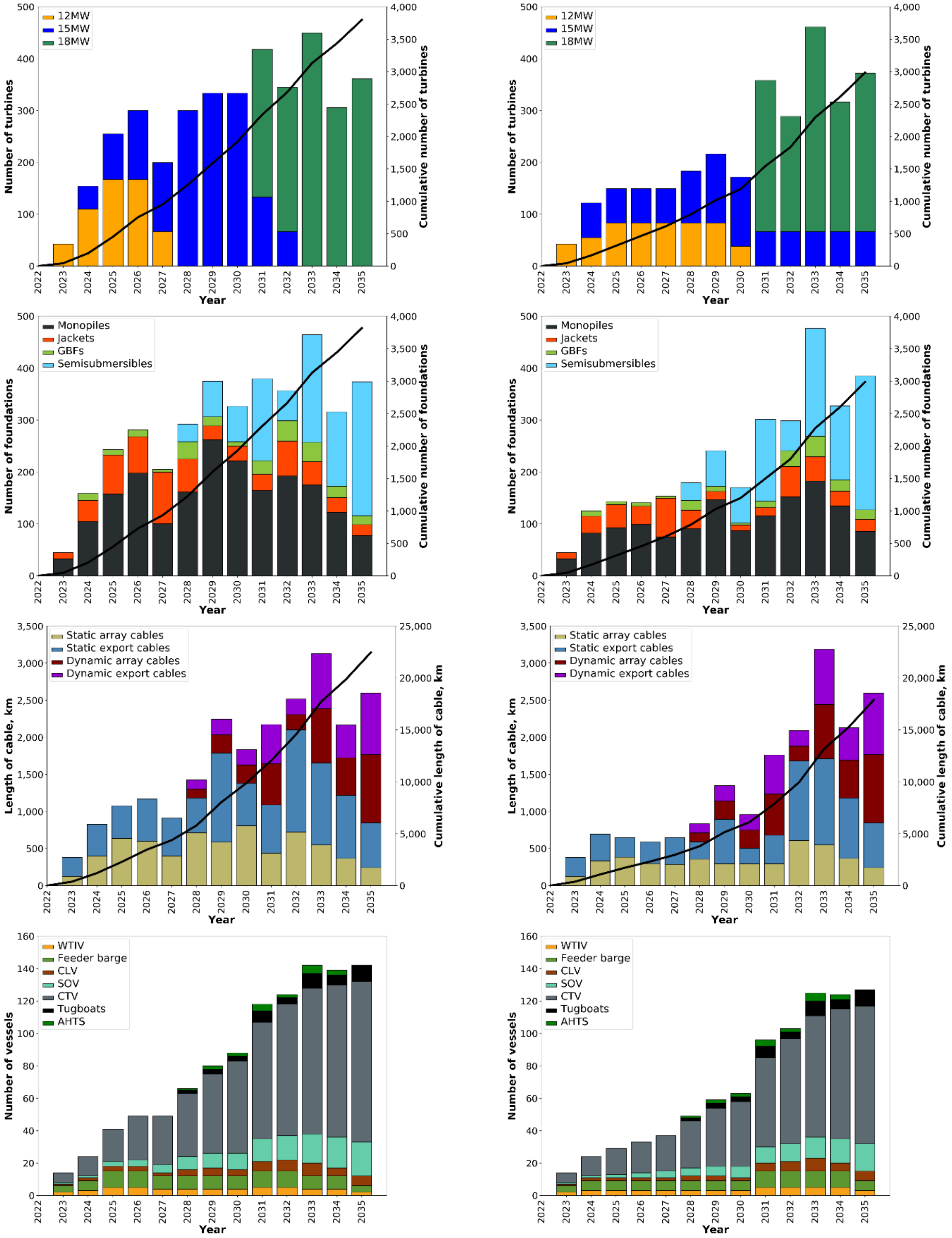

Figure 6. Annual and cumulative component demand for the moderately (left) and significantly (right) constrained scenarios. Component plots show (from top to bottom) wind turbines, foundations, cables, and vessels. A wind turbine includes three rotor blades, one nacelle, and one tower.

2.4.3 Uniform Foundation Market Share Scenario

For fixed-bottom offshore wind turbine installations, monopile foundations are the lowest cost substructure option in the majority of lease areas and are preferred when the geological conditions and water depth are appropriate. Approximately 65% of U.S. offshore turbines planned for the Atlantic Coast are likely to use monopile foundations. Another 25% are likely to be supported by jacket foundations. The remaining 10% of wind turbines could potentially be GBF or some other foundation design (e.g., tripod). This breakdown in fixed-bottom foundation types is based on the historical European market; however, it is possible that the U.S. market may develop a different foundation market share based on site conditions and local resources.

In this uniform foundation scenario, we conducted a sensitivity study on impact of assuming that 33% of all fixed-bottom wind turbines installed in the United States would employ GBFs (as opposed to the 10% assumption in the baseline). We simply modified the baseline scenario to change the overall market share of the different foundation types without adjusting the overall deployment. As shown in Figure 7, this affects the number of the individual foundations required per type as well as the number of WTIVs (as GBFs do not require WTIVs for installation). Because the overall deployment pipeline, number of wind turbines, and length of cable are not affected, we do not show those results. This scenario requires 622 of each type of fixed-bottom foundation and reduces the number of years in which the peak demand of 5 WTIVs is required; however, as GBFs comprise a relatively small fraction of the pipeline, this shift in foundation market share does not significantly alter the number of WTIVs required.

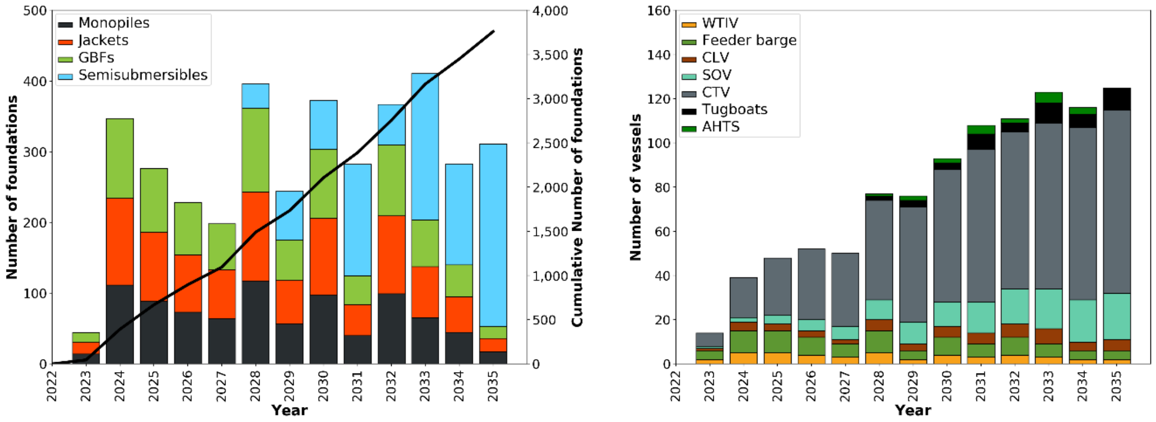

Figure 7. Annual and cumulative component demand for foundations (left) and vessels (right), assuming an even market share for monopiles, jackets, and GBFs

2.4.4 Monopile-Only Scenario

The final scenario takes a similar approach to the uniform foundation market share scenario but assumes that all of the fixed-bottom foundations installed in the United States are monopiles. This assumption represents a somewhat extreme case but, along with the uniform foundation market share scenario, helps to provide a bound on the types of vessels that would be required to support the deployment pipeline for a range of foundation types. The extensive track record of monopiles in Europe makes them an attractive and bankable design for U.S. projects, although more work is required to understand if they are an ideal solution for conditions in the U.S. As shown in Figure 8, this scenario increases the peak demand to 6 WTIVs and 12 feeder barges.

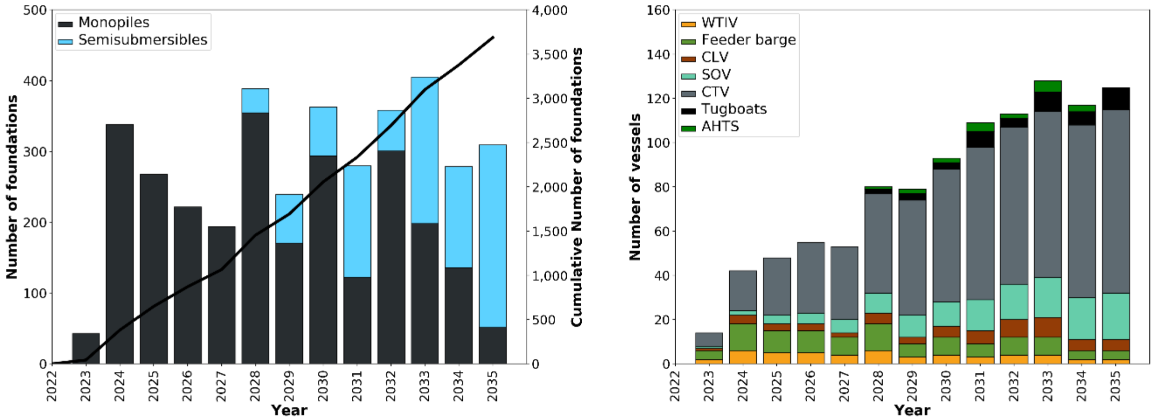

Figure 8. Annual and cumulative component demand for foundations (left) and vessels (right) assuming 100% market share for monopiles

3 U.S. Port and Vessel Assessment

The deployment pipelines in Section 2 will require substantial port and vessel investment, particularly as more manufacturing moves to the United States. In this section, we provide a high-level description of the ports that may contribute to the domestic offshore wind energy industry as well as the type of vessels that will help install projects. The port analysis highlights the key characteristics relative to offshore wind deployments, including both fixed-bottom and floating substructure configurations, such as berthage, laydown areas, manufacturing facilities, accessibility, and potential upgrade requirements including required channel dredging, bearing capacity reinforcement, and larger cranes. We evaluated the aggregate port facility needs for all projects in the total deployment pipeline and conducted a top-level assessment of the readiness of existing or announced port facilities along the East and West coasts.

3.1 Technical Port Parameters

Offshore wind energy project construction can involve four distinct phases that take place at a port:

- Storage/staging substructure and wind turbine components until needed
- Assembly of substructure and/or wind turbines
- Integration of each wind turbine/substructure unit (if being done quayside)
- Offshore staging, where any additional substructure equipment, such as mooring lines, are installed prior to delivering to the project site.

We derived the key port characteristics from the different wind turbine/substructure configurations established during project design and used these characteristics to specify minimum port requirements to support fixed-bottom or floating project construction. The configurations we considered as drivers for the most important port characteristics are:

- Substructure fabrication (whether at a manufacturing facility or at the port)
- Substructure assembly (applies particularly to floating offshore wind installations)
- Wind turbine integration and offshore staging.

Within each category, we considered the following technical parameters to evaluate the port readiness level:

- **Laydown area**: An area of a port that is potentially available for storing modular substructure components. The available laydown area can also be a key driver during substructure assembly and wind turbine generator/substructure integration depending on the buffer needs at the port. This port characteristic is necessary from the substructure fabrication phase to the wind turbine generator integration phase. While there are extensive laydown areas in ports such as the Ports of Los Angeles and Long Beach, they already host significant established industries. Therefore, it is not clear how much, if any, laydown area or berth space can be dedicated to offshore wind energy activities.
- **Quayside length**: Total length where vessels may dock. The total quayside length is subdivided into specific berths. This parameter can be a key driver for substructure fabrication and assembly, wind turbine integration, and load-out configuration. This is also considered one of the most limiting parameters for offshore wind energy deployments, as the

berth length costs at key ports for the industry can be quite high due to cross-industry competitiveness.

- **Berth depth**: Depth at quayside must be sufficient to accommodate all necessary activity and varies widely depending on project type (fixed or floating) and substructure design. For fixed-bottom installations, a berth depth of 12 m is considered adequate, although shallower berths can be accessed by feeder barges. Currently, most floating wind substructure technologies require a water depth of more than 12 m to integrate wind turbines up to 10 MW. However, this threshold value of 12 m can be mitigated to some extent using ancillary equipment to provide additional buoyancy, which is compatible with certain floating offshore wind substructure concepts.
    - As the industry evolves, rated capacity of wind turbines is expected to grow further, leading to increased size and weight. Therefore, the necessary depth at quayside for integration with the substructure is also expected to increase. As a result, developing the port infrastructure with this in mind is considered one of the main challenges for floating offshore wind. Table 9 and Table 11 show that many U.S. ports lack even the minimum 12-m depth requirement at quayside.
- **Channel depth**: Similar to berth depth, the minimum entry channel depth must be able to accommodate a draft of approximately 12 m, whether for a WTIV or an assembled floating substructure with a wind turbine unit. Shallower channels may still be functional for installation strategies that use feeder barges.
- **Bearing capacity**: The load-bearing capability of a laydown area or quayside. Ports that currently have available laydown area may still need to upgrade load-bearing capacity to be able to handle offshore wind components and activities such as lifting and assembly.
- **Air draft limit**: Refers to the maximum air draft (distance from the surface of the water to the highest point on a vessel) allowed at the port.

Additional parameters that were not included in this high-level assessment but that would be important to consider in a more detailed port evaluation include:

- Channel width[5]
- Heavy lifting crane capability
- Load-out equipment capability and availability
- Steel cutting and beveling; prebending and rolling; and longitudinal welding and assembly capabilities
- Dry dock availability.

3.2 Demand for Port Capacity

The port infrastructure needs of the offshore wind energy industry will depend on both the capabilities of individual ports as well as the types of components used for the project. In order to estimate the total demand for port capacity based on the baseline scenario, we consider the interactions with the individual projects in the pipeline with the marshalling port at which the

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[5] The navigation channel must be sufficiently wide to allow room to tow out a floating substructure. Most East Coast ports do not have sufficient channel width for floating foundations.

main elements of the project are shipped, stored, preassembled, and loaded onto installation vessels (or wet-towed in the case of floating projects). We exclusively focus on construction port requirements in this study, although it is important to remember that operation and maintenance (O&M) activities will require an increasingly more resources as the number of installed projects grows. In this section, we outline the project assumptions and estimated demand separately for East Coast and West Coast ports.

3.2.1 Demand for port berths

In order to assess the demand for port resources, we estimate the number of berths that are required to support the annual deployment pipeline, as they represent the interface between the port and the installation vessels. We used the following approach to estimate this aspect of the annual deployment pipeline, which roughly follows the methodology from Lantz et al. (2021):

- We derive the number of fixed-bottom port berths required directly from the number of active WTIVs, considering that for each WTIV, two feeder barges/vessels work concurrently to supply the vessel. We therefore assume an average of 1.5 berths per active WTIV to account for the potential standby or overlap of feeder barges in the port.
- We assume that a floating wind project requires a quayside length of 1,250 m to install 35 fully assembled wind turbines per year. This total quayside length is subdivided into separate berths for foundation assembly, wind turbine installation, and anchor/mooring marshalling (see Figure 10). We assume an average berth length of 180 m to calculate the total number of berths required to meet the annual demand. These berths do not necessarily need to be continuous and could even be located at separate ports.
- GBFs, cables, and offshore substations do not impact the marshalling port, as they are directly transported from the manufacturing facility to the project site.

This approach results in simple estimates of the total number of berths needed for each year in the pipeline (see Figure 9). This demand does not include additional space required for fabricating foundations or conducting O&M activities. Fixed-bottom offshore wind energy activities will require up to 8 dedicated berths for several years leading up to 2030, although the demand fluctuates along with the deployment pipeline. The expansion of floating wind deployment in the 2030s leads to a significant growth in demand for appropriate berths because each project effectively requires 3 berths for foundation assembly, wind turbine installation, and anchor/mooring marshalling.

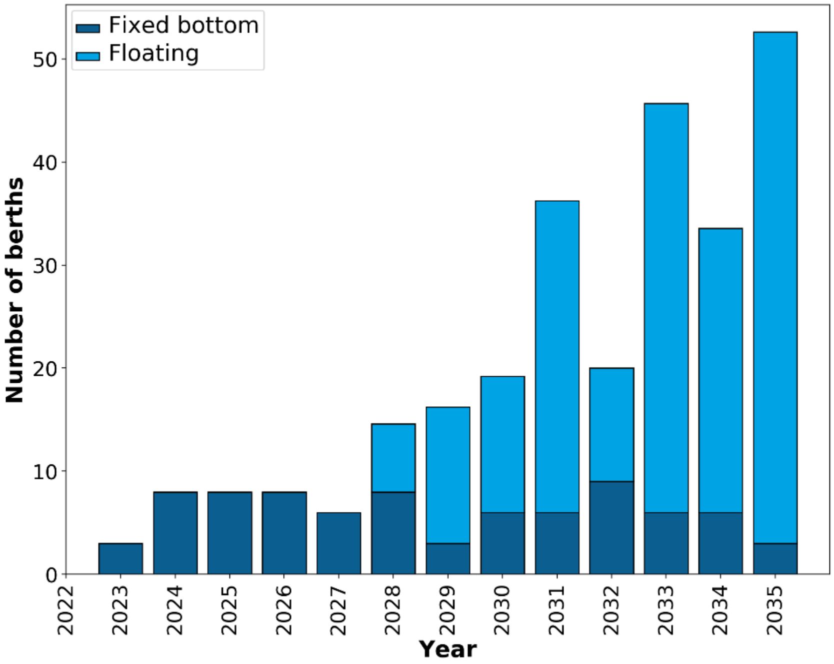

Figure 9. Annual demand for berths for the baseline scenario

3.2.2 Port requirements for fixed-bottom projects

The fixed-bottom projects that will be installed on the East Coast through 2030 will use a marshalling port for the installation of the foundation and the wind turbine, which we assume will be carried out in two consecutive phases. For each those phases, the Tier 1 foundation components (e.g., monopiles, transition pieces, jackets, and GBFs) and wind turbine Tier 2 components (e.g., blades, tower sections, and nacelles) will be delivered to the port, staged in the laydown area, loaded onto an installation vessel, and transported to the installation site. Therefore, the port needs sufficient storage space to maintain a large enough buffer of project components, strong enough bearing capacity to support the weight of large offshore wind components, and berths that are sufficiently wide and deep to accommodate the installation vessels. The port requirements are different for alternate installation vessel strategies. If the WTIV transits directly to the port to load out components, a deeper draft and longer berth are required, whereas using feeder barges to shuttle components between the port and the installation site can accommodate a shallower draft. In both cases, the vessel that docks at the port needs to be Jones-Act compliant. Table 7 lists the minimum requirements for a marshalling port that we consider in this analysis.

Table 7. Minimum Port Requirements for Fixed-Bottom Marshalling Activities

Parameter	Minimum Value
Draft (feeder barge)	6 –7 m
Draft (WTIV)	12 m
Air draft	150 m
Lay-down area[6]	25 acres
Quayside length	500 m
Bearing capacity[7]	15 tonnes (t)/square meter (m^2)

3.2.3 Port requirements for floating projects

The main construction activities happening at port to facilitate the construction of a floating offshore wind energy project are expected to be:

- Assembly of the floating foundation
- Assembly of wind turbines on the foundation
- Storing and marshalling the mooring lines and anchors in preparation for tow-out.

Each of those activities requires different infrastructure and may occur in different locations. However, unlike the fixed-bottom project construction activities that occur serially, the construction activities mentioned here mostly take place simultaneously. The wind turbine and semisubmersible platform are assembled on-site from components that are delivered by barge. The anchors and mooring lines are staged on-site but do not require further assembly prior to installation. Each of those components requires different berth lengths and depths along with different laydown areas and assembly facilities. The activities are depicted in Figure 10, which shows the space requirements and coordination among different phases if all activities were to take place at the same port. The minimum port requirements (assuming that all activities take place at the same port) are provided in Table 8. In this summary table, we use the berth requirements for the wind turbine assembly as these are the most constrictive of the three phases shown in Figure 10, but aggregate the required laydown area.

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[6] OEMs typically prefer 50 acres of laydown area, but will still marshal out of ports with as little as 25 acres. The smaller laydown area introduces additional logistical complexities for the project as fewer components can be stored at the port as a buffer against delays.

[7] Higher bearing capacities are required at quayside loading areas.

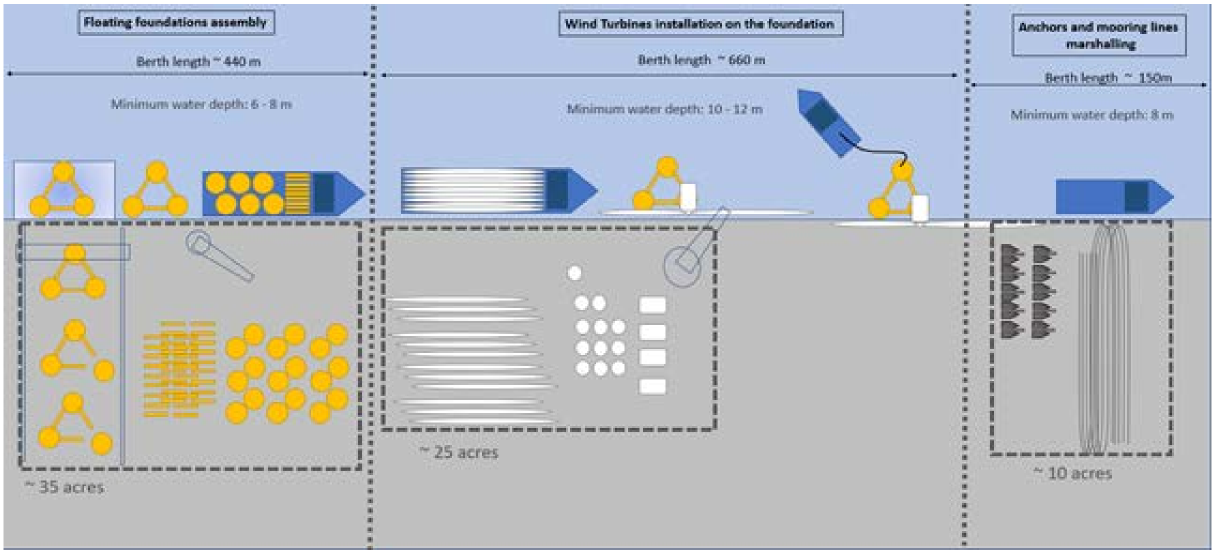

Figure 10. Fabrication and marshalling activities at a floating wind port

Table 8. Minimum Port Requirements for Floating Wind Fabrication and Marshalling Activities

Parameter	Minimum Value
Draft (wind turbine installation)	12 m
Air draft	150 m
Laydown area (total)	70 acres
Quayside length	660 m
Bearing capacity	15 t/m^2

3.3 High-Level Assessment of Existing Ports

We conducted a preliminary survey of individual ports on the East and West coasts to compile publicly available information about the relevant categories described in Section 3.1 and then compared those values against the minimum port requirements listed in Section 3.2. We restricted the list of ports on the East Coast to geographic regions that have the closest proximity to planned projects in the pipeline, specifically the Northeast, Central, and Southeast regions. A number of the ports in the related tables have announced or implemented upgrades specifically for offshore wind energy; for greater description on those investments, see Musial et al. (2021).

By comparing the parameters of the individual ports against the minimum port requirements in Table 7 and Table 8, we assess the readiness level of individual ports to support offshore wind installation operations for either WTIVs, feeder barges or floating platforms. We use this comparison to characterize each port using the following "stoplight" system:

- Green: The port meets all minimum requirements for offshore wind energy.
- Yellow: The port does not meet one of the minimum requirements but meets all others.
- Red: The port does not meet two or more of the minimum requirements for offshore wind energy.

The ports analysis is primarily qualitative, and so some leniency is provided for certain ports; for example, if one of the categories of a port is close to the minimum requirements for offshore wind we count this category as satisfactorily meeting the criteria. In addition, we assume that offshore wind ports that have already been identified as marshalling ports for offshore wind energy projects (e.g., New Bedford, New London State Pier, and the New Jersey Wind Port) have sufficient bearing capacity for offshore wind components even if the individual port's data are not publicly available. Finally, we assume that air draft restrictions only apply to WTIVs accessing the port and are not counted against feeder barge strategies at that port. Missing information for other ports is counted against the ability of that port to support offshore wind. The failed criteria for individual ports are listed in the stoplight columns in Table 9 and 11. It is important to note that this is a high-level assessment intended to provide a broad idea of the challenges facing offshore wind energy projects; a more detailed assessment of the capabilities that individual ports can play to help the deployment of specific projects is still necessary, but outside the scope of this study.

3.3.1 East Coast Port Assessment

We present the capabilities and readiness level of 22 ports on the East Coast in Table 9. Ports that been identified as potential offshore wind marshalling ports are explicitly listed in the table, and other ports are grouped into 'Other port' categories. Complete tables of these 22 ports are available in Appendix A.

The immediate takeaway is that there is a limited number of ideal offshore wind ports on the East Coast. Yet, even dedicated offshore wind ports would require significant dredging campaigns to accommodate the next-generation WTIVs, such as Dominion's Charybdis, which exceeds a 12-m draft. This limitation makes it more likely that project developers will use a feeder barge strategy for project installation, as dredging and port upgrades are expensive and require additional permitting processes. In addition to the 6 ports explicitly listed in Table 9, 5 additional ports on the East Coast are moderately ready to support feeder barge loadout and 9 additional ports are unable to support feeder barge or WTIV loadout.

Table 9. Summary of East Coast Marshalling Port Capabilities and Assessments

Port Name	State	Laydown Area (acres)	Quayside Length (m)	Number of berths	Berth Depth (m)	Channel Depth (m)	Bearing Capacity (t/m^2)	Air Draft Limit (m)	Readiness Level (WTIV)	Readiness Level (Feeders)
New Bedford[8]	MA	29	366	3	9.1	9.1	20 t/m^2	None	🟥 Berth/channel depth, and quayside length	🟩 Quayside length
New London State Pier[9]	CT	30	1244	4	12.2	10	Assume > 15	None	🟨 Channel depth	🟩
South Brooklyn Marine Terminal	NY	88	417	2	10.7	12.2	30	60	🟥 Berth depth, quayside length and air draft	🟨 Quayside length
New Jersey Wind Port[10]	NJ	70	854	4	11.5	9.88	29.8	None	🟩	🟩
Tradepoint Atlantic[11]	MD	3,300	1,021	2	10.97	10.97		None	🟥 Berth/channel depth, bearing capacity	🟨 Bearing capacity
Portsmouth Marine Terminal	VA	287	1,079	3	13.11	13.11	Assume >15 t/m^2	None	🟩	🟩
Other ports (1)	-	-	-	-	-	-	-	-	🟨	🟨
Other ports (4)	-	-	-	-	-	-	-	-	🟥	🟨
Other ports (9)	-	-	-	-	-	-	-	-	🟥	🟥

We aggregated the characteristics of ports by different stoplight criteria in Table 10 for both WTIV and feeder barge installation strategies[12]. The results indicate that the port infrastructure

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[8] New Bedford is already under contract as a marshalling port although its total quayside length and laydown area are smaller than port requirements suggested by wind turbine OEMs. The size constraints will likely drive project developers to use feeder barges for installation. Therefore, we assign a ‘green’ readiness level for this strategy.

[9] New London State Pier is undergoing infrastructure upgrades to re-make it as a heavy-lift capable port for offshore wind (Musial et al. 2021); therefore, we assume that it has sufficient bearing capacity even though this information is not publicly available.

[10] The New Jersey Wind Port berth and channel depths are slightly lower than the required values; however, consultation with the New Jersey Economic Development Authority indicated they have confidence that a WTIV can navigate the Delaware River and reach the port. Therefore, we assign a ‘green’ readiness level for the WTIV strategy.

[11] Tradepoint Atlantic has invested in bearing capacity upgrades (Musial et al. 2021) but these data are not public and the port has not entered into any agreements to marshal offshore wind projects. As a result, we list bearing capacity as an outstanding uncertainty for Tradepoint Atlantic.

[12] The ports of Coeymans and Albany are being planned as offshore wind manufacturing ports and do not intend to support WTIV access; therefore, we do not assess their readiness level for WTIVs. As a result, we do not count them in the aggregate WTIV port characteristics.

on the East Coast is in the process of being adapted to support offshore wind energy but places inherent limitations on the logistics of constructing these projects. There are only two ports on the East Coast that are currently suited for WTIV operations. Even ports that are currently expected to be used as offshore wind marshalling facilities, such as the New Bedford Marine Commerce Terminal, have size or spatial limitations that will drive project developers towards using feeder barges. Although these approaches may reduce costs (because the more expensive WTIV does not spend time transiting to-and-from the port), they also introduce additional risk and logistic complexity to transfer components from the barge to the WTIV at sea. There are more ports which are accessible to feeder barges, which provides offshore wind projects with several options to choose from; however, the availability of 'Green' ports is likely insufficient to support demand. As developers are pushed towards 'Yellow' ports, the complexity and costs of installation will increase due to limitations of the facilities or further distances from the offshore wind project. Delays and bottlenecks are more likely to accrue for projects staged out of suboptimal ports. Additional factors such as commitments of ports to other industries and additional demand introduced by O&M activities will further constrain the abilities of existing ports to support offshore wind project construction. Additional investment may help to alleviate these risks; for example, channels could be dredged to greater depths or additional ports could receive bearing capacity upgrades. Further analysis is required to understand the full impact of East Coast port limitations on the deployment pipeline and how to strategically make investments to address the most significant bottlenecks.

Table 10. Summary of East Coast Marshalling Port Categorization

	Green ports		Yellow ports		Red ports	
	WTIV	Feeders	WTIV	Feeders	WTIV	Feeders
Northeast region	0	3	1	2	8	6
Central region	1	1	0	3	5	2
Southern region	1	1	1	3	3	1
Total	**2**	**5**	**2**	**8**	**16**	**9**

3.3.2 West Coast Port Assessment

The offshore wind energy industry on the West Coast is significantly less developed than on the East Coast, with comparatively lower infrastructure readiness. The West Coast port status, shown in Table 11, can be clustered into the following three groups:

- Ports with a high level of potential readiness in terms of infrastructure but limited available berth or laydown space to dedicate to offshore wind energy. The ports of Long Beach, Los Angeles, and Seattle are good examples of this category, although Seattle is currently exploring ways to bring offshore wind energy activity to its main port.
- Ports with significant limitations that could impact offshore wind development, such as the San Francisco Bay area ports, which are all unsuitable for quayside assembly of floating wind systems due to the air-gap restriction at the Golden Gate Bridge. Also, ports adjacent to established military presence, such as the U.S. Navy in San Diego, can preclude the development of offshore wind energy projects and therefore discourage port upgrades.
- Ports that are close to important offshore wind energy development areas but lack adequate infrastructure, such as Humboldt Bay and Port of Hueneme. Those ports currently have

inadequate berth length and depth, but their relatively close proximity to the Humboldt and the Morro Bay WEAs might justify investment in their facilities to serve the nearby projects.

Table 11. West Coast Ports Marshalling Capabilities and Assessment

Port Name	State		Laydown Area (acres)	Quayside Length (m)	Number of berths	Berth Depth (m)	Channel Depth (m)	Bearing Capacity (t/m^2)	Air-Draft Limit (m)	Readiness Level (Floating Substructure)
Port of Seattle	WA		1,541.9	2,400	20	23.2	>30		None	🟥 High congestion and bearing capacity
Astoria	OR		20.55	1551	5	12.2	14		None	🟥 Laydown and bearing capacity
Port at Coos Bay[13]	OR		1,335	80	7	11.28	11.28		Select areas limited	🟨 Bearing capacity and quayside length
Humboldt Marine Terminal	CA		150	703	2	11.6	10.67	Assume > 15	None	🟨 Channel depth
Morro Bay	CA			80	1	5.5	5.5		None	🟥 Laydown area, quayside length, berth/channel depth, and bearing capacity
San Francisco	CA			870		15.2	15		67	🟥 Laydown area, bearing capacity, and air draft
Oakland	CA		1,300	7,800	185	15	15		67	🟥 Bearing capacity and air draft
Richmond	CA		195	2,350	7	11.5	11.5		67	🟥 Bearing capacity and air draft
Benicia	CA		645	1,550	4	11.5	11.5		67	🟥 Bearing capacity and air draft
Hueneme[14]	CA		120	800	5	10.5	11		None	🟨 Berth depth

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[13] Coos Bay does not have the existing infrastructure to support floating offshore wind deployment but has the appropriate physical site characteristics for port development and has plans to widen and deepen navigation channels (Mott MacDonald, 2022). There are locations within the bay that have the potential to support the construction of floating wind turbine integration and assembly facilities (Mott MacDonald, 2022). Therefore, we rate the Port at Coos Bay as “yellow” to reflect its potential to be developed into a serviceable marshalling port.

[14] Hueneme does not list their quayside bearing capacity but Porter and Philipps (2016) identified it as a good port for floating wind operations. Therefore we list it as a “yellow” port.

Port Name	State		Laydown Area (acres)	Quayside Length (m)	Number of berths	Berth Depth (m)	Channel Depth (m)	Bearing Capacity (t/m^2)	Air-Draft Limit (m)	Readiness Level (Floating Substructure)
Los Angeles	CA		7,500	3,650	25	12	12		Select areas limited	High congestion
Long Beach	CA		525	4,750	10	25	25		Select areas limited	High congestion
San Diego	CA		96	750	8	12.8	12.8		None	High congestion

Similar to the East Coast ports, we summarized the capabilities of West Coast ports in Table 12. The results highlight that no ports are fully ready to support commercial-scale floating wind energy deployment. Even the “yellow” ports on the West Coast, such as Los Angeles, Long Beach, and San Diego, which have sufficient physical capabilities to support offshore wind, face additional complexities because of their existing business models and congestion and may not be appropriate for long-term offshore wind leases. A more detailed port assessment is required to better understand the capabilities and limitations of those ports; for example, Porter and Philipps (2016) provide a more detailed assessment of West Coast ports for offshore wind energy activities.

Table 12. Summary of West Coast Marshalling Port Categorization

	Green Ports	Yellow Ports	Red Ports
Total	**0**	**4**	**9**

3.4 Offshore Wind Vessels

DNV maintains a database of vessels that includes vessel type, name, owner, base port, vessel length, crane capacity, largest wind turbine size the vessel can install, and whether the vessel is Jones-Act compliant. Most vessels currently in use for the construction and O&M phases of European offshore wind energy projects are based in Europe and operated by European companies. The European fleet of vessels for the offshore wind industry has evolved along with the wind turbine size. However, a significant portion of the existing global WTIV fleet is not capable of installing the latest (largest) turbine models currently under development without undergoing major modifications.

Ship owners and operators have been regularly ordering and announcing the construction of new vessels with increased installation capacities, meaning the global fleet is continuously evolving to meet the coming demand to transport and install ever larger wind turbine models. The current situation is summarized in Table 13, which indicates there are currently a total of 16 WTIVs in operation. Of those, four have the capacity to install 12-MW wind turbines, and of those only two have the capacity to install 15-MW turbines. None is able to install 18-MW wind turbines. However, six WTIVs are in some phase of construction and all of those will be able to install up to 18-MW turbines. Given the vessel demands shown in Section 2.4, even the significantly constrained supply scenario still requires three WTIVs to install 2 GW of 15-MW turbines per year from 2025 through 2030, which would be significantly below the target needed to get to 30 GW by 2030.

Table 14 shows that one of the planned WTIVs will be Jones-Act-compliant[15]. Dominion Energy's Charybdis is being constructed by the Keppel AmFELS shipyard in Brownsville, Texas, and is expected to be completed by late 2023. Additionally, in December 2020, Lloyd's Register North America, Inc. announced an agreement for a joint development project with Northeast Technical Services Co., Inc. to design and develop a Jones-Act-compliant WTIV to meet the offshore wind energy industry's needs for projects planned for the East Coast and Great Lakes. Those new vessels will eventually help the U.S. market to some extent, but more WTIVs will likely be needed. As for Europe, because they are gearing up to install nearly 12 GW per year beginning in 2026 and projected to maintain that pace of installation at least through 2030, the two new WTIVs targeted for Europe are not going to be enough for them to meet even their own goals.

Table 13. Active Offshore Wind Installation Fleet in Europe as of June, 2021. Six Additional WTIVs Are Under Construction Globally

	Total	12 MW	15 MW	18 MW
WTIV	16	4	2	0
HLV/semisubmersible crane vessel (<2,500 t still water level)	9			
CLV	15			
Survey vessel	16			

Table 14. Planned or Under Construction WTIVs Capable of Installing 18-MW Turbines

Vessel Name	Home Port	Capacity	Delivery
Voltaire	Northern Europe	3,000 t	End of 2021
Eneti (unnamed)	South Korea	2,600 t	2024
Shimizu Corp. NB	Japan	2,500 t	2022
Penta Ocean	Japan	1,600 t	?
Charybdis	USA	2,200 t	Late 2023
Vind 1	Northern Europe	2,500 t	2023

The demand for HLVs or semisubmersible crane vessels, necessary for installing offshore substations and certain foundations, may also become a bottleneck. As those vessel types are also involved in offshore oil and gas construction, their availability to support the offshore wind energy pipeline is difficult to predict. Limited availability of other types of vessels, such as CTVs or SOVs, may also become bottlenecks to increasing installation capacity. The oil and gas industry uses a large amount of Platform Supply Vessels, mainly in the Gulf of Mexico, which could be adapted for supporting the offshore wind industry as SOVs; however, they are not likely to be used as offshore wind CTVs.

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[15] In 2021, Eneti announced plans to build a Jones-Act-compliant WTIV but discontinued these plans in February of 2022.

As part of their core missions, CTVs and SOVs transport goods and personnel between ports and offshore infrastructure. In the United States, the Jones Act requires that such missions, deemed "cabotage," be performed by U.S.-built, flagged, and owned vessels. Therefore, the U.S. industry cannot rely on the European fleet or European shipbuilding capabilities for this type of vessel. According to the U.S. government, those and other types of special-purpose offshore wind vessels are being built. CLVs are currently exempt from the Jones Act and foreign-flagged vessels may be used to install power cables in the United States, although those vessels are still subject to the same bottlenecks from the global supply chain as non-U.S.-flagged WTIVs. Furthermore, if U.S. Customs and Border Protection regulations change, then the market will face a sudden shortage of CLVs. Fall pipe vessels are highly specialized vessels used to precisely lay layers of rock and concrete on the seabed, and those vessels will be required to install the scour protection, mainly around the monopiles and high-risk sections of buried cables, such as cable crossings or traverses over steep geological features on the seafloor. As the transport of rocks from a U.S. port to the seabed may a require a Jones-Act-compliant vessel under certain conditions (U.S. Customs and Border Protection. 2020), the existing European fleet will not be sufficient to support U.S. offshore wind energy development. A Jones-Act-compliant rock installation vessel has been ordered by Great Lakes Dredge and Dock's to support the U.S. offshore wind industry. Scour protection vessels are highly specialized, but we estimate a relatively low demand (a maximum of two per year); and as a result, we consider them to pose a moderate risk to fulfilling the 30-GW national offshore wind energy target.

To summarize, construction of new vessels and modernization of the fleet needs to happen in both Europe and the United States to meet the expected demand through the end of the decade. An estimation of construction timelines in the United States is summarized in Table 15.

Table 15. Estimates of Construction Timeline for Different Types of Vessels

Vessel Type	Estimated Construction Timeline
CTV	8–12 months
SOV	2–3 years
Platform supply vessel conversion to SOV	3–9 months
CLV	3 years
WTIV	3 years

On the West Coast, the installation of floating offshore wind turbines will require a different vessel fleet:

- **Long haul tugs** will tow the floating structures from the construction port to the offshore site. In addition, if the substructure construction and the wind turbine assembly on the substructure are happening in different locations, the substructure will also be towed by tugs between those two locations. This type of vessel is widely used in other offshore industries such as oil and gas and a Jones-Act-compliant fleet exists.
- **Anchor handling vessels** will install the anchors and mooring lines and hook up the floating wind turbines. This type of vessel is widely used in other offshore industries such as oil and gas and a Jones-Act-compliant fleet exists.
- **CLVs** are involved in laying the interarray and export cables. However, the much deeper water depth on the West Coast may require different cable configuration and CLV capabilities than for bottom-fixed offshore wind energy projects.

- Other vessels, such as CTVs or SOVs, are expected to have similar involvement with the West Coast floating projects as they do on the East Coast.

In Table 16 and Table 17, we summarize the types of vessels required for broad-scale offshore wind energy buildout and estimate the risk that each poses to achieving the national offshore wind energy target. We also include the estimated cost to construct a new vessel and, in some cases, the lead time required to do so. The cost, demand, and availability of different vessel types are qualitatively aggregated into the following stoplight system:

- **Green**: The vessel class is already widely available in the United States.
- **Yellow**: Additional vessels will be required to support the deployment pipeline. The new vessels will be either relatively inexpensive to build (less than $100 million), will have relatively low demand (1–2 vessels), can be European-flagged vessels, or can be retrofits of existing vessels.
- **Red**: Additional vessels will be required to support the deployment pipeline. The new vessels will be relatively expensive (greater than $100 million each), will have relatively high demand (greater than 2), or are highly specialized designs that require new builds in the United States.

Based on this stoplight criteria, WTIVs pose the highest risk to the deployment pipeline, particularly Jones-Act-compliant vessels. Although they are not necessarily required to install U.S. projects (if the project uses feeder barges to transfer components from port to site), foreign-flagged WTIVs may be committed to other global projects and domestically-produced vessels are more likely to be dedicated to U.S. projects. In Table 16, we identify these vessels as ‘U.S.-dedicated WTIVs’ to clarify that these installation vessels could be foreign-flagged but that achieving the 30 GW pipeline would require at least 5 committed WTIVs.

Table 16. Vessels That Pose a High or Moderate Risk To Achieving the National Offshore Wind Energy Target

Vessel Type	Estimated Cost	Estimated Construction Time	# Existing	Estimated Peak Demand to 2030	Risk to 30-GW Target
U.S.-dedicated WTIV	\$250–\$500 million	3 years	0 (1 under construction)	5	🟥
CLV	\$250 million	3 years	0	4	🟨
Feeder barge/vessel	\$150–\$200 million new, \$10–\$20 million retrofit	Depends on design	20 jack-ups, 44 barges	10	🟨
SOV	\$50–\$100 million new, \$10–\$50 million retrofit	2-3 years	0 (2 under construction, multiple oil and gas vessels which could be adapted)	13+	🟨
CTV	\$5–\$10 million	1- 2 years	3	58	🟨
Scour protection vessel	\$200 million	3 years	0 (1 under construction)	2	🟨
Heavy lift vessel	Depends on design		18	Depends on installation strategy	🟨
Anchor handling tug supply vessel	\$100 - \$200 million	2 years	Limited supply	2	🟨

Table 17. Vessels That Pose a Low Risk To Achieving the National Offshore Wind Energy Target

Vessel Type	Estimated Cost	# Existing	Estimated Peak Demand to 2030	Risk to 30-GW Target
Tug	-	Widely available	15–18	🟩
Additional support vessels[16]	-	Widely available	At least 5 types per project	🟩

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[16] Additional support vessels may include survey vessels for environmental, geotechnical, geophysical, or metocean conditions; safety vessels to coordinate with ongoing marine traffic; scout vessels that locate obstacles in the water column during surveying; accommodation vessels for housing crew during construction; noise mitigation vessels providing bubble curtains during pile driving; diving/remotely operated vehicle support vessels to carry out subsea inspections; and guard vessels for operational safety (American Clean Power, 2021). Projects may use multiple support vessels of the same type. Although many types of support vessels are required for an offshore wind project, they will be at the construction site for various durations and some may support the installation of multiple projects in parallel.

4 Jobs and Economic Sensitivities for a Domestic Supply Chain

4.1 Current State of the Domestic Offshore Wind Energy Workforce

Creating U.S. jobs in the offshore wind energy industry is directly associated with developing a domestic manufacturing and supply chain capable of supplying the demand for major fixed-bottom and floating offshore wind components. The national offshore wind energy target of 30 GW by 2030 established by the Biden administration strives to ensure that production facilities employ U.S. workers with good-paying jobs and a strong domestic supply chain (White House 2021).

The current offshore wind manufacturing and supply chain workforce in the United States is limited; however, public announcements regarding the manufacturing of components in the United States point to a critical need to train and hire workers to fill key jobs within the next 5 years.

The jobs represent an inclusive workforce, which requires many different occupations, roles, and skillsets. Manufacturing and supply chain will support plant-level workers, plant-level management, design and engineering, quality and safety, and facilities maintenance. Plant-level workers typically are highly skilled roles, such as welders, electricians, machine operators, and assemblers. Plant-level management oversees the plant-level workers and includes roles such as production engineers, manufacturing engineers, and plant and operations managers. Design and engineering roles support component design prior to production, such as design engineers, testing engineers, and supply chain analysts. Facilities maintenance workers are typically in supervisor and technician roles that ensure the plant is operating by performing preventative and corrective maintenance.

State-level preferences for in-state or domestic sourcing of Tier 1 components have signaled the need for the offshore wind energy industry to support domestic workforce and training programs. Community colleges and labor unions are often well suited to address many of the key educational and training requirements for the offshore wind industry, especially for plant-level workers. Close cooperation among unions, other educational and training organizations, and the industry to support job pathways, training programs, and respect for workers' labor rights will help spur workforce development in manufacturing facilities (Stefek et al. forthcoming).

4.2 Objective and Scope

During this study, we estimated the potential to support jobs (full-time equivalents [FTEs]) and gross domestic product (GDP) from the manufacturing of components in the United States and activating a domestic supply chain to support the deployment pipeline defined in Section 2.

This estimation involved conducting an economic impact assessment for each component using an analysis-by-parts approach. A previous study indicated that component manufacturing and a corresponding supply chain could support 29,000 offshore wind energy jobs by 2030 (Lantz et al. 2021). This effort breaks down this high-level job estimate for each component over time using a production pipeline based on the demand scenarios. For this analysis, we also developed an expanded and economic framework to provide a more accurate and robust economic impact assessment.

The job estimates show growth potential based on a sensitivity analysis with varying domestic content assumptions (e.g., ranging from 25% to 100% domestic content) indicates a range of the number of potential jobs the industry may need to train and hire as the U.S. offshore wind energy supply chain and manufacturing grows while also providing an indication of the highest domestic job estimate for each component. We also highlight the economic benefits of those varying levels of domestic content by providing estimates for GDP and induced job impacts from a domestic supply chain.

The job and economic impacts are high-level manufacturing and supply chain estimates associated with offshore wind component production. We did not estimate the impacts from the development, installation (e.g., vessels and ports), or O&M of those components. In future work, the scope will expand to provide detailed assumptions on the regional specificity of workforce needs while developing a baseline of future workforce potential considering manufacturing and supply chain announcements. We estimate the direct and indirect economic impacts of manufacturing each component in the United States using a modified version of the Job and Economic Development Impact (JEDI) model, which uses an input-output (I-O) methodology with IMPLAN economic data.[17]

Limitations to the scope of this analysis include the following:

- The estimates are indicative of a national-level estimate and do not specify in what region or states the workforce will likely develop.
- Results are provided as a sensitivity to show the potential of manufacturing and supply chain in the United States based on demand for components over time. We did not develop baseline domestic content assumptions about the current manufacturing and supply chain ability to source labor and materials from the United States. The scope of this section also does not make assumptions about when or to what extent the supply chain matures. The results are a sensitivity analysis to provide insight into the potential contribution of each component assuming the United States develops a supply chain capable of producing multiple tiers of components, subassembly, subcomponents, and materials.

Limitations of I-O economic impact models include the following:

- I-O models in general use fixed, proportional relationships between economy sectors. Factors that could change economic sectors, such as price changes that lead households to alter consumption patterns, are not considered.
- Results reflect gross economic impacts and not net impacts. The model calculates what economic activity would be supported by demand created by project expenditures. The

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[17] More information and a public version of the JEDI model is available at: https://www.nrel.gov/analysis/jedi/.

results do not reflect many other economic impacts that could affect real-world impacts on jobs from supply chain development.[18]

4.3 Approach and Method

We developed an I-O economic impact model, based on the JEDI model, to conduct an analysis-by-parts framework for all components to assess the direct and indirect impacts of manufacturing and the supply chain. The primary inputs include the supply chain throughput, total production cost for each component, and domestic content assumptions that provide sensitivities for how much labor and material is sourced from the United States. IMPLAN economic data provide direct, indirect, and induced I-O multipliers to estimate the employment and GDP impacts of expenditures from component production.

The supply chain throughput is based on component demand for the baseline, moderate supply constraint, and significant supply constraint scenarios for fixed-bottom and floating technologies. Figure 4 shows the total number of all components for the baseline scenarios. The total of all components for the moderate and significant supply constraints are shown in Figure 6. Procurement and manufacturing are assumed to occur 2 years prior to offshore wind plant COD for all components, except the offshore substation topside, which occurs 3 years prior to COD. Due to the inherent uncertainty in these numbers, we report the annual job demand using a 3-year moving average. The throughput in terms of number of components was converted to a throughput in terms of production based on total capacity to assign a dollar-per-kilowatt value to components based on different turbine nameplate capacities.

Total component costs are component-specific and represent the labor and material expenditure to manufacture and purchase all components, subcomponents, parts, and materials from Tier 1 to Tier 4 suppliers. We applied a learning rate of 7.3% to all costs to add a percent reduction in capital costs each year to 2035 (Beiter et al. 2020). The component costs are multiplied by the number of components for each turbine rating to determine a production cost for each component. The sources for component costs include:

- **Wind turbines.** We modeled a total wind turbine cost of $1,301/kilowatt based on the turbine capital cost reported in the "2019 Cost of Wind Energy Review" (Stehly 2020). This total turbine cost was broken down into rotor blades, nacelles, and towers costs (e.g., Tier 2 subassemblies) using the National Renewable Energy Laboratory's (NREL's) Wind-Plant Integrated System Design and Engineering Model (WISDEM®) for a 12-MW, 15-MW, and 18-MW turbine rating.[19] To further break down the cost of towers and rotor blades, the "U.S. Wind Energy Manufacturing and Supply Chain: A Competitiveness Analysis" (Global Wind Network 2014) provides the Tier 3 subcomponent cost. The "Guide to an offshore wind farm" (BVG Associates 2019) revised a breakdown for nacelle (gearbox) Tier 3

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[18] Other macroscopic economic changes may take place that JEDI does not consider, including supply-side impacts, such as price changes, changes in taxes or subsidies, tariffs on foreign steel, or utility rate changes. JEDI also does not incorporate far-reaching effects such as those caused by greenhouse gas emissions, displacement of some other type of economic activity due to investment in this particular project, or potential side effects of a project such as recreation or tourism.

[19] More information on WISDEM is available at https://www.nrel.gov/wind/systems-engineering-models-tools.html.

subcomponents. Wind turbine technology for floating systems assumes the same costs as fixed-bottom.

- **Foundations.** A capital cost for the entire monopile and transition piece system is obtained from the Offshore Renewables Balance-of-system Installation Tool (ORBIT) for a 12-MW, 15-MW, and 18-MW turbine rating.[20] A breakdown of two-thirds of the costs is associated with the monopile and one-third of the cost associated with the transition piece agrees with the BVG Associates (2019) report. Jacket substructure costs are also sourced from the BVG Associates (2019) report. The costs for gravity-based foundations are sourced from internal NREL cost estimates. The floating technology assumed a semisubmersible design with a suction pile anchor mooring system. We estimated the costs for the floating system using ORBIT.
- **Substations.** The offshore substation topside and jacket substructure costs are sourced from the BVG Associates (2019) report. The topside assumes a high-voltage alternative current substation for a 1-GW plant capacity. The costs of floating offshore substation structures are assumed to be similar to floating semisubmersibles for the wind turbines.
- **Cables.** The costs of a 66-kilovolt, 630-mm^2 cross section array cable and a 220-kilovolt, 1,000-mm^2 cross section for an export cable are sourced from NREL's ORBIT model. Costs are stated on a dollar-per-kilometer basis. We assign a 20% premium for dynamic array and export cable costs used in floating designs relative to static cables.

We conducted a sensitivity analysis by varying the domestic content assumption from 25% to 100% for each component. Those assumptions calculate the domestic expenditures (e.g., costs spent within the United States) to model using a custom IMPLAN sector industry aggregation. The domestic expenditures for each component are multiplied by the direct and indirect I-O multipliers based on the IMPLAN sector industry aggregation for the entire United States.

The Tier 1, 2, or 3 components can also be assumed to be independent industries for the purposes of calculating direct and indirect jobs (FTE) specific to each tier. The definitions of direct and indirect impacts for this analysis include:

- **Direct:** represents the total jobs (FTEs) to produce the component (Tier 1), subassembly (Tier 2), or subcomponent (Tier 3) at a particular manufacturing plant. The impact estimates the number of jobs based on expenditures spent in the sector industry aggregation.
- **Indirect:** represents all of the in the supporting supply chain need to manufacture a component (Tier 1), subassembly (Tier 2), or subcomponent (Tier 3). The impact represents the number of jobs per $1,000,000 of business-to-business purchases by all resultant rounds of domestic purchases (IMPLAN 2021).

The summation of the direct and indirect impacts estimates the entire job requirements to produce each component. Adding all of the components together provides the job potential for the U.S. manufacturing and supply chain to produce the number of components based on the pipeline projection and demand scenarios.

The domestic expenditures for each component are also multiplied by the induced I-O multipliers to assess the induced job impacts from producing the component demand for the

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[20] More information on NREL's ORBIT model is available at https://www.nrel.gov/docs/fy20osti/77081.pdf.

baseline scenarios. Induced impacts refer to jobs that result from spending by workers. Sectors that are affected by induced impacts include retail, lodging, restaurants, and other service and hospitality businesses.

This analysis estimates the direct and indirect jobs (FTEs) for each component, the total of induced jobs (FTEs), and the direct and indirect gross domestic product (GDP) from all components. Those economic impacts are defined as follows:

- **Jobs:** expressed as FTE. One job is the equivalent of one person working 40 hours per week, year-round. Two people working full time for 6 months equal one FTE. Two people working 20 hours per week for 12 months also equal one FTE. An FTE could alternately be referred to as a person-year or job-year. Jobs are not limited to those who work for an employer; they could include other types of workers, such as self-employed ("sole proprietors").
- **GDP:** the value of an industry's production to the region of analysis. It comprises labor payments, property-type income (including profits), and taxes. Also akin to value added.

4.4 Scenario Job Estimates

To estimate the jobs (FTEs) for the entire supply chain between 2023 and 2030, all demand scenarios are modeled with prescribed levels of domestic content between 25% to 100% to represent varying levels of U.S. manufacturing and supply chain contributions. The actual offshore wind workforce that develops in the 2020s will likely be somewhere in the middle of this range and will ramp up over time as projects begin to deploy and workforce training programs are initiated. Component manufacturing for early-stage projects will primarily be located in Europe as the U.S. supply chain will take time to develop. We use a 3-year moving average to account for uncertainty in when the components will be manufactured for any given project; as a result, the jobs estimates begin in 2023. Job estimates are correlated to the component demand scenarios and the total production cost. Key insights emerge from the analysis including the range of job estimates, maximum job potential, timing of jobs, and the considerations of how constraints on turbine supply affect workforce efficiency.

4.4.1 Baseline Scenario

The average number of jobs required between 2023 and 2030 ranges between 12,300 and 49,000 FTEs, averaging over the significant variation in workforce demand due to unsteady production rates in the demand scenarios.[21] Figure 11 shows the job estimates over time based on the component demand each year for the baseline scenario.

This scenario represents the job estimates to achieve the 30-GW-by-2030 target, as it is the only scenario that maps the component needs based on a pipeline projection without any consideration of supply chain limits.

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[21] This range is dependent on a low and high assumption for domestic content utilization. It is likely that the actual offshore wind employment related to manufacturing and supply chain will be between this range.

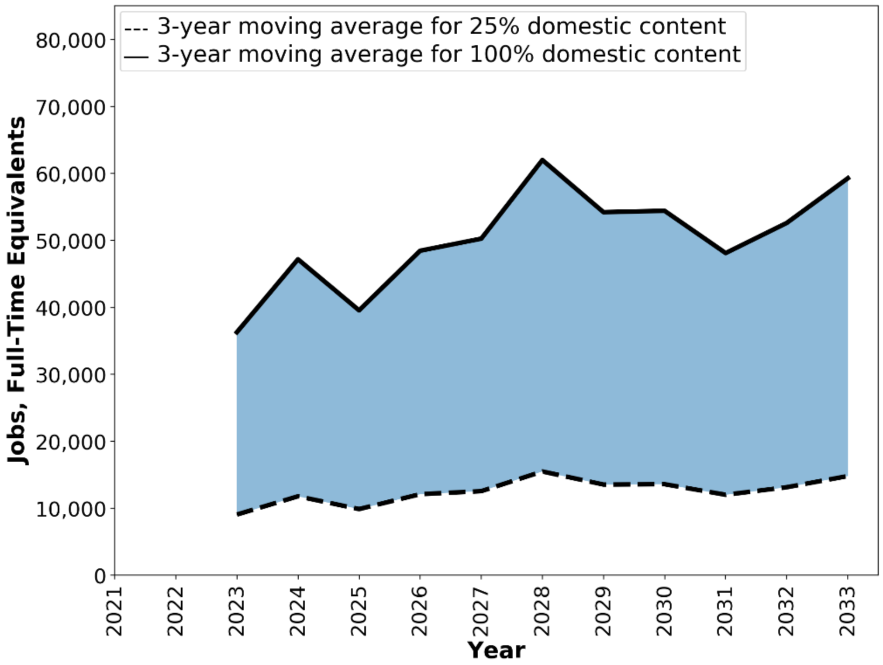

Figure 11. Baseline scenario - number of jobs (FTEs) for all component demand based on scaling domestic content for the entire supply chain

For the total component demand of the baseline scenarios, the highest manufacturing and supply chain job potential occurs in 2028 to meet a pipeline projection of 5,729 MW installed in 2030. Depending on the level of domestic content, between 15,500 and 62,000 jobs would be needed to meet component demand. This job potential indicates the maximum workforce that will need to be trained depending on how the supply chain matures. It is likely that the actual job estimate of the U.S. offshore wind manufacturing and supply chain will fall between this range. For each component, the domestic content will grow over time as new manufacturing plants are built and suppliers provide subcomponent, parts, and materials, so the job estimate will depend on the level of domestic content for each component.

Fewer workers are needed in years when component demand is lower. The jobs estimates fluctuate between 2024 (47,000 jobs), 2025 (39,500 jobs), and 2026 (48,500 jobs), assuming 100% domestic content. This scenario may indicate that plants may have to ramp their workforce up and down to meet component demand, which leads to uncertainty for workers.

In addition, ramping up during 2021 and 2022 to approach the average job numbers provided in Figure 11 demonstrates that if the United States develops a domestic supply chain to meet the 30-GW-by-2030 target, there is an immediate need for workforce development. Educational institutions, unions, OEMs, and developers could work together to ensure workers are adequately trained and ready to hire as U.S. manufacturing begins production. The reported workforce growth after 2030 relies on the expansion of available offshore wind lease areas.

4.4.2 Supply Constraints and Workforce Estimates

The moderate and significant supply chain constraints lead to a lower component demand and shifts in component demand for using U.S. domestic content, which have important workforce considerations. Appendix B provides charts and details for the moderate and significant supply chain constraints scenarios.

Comparing the average number of jobs between the moderate and significant supply constraints and baseline scenario (30 GW by 2030) indicates there is a higher workforce need to produce more components at a faster rate under the baseline scenario. The average number of jobs required in the 2020s for each scenario to support component demand production each year range between:

- Baseline: 12,300 and 49,000 jobs
- Moderate supply constraints: 9,400 and 37,700 jobs
- Significant supply constraints: 5,200 and 20,700 jobs.

On average, there is a 58% reduction in jobs due to lower component production and shifting demand from the baseline to the significant supply constraint scenario. The range of job estimates depends on how quickly manufacturing plants are built in the United States and how fast the supply chain matures.

By considering the moderate and significant supply constraint demand scenarios, the analysis also indicates that by reducing component demand and shifting component demand to later years, there is less fluctuation in the workforce need between each year. The more stable production allows for a more efficient use of the manufacturing and supply chain workforce and lessens the uncertainty for hiring and layoffs over time, thereby enabling more certainty for workers and companies. However, under these scenarios, the U.S. offshore industry does not meet the 30- GW-by-2030 target and there is a lower demand for U.S. workers because fewer components are manufactured, requiring fewer labor hours to produce the components each year.

In addition, the ramp up in jobs needed to reach a sustainable workforce in the early 2020s demonstrates that as offshore wind energy manufacturing and supply chain plants open in the United States, there could be a rapid increase in workforce demand, indicating an immediate need to have trained workers ready to hire. However, the ramp up to supply workers for the industry is more gradual in the moderate and significant supply constraint scenario than the baseline scenario. The more gradual ramp up could allow more time for training and hiring and developing an efficient and sustainable workforce to produce components.

Comparing the demand scenarios demonstrates that to reach the 30-GW-by-2030 target, while maximizing the workforce opportunity, the United States will need to establish a partnership between developers, manufacturers, and suppliers. Together, they will need to efficiently plan to meet the expected growth in the U.S. offshore wind pipeline, ensuring consistent production and employment for the industry. To ensure an adequate supply of workers, training programs (e.g., vocational programs, community colleges, and unions) could involve OEMs and suppliers to ensure trade workers have the required skills and certifications necessary to produce each component.

4.5 Component Job Estimates

Each component contributes discrete job estimates for the baseline scenario supply chain estimates detailed in Section 2.4.1. Those estimates represent all the jobs needed to fabricate and assemble all the components, subcomponents, parts, and materials for all tiers of the manufacturing and supply chain, not just Tier 1 component fabrication and assembly.

This section discusses the job estimates per component for all demand scenarios using a 25% domestic content to represent the minimum job estimates and a 100% domestic content to represent the maximum potential job estimates. Appendix B shows the breakdown of each component over time for the different domestic content assumptions, highlighting the baseline, moderate, and significant supply constraint demand scenarios.

Direct and indirect job contributions provide insight into the areas where supply chain growth has the potential to increase domestic workforce opportunity.

4.5.1 Fixed-Bottom Job Demand

The average number of jobs from 2023 to 2030 required to fabricate and assemble all fixed-bottom components is between 10,500 and 41,000 FTEs, depending on how the supply chain matures (the number of investments in U.S. manufacturing plants and how many suppliers participate). The maximum demand is expected to occur in 2028. Figure 12 shows how these total job estimates break down per component.

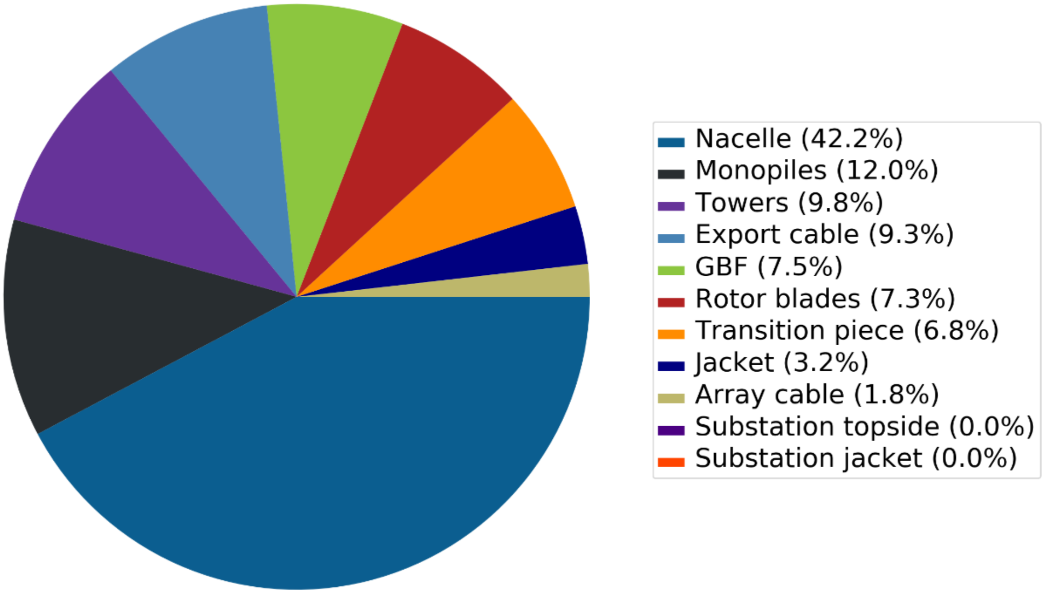

Figure 12. Baseline scenario – breakdown of jobs (FTEs) for fixed-bottom components

The nacelle has the largest potential for jobs out of all components in the offshore wind industry. In addition, the jobs related to nacelle assembly would be supported through the fabrication and assembly of the many internal subcomponents (e.g., generators, gearboxes, and power converters), which all require individual supply chains for parts and materials. Another significant opportunity for jobs is related to metal fabrication of substructures, such as towers, monopiles, transition pieces, and jacket foundations. Offshore substation components have a lower job potential because each offshore wind energy project only requires one or two substations, resulting in a low number of FTEs.

Table 18 lists the average number of jobs and maximum job demand for each component shown in Figure 12. The average number of jobs indicates how many jobs could be supported when averaging out the significant variation in workforce demand due to unsteady production rates in the demand scenarios. The maximum job demand indicates the maximum workforce that the United States may need to supply depending on domestic content each year. Those estimates are shown for 25% and 100% domestic content to reflect uncertainty in how quickly manufacturing plants are built in the United States and how fast the supply chain matures. It is likely that the actual offshore wind energy employment related to manufacturing and supply chain will be between this range.

Table 18. Average and Maximum Number of Jobs for All Fixed-Bottom Components in the Baseline Scenario

	Average Number of Jobs (2023–2030)		Maximum Job Demand (2023–2030)	
Component	25% Domestic Content	100% Domestic Content	25% Domestic Content	100% Domestic Content
Nacelle	4,600	18,600	5,300	21,200
Rotor blade	900	3,500	1,100	4,300
Towers	1,200	4,700	1,500	5,900
Monopile	1,300	5,400	1,600	6,600
Transition piece	800	3,100	1,000	3,800
Jacket	500	2,000	700	2,900
GBF	400	1,500	500	2,000
Substation topside	30	100	30	100
Array cable	300	1,100	300	1,300
Export cable	600	2,300	700	2,900

Those job estimates include both the direct and indirect impacts from manufacturing components (Tier 1), subassemblies (Tier 2), subcomponents (Tier 3), and materials (Tier 4). In general, the direct jobs are associated with fabricating or assembling a component or subcomponent at a manufacturing plant. The indirect jobs are associated with using a supply chain to produce parts or materials for the component or subcomponent. Table 19 lists the proportion of direct and indirect impacts for each component and subcomponent and their contribution to the overall job estimate based on the unique industry aggregation.

Table 19. Summation of the Breakdown of Direct and Indirect Jobs Impacts for Each Component

	Breakdown of Job Estimates	
Component	**Direct**	**Indirect**
Nacelle	35.6%	64.4%
Rotor blade	48.3%	51.9%
Towers	43.7%	56.4%
Monopile	34.3%	65.7%
Transition piece	34.3%	65.7%
Jacket (for turbine)	34.3%	65.7%
GBF	38.5%	61.5%
Jacket (for substation)	34.3%	65.7%
Substation topside	71.3%	28.7%
Array cable	38.4%	61.6%
Export cable	38.4%	61.6%

For all components (except substation topside), indirect impacts represent the largest contribution of jobs. A larger indirect contribution indicates that suppliers represent the largest potential for supporting domestic jobs; if the United States activated a robust supply chain to provide parts and materials into the major components, it would support more jobs.

Nacelle, rotor blades, and substations have a higher direct impact because they require the fabrication and assembly of several additional subcomponents in addition to fabrication and assembly of the component at a Tier 1 manufacturing plant. For substructures, (e.g., monopiles, transition piece, jackets), the driver for those components is steel. Direct jobs would be related to fabricating steel plants into a substructure. Because steel is a driver for material and labor costs, it would support a larger indirect impact. Similarly, cables typically require many parts and materials and fabrication of the array and export cable component must be done at a Tier 1 plant; therefore their indirect impact is larger.

4.5.2 Floating Systems Job Demand

The average number of jobs from 2026 and 2030 required to fabricate and assemble floating technology indicates between 2,800 and 12,000 jobs would be needed support the production to meet baseline scenario demand. Figure 13 shows how these total jobs break down by component.

This scenario assumes a semisubmersible design and represents the demand for floating technology without considering supply chain limits.[22] The installed capacity of floating projects on the West Coast in the baseline scenario enables the pipeline projection to achieve the 30-GW-by-2030 target. We report the floating wind turbine components, substructures, and dynamic cables job estimates separately from the fixed-bottom job estimates in Table 18 because of the

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[22] The design is based on a steel semisubmersible, as detailed in Section 5.3.6.

technological differences as well as the potential for geographic variation in manufacturing plant locations.

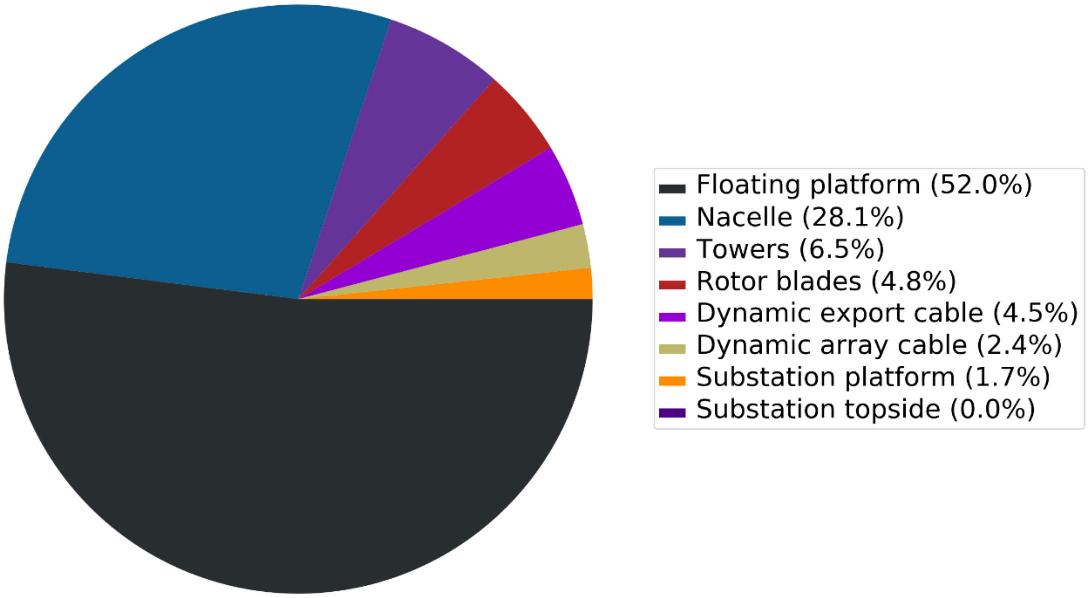

Figure 13. Baseline scenario – breakdown of jobs (FTEs) for floating components

Table 20 lists the average number of jobs and maximum job demand for each component shown in Figure 13.

Table 20. Average and Maximum Number of Jobs for All Components in the Baseline West Coast Demand Scenario

	Average Number of Jobs (2026–2030)		Maximum Job Demand (2026–2030)	
Component	25% Domestic Content	100% Domestic Content	25% Domestic Content	100% Domestic Content
Nacelle	1,100	4,600	1,900	7,700
Rotor blade	200	800	300	1,300
Towers	300	1,100	400	1,800
Floating (semisubmersible) structure	2,200	8,700	3,600	14,700
Substation topside	3	15	15	60
Dynamic array cable	100	400	200	700
Dynamic export cable	200	800	300	1,400

A unique component for floating systems is the floating substructure for the wind turbine and offshore substation.[23] The average job estimates for the semisubmersibles used to support the wind turbines and offshore substations from 2026 to 2030 is between 2,200 and 8,700 jobs (FTEs) for the baseline scenario, which achieves 30 GW of offshore wind energy by 2030. The maximum job potential occurs in 2029 when between 3,600 and 14,700 jobs would be supported under this demand scenario. Figure 14 shows the job estimates over time for the entire manufacturing and supply chain for the wind turbine floating (semisubmersible) structure component. Those job estimates comprise the direct and indirect impacts activating all tiers of the supply chain at 25% and 100% domestic content assumptions.

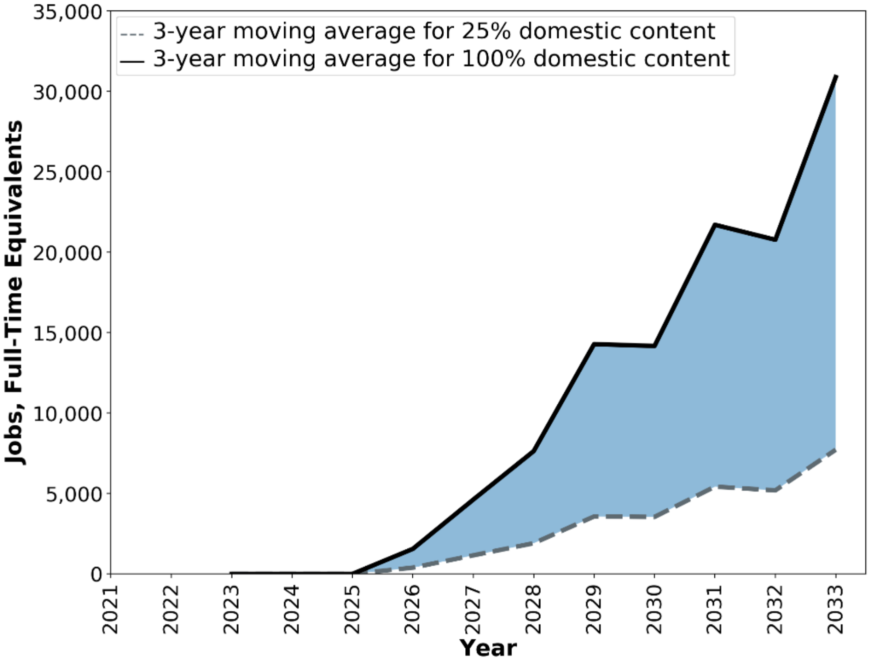

Figure 14. Baseline West Coast – number of jobs (FTEs) for floating (semisubmersible) substructure demand based on a 25% and 100% domestic content scenario

Table 21 shows how the job estimates in Figure 14 are broken down into direct and indirect job contribution percentages. The direct jobs related to the floating (semisubmersible) substructure represent the potential labor needed to complete the Tier 2 subassemblies and Tier 3 manufacturing of each individual subcomponent. The Tier 3 indirect impacts would represent the workers who support the preparation and creation of materials, such as steel (Tier 4) for use in the subcomponent fabrication. The highest potential for increasing jobs would be to develop the supply chain for steel materials, especially for secondary steel subcomponents.

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[23] The workforce demand in Figure 14 is specifically for the floating platforms that will support wind turbines and does not include platforms designed to support substations. However, the job breakdown in Table 22 applies to both the floating wind turbine and substation as the analysis assume a similar technology, cost per tonne, and economic framework.

Table 21. Floating (Semisubmersible) Substructure Jobs Breakdown by Subcomponents

Subcomponents	Direct	Indirect
Stiffened column	3.5%	6.7%
Truss structure	7.0%	13.4%
Heave plate	7.0%	13.4%
Secondary steel	8.1%	15.6%
Mooring line	2.8%	4.9%
Drag embedment anchor	6.0%	11.5%
Total	**34.5%**	**65.5%**

4.6 Economic Opportunity

In addition to job potential, the production of offshore wind energy components has additional economic impacts for the United States. To show the potential domestic economic opportunity, GDP and induced impacts are reported based on the total component demand for the baseline scenario, which achieves the goal of 30 GW of offshore wind energy by 2030.

Figure 15 shows the total GDP supported from the manufacturing and supply chain activity of all components for the baseline scenario. GDP is the value of an industry's production to the region of analysis. Using between 25% and 100% domestic labor and materials would add between $2,200 and $8,800 million to the U.S. Between 2023 and 2030, GDP at the peak in 2030 when the maximum manufacturing demand requires the highest amount of components to be purchased and wages to be paid to workers. Overall GDP continues to grow beyond 2030 as floating wind projects become more prevalent. On average each year, $1,600 to $6,200 million could be supported across the U.S. economy, depending on how the supply chain matures, including how many manufacturing plants are invested in and how much of a domestic workforce is available to support the plants.

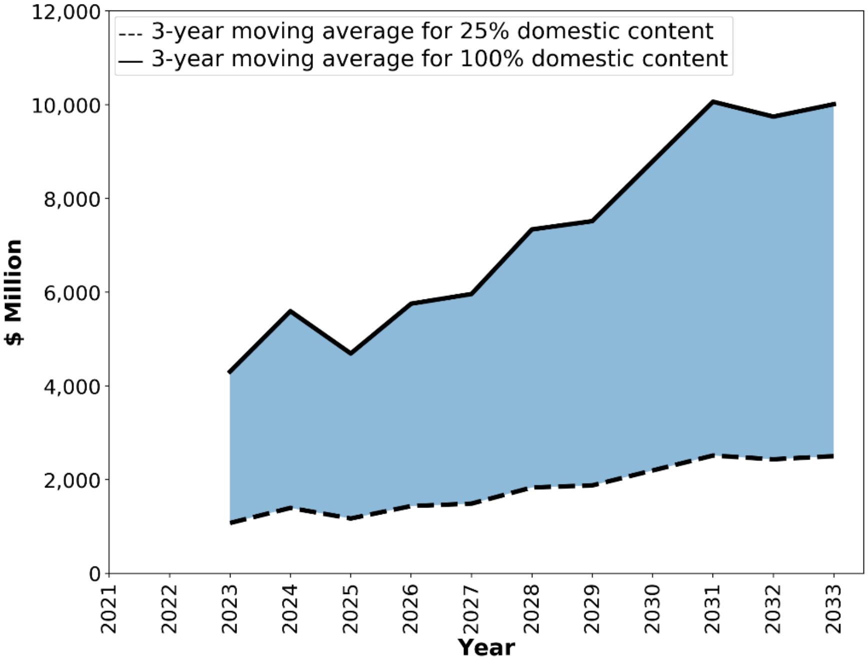

Figure 15. Total GDP ($ million) supported from the production of the component demand based on the baseline scenario with varying domestic content assumptions

Figure 16 shows the total induced jobs impact estimated from the manufacturing and supply chain activity of all components for the baseline scenario. Induced impacts accrue as money circulates in an economy, such as workers spending their earnings. Sectors that are affected by induced impacts include retail, lodging, restaurants, and other service and hospitality businesses. Between 2023 and 2030, using between 25% and 100% domestic content would add between 11,800 and 47,000 jobs to the U.S. economy in 2030 when the most workers would receive earnings.

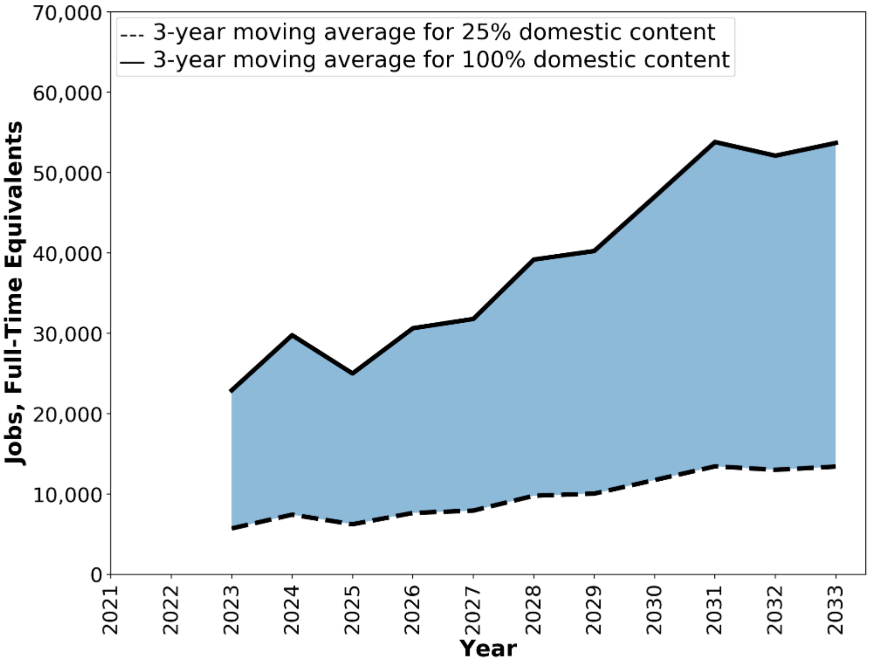

Figure 16. Total induced impact (FTE) supported from the production of the component demand based on the baseline scenario with varying domestic content assumptions

Again, the additional economic opportunity largely depends on how much domestic manufacturing plants, labor, and materials contribute to the manufacturing and supply chain of offshore wind energy components. The sensitivity analysis indicates there is great potential for the U.S. offshore wind industry.

5 The Required Components in an Offshore Wind Energy Supply Chain

5.1 Objectives and Scope

The previous sections of this report have characterized the deployment schedule and workforce requirements for major Tier 1 offshore wind energy components. In this section, we provide a description of the Tier 1 components including the subcomponents, subassemblies, and materials required for an offshore wind energy project. It is through this taxonomy of the components that we can assess the current readiness of the domestic supply chain to provide the required subassemblies to support domestic Tier 1 component manufacturing. Furthermore, we can better understand the capabilities of domestic manufacturers of Tier 2 and Tier 3 components to export materials for the global market. Most of the Tier 1 components cannot be manufactured domestically and will require significant investment in new facilities to develop the needed capabilities; however, each of the Tier 1 components has a wide range of Tier 2 subassemblies and Tier 3 subcomponents that also have the potential to be manufactured in the United States.

It is possible that existing suppliers for other industries, such as land-based wind energy, aerospace, oil and gas, or shipbuilding, can leverage their existing capabilities to develop those lower-tier components and begin to shift manufacturing and workforce expertise to the United States. For example, land-based wind production facilities may be able to expand their operations and use their existing trained workforce to produce offshore wind components, although the sheer size of offshore components would require retooling, factory expansion, and proximity to waterways to transport finished products. This manufacturing capability represents an opportunity to help transition to a fully domestic supply chain as more of the underlying components are built locally. However, the specialized components required for offshore wind energy projects also represent a challenge for industries that do not already have sufficient expertise or certifications to deliver the quality of projects required by offshore wind OEMs.

In order to better understand the opportunity space for existing domestic suppliers, we developed a hierarchical breakdown of all major fixed-bottom and floating wind Tier 1 components. By identifying all of the subassemblies and subcomponents that make up each Tier 1's unique supply chain, we can assess the strengths and gaps of the existing domestic manufacturing landscape. The hierarchy provides baseline information for assessing required domestic manufacturing throughput. In this report, we present these lists of Tier 1, 2, 3, and (in some cases) 4 components and materials and discuss the most critical path items facing the domestic supply chain. The second report in this study will compare the demand for critical components in all sectors of the supply chain with the capabilities of existing manufacturers to understand the readiness level of the current supply chain to support the anticipated deployment pipeline through 2030.

One of the main goals of the hierarchy maps is to provide an understanding of the intricate nature of the offshore wind supply chain. An important aspect of this report is depicting the supply chain in a comprehensive fashion so that both those who are familiar with the industry and those who are inexperienced can fully grasp the supply chain's depth. Moreover, it will help stakeholders recognize where they might fit within the many layers of the supply chain.

The historic lack of an offshore wind energy industry in the United States offers an opportunity for many new participants to enter the supply chain but uncertainty about deployment makes it difficult for individual suppliers to understand their potential role. Through the component hierarchies, an organizational understanding of the industry's supply chain will be achieved.

Another reason for breaking out the supply chain into hierarchies is to help Tier 2, Tier 3, and Tier 4 domestic suppliers, researchers, policymakers, and other interested groups understand the locations of companies with the capacity to provide products for the offshore wind energy supply chain. This assessment of regional capabilities includes tracking businesses that currently produce a product needed within the offshore wind supply chain and assess where those businesses fit into it. Moreover, it is important to know where companies that produce similar or adjacent products can fold into the offshore wind supply chain. This work will be a focus of the second report in this study.

5.2 Approach and Methodology

We conducted the research used to compile the offshore wind component hierarchy using a multifaceted approach that was designed to ensure an accurate, but non-exhaustive, representation of the components (Tier 1), subassemblies (Tier 2), and subcomponents (Tier 3) needed to create an offshore wind energy project.

Following a thorough literature survey, we conducted interviews with internal and external component-specific subject matter experts. Those interviews expanded the component hierarchies and provided important insights into component-related details (e.g., mass, dimensions, and materials), the fabrication process, and logistical considerations. The findings were reviewed by industry practitioners to ensure that the compiled component hierarchies and related assumptions were accurate. Throughout the interview and review process, participants identified critical components[24] and other bottlenecks that could potentially hamper the deployment of offshore wind energy in the United States. In parallel, the Business Network for Offshore Wind's existing Supply Chain Connect (SCC) company registry was expanded to include each subassembly and subcomponent.[25] As part of the updated SCC, the network added fields for data collection. The fields not only included new categories of products for companies to register under but also data fields seeking manufacturing throughput. The information collected in SCC will be analyzed and the capabilities of the companies will be compared to the deployment pipeline to understand the strengths and weaknesses of the existing supply chain as part of a follow-on report.

For each of the Tier 1 hierarchies, we asked component-specific stakeholders to provide feedback, recommendations, and input on the structure, breakdown, and content of each model. The reviewers were a mix of supply chain participants, including project developers, Tier 1

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[24] Critical components are finished components, subcomponents, or subassemblies that require specialized work or capabilities from the manufacturer's perspective.

[25] Interested suppliers can register with the Supply Chain Connect database at https://www.offshorewindus.org/supplychain/.

manufacturers, and lower-level suppliers. Furthermore, the project team gathered feedback from a diverse set of viewpoints ranging throughout the supply chain levels.

We conducted several virtual meetings with industry representatives involved in making supply chain decisions for their companies. Prior to those meetings, the reviewers were given the latest draft of the component-specific hierarchy. More often than not, each reviewer had input of their own before the meeting ever began. During the meeting itself, discussion on the contents and scopes of the hierarchies occurred. The experts would give explicit and descriptive feedback on the models, highlighting areas that would benefit from reorganization or renaming. Often, multiple meetings with the same person were organized to create a precise representation of the supply chain. Numerous email exchanges occurred between parties, including multiple revisions to the hierarchies. The comments ranged from general thoughts on the scope of the flowcharts to the depth to which the study explored the supply chain. Reviewers provided specific feedback relating to location of a component, subassembly, or part in the hierarchy or feedback on the names provided for a component, subassembly, or part.

By tapping into the existing knowledge of established participants in the offshore wind energy supply chain, the accuracy and precision of the hierarchies increased significantly. Each component's hierarchy was revised several times, with each iteration altered to implement the continuous feedback the industry reviewers provided. Through this process, the hierarchies evolved into their final form, backed by some of the industry's leading professionals. After the completion of the industry review process, the hierarchical breakdown was used to update the existing SCC categories and begin the gaps analysis.

5.3 Component Hierarchy Maps

The hierarchy maps are component-by-component flowcharts that collectively represent an offshore wind energy project. To ensure accurate representation of available fixed-bottom and floating technologies, we divided an offshore wind project into the following Tier 1 components:

- Wind turbines
- Monopile foundations
- Monopile transition pieces
- Jacket foundations
- Gravity-based foundations
- Floating semisubmersible platform
- Mooring system
- Cables
- Offshore substations
- Onshore electrical.

Hierarchy maps for the Tier 1 components are presented in a uniform fashion (see Figure 17) beginning with Tier 1 component (top layer), then Tier 2 components (second layer), and finally Tier 3 (bottom layer). Tier 3 components are also grouped by function, which is identified to the left of the list of Tier 3 components.

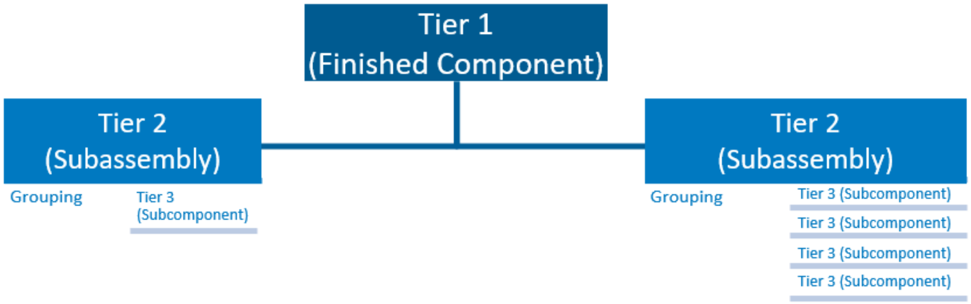

Figure 17. A key for hierarchy maps that begin at the Tier 1 level

Hierarchy maps that begin at Tier 2 list the Tier 2 subassembly at the top followed by the grouping and then the Tier 3 subcomponent (see Figure 18).

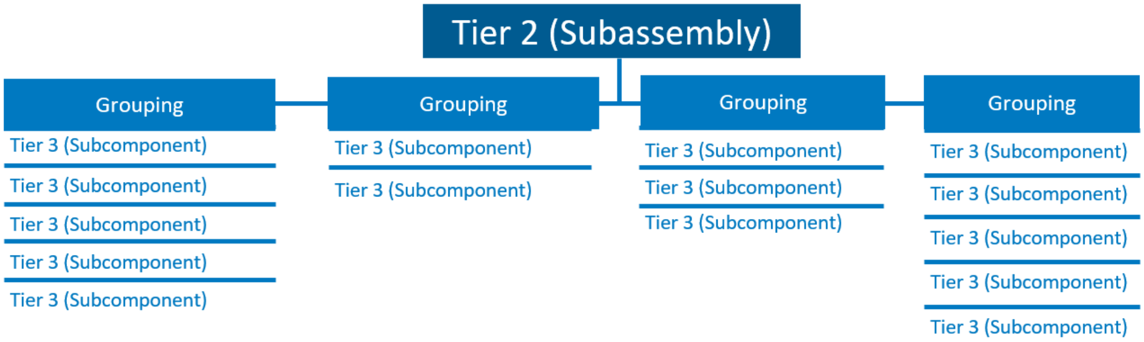

Figure 18. A key for hierarchy maps that begin at the Tier 2 level

In addition to the hierarchy maps, this section also includes a brief summary of the key insights attained during interviews with internal and external component-specific subject matter experts and during industry practitioner reviews.

A component glossary that defines the components identified in the hierarchy map is presented in Appendix D.

5.3.1 Wind Turbines

Because of the differences in nacelle drivetrain options, the wind turbine section of the component hierarchy map features separate scenarios that differentiate depending on whether the nacelle features a direct-drive system or gearbox-driven system. While direct-drive systems (see Figure 19) use a large permanent magnet to convert wind energy into electricity, geared systems (see Figure 20) feature a multistage gearbox that contains a large variety of moving components to convert wind energy into electricity.

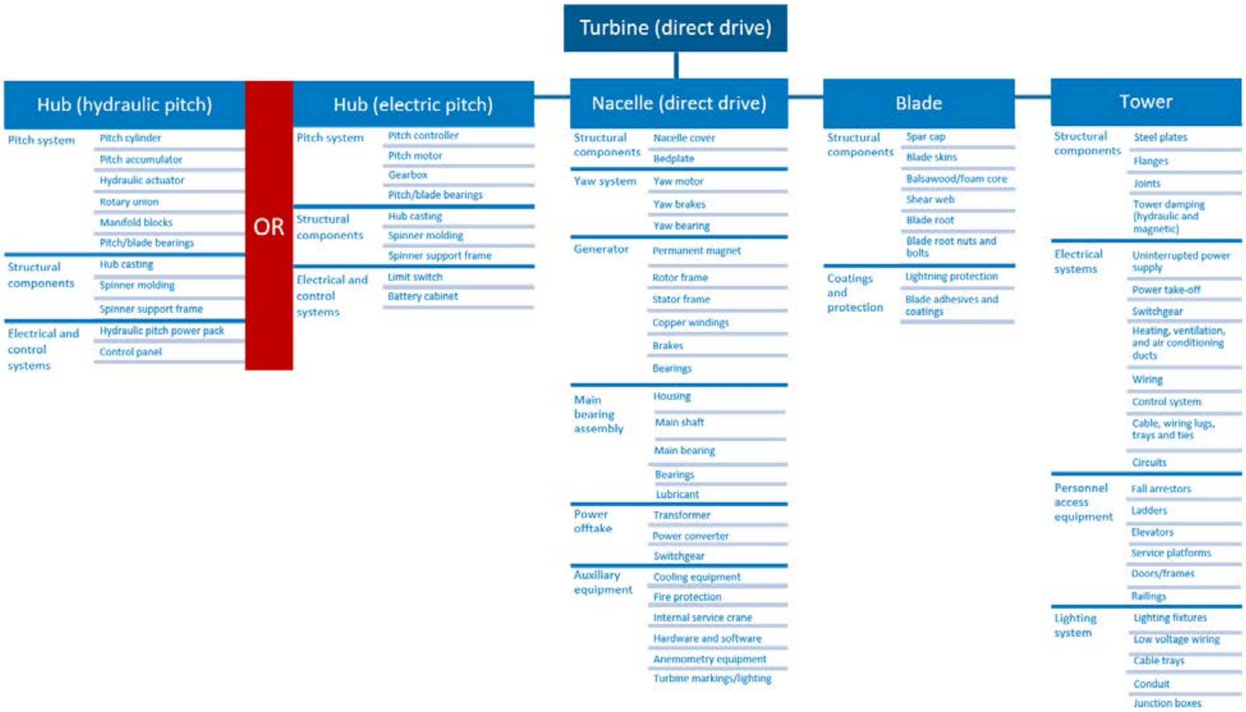

Figure 19. The various subassemblies and subcomponents that are part of a direct-drive offshore wind turbine

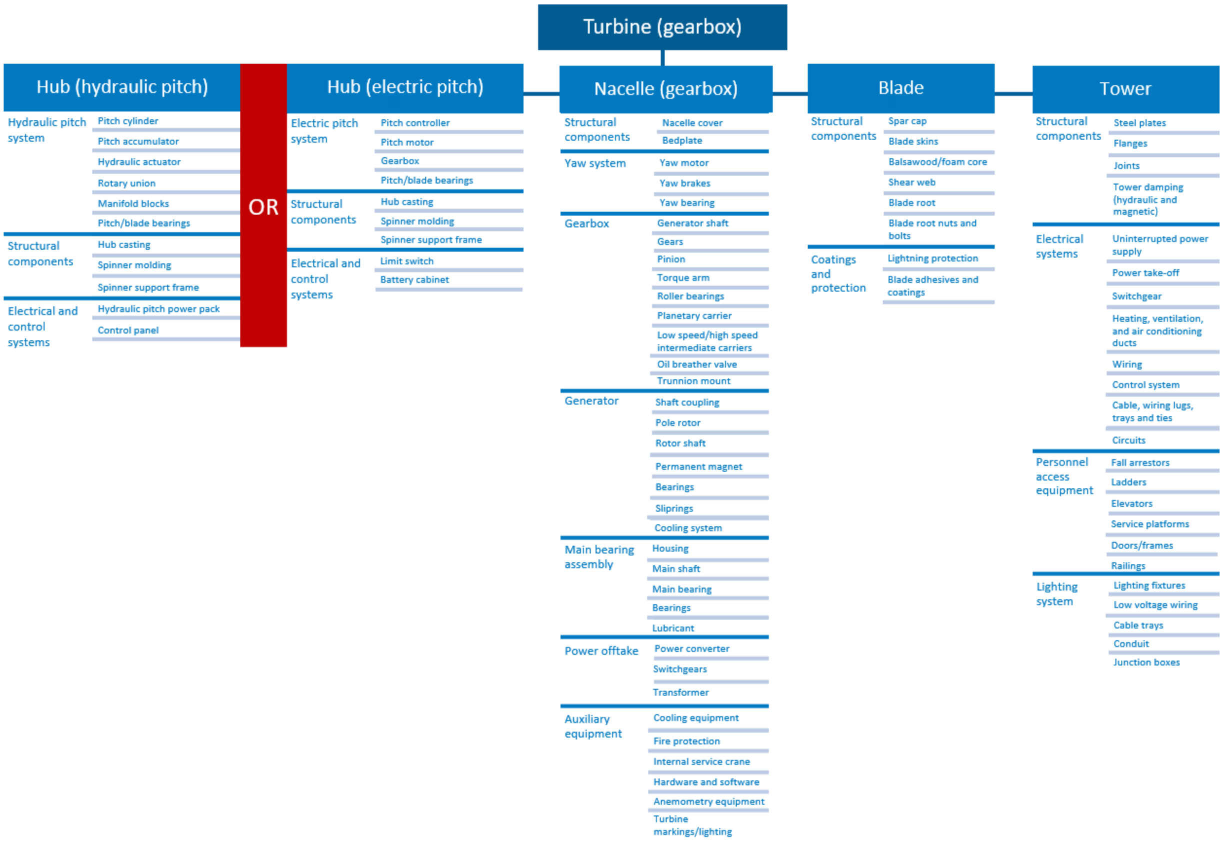

Figure 20. The various subassemblies and subcomponents that are part of a geared offshore wind turbine

In addition to the drivetrain options, offshore wind turbine hubs can feature electric or hydraulic pitch systems, creating a second subassembly differentiation that is portrayed in the turbine section of the component hierarchy map. Additional subassemblies that are included in the turbine section of the component hierarchy maps are blades and towers.

5.3.1.1 Nacelle drivetrain (direct drive and gearbox)

Offshore wind turbines can feature direct-drive or gearbox systems that have a large volume of nacelle drivetrain subassemblies and subcomponents that are individually manufactured by outside domestic or international vendors before being transported to a single facility and assembled to create the nacelle drivetrain. Nacelle drivetrain subassemblies and subcomponents for direct-drive offshore wind turbines include the main shaft and bearing, generator, yaw system, power offtake, and structural components (see Figure 21).

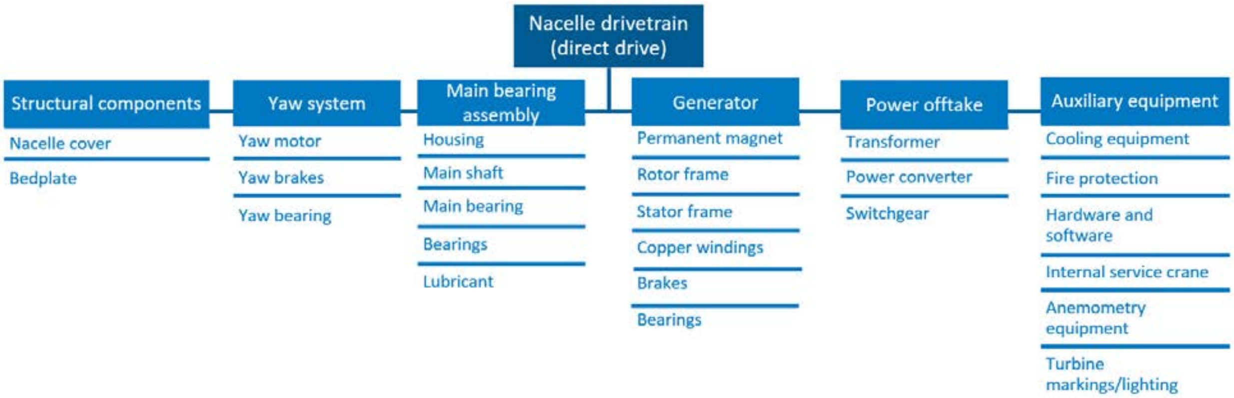

Figure 21. The various subassemblies and subcomponents that are part of the nacelle drivetrain for a direct-drive offshore wind turbine

Nacelle drivetrain subassemblies and subcomponents for geared offshore wind turbines include the main shaft and bearing, generator, gearbox, yaw system, power offtake, and structural components (see Figure 22).

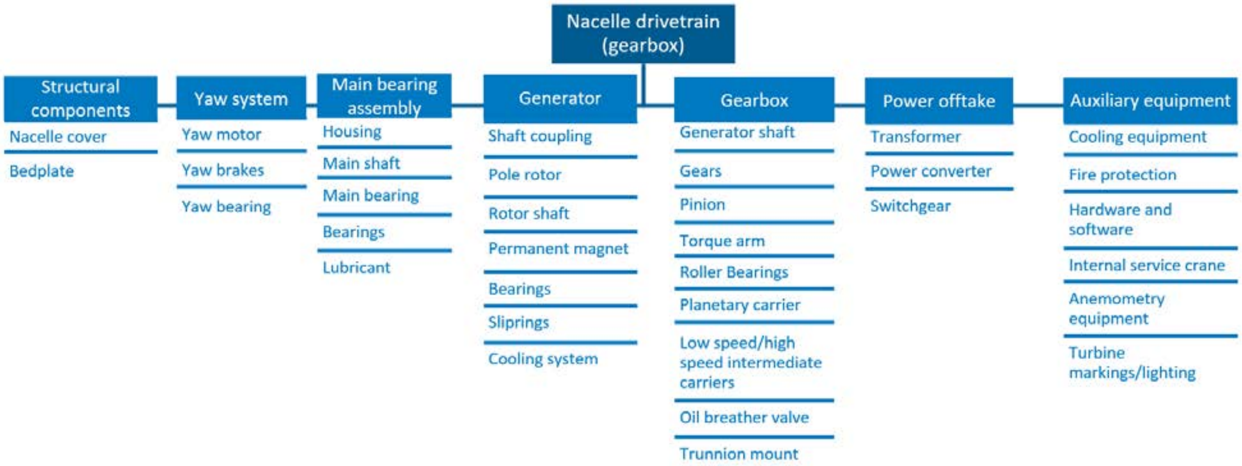

Figure 22. The various subassemblies and subcomponents that are part of the nacelle drivetrain for a geared offshore wind turbine

The size of nacelle drivetrains and many subassemblies and subcomponents requires large assembly facilities with specialized lifting equipment, adequate space for storage, and coastal access to support component delivery to project sites. Some secondary subassemblies and subcomponents can be manufactured by outside vendors, but the actual nacelle drivetrain will typically be assembled at a single location.

Although there are no technological constraints that currently inhibit the domestic fabrication and assembly of direct-drive or gearbox systems and any related subassemblies or subcomponents, current domestic manufacturing capabilities are unable to support the fabrication and assembly of some critical subcomponents and subassemblies. For instance, permanent magnets are an integral part of the generator for an offshore wind direct-drive system and can require up to 1 tonne (t) of materials per megawatt of capacity. Although there have been efforts to establish domestic rare-earth mining operations, there is also a lack of facilities that can process those materials into permanent magnets that are large enough for direct-drive systems. As a result, permanent magnets are primarily produced overseas. While geared turbines use smaller amounts of permanent magnets than a direct-drive system, the same material constraints and subsequent lack of manufacturing exists for that system as well.

Additional critical components include yaw bearings, pitch bearings, main bearings, and hub castings. While U.S. bearing manufacturers exist, there are a limited number of facilities (if any) in the country that are currently capable of producing specialized bearings with diameters that are represented in offshore wind energy turbines. Yaw bearings have diameters that are equivalent to the top of wind turbine towers while the diameter for main bearings exceeds 4 m and the diameter for pitch bearings can be larger than 6 m. Limited domestic production capabilities for hub castings are attributed to the environmental impact of the foundries that produce them. Furthermore, the number of foundries that can produce those components is limited globally. Gearboxes that are used in geared systems are a specialized subcomponent and as such are limited to a small number of manufacturers and regions. While not specifically listed as a nacelle drivetrain component, microchips are used in control panels and are currently considered a critical component that requires specialized manufacturing. The production of microchips is primarily dominated by a small number of overseas manufacturers though some domestic manufacturing capabilities exist.

5.3.1.2 Tower

With a base diameter of up to 10 m and heights that can reach over 130 m, offshore wind towers are massive components whose size creates logistical challenges in terms of fabrication, storage, and transportation. Offshore wind turbine tower subassemblies and subcomponents include various structural components, electrical systems, personal access equipment, and lighting systems (see Figure 23).

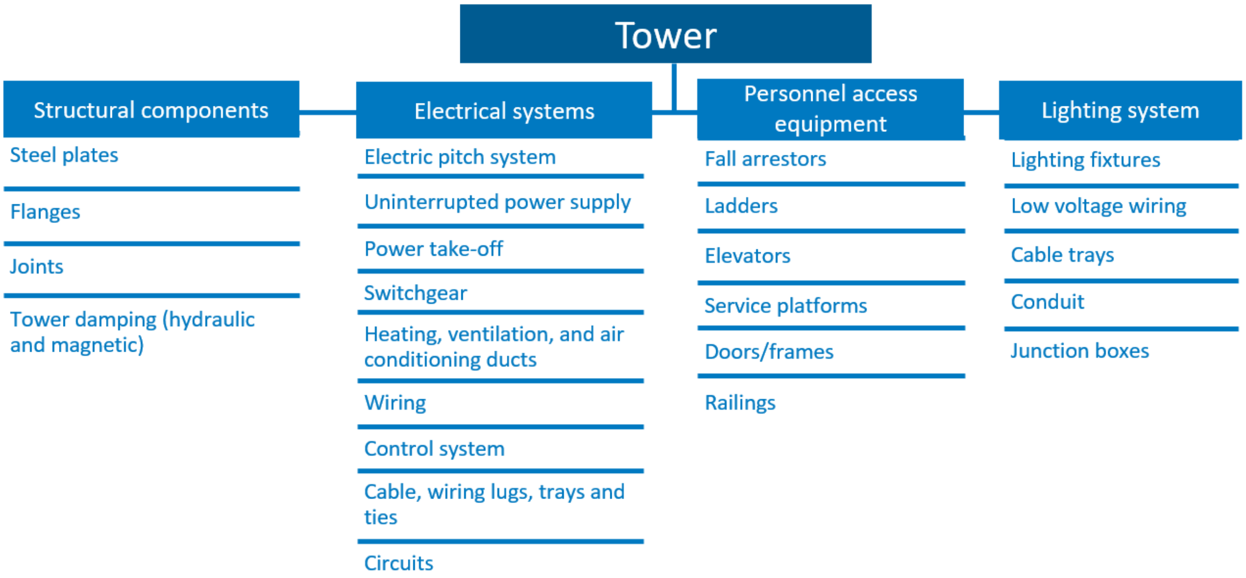

Figure 23. The various subassemblies and subcomponents that are part of the tower for an offshore wind turbine

Though a number of tower subcomponents are manufactured by secondary vendors, offshore wind turbine towers are typically fabricated by an OEM at a single location in four or more flanged sections. Those sections are then staged so subcomponents can be added before the tower is individually assembled on-site during project construction. A single tower can comprise up to 45 individually rolled plates of steel, so manufacturers will need to have the ability (equipment and space) to bend large steel plates to create individual large-diameter tower pieces that are welded together to create the individual tower sections.

In addition to the specialized equipment and manufacturing space needed to fabricate and assemble offshore wind turbine towers, those facilities will require storage space and coastal access to support component delivery to project sites. Though coastal access requirements will limit the number of locations that can host an offshore wind turbine tower manufacturing facility, many subassemblies (i.e., tower internals, access equipment, steel plates) can be fabricated in noncoastal locations and transported to the tower manufacturing/assembly site.

Although there are no technological constraints that currently inhibit the domestic fabrication and assembly of offshore wind turbine towers and any related subassemblies or subcomponents, current domestic manufacturing capabilities are unable to support the fabrication and assembly of some critical subcomponents and subassemblies. In particular, the flanges used to connect the individual sections to form an offshore wind tower were identified as a critical component as a result of the lack of U.S.-based manufacturers capable of fabricating those large-diameter forged components.

5.3.1.3 Blades

Offshore wind turbines use composite blades that can be up to 115 m in length (Vestas 2021) and have a total mass of up to 50 t (GE 2019). Offshore wind turbine blade subassemblies and subcomponents include various structural components, as well as coatings and protection (see Figure 24).

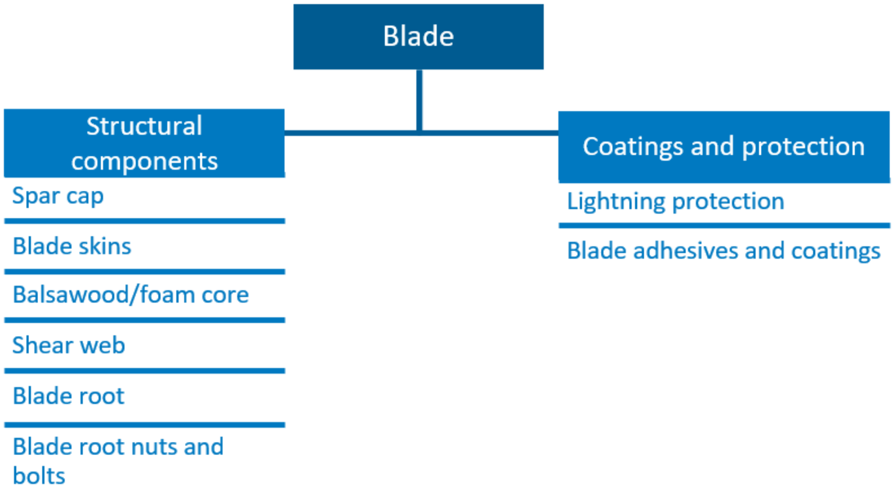

Figure 24. The various subassemblies and subcomponents that are part of the blades for an offshore wind turbine

The size of an offshore wind turbine blade requires manufacturers to have large facilities with specialized equipment and adequate space for fabrication, storage, and coastal access to support component delivery to project sites. Though a majority of the composite material for offshore wind turbine blades will be epoxy- and fiberglass-based, some subcomponents like spar caps will be manufactured with carbon fiber.

Many blade manufacturers order fiberglass subassembly kits from secondary vendors that are precut to streamline the manufacturing process. Those pieces are ultimately assembled alongside other subassemblies/subcomponents and integrated using epoxy resin to form an individual blade. Though many subassemblies and subcomponents are fabricated in-house as part of the blade manufacturing process (e.g., shear web, blade skin, spar caps) some subassemblies, like balsa wood or foam cores, or subassembly components, like the nuts and bolts that are part of the blade root, can be fabricated by outside vendors that are not coastally located.

Although there are no technological constraints that currently inhibit the domestic manufacturing of offshore wind turbine blades and any related subassemblies or subcomponents, current domestic resources are unable to support the fabrication and assembly of some critical offshore wind turbine blade subcomponents and subassemblies. In particular, balsa wood is one of two options used to create blade cores, but this material is primarily sourced from a single country that has created a bottleneck in the supply chain and made balsa wood cores a critical subcomponent/subassembly in the offshore wind turbine blade hierarchy. Additionally, land-based blade manufacturing facilities cannot easily be repurposed for offshore manufacturing purposes because of facility size constraints.

5.3.2 Monopiles

Offshore wind turbine monopile foundations are steel components that can have base diameters of 9 m or more and weigh up to 2,500 t. Offshore wind turbine monopile foundation subassemblies and subcomponents include various structural and secondary components (see Figure 25).

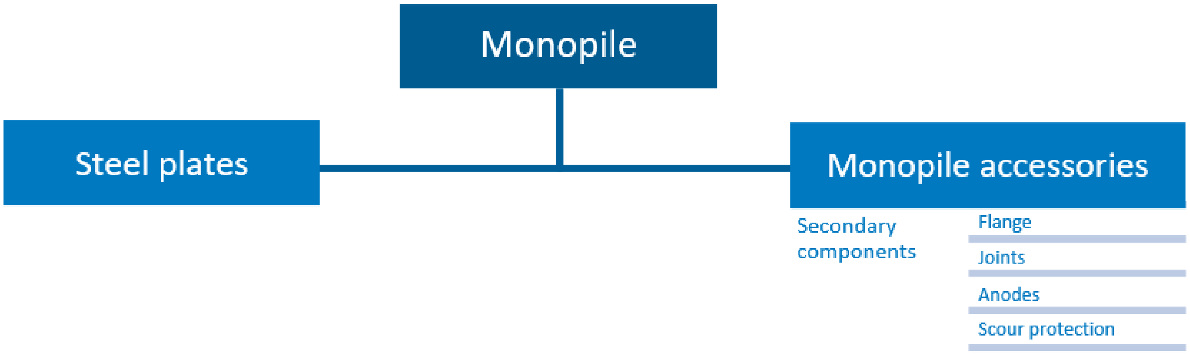

Figure 25. The various subassemblies and subcomponents that are part of the monopile foundation for an offshore wind turbine

The size of a monopile requires manufacturers to have large facilities with specialized equipment and adequate space for fabrication, storage, and coastal access to support component delivery to project sites, as well as subcomponent delivery to the manufacturing facility. In terms of specialized equipment, monopile manufacturers need to have machinery capable of bending large steel plates to create individual large diameter pieces (cans) that are welded together to create a monopile foundation.

Current domestic resources are unable to support the fabrication and assembly of monopiles and some critical subcomponents and subassemblies. In particular, flanges used to connect monopile foundations to a turbine tower or transition piece were identified as a critical component due to the lack of U.S.-based manufacturers capable of fabricating those large-diameter forged components. Additionally, while some U.S. manufacturers will be able to fabricate the smaller steel plates needed for monopile manufacturing, the larger plates will need to be imported because of a current inability to domestically produce plates that size. There is a domestic sourcing issue associated with the type of steel used in monopile foundations (S355ML) with limited suppliers being located in the United States. Finally, the technological capabilities for welding 150 millimeter-thick steel plates do not currently exist in the U.S.

5.3.3 Transition Piece (Monopile)

Unlike other offshore wind foundation types that have built-in transition pieces to house access and safety equipment and act as a connection between the tower and foundation, some monopiles use a transition piece that is a separately manufactured component (see Figure 26) that can be fabricated by monopile manufactures or other outside vendors. While future monopile designs are shifting away from the use of traditional transition pieces, it is included in this report as a representation of current technology.

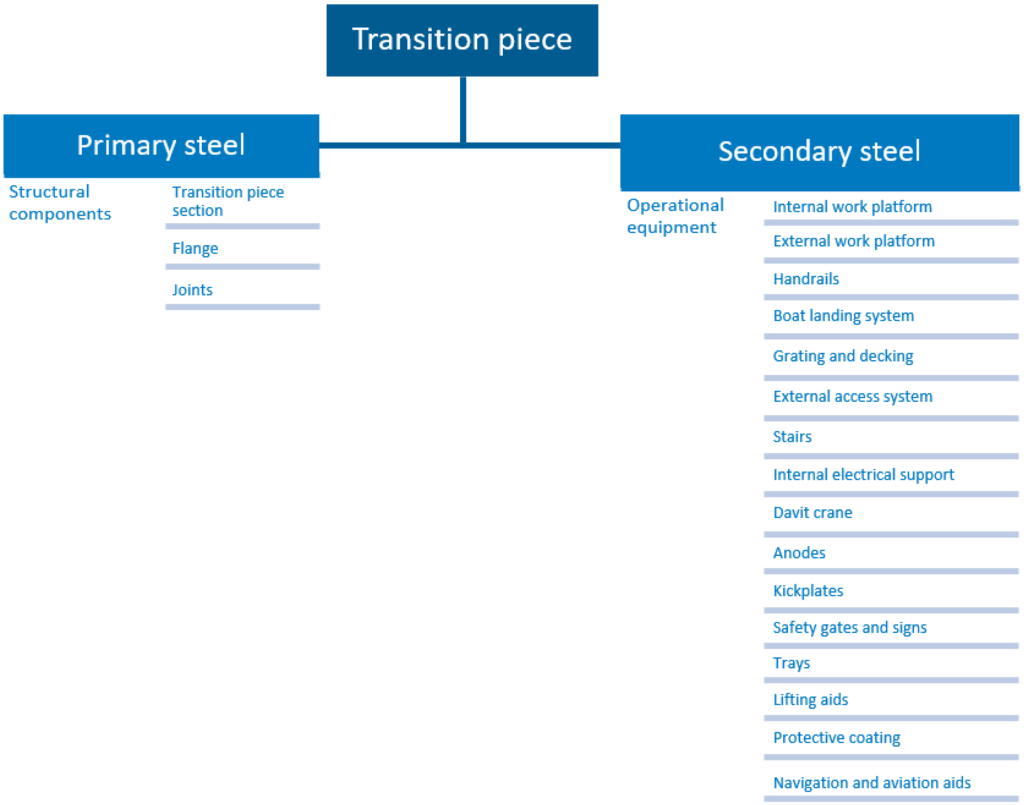

Figure 26. The various subassemblies and subcomponents that are part of the transition piece for an offshore wind turbine

With diameters that are equal to the upper part of a monopile foundation and an offshore wind turbine tower, monopile transition pieces are large steel components that can weigh more than 500 t (BVG Associates 2019).

The size of this component requires manufacturers to have large facilities with specialized lifting equipment, adequate space for fabrication, storage, and coastal access to support component delivery to project sites. Some secondary subassemblies and subcomponents can be manufactured by outside vendors, but the actual monopile transition piece will typically be fabricated at a single location with subassemblies and subcomponents assembled into the final product.

Although there are no technological constraints that currently inhibit the domestic fabrication and assembly of offshore wind turbine monopile transition pieces and any related subassemblies or subcomponents, current domestic resources are unable to support the fabrication and assembly of some critical transition piece subcomponents and subassemblies. In particular, flanges used to connect monopile foundations to a turbine tower or transition piece were identified as a critical component because of the lack of U.S.-based manufacturers capable of fabricating those large-diameter forged components.

5.3.4 Jacket Foundation

Offshore wind turbine jacket foundations are steel components that can be more than 85-m tall with a mass of more than 1,000 t. Offshore wind turbine jacket foundations include subassemblies and subcomponents that make up the pile system, truss, secondary steel, and transition piece (see Figure 27).

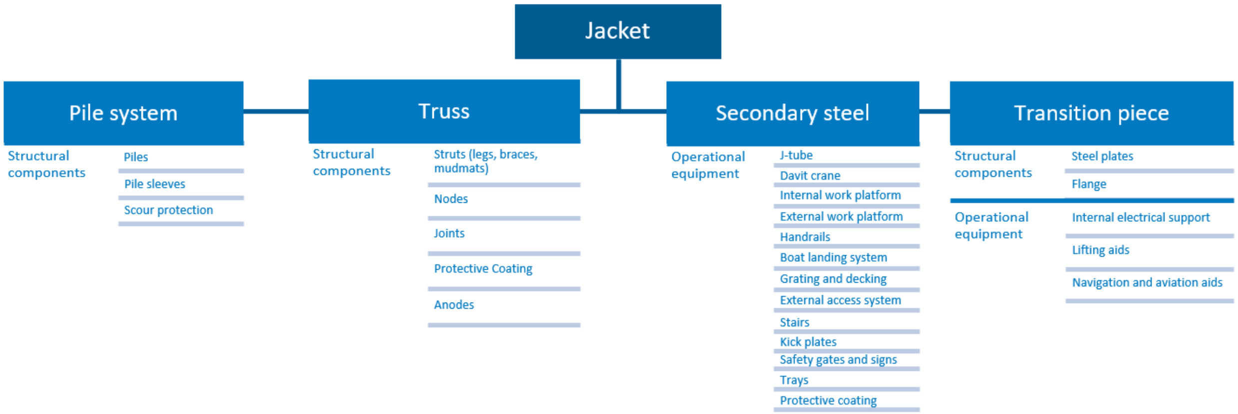

Figure 27. The various subassemblies and subcomponents that are part of the jacket foundation for an offshore wind turbine

The struts, nodes, piles, and mats for this component are typically ordered through outside vendors and then assembled and welded together at a manufacturing facility to create a single jacket foundation. The jacket foundation contains a built-in transition piece that connects the foundation to the tower.

The size of this component requires manufacturers to have large facilities with specialized lifting equipment, adequate space for fabrication, storage, and coastal access to support component delivery to project sites. Some secondary subassemblies and subcomponents can be manufactured by outside vendors, but the actual jacket foundation will typically be fabricated at a single location.

Although there are no technological constraints that currently inhibit the domestic fabrication and assembly of offshore wind turbine jacket foundations and any related subassemblies or subcomponents, current domestic resources are unable to support the fabrication and assembly of some critical transition piece subcomponents and subassemblies. In particular, flanges used to connect jacket foundations to a turbine tower or transition piece were identified as a critical component because of the lack of U.S.-based manufacturers capable of fabricating those large-diameter forged components.

5.3.5 Gravity-Based Foundation

Gravity-based foundations are a concrete-and-steel-reinforced component that can have a base diameter of 58 m and require up to 7,000 m^3 of concrete and 2,450 t of steel reinforcement (SMart Wind 2015). Offshore wind turbine gravity-based foundations include subassemblies and subcomponents that make up the shaft, skirt, and accessories for this component (see Figure 28).

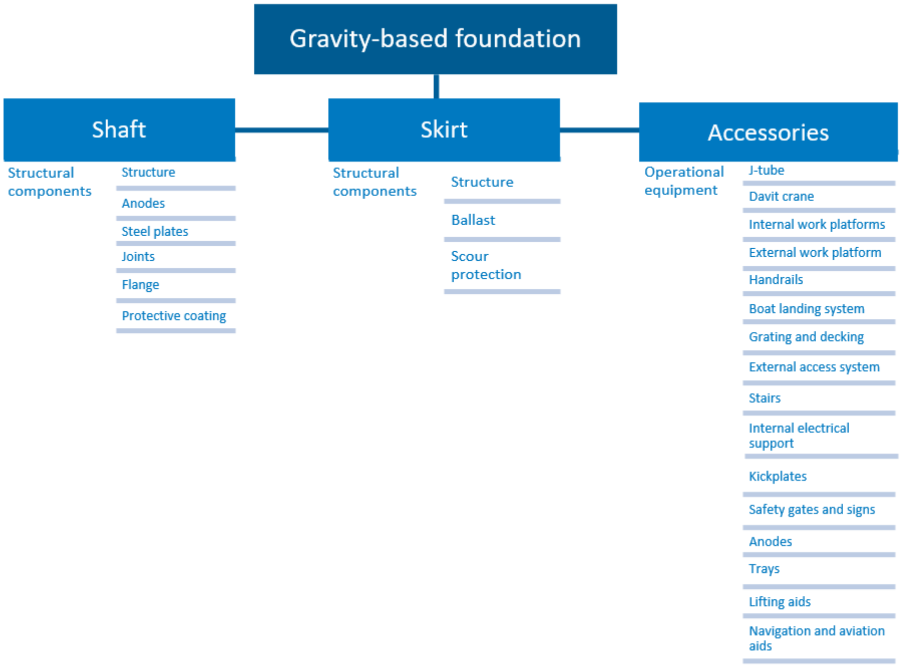

Figure 28. The various subassemblies and subcomponents that are part of the gravity-based foundation for an offshore wind turbine

With a mass and footprint greater than a monopile foundation, the size of this component requires manufacturers to have large facilities with adequate space for fabrication, wet storage, and coastal access to support component delivery to project sites. Some secondary subassemblies and subcomponents can be manufactured by outside vendors, but the actual gravity-based foundation will typically be fabricated at a single location.

Although there are no technological constraints that currently inhibit the domestic fabrication and assembly of offshore wind turbine gravity-based foundations and any related subassemblies or subcomponents, current domestic resources are unable to support the fabrication and assembly of some critical transition piece subcomponents and subassemblies. In particular, flanges used to connect gravity-based foundations to a turbine tower, or transition piece, were identified as a critical component because of the lack of U.S.-based manufacturers currently capable of fabricating those large-diameter forged components. Additionally, the large diameter of a gravity-based foundation means a massive volume of scour protection is needed. High-density rock is preferred to the extent that some project developers have considered scenarios where this type of rock will be imported from other countries to accommodate the demand.

Other potential bottlenecks for gravity-based foundations include the immediate and localized availability of concrete as a result of future commitments to other industries. With only a limited number of concrete suppliers available, new batch plants may need to be developed near gravity-based foundation manufacturers to address this need.

5.3.6 Semisubmersible Floating Foundation

In this study we assume that semisubmersibles will be the primary floating platform deployed in the United States through 2035. Over 75% of anticipated global floating wind projects are expected to use semisubmersibles due to their relatively shallow draft and hydrodynamic stability during tow-out (Musial et al. 2021). There are still a wide variety of semisubmersible concepts being developed and a clear favorite has yet to emerge in the nascent floating wind market. This study is based on the UMaine VolturnUS-S semisubmersible platform designed to support the International Energy Agency 15-MW reference wind turbine. Semisubmersible floating platforms for offshore wind turbines feature multiple subcomponents that make up the columns, support structure, and auxiliary equipment of this component (see Figure 29). An adoption of different platforms or semisubmersible designs may alter the demands on the supply chain.

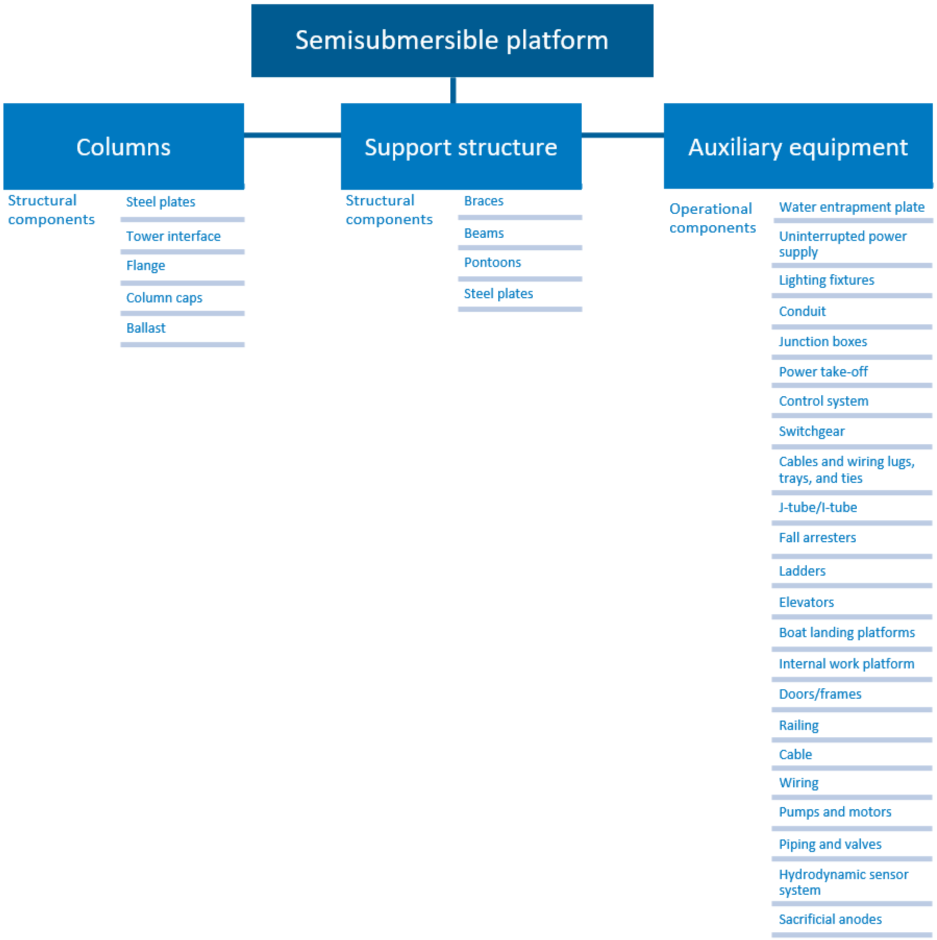

Figure 29. The various subassemblies and subcomponents that are part of a semisubmersible floating foundation for an offshore wind turbine

The 4,000-t hull comprises four buoyant columns with three radial columns connected to one central column hosting the platform-tower interface. The outer columns are connected to the central column by three rectangular pontoons and steel braces. An iron-ore-concrete ballast is distributed at the bases of the outer columns. Semisubmersible floating platforms often feature both a passive ballast and active ballast system to compensate for the hydrodynamic changes to the platform.

The size of the semisubmersible platform requires manufacturers to have large facilities with specialized lifting equipment, adequate space for fabrication and storage, and coastal access to support component delivery to project sites. Many subassemblies (i.e., personnel access equipment, lighting systems, auxiliary equipment) can be manufactured by secondary vendors; however, the semisubmersible platform pieces will typically be fabricated at a single location. It is also possible to manufacture large components such as the buoyant columns in one location and ship these to an assembly port to be connected.

The technological constraints of this component can be largely summed up to the infancy of this sector of the offshore wind turbine industry. In addition to the infancy of deployed floating assemblies, current domestic resources are unable to support the fabrication and assembly of some critical semisubmersible floating platform subcomponents and subassemblies. The steel columns making up the hull structure present manufacturers with fabrication and material processing challenges.

5.3.7 Mooring System

Offshore mooring systems connect the floating platform to the seafloor using multiple mooring lines, anchors, and connecting elements. The mooring lines involve some combination of chains, wire rope, and/or synthetic rope. In-line tensioners and various connecting elements are used along the mooring lines to accommodate different mooring system configurations and water depths (see Figure 30 and Figure 31). Different anchors are chosen based on water depth and seafloor conditions. Catenary mooring systems for shallow-water semisubmersible turbines employ drag embedment anchors and several mooring lines. The mooring lines for catenary systems are suspended in the water and accompanied by buoyancy modules. Clump weights attached to mooring lines provide additional weight to act as a restoring force. Taut mooring systems utilize suction caissons to secure deep-water semisubmersibles. The mooring lines are pretensioned using in-line tensioners to offset the mean load of the system.

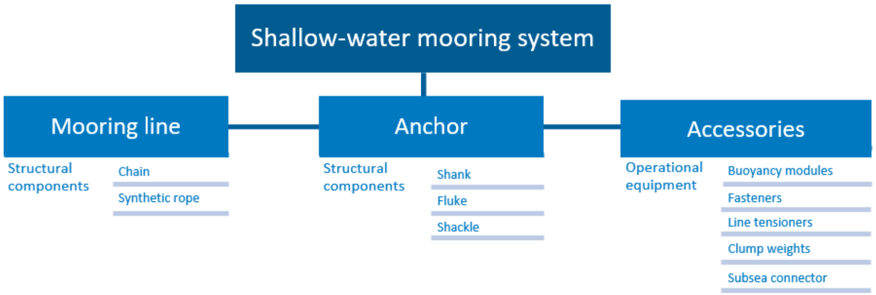

Figure 30. The various subassemblies and subcomponents that are part of the shallow-water mooring system for a floating offshore wind turbine

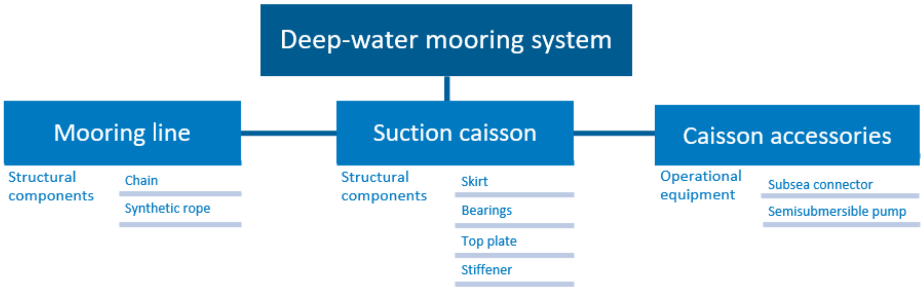

Figure 31. The various subassemblies and subcomponents that are part of the deep-water mooring system for a floating offshore wind turbine

The size and mass of the anchors require manufacturers to have large facilities with specialized lifting equipment, adequate space for fabrication and storage, and coastal access to support component delivery to project sites. Other mooring line components have fewer restrictions on lifting equipment, storage, and coastal access. The volume of steel required for both anchors and chains can create transportation and manufacturing challenges for wind energy project suppliers.

Suction caisson anchors require manufacturers to have machinery capable of bending large steel plates to create large cylindrical sections of 10 m in diameter.

Current domestic resources are unable to support the fabrication and assembly of some critical mooring line subcomponents and subassemblies primarily due to raw material constraints. The chain links require a higher-grade steel than typical vessel mooring systems because of the longevity of deployment of semisubmersible turbines. Current manufacturers do not have access to a domestic supply of the ingots needed for mooring chains and many facilities do not have the forging capabilities to process the ingots. The global supply chain for mooring chain may have a difficult time supporting the demand for a single deep-water offshore wind project, indicating a need for expanding manufacturing capabilities worldwide to support the anticipated pipeline of floating wind projects.

5.3.8 Cables

Array cables link individual wind turbines to the offshore substation in various configurations. They are connected to each turbine using J-tubes and buried in the seabed or covered with concrete mattresses. Interarray cables contain three copper conductors layered with insulation and waterproofing. Static export cables run from the offshore substation to the onshore substation at a higher voltage than interarray cables.

The size of static cables requires manufacturers to have large facilities with adequate storage space, specialized fabrication equipment, and coastal access to support material delivery to project sites. Cable manufacturers import raw materials and output finished products, which are shipped directly to the project site, so there are no secondary subassemblies and subcomponents outside of cable accessories that are manufactured by outside vendors for this component. A description of the cable components and accessories is provided in Figure 32.

Current U.S. manufacturers are not equipped to produce the volume needed to support the entirety of the 30-GW target, although the only currently operational domestic Tier 1 manufacturing facility is the Nexans export cable plant in South Carolina. The primary constraint in the cable supply chain is the availability of the raw materials, specifically the specialty plastics and lead alloys that are required.

Dynamic export and array cables serve the same purpose as static cables but are specifically required for floating wind energy projects. Beyond export and array cables, dynamic cables also include the operational accessories that allow this component to be properly installed (see Figure 32).

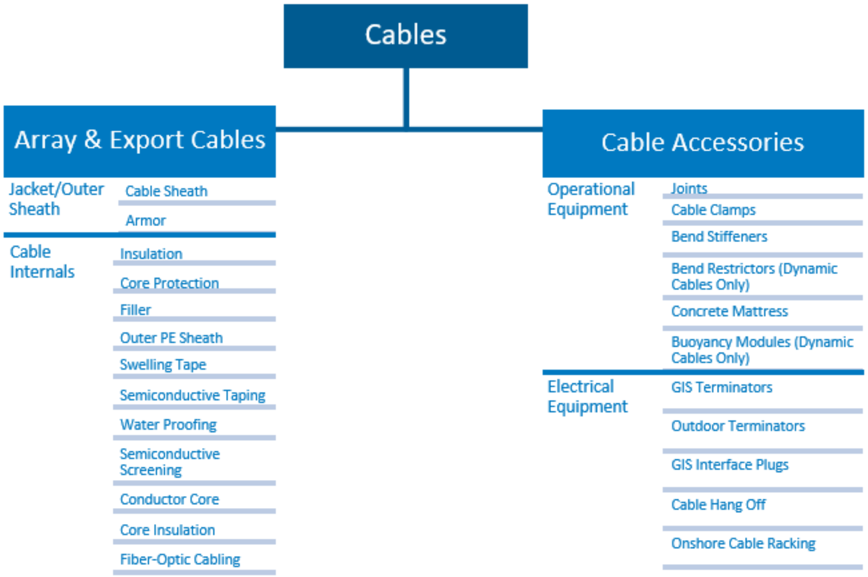

Figure 32. The various subassemblies and subcomponents that are part of static and dynamic offshore wind array and export cables

The cables are fully or partially suspended in the water column instead of being buried under the seafloor and are consequently subjected to additional loads from the motion of the floating platform and subsea currents. Dynamic export cables require more armor and have larger conductor cores than dynamic array cables.

5.3.9 Offshore Substation

Offshore wind substations collect electrical power from individual wind turbines, step it up to higher voltage, and transmit the power to an onshore grid connection via an export cable. They include an assortment of electrical equipment (including power collection, conversion, and transmission components), telecommunications equipment, and auxiliary equipment housed in a large topside steel structure that can be over 20 m tall (Cobra undated) and weigh over 2,000 t when fully assembled (Offshore WIND 2016). Fixed-bottom offshore substations typically use jacket foundations. These systems and subcomponents are listed in Figure 33.

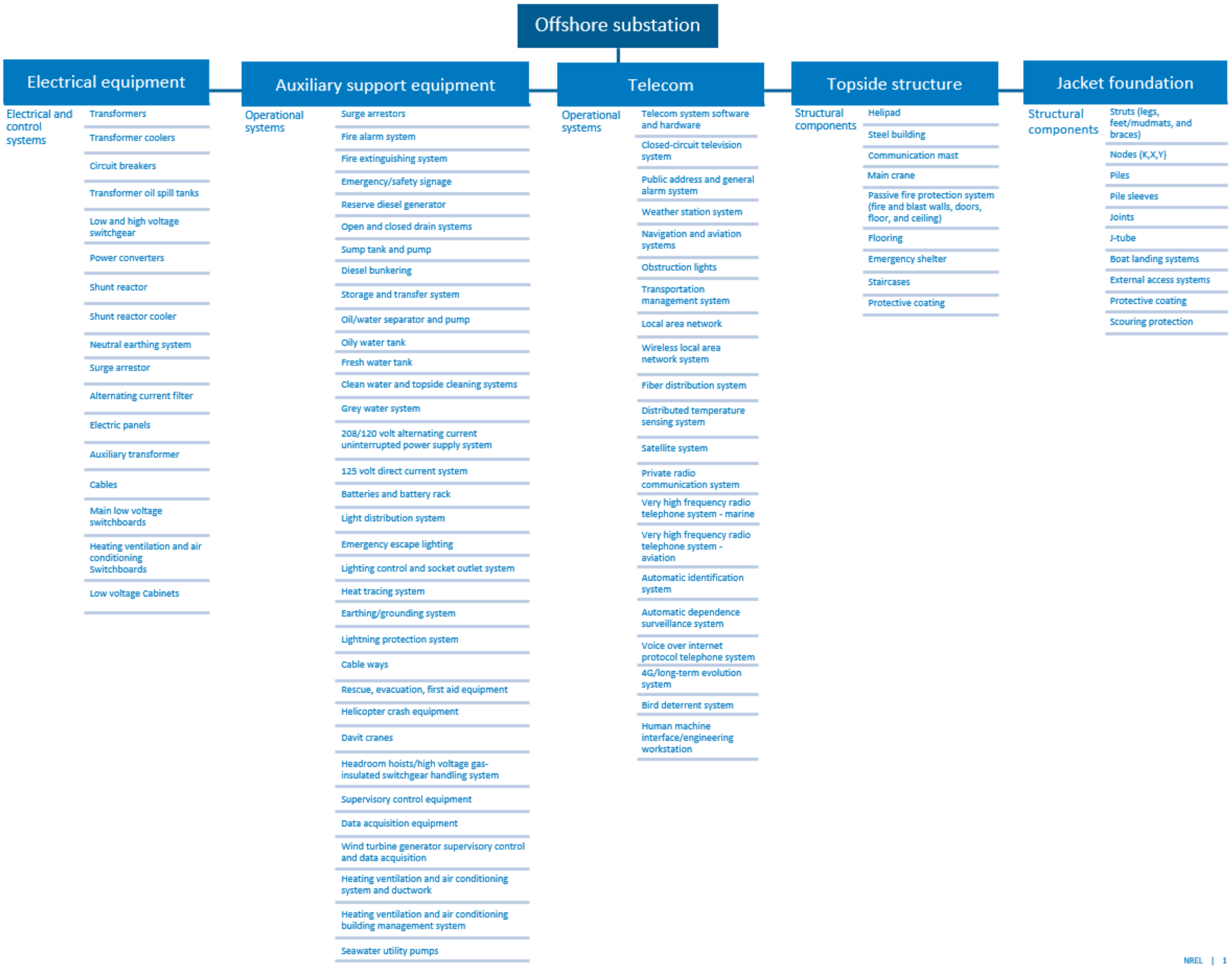

Figure 33. The various subassemblies and subcomponents that are part of the substation for an offshore wind energy project

The offshore wind substation topside is assembled at a shipyard instead of a bespoke manufacturing facility like most offshore wind energy components. Subcomponents and subassemblies are manufactured by outside vendors and are integrated into the substation as the topside structure is being fabricated.

The size of this component and the simultaneous nature of its assembly/fabrication process creates a unique supply chain scenario wherein the demand for substation subassemblies and subcomponents is directly tied to the potential for a domestic substation fabrication facility. Importing subassemblies and subcomponents to be integrated with a topside being fabricated at a U.S. shipyard may introduce sufficient logistical complexities that technology providers prefer to conduct the full assembly internationally and ship the finished substation to the project site.

Once the topside structure is fully constructed, it is moved from the fabrication facility to the project for installation. The dimensions of this component require manufacturers to have large facilities with specialized lifting equipment, adequate space for fabrication, and coastal access to support component delivery to project sites.

Although there are no technological constraints that currently inhibit the domestic fabrication and assembly of an offshore wind substation and any related subassemblies or subcomponents, current domestic resources are unable to support the fabrication and assembly of some critical transition piece subcomponents and subassemblies. In particular, gas-insulated switchgears and shunt reactors are two components that were identified as potential concerns because they are not commonly used for anything other than offshore wind energy, so they are not currently made by existing U.S. manufacturers. Those type of components are made for land-based applications but would require additional marinization and certification to be suitable for offshore wind energy projects. Similarly, transformers are not fabricated in the U.S. with the type of marinization requirements needed for offshore wind energy projects. Developing these capabilities domestically would increase the likelihood of assembling the entire substation in the U.S.; however, the relatively low demand for offshore substations relative to other offshore wind energy components (1–2 substations per project) make it a more challenging business case to invest in new domestic manufacturing capabilities.

5.3.10 Onshore Electrical

Onshore electrical components for an offshore wind project transitions the power that is transported through export cables from a subsea to land-based focus and includes cable equipment and onshore substation subassemblies and subcomponents (see Figure 34).

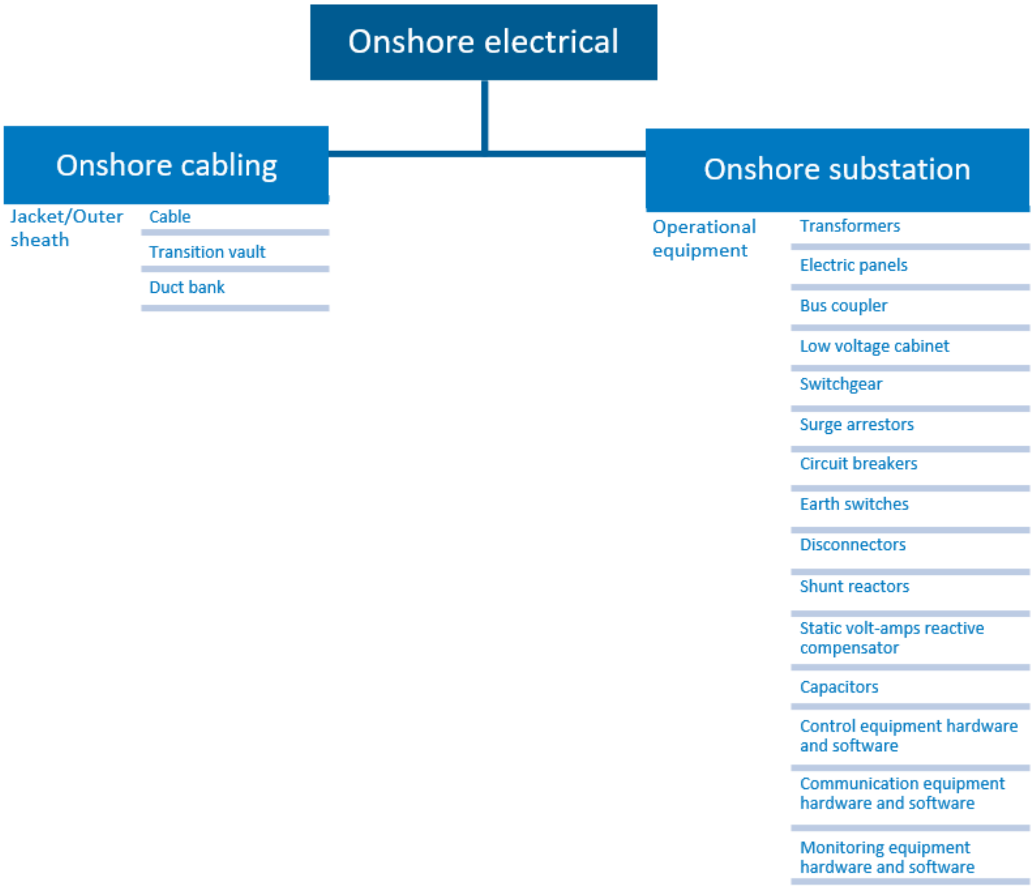

Figure 34. The various subassemblies and subcomponents that are part of the onshore electrical component of an offshore wind energy project

Subcomponents and subassemblies for the onshore electrical components for an offshore wind project are manufactured by a variety of vendors and are transported on-site to create an onshore substation that is used to increase the voltage of the energy generated at an offshore wind project. There are no technological constraints that currently inhibit the domestic fabrication and assembly of onshore electrical components and any related subassemblies or subcomponents.

6 Conclusions and Future Work

In this report, we investigated the high-level demand for resources that will be required to achieve the national offshore wind energy target of 30 GW by 2030. This assessment includes a description of the overall deployment pipeline as well as the demand schedule for major Tier 1 components, along with an estimate of how those deployment timelines could vary under different global supply chain bottlenecks or leasing scenarios in the United States. We used the deployment pipeline to assess the demand for ports, vessels, and workforce that would be required to install the offshore wind energy projects. The economic modeling also includes an estimate of the potential benefits to gross domestic product that would be induced under varying levels of domestic content. Finally, we list the types of Tier 1, 2, and 3 components that are required for fixed-bottom and floating offshore wind projects and discuss critical path items that may present challenges for a future domestic supply chain.

The key findings of the report include:

- Deploying 30 GW by 2030 is achievable with the current lease areas that have been awarded by BOEM, although disruptions or bottlenecks in the global supply chain pose significant risks to this opportunity. This potential constraint represents a motivation for a domestic supply chain that can de-risk the 30-GW target by developing facilities that produce components dedicated to the U.S. market.
- Expanded leasing that generates a consistent deployment after 2030 is critical for suppliers planning on investing in new domestic facilities. We anticipate future leasing in the Gulf of Mexico, Central Atlantic, California, Oregon, Hawai`i, and Gulf of Maine regions that will satisfy this demand and help build a sustainable offshore wind pipeline and supporting supply chain.
- A domestic offshore wind manufacturing industry would require a significant number of workers to be available as soon as the early 2020s, with average annual jobs between 12,300 and 49,000 FTEs, resulting in an immediate need for workforce training.
- The huge quantity and types of components that are required to build offshore wind energy projects provide an opportunity for domestic manufacturers to leverage their existing strengths to support the deployment pipeline. We identified a number of components that cannot currently be manufactured in the United States, such as permanent magnets, large diameter flanges and bearings, wind turbine blades, and mooring chains. This inability represents a challenge to establishing a domestic supply chain, but also an opportunity for first-movers in the industry to develop the capabilities within the United States.

The results of this study form the basis for the second phase of the supply chain road map project, which will analyze how the strengths of the existing supply chain can best be leveraged to build a domestic supply chain. Phase two will also evaluate the potential benefits of such a supply chain. The next steps for the study include:

- Populating Supply Chain Connect, the national offshore wind supply chain database maintained by the Business Network for Offshore Wind, with companies interested in supporting the offshore wind energy industry. This database already has over 2,100 registered companies and outreach activities are currently underway to advertise the database and industry to new participants.

- Translating the demand pipeline for Tier 1 components to critical Tier 2 and Tier 3 components to understand the annual demand for those subassemblies and subcomponents.
- Comparing the demand for critical Tier 1, 2, and 3 components with the capabilities of existing suppliers from Supply Chain Connect and soliciting additional insight from industry professionals to understand the readiness level of the current supplier network to support offshore wind energy deployment.
- Developing future domestic supply chain scenarios in which all Tier 1 components and critical Tier 2 and Tier 3 subassemblies and subcomponents (or as many as practical) are fabricated within the United States. The scenarios will be developed based on our understanding of the readiness level and locations of existing suppliers, achievable time frames and costs for developing new facilities, and the potential impact of new supply chain facilities on underserved communities. This latter point will be evaluated with new energy justice metrics being developed at NREL.
- Evaluating and comparing the benefits of the domestic supply chain scenarios, including regional workforce and economic benefits and impacts on project cost or logistics.

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Appendix A. East Coast Port Assessments

In this section we expand upon the summary East Coast port assessments in Table 9 to include the specifications for all 22 ports investigated in this study. Tables A1, A2, and A3 present the marshalling port capabilities for Northeast, Central, and Southeast Atlantic ports (respectively).

Table A1. Northeast East Coast Port Marshalling Capabilities and Assessment

Port Name	State	Laydown Area (acres)	Quayside Length (m)	Number of berths	Berth Depth (m)	Channel Depth (m)	Bearing Capacity (t/m^2)	Air Draft Limit (m)	Readiness Level (WTIV)	Readiness Level (Feeders)
Searsport	ME	70	270	2	12.2	11	5	None	🟥 Quayside length and bearing capacity	🟥 Bearing capacity, quayside length
Brayton Point	MA	140	210	2	10.5	10.16	9.8	41.2	🟥 Berth/channel depth, quayside length, and bearing capacity	🟥 Bearing capacity, quayside length
New Bedford[26]	MA	29	366	3	9.1	9.1	20 t/m^2	None	🟥 Berth/channel depth, and quayside length	🟩 Quayside length
Salem	MA	42	420	2	9.1	8.5		None	🟥 Berth/channel depth, quayside length and bearing capacity	🟥 Bearing capacity and quayside length
Boston Autoport	MA	81	332	4	11.89	11.1	9.8 t/m^2	41	🟥 Quayside length, bearing capacity, and air draft	🟥 Bearing capacity and quayside length
Port of Providence – South Quay	RI	20	1,280	3	11.5	10.67		62.8	🟥 Laydown area, channel depth, bearing capacity, and air draft	🟥 Bearing capacity and laydown area
Quonset Point	RI	60	1,400	4	9.75	9.75		62.8	🟥 Berth/channel depth, bearing capacity, and air draft	🟨 Bearing capacity

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[26] New Bedford is already under contract as a marshalling port although its total quayside length and laydown area are smaller than port requirements suggested by wind turbine OEMs. The size constraints will likely drive project developers to use feeder barges for installation. Therefore, we assign a 'green' readiness level for this strategy.

Port Name	State	Laydown Area (acres)	Quayside Length (m)	Number of berths	Berth Depth (m)	Channel Depth (m)	Bearing Capacity (t/m^2)	Air Draft Limit (m)	Readiness Level (WTIV)	Readiness Level (Feeders)
New London State Pier[27]	CT	30	1244	4	12.2	10	Assume > 15	None	Channel depth	🟩
Port of Bridgeport	CT	18.3	375	3	9.8	8.5		None	Laydown area, quayside length, berth/channel depth and bearing capacity	Laydown area, quayside length and bearing capacity
Port of Coeymans[28]	NY	125	1,067	3	9.14	9.14	19.5 t/m^2	41.2	N/A	🟩
Port of Albany[26]	NY	300	1,798	3	9.14	9.14	5 t/m^2 and 10 t/m^2	40.2	N/A	Bearing capacity

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[27] New London State Pier is undergoing infrastructure upgrades to re-make it as a heavy-lift capable port for offshore wind (Musial et al. 2021); therefore, we assume that it has sufficient bearing capacity even though this information is not publicly available.

[28] The ports of Coeymans and Albany are being planned as offshore wind manufacturing ports and do not intend to support WTIV access; therefore, we do not assess their readiness level for WTIVs.

Table A2. Central East Coast Ports Marshalling Capabilities and Assessment

Port Name	State	Laydown Area (acres)	Quayside Length (m)	Number of berths	Berth Depth (m)	Channel Depth (m)	Bearing Capacity (t/m^2)	Air Draft Limit (m)	Readiness Level (WTIV)	Readiness Level (Feeders)
South Brooklyn Marine Terminal	NY	88	417	2	10.7	12.2	30	60	Berth depth, quayside length and air draft	Quayside length
Homeport	NY	35	430	2				35	Berth/channel depth, quayside length, bearing capacity, and air draft	Berth/channel depth, quayside length, and bearing capacity
Arthur Kill Terminal	NY	32	411	2	10.7	10.7	30	None	Berth/channel depth andquayside length	Quayside length
New Jersey Wind Port	NJ	70	854	4	11.5	9.88	29.8	None	🟩	🟩
Port of Paulsboro	NJ	195	260	3	12.2	13.7		53	Air draft, quayside length and bearing capacity	Quayside length and bearing capacity
Tradepoint Atlantic[29]	MD	3,300	1,021	2	10.97	10.97		None	Berth/channel depth, bearing capacity	Bearing capacity

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[29] Tradepoint Atlantic has invested in bearing capacity upgrades (Musial et al. 2021) but these data are not public and the port has not entered into any agreements to marshal offshore wind projects. As a result, we list bearing capacity as an outstanding uncertainty for Tradepoint Atlantic.

Table A3. Southeast East Coast Ports Marshalling Capabilities and Assessment

Port Name	State	Laydown Area (acres)	Quayside Length (m)	Number of berths	Berth Depth (m)	Channel Depth (m)	Bearing Capacity (t/m^2)	Air Draft Limit (m)	Readiness Level (WTIV)	Readiness Level (Feeders)
Portsmouth Marine Terminal	VA	287	1,079	3	13.11	13.11	Assume >15 t/m^2	None	🟩	🟩
Newport News Marine Terminal	VA	165	1,061	4	12.19	12.19		Yes	Air draft, bearing capacity	Bearing capacity
Morehead	NC	128	1,635	9	11-14	14		None	Bearing capacity	Bearing capacity
Wilmington	NC	284	2,060	9	13	13		64	Bearing capacity and air draft	Bearing capacity
Charleston	SC	286	1,070	3	15.85	15.85		Yes	Bearing capacity and air draft	Bearing capacity

Appendix B. Workforce Estimates–Additional Scenarios and Data

6.1.1 Moderate Supply Chain Constraints

The average job estimate between 2023 and 2030 indicates 9,400 and 37,700 jobs could support the component demand of fixed-bottom components for the moderate supply chain constraint scenario each year. As noted in Section 2.4.2, it is likely that the United States will experience wind turbine supply bottlenecks if the industry exclusively relies on imports from European suppliers. This constraint will primarily affect the East Coast projects; as a result, we report the impact on jobs exclusively for the East Coast pipeline. For the job analysis, we assume that the 4 gigawatts (GW) of European imports are produced by a U.S. market and some components are produced after 2030. This assumption leads to a greater understanding of the U.S. domestic workforce considerations when there is a lower component production in U.S. facilities and when the component demand is shifted to later years. Figure B1 shows the job estimates over time based on the component demand each year for the moderate supply constraint scenario.

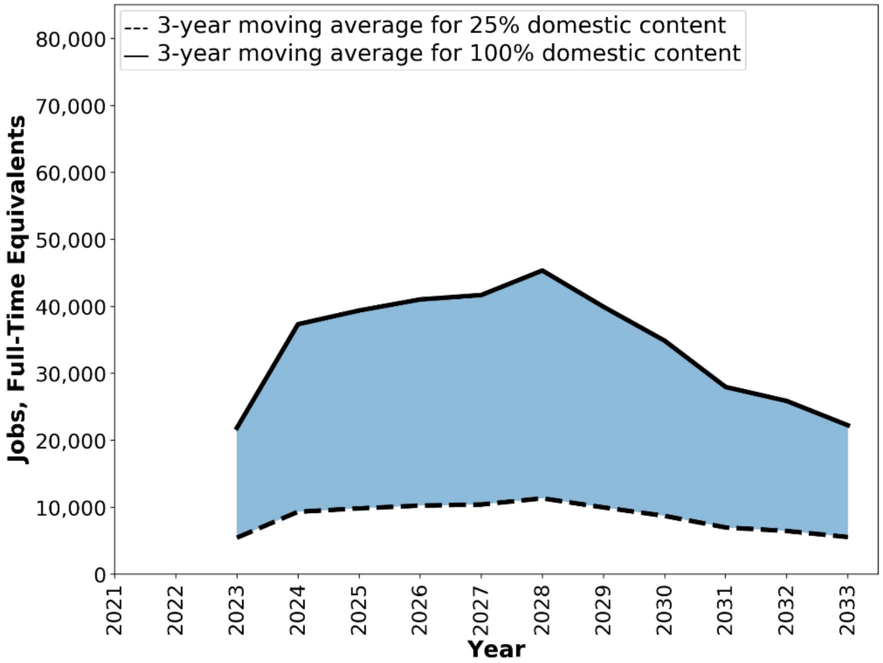


Figure B1. Moderate supply chain constraint scenario – number of jobs (full-time equivalents [FTEs]) for all fixed-bottom component demand based on scaling domestic content for the entire supply chain

For the moderate supply chain constraint scenario, the highest manufacturing and supply chain job potential occurs in 2028 to meet a pipeline projection of 4,000 megawatts (MW) installed in 2030. Depending on the level of domestic content, between 11,300 and 45,400 jobs would be needed to meet component demand. This job potential indicates the maximum workforce that will need to be trained depending on how the supply chain matures. It is likely that the actual job estimate of the U.S. offshore wind manufacturing and supply chain will fall between this range.

Because this demand scenario assumes European original equipment manufacturers (OEMs) have the bandwidth to export up to 4 GW of wind turbines and demand shifted to later years, the workforce estimate is lower than the fixed-bottom component demand in the baseline scenario. Despite a reduction in job potential in a single year, the number of jobs over time is more consistent due to the component demand shift, leading to an average workforce estimate similar to the baseline scenario.

In addition, the required ramp up in the early 2020s demonstrates that if the United States develops a domestic supply chain with good-paying jobs, there is an immediate need for workforce development. Educational institutions, unions, OEMs, and developers could work together to ensure workers are adequately trained and ready to hire as U.S. manufacturing begins production. However, the ramp up to supply workers for the industry is more gradual than the baseline scenario.

6.1.1 Significant Supply Chain Constraints

The average job estimate between 2023 and 2030 indicates 5,200 and 20,700 jobs could support the component demand of the significant supply chain constraint scenario each year. Again, we focus on fixed-bottom component jobs because East Coast projects will be primarily impacted by bottlenecks in the supply of components from Europe. This job estimate shows workforce implications when component demand is further reduced by 2030, and component demand is shifted to production years after 2030. Figure B2 shows the job estimates over time based on the component demand each year for the significant supply constraint scenario.

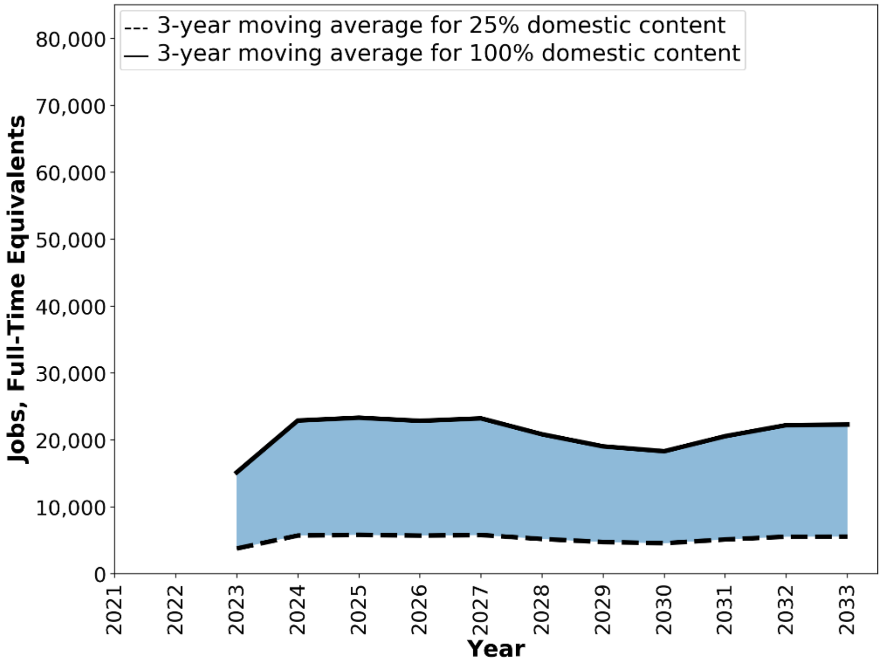


Figure B2. Significant supply chain constraints scenario – number of jobs (FTEs) for all fixed-bottom component demand based on scaling domestic content for the entire supply chain

For the significant supply constraints East Coast scenario, the highest manufacturing and supply chain job potential occurs in 2025 to meet a pipeline projection of 2,000 MW installed in 2027. Depending on the level of domestic content, between 5,800 and 23,300 jobs would be needed to meet component demand. This job potential indicates that the maximum workforce will need to be trained depending on how the supply chain matures. It is likely that the actual job estimate of the U.S. offshore wind manufacturing and supply chain will fall between this range.

Because this demand scenario assumes European OEMs have bandwidth to export up to 2 GW of wind turbines, the job estimates are lower than the unconstrained baseline and moderate supply constraint scenarios. Furthermore, there are fewer expenditures, leading to lower job estimates to produce fewer components with a reduced component demand in the United States. On average, there is a 58% reduction from the baseline scenario to the significant supply chain constraint scenario.

6.1.2 Detailed Fixed-Bottom Component Job Estimates

6.1.2.1 Wind Turbines

6.1.2.1.1 Nacelles

The average number of jobs from 2023 and 2030 required to fabricate and assemble all nacelle components is between 4,600 and 18,600 jobs (FTEs) for the baseline scenario, which achieves the 30 GW of offshore wind energy by 2030 target. The maximum job potential occurs in 2028 when between 5,300 and 21,200 jobs would be supported under this demand scenario. Figure B3 shows the job estimates over time for the entire manufacturing and supply chain for the nacelle. Those job estimates comprise the direct and indirect impacts, thereby activating all tiers of the supply chain at 25% and 100% domestic content assumptions.

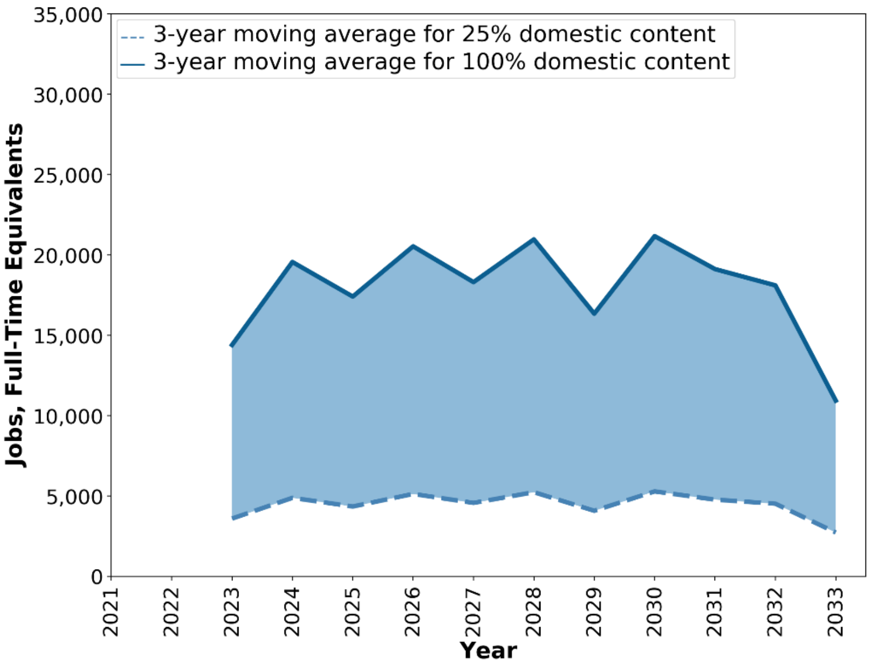


Figure B3. Baseline scenario – number of jobs (FTEs) for nacelle (gearbox) demand based on 25% and 100% domestic content scenarios

Table B1 shows how the job estimates in Figure B3 are broken down into direct and indirect job contribution percentages. Each subcomponent is considered to have its own industry. In general, the direct jobs are associated with producing that subassembly or subcomponent at a manufacturing plant and the indirect jobs are associated with using a supply chain to produce parts or materials for the subcomponent. The largest contribution of jobs is related to producing generators, which represents 25% of the nacelle job estimates. Also comparing the direct and indirect estimates indicates the total number of indirect jobs could be significant, indicating an opportunity to increase domestic content with lower-tier suppliers.

Table B1. Nacelle-Related Jobs Based on Tier 3 Subcomponents

Subcomponents	Tier	Direct	Indirect
Nacelle cover	3	1.0%	1.9%
Bedplate	3	1.9%	3.7%
Main shaft	3	1.9%	3.7%
Main bearing	3	1.2%	3.3%
Yaw system	3	2.1%	3.7%
Gearbox	3	4.2%	11.5%
Generator	3	10.1%	15.1%
Power converter	3	7.1%	10.6%
Auxiliary equipment	3	6.1%	10.9%
Total		**35.6%**	**64.4%**

Figure B4 shows the nacelle job estimates for each constrained demand scenario assuming 25% and 100% domestic content. This figure is provided to show the component contribution for the constrained scenarios over time with reduced and shifted demand.

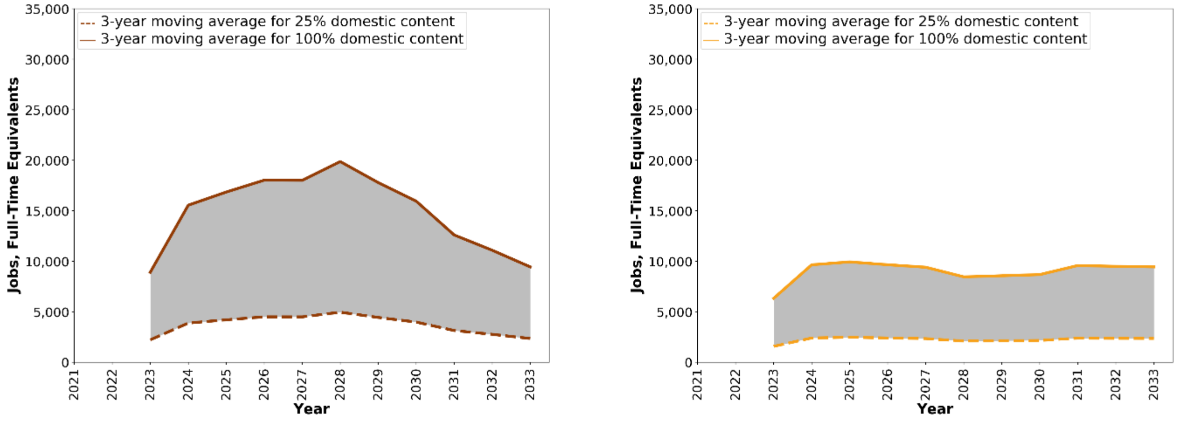


Figure B4. Moderate (left) and significantly (right) constrained fixed-bottom supply chain scenarios – number of jobs (FTEs) for nacelle (gearbox) demand based on 25% and 100% domestic content scenarios

6.1.2.1.2 Towers

The average number of jobs from 2023 and 2030 required to fabricate all tower components is between 1,200 and 4,700 jobs (FTEs) for the baseline scenario, which achieves 30 GW of offshore wind energy by 2030. The maximum job potential occurs in 2024 when between 1,500 and 5,900 jobs would be supported under this demand scenario. Figure B5 shows the job estimates over time for the entire manufacturing and supply chain for the tower. Those job estimates comprise the direct and indirect impacts activating all tiers of the supply chain at 25% and 100% domestic content assumptions.

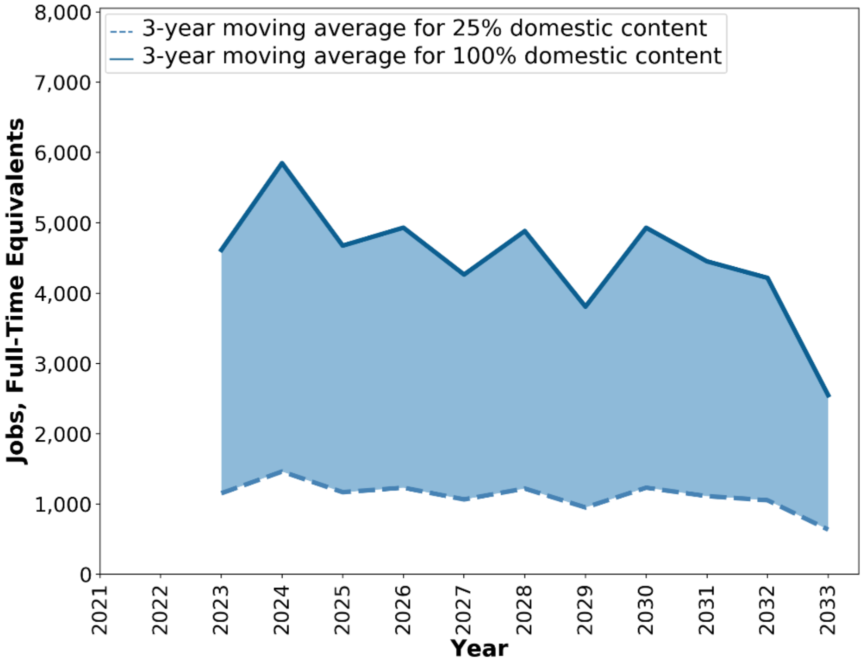


Figure B5. Baseline scenario – number of jobs (FTEs) for tower demand based on 25% and 100% domestic content scenarios

Table B2 shows how the job estimates in Figure B5 are categorized according to direct and indirect job contribution percentages. The direct jobs related to the tower manufacturing plant (Tier 2 subassembly) represent the potential labor to complete tower fabrication, such as rolling and welding as well as all plant operations. The steel cans (Tier 3 subcomponents) are another significant cost in tower production. The direct jobs for steel cans represent the labor needed to produce the steel cans prior to transporting to a tower manufacturing facility. Whereas the indirect jobs for steel cans would represent the business-to-business transaction in the supply chain, such as purchasing steel (Tier 4).

Table B2. Tower Jobs According to Tier 2 Subassembly and Tier 3 Components

Component	Tier	Direct	Indirect
Tower manufacturing plant	2	22.9%	16.1%
Steel cans	3	13.2%	25.2%
Flanges	3	3.7%	7.0%
Personnel access equipment	3	0.2%	0.4%
Paint	3	1.1%	2.7%
Bolts, washers, nuts, weld wire	3	2.6%	5.0%
Total		**43.7%**	**56.4%**

Figure B6 shows the tower component job estimates for each constrained demand scenarios assuming 25% and 100% domestic content. This figure shows the component contribution for the constrained scenarios over time with reduced and shifted demand.

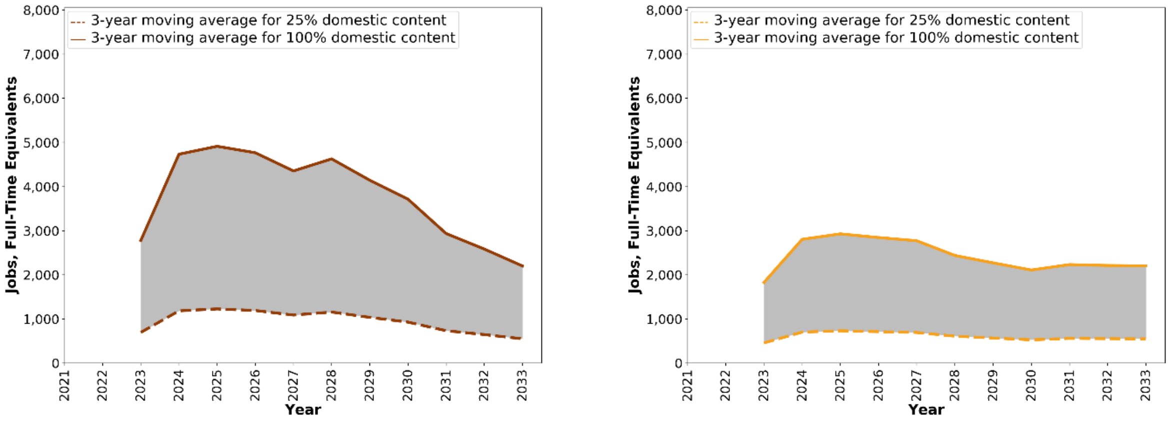


Figure B6. Moderate (left) and significantly (right) constrained fixed-bottom supply chain scenarios – number of jobs (FTEs) for tower demand based on 25% and 100% domestic content scenarios

6.1.2.1.3 Rotor blades

The average number of jobs from 2023 and 2030 required to fabricate and assemble all rotor blade components is between 900 and 3,500 jobs (FTEs) for the baseline scenario, which achieves 30 GW of offshore wind energy by 2030. The maximum job potential occurs in 2024 when between 1,100 and 4,300 jobs would be supported under this demand scenario. Figure B7 shows the job estimates over time for the entire manufacturing and supply chain for the rotor blade component. Those job estimates comprise the direct and indirect impacts activating all tiers of the supply chain at 25% and 100% domestic content assumptions.

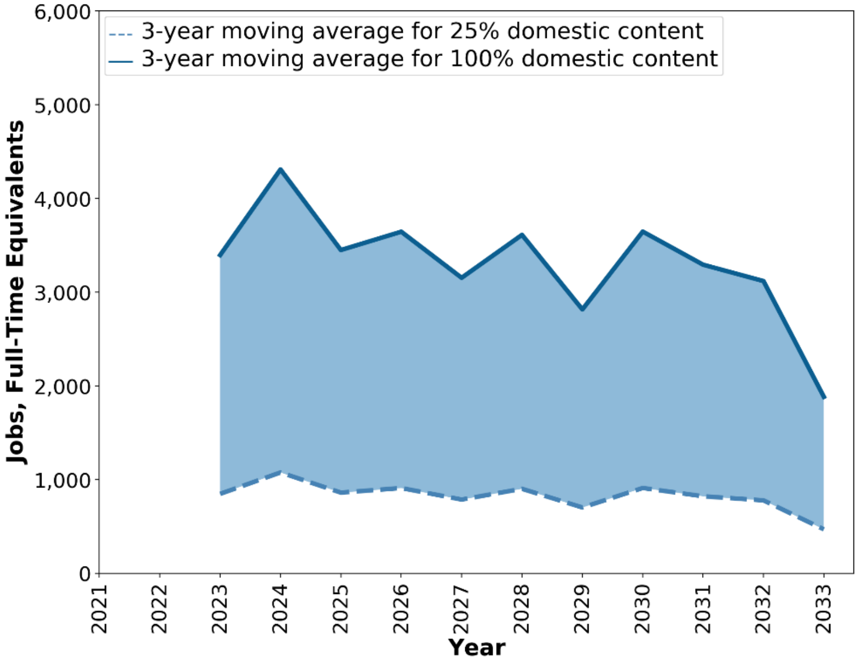


Figure B7. Baseline scenario – number of jobs (FTEs) for rotor blade demand based on 25% and 100% domestic content scenarios

Table B3 shows how the job estimates in Figure B7 are organized according to direct and indirect job contribution percentages. The direct jobs related to the wind turbine blade manufacturing plant (Tier 2 subassembly) represent the potential labor needed to complete blade fabrication, such as infusing the materials into the mold. The blade manufacturing plant indirect jobs would represent the jobs supported by business-to-business transactions to support the plant operations and its workers. The Tier 3 subcomponents direct impacts are related to manufacturing those subcomponents separately from the final blade fabrication. The Tier 3 indirect impacts would represent the workers who support the preparation and creation of materials, such as carbon fiber, fiberglass, and resins (Tier 4) for use in the subcomponent fabrication.

Table B3. Blade Jobs Organized According to Tier 2 Subassembly and Tier 3 Components

Component	Tier	Direct	Indirect
Blade manufacturing plant	2	33.6%	22.2%
Spar cap	3	3.9%	9.3%
Blade skins	3	2.7%	4.7%
Balsawood/foam core	3	3.7%	6.4%
Shear web	3	0.2%	0.6%
Blade root	3	2.2%	5.2%
Nuts and bolts	3	0.5%	0.9%
Blade adhesives and coatings	3	1.5%	2.6%
Total		**48.3%**	**51.9%**

Figure B8 shows the rotor blade component job estimates for each constrained demand scenario assuming 25% and 100% domestic content. This figure shows the component contribution for the constrained scenarios over time with reduced and shifted demand.

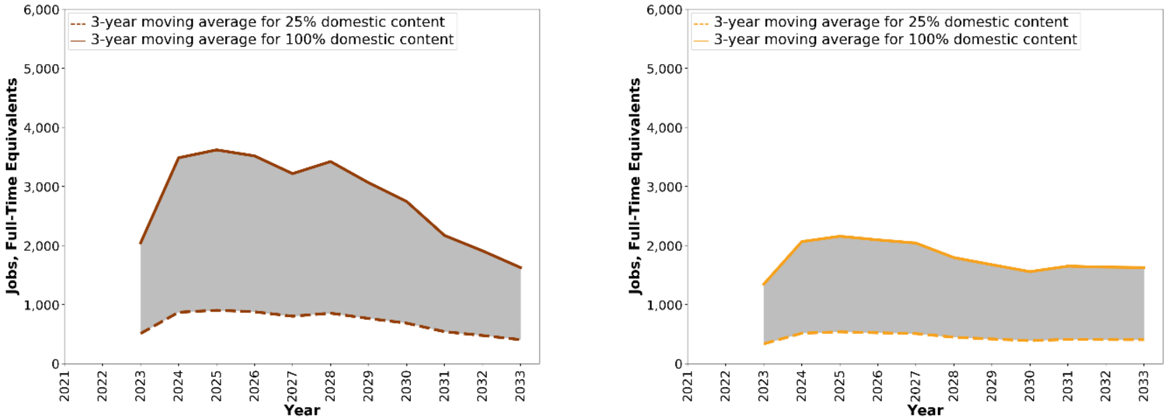


Figure B8. Moderate (left) and significantly (right) constrained fixed-bottom supply chain scenarios – number of jobs (FTEs) for rotor blade demand based on 25% and 100% domestic content scenarios

6.1.2.2 Foundations

6.1.2.2.1 Monopiles

The average number of jobs from 2023 and 2030 required to fabricate all monopile components is between 1,300 and 5,400 jobs (FTEs) for the baseline scenario, which achieves 30 GW of offshore wind energy by 2030. The maximum job potential occurs in 2028 when between 1,600 and 6,600 jobs would be supported under this demand scenario. Figure B9 shows the job estimates over time for the entire manufacturing and supply chain for the monopile component. Those job estimates comprise the direct and indirect impacts activating all tiers of the supply chain at 25% and 100% domestic content assumptions.

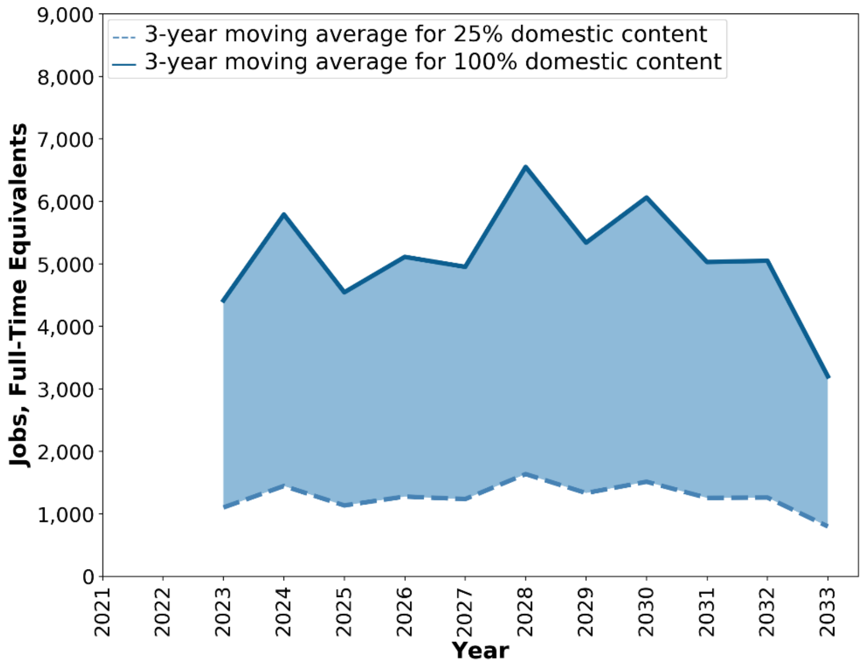


Figure B9. Baseline scenario – number of jobs (FTEs) for monopile demand based on 25% and 100% domestic content scenarios

Table B4 shows how the job estimates in Figure B9 are categorized according to direct and indirect job contribution percentages. The direct jobs related the monopiles (Tier 1 component) represent the potential labor to complete monopile fabrication and Tier 2 subassembly process, such as rolling and welding steel plates. Whereas the indirect jobs represent the production of subcomponents and materials, such as steel plates and flanges that are purchased for the monopile fabrication. Because the analysis considers the entire U.S. capability for steel fabrication and steel materials represent a significant supply chain purchase for the component, there is a higher indirect impact, primarily spurred in the industry represented by the wire and metal sector industry aggregation.

Table B4. Monopile Jobs Related to Tier 1 Components

Component	Tier	Direct	Indirect
Monopiles	1	34.3%	65.7%

Figure B10 shows the tower component job estimates for each constrained demand scenario assuming 25% and 100% domestic content. This figure shows the component contribution for the constrained scenarios over time with reduced and shifted demand.

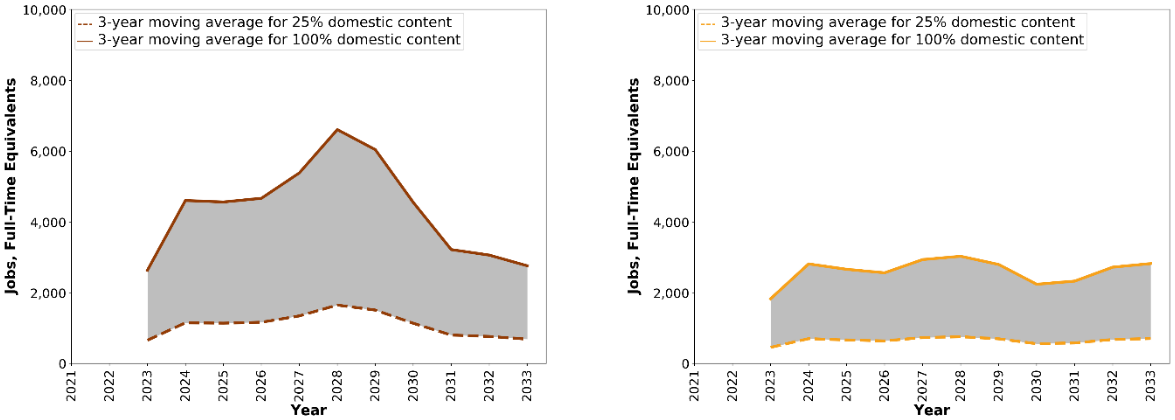


Figure B10. Moderate (left) and significantly (right) constrained fixed-bottom supply chain scenarios – number of jobs (FTEs) for monopile demand based on 25% and 100% domestic content scenarios

6.1.2.2.2 Transition piece

The average number of jobs from 2023 and 2030 required to fabricate and assemble all transition pieces is between 800 and 3,100 jobs (FTEs) for the baseline scenario, which achieves 30 GW of offshore wind energy by 2030. The maximum job potential occurs in 2028 when between 1,000 and 3,800 jobs would be supported under this demand scenario. Figure B11 shows the job estimates over time for the entire manufacturing and supply chain for the transition piece component. Those job estimates comprise the direct and indirect impacts activating all tiers of the supply chain at 25% and 100% domestic content assumptions.

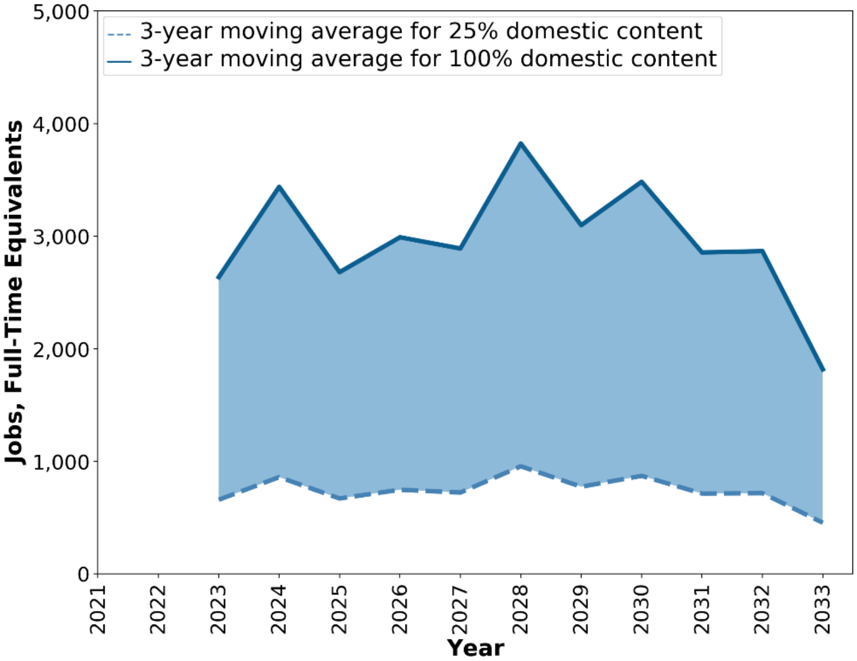


Figure B11. Baseline scenario – number of jobs (FTEs) for transition piece demand based on 25% and 100% domestic content scenarios

Table B5 shows how the job estimates in Figure B11 are categorized into direct and indirect job contribution percentages. The direct jobs related to the transition piece (Tier 1 component) represent the potential labor to complete transition piece fabrication and Tier 2 subassembly process, such as heavy metal fabrication and installing secondary steel subcomponents. Whereas the indirect jobs represent the production of the Tier 3 and 4 subcomponents and materials, such as flanges, external work platforms, handrails, stairs, and so on that are purchased for the transition piece fabrication.

Table B5. Transition Piece Jobs According to Tier 2 Subassembly and Tier 3 Components

Component	Tier	Direct	Indirect
Transition piece	1	34.3%	65.7%

Figure B12 shows the transition piece component job estimates for each constrained demand scenario assuming 25% and 100% domestic content. This figure shows the component contribution for the constrained scenarios over time with reduced and shifted demand.

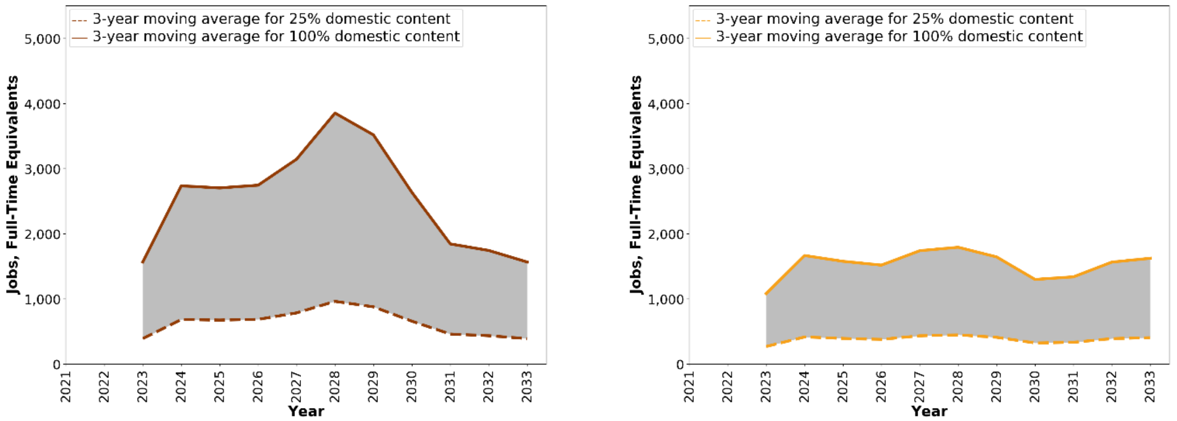


Figure B12. Moderate (left) and significantly (right) constrained fixed-bottom supply chain scenarios – number of jobs (FTEs) for transition piece demand based on 25% and 100% domestic content scenarios

6.1.2.2.3 Jacket (for wind turbine)

The average number of jobs from 2023 and 2030 required to fabricate all jacket substructure components for wind turbines is between 500 and 2,000 jobs (FTEs) for the baseline scenario, which achieves 30 GW of offshore wind energy by 2030. The maximum job potential occurs in 2026 when between 700 and 2,900 jobs would be supported under this demand scenario. Figure B13 shows the job estimates over time for the entire manufacturing and supply chain for the jacket substructure. Those job estimates comprise the direct and indirect impacts activating all tiers of the supply chain at 25% and 100% domestic content assumptions.

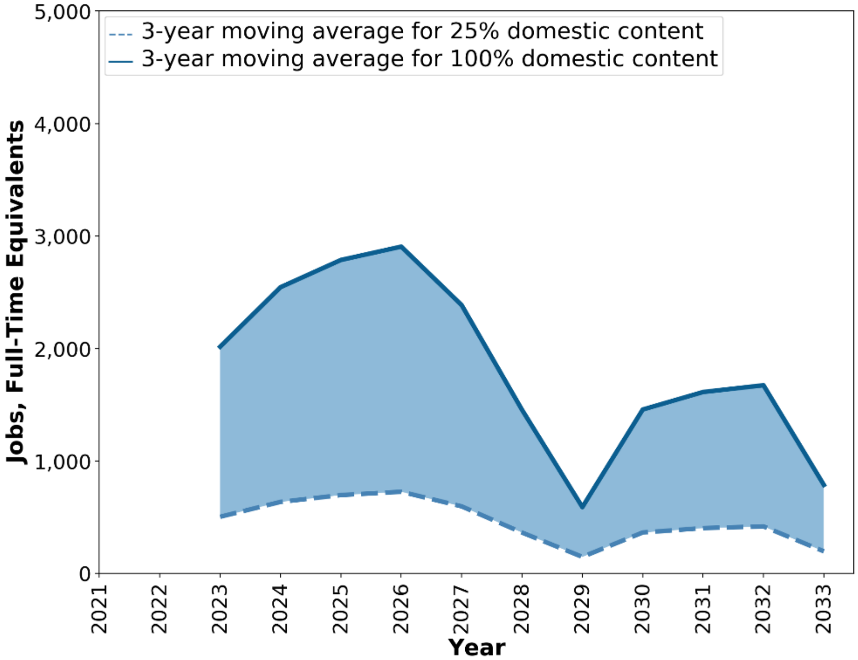


Figure B13. Baseline scenario – number of jobs (FTEs) for jacket demand (for wind turbines) based on 25% and 100% domestic content scenarios

Table B6 shows how the job estimates in Figure B13 are categorized into direct and indirect job contribution percentages. The direct jobs related to the jacket substructure (for a wind turbine) represent the potential labor needed to complete the Tier 1 component fabrication and Tier 2 subassembly processes, such fabricating and assembling the truss, transition piece, secondary steel, and pile system. Whereas the indirect jobs represent the production of the Tier 3 and 4 subcomponents and materials, such as struts, steel plates, protective coatings, handrails, piles, and so on that are purchased for the jacket substructure (for the wind turbine) fabrication.

Table B6. Jacket (For a Wind Turbine) Jobs According to Tier 1 Components

Component	Tier	Direct	Indirect
Jacket	1	34.3%	65.7%

Figure B14 shows the jacket substructure for the wind turbine component job estimates for each constrained demand scenario assuming 25% and 100% domestic content. This figure is provided shows the component contribution for the constrained scenarios over time with reduced and shifted demand.

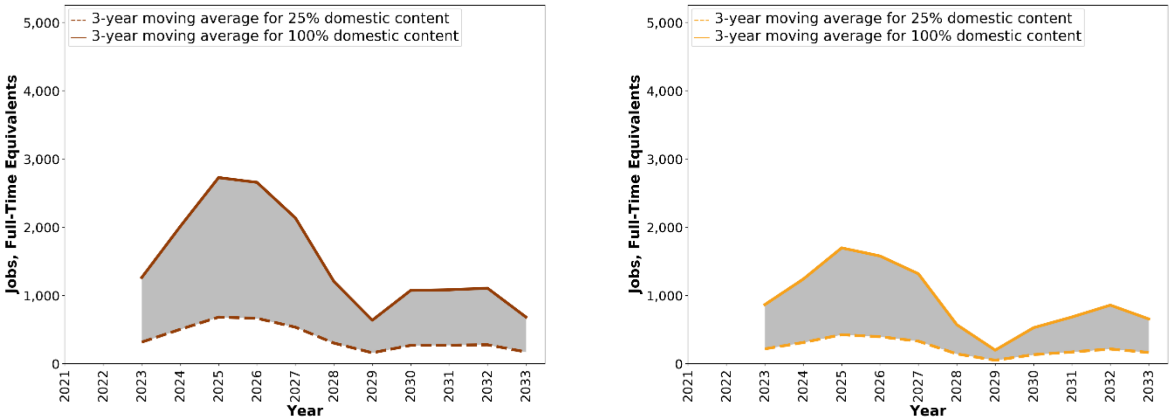


Figure B14. Moderate (left) and significantly (right) constrained fixed-bottom supply chain scenarios – number of jobs (FTEs) for jacket demand (for wind turbines) based on 25% and 100% domestic content scenarios

6.1.2.2.4 Gravity-based foundation

The average number of jobs from 2023 and 2030 required to fabricate all gravity-based-foundation (GBF) components is between 400 and 1,500 jobs (FTEs) for the baseline scenario, which achieves 30 GW of offshore wind energy by 2030. The maximum job potential occurs in 2028 when between 500 and 2,000 jobs would be supported under this demand scenario. Figure B15 shows the job estimates over time for the entire manufacturing and supply chain for the GBF component. Those job estimates comprise the direct and indirect impacts activating all tiers of the supply chain at 25% and 100% domestic content assumptions.

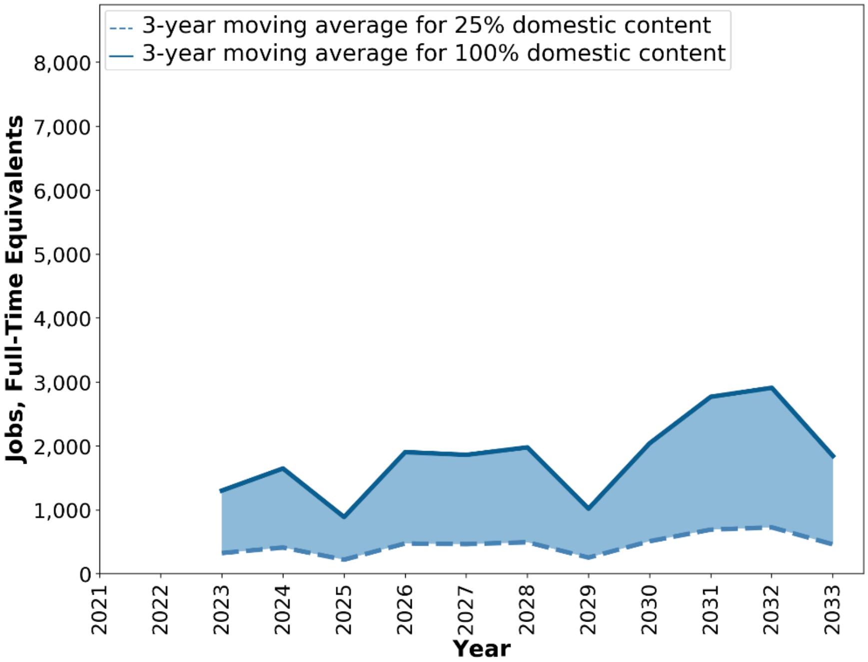


Figure B15. Baseline scenario – number of jobs (FTEs) for the gravity-based foundation demand based on 25% and 100% domestic content scenarios

Table B7 shows how the job estimates in Figure B15 are categorized into direct and indirect job contribution percentages. The production costs associated for GBF included the costs of concrete and steel. Therefore, the direct jobs related to the shaft/skirt represent the concrete fabrication associated with the Tier 1 component and Tier 2 subassembly. Whereas the indirect jobs represent the workers who produce the Tier 3 and 4 subcomponents and materials, such as the purchase of cement materials. The amount of steel was significantly less than concrete; therefore, it has less of a labor impact on the entire supply chain.

Table B7. GBF Jobs According to Tier 2 Subassembly

Component	Tier	Direct	Indirect
Shaft/skirt (concrete)	2	37.8%	60.1%
Secondary steel	2	0.7%	1.4%
Total		**38.5%**	**61.5%**

Figure B16 shows the GBF component job estimates for each constrained demand scenario assuming 25% and 100% domestic content. This figure shows the component contribution for the constrained scenarios over time with reduced and shifted demand.

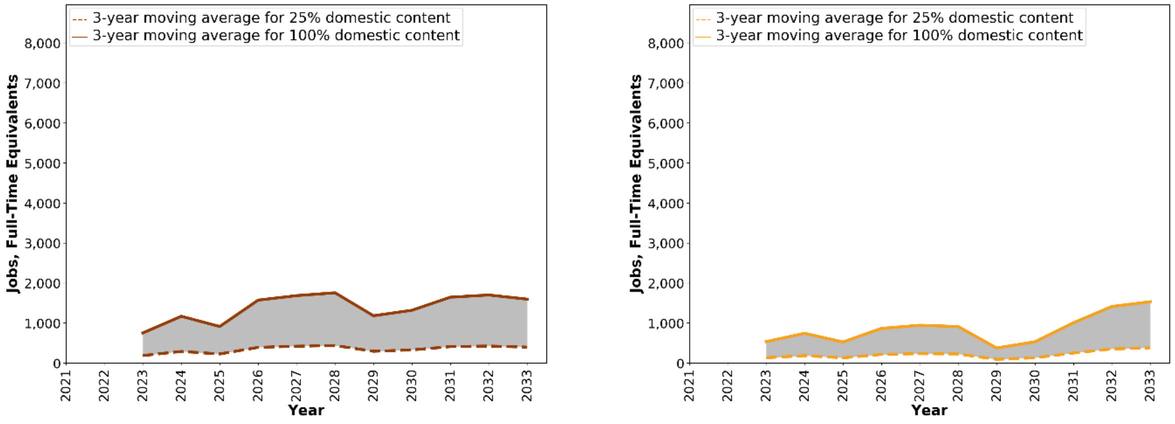


Figure B16. Moderate (left) and significantly (right) constrained fixed-bottom supply chain scenarios – number of jobs (FTEs) for GBF demand based on 25% and 100% domestic content scenarios

6.1.2.3 Offshore substations

6.1.2.3.1 Offshore substation topside

The average number of jobs from 2023 and 2030 required to fabricate and assemble all substation components is between 30 and 100 jobs (FTEs) for the baseline scenario, which achieves 30 GW of offshore wind energy by 2030. The maximum job potential occurs in 2023 and matches the average job demand (between 30 and 100 FTEs). Figure B17 shows the job estimates over time for the entire manufacturing and supply chain for the offshore substation topside component. Those job estimates comprise the direct and indirect impacts activating all tiers of the supply chain at 25% and 100% domestic content assumptions.

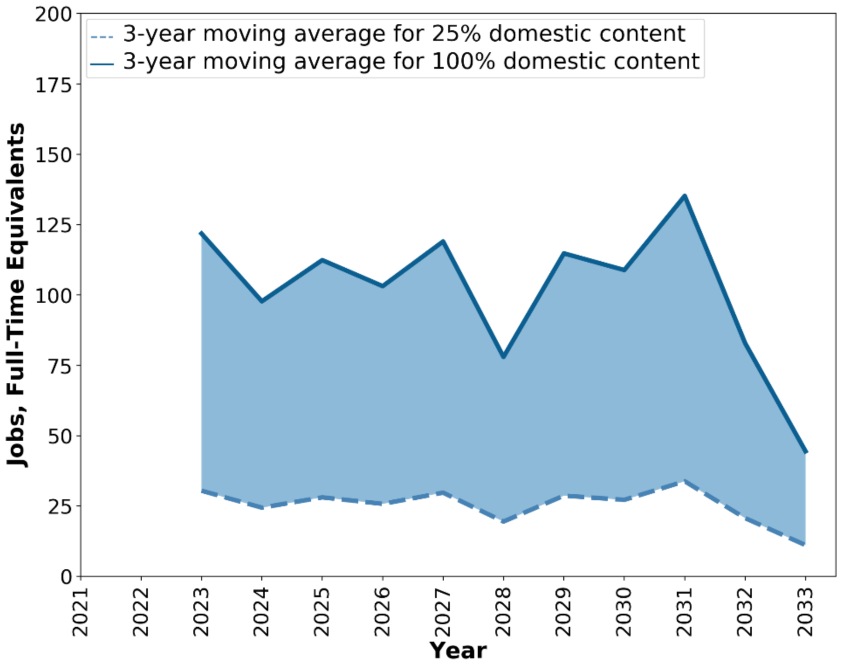


Figure B17. Baseline scenario – number of jobs (FTEs) for offshore substation topside demand based on 25% and 100% domestic content scenarios

Table B8 shows how the job estimates in Figure B17 are categorized into direct and indirect job contribution percentages. The direct jobs related the offshore substation topside represent the potential labor to complete the Tier 2 subassembly process, such as assembling the steel building, electrical equipment, and auxiliary systems. Whereas the indirect jobs represent the production of the Tier 3 subcomponents purchases, such as transformers, switchgear, electrical cables, steel building, and other subcomponents that are assembled in the offshore substation topside. The lower contribution of indirect impacts may indicate a lower U.S. capability to produce key components such as transformers or switchgear. The sector industry aggregation for the offshore substation topside represents the construction of new power and communication structures, so the direct and indirect impacts would solely represent industries that contribute to substation production.

Table B8. Offshore Substation Topside Jobs According to Tier 1 Components

Component	Tier	Direct	Indirect
Offshore substation	1	71.3%	28.7%

Figure B18 shows the offshore substation topside component job estimates for each constrained demand scenario assuming 25% and 100% domestic content. This figure shows the component contribution for the constrained scenarios over time with reduced and shifted demand.

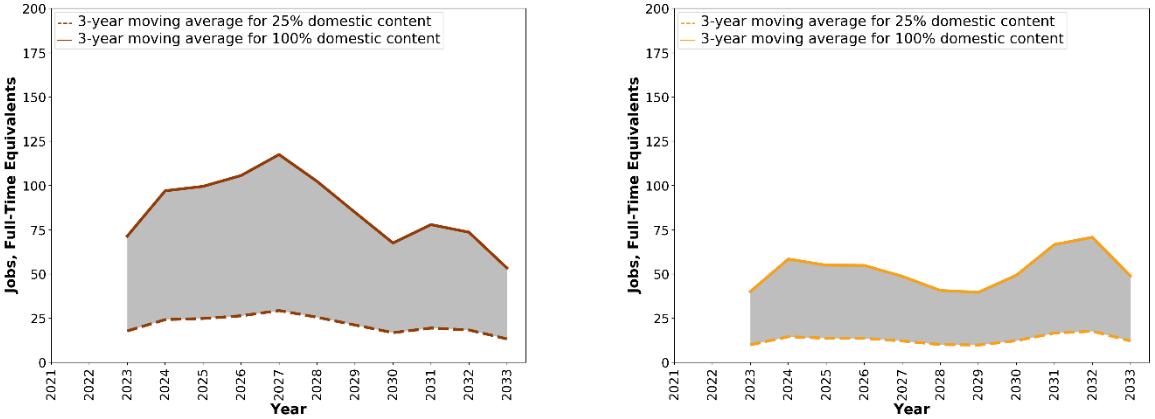


Figure B18. Moderate (left) and significantly (right) constrained fixed-bottom supply chain scenarios – number of jobs (FTEs) for offshore substation topside demand based on 25% and 100% domestic content scenarios

6.1.2.3.2 Jacket (for substation)

The average number of jobs from 2023 and 2030 required to fabricate and assemble all jacket substructure components for offshore substations is less than 10 (FTEs) for the baseline scenario, which achieves 30 GW of offshore wind energy by 2030. Substation jackets produce a low number of FTEs because only 1 or 2 of these components are required for each project, resulting in a relatively short manufacturing timeframe and limited annual throughput. The FTE estimate therefore represents multiple workers working over a time period shorter than 1 year to fabricate and assemble the jackets; for example, 50 people working 8 hours per day for one month would represent 12,000 labor hours or 5.8 FTEs. Figure B19 shows the job estimates over time for the entire manufacturing and supply chain for the jacket substructure for the offshore substation component. Those job estimates comprise the direct and indirect impacts activating all tiers of the supply chain at 25% and 100% domestic content assumptions.

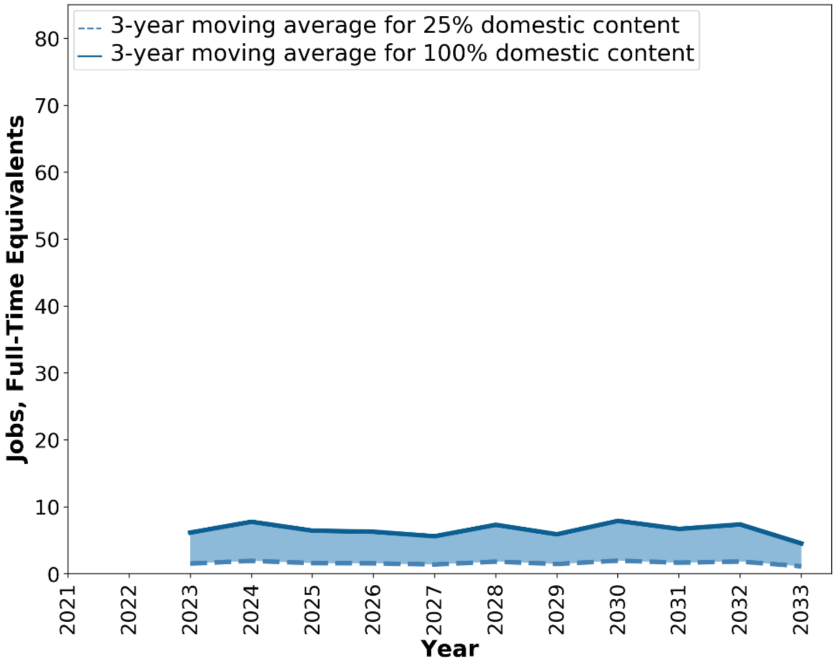


Figure B19. Baseline scenario – number of jobs (FTEs) for jacket demand (for offshore substations) based on 25% and 100% domestic content scenarios

Table B9 shows how the job estimates in Figure B19 are categorized into direct and indirect job contribution percentages. The direct jobs related to the jacket substructure (for the substation) represent the potential labor needed to complete the Tier 2 subassembly process, such as fabricating and assembling the truss, transition piece, secondary steel, and pile system. Whereas the indirect jobs represent the production of the Tier 3 and 4 subcomponents and materials, such as steel, that are purchased for the jacket substructure (for the substation) fabrication.

Table B9. Jacket (For Substation) Jobs According to Tier 1 Components

Component	Tier	Direct	Indirect
Jacket (for substation)	2	34.3%	65.7%

Figure B20 shows the jacket substructure for the offshore substation component job estimates for each constrained demand scenario assuming 25% and 100% domestic content. This figure shows the component contribution for the constrained scenarios over time with reduced and shifted demand.

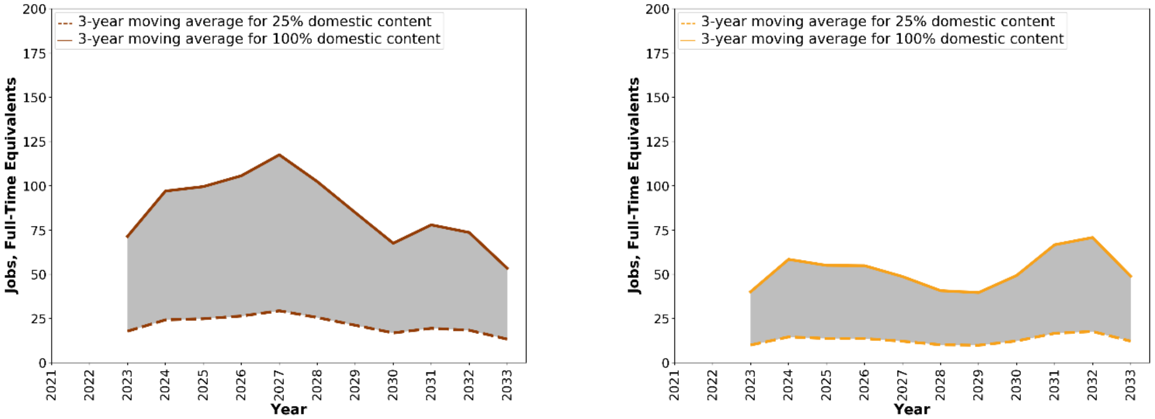


Figure B20. Moderate (left) and significantly (right) constrained fixed-bottom supply chain scenarios – number of jobs (FTEs) for jacket demand (for offshore substations) based on 25% and 100% domestic content scenarios

6.1.2.4 Cables

6.1.2.4.1 Array cable

The average number of jobs from 2023 and 2030 required to fabricate all array cable components is between 300 and 1,100 jobs (FTEs) for the baseline scenario, which achieves 30 GW of offshore wind energy by 2030. The maximum job potential occurs in 2024 when between 300 and 1,300 jobs would be supported under this demand scenario. Figure B21 shows the job estimates over time for the entire manufacturing and supply chain for the array cable component. Those job estimates comprise the direct and indirect impacts activating all tiers of the supply chain at 25% and 100% domestic content assumptions.

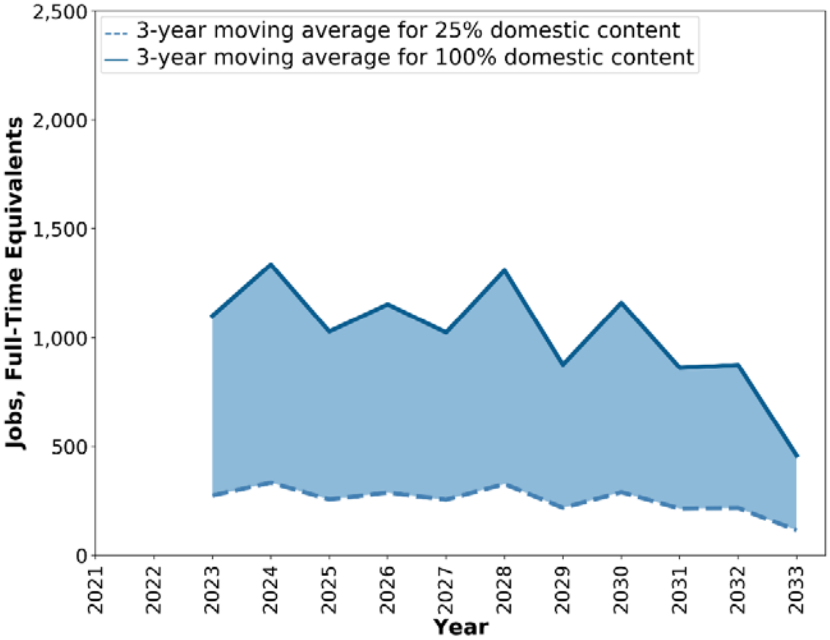


Figure B21. Baseline scenario – number of jobs (FTEs) for array cable demand based on 25% and 100% domestic content scenarios

Table B10 shows how the job requirements in Figure B21 are categorized into direct and indirect job contribution percentages. The direct jobs related to the array cable represent the potential labor needed to complete the Tier 2 subassembly process, including extruding, drawing, stranding, assembling, screening, jacketing, rewind line, and testing of Tier 3 subcomponents, such as cable sheaths, insulation, conductor cores, and other cable internals. The indirect jobs represent the workers who would produce the subcomponents after purchasing materials such as specialty plastics, aluminum, or copper.

Table B10. Array Cable Jobs According to Tier 2 Components

Component	Tier	Direct	Indirect
Array cables	2	38.4%	61.6%

Figure B22 shows the array cable component job estimates for each constrained demand scenario assuming 25% and 100% domestic content. This figure shows the component contribution for the constrained scenarios over time with reduced and shifted demand.

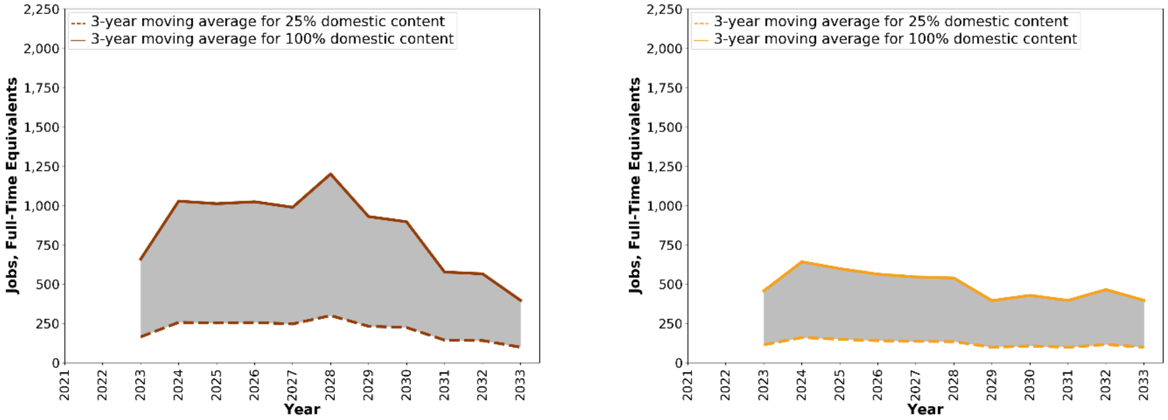


Figure B22. Moderate (left) and significantly (right) constrained fixed-bottom supply chain scenarios – number of jobs (FTEs) for array cable demand based on 25% and 100% domestic content scenarios

6.1.2.4.2 Export cable

The average number of jobs from 2023 and 2030 required to fabricate all export cable components is between 600 and 2,300 jobs (FTEs) for the baseline scenario, which achieves 30 GW of offshore wind energy by 2030. The maximum job potential occurs in 2024 when between 700 and 2,900 jobs would be supported under this demand scenario. Figure B23 shows the job estimates over time for the entire manufacturing and supply chain of export cables. Those job estimates comprise the direct and indirect impacts activating all tiers of the supply chain at 25% and 100% domestic content assumptions.

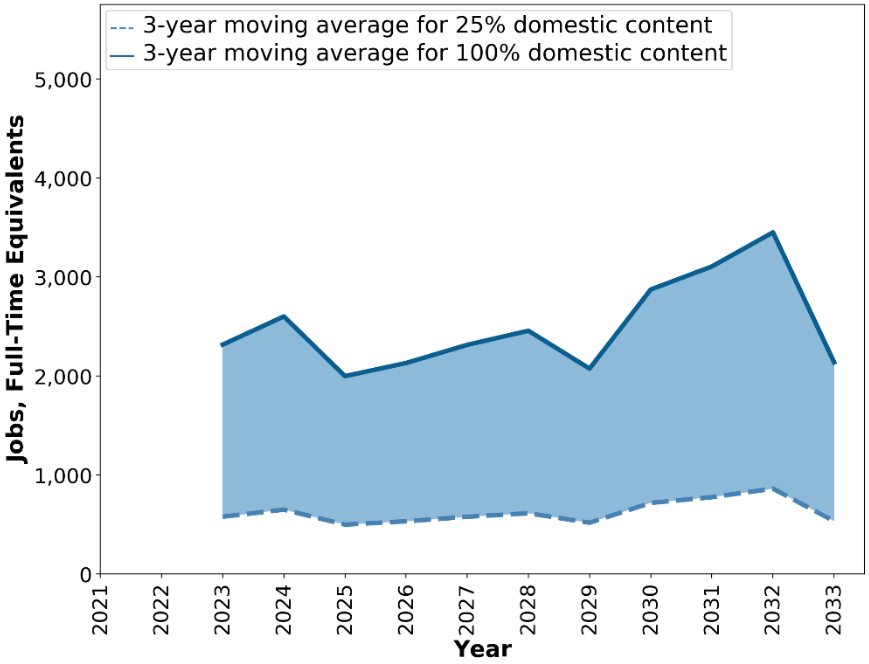


Figure B23. Baseline scenario – number of jobs (FTEs) for export cable demand based on 25% and 100% domestic content scenarios

Table B11 shows how the job requirements in Figure B23 are categorized into direct and indirect job contribution percentages. The direct jobs related to the export cable represent the potential labor needed to complete the Tier 2 subassembly process, including extruding, drawing, stranding, assembling, screening, jacketing, rewind line, and testing of Tier 3 subcomponents, such as cable sheaths, insulation, conductor cores, and other cable internals. The indirect jobs represent the workers who would produce the subcomponents after purchasing materials such as specialty plastics, aluminum, or copper.

Table B11. Export Cable Jobs According to Tier 2 Components

Component	Tier	Direct	Indirect
Export cables	2	38.4%	61.6%

Figure B24 shows the export cable component job estimates for each constrained demand scenario assuming 25% and 100% domestic content. This figure shows the component contribution for the constrained scenarios over time with reduced and shifted demand.

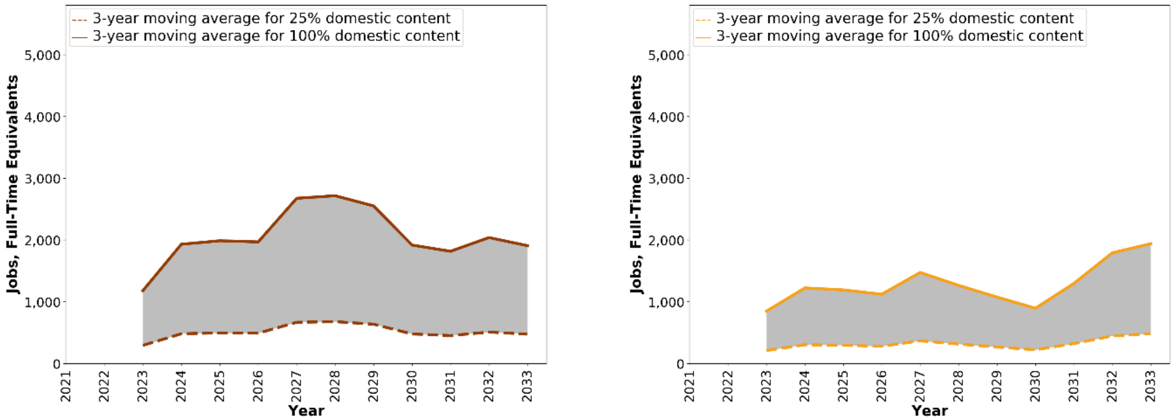


Figure B24. Moderate (left) and significantly (right) constrained fixed-bottom supply chain scenarios – number of jobs (FTEs) for export cable demand based on 25% and 100% domestic content scenarios

6.1.3 Floating Systems Job Estimates

6.1.3.1 Wind turbines

6.1.3.1.1 Nacelles

The average number of jobs from 2026 and 2030 required to fabricate and assemble all nacelle components is between 1,100 and 4,600 jobs (FTEs) for the baseline scenario, which achieves the 30 GW of offshore wind energy by 2030 target. The maximum job potential before 2030 occurs in 2029 when between 1,900 and 7,700 jobs would be supported under this demand scenario. Figure B25 shows the job estimates over time for the entire manufacturing and supply chain for the nacelle. Those job estimates comprise the direct and indirect impacts, thereby activating all tiers of the supply chain at 25% and 100% domestic content assumptions. Figure B25 shows that, as fixed-bottom deployment shifts to floating deployment in the mid-2030s, a higher percentage of the overall workforce will transition to manufacturing floating wind components.

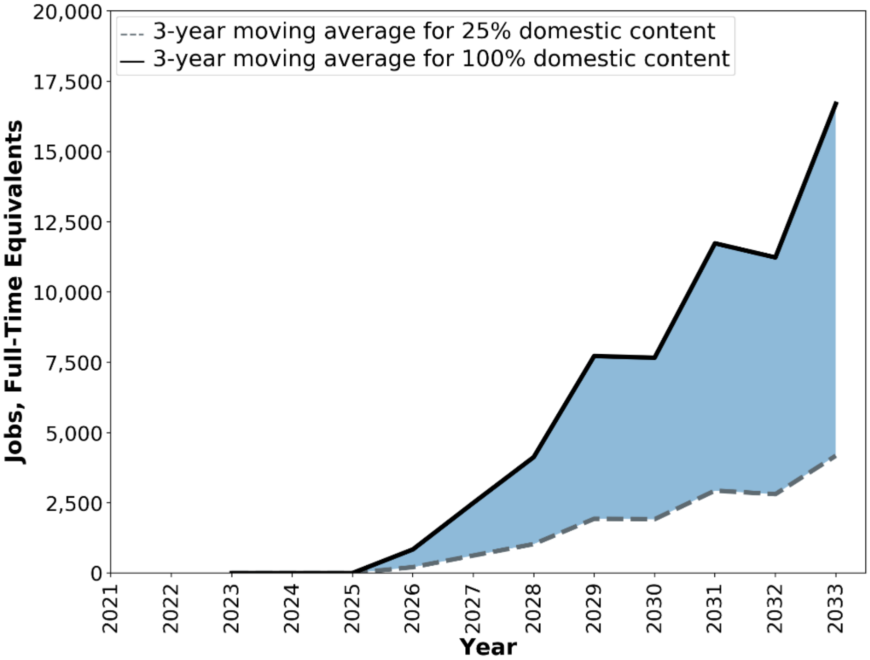


Figure B25. Baseline scenario – number of jobs (FTEs) for nacelle (gearbox) demand based on 25% and 100% domestic content scenarios

6.1.3.1.2 Towers

The average number of jobs from 2026 and 2030 required to fabricate all tower components is between 200 and 800 jobs (FTEs) for the baseline scenario, which achieves 30 GW of offshore wind energy by 2030. The maximum job potential before 2030 occurs in 2029 when between 300 and 1,300 jobs would be supported under this demand scenario. Figure B26 shows the job estimates over time for the entire manufacturing and supply chain for the tower. Those job estimates comprise the direct and indirect impacts activating all tiers of the supply chain at 25% and 100% domestic content assumptions. Figure B26 shows that, as fixed-bottom deployment shifts to floating deployment in the mid-2030s, a higher percentage of the overall workforce will transition to manufacturing floating wind components.

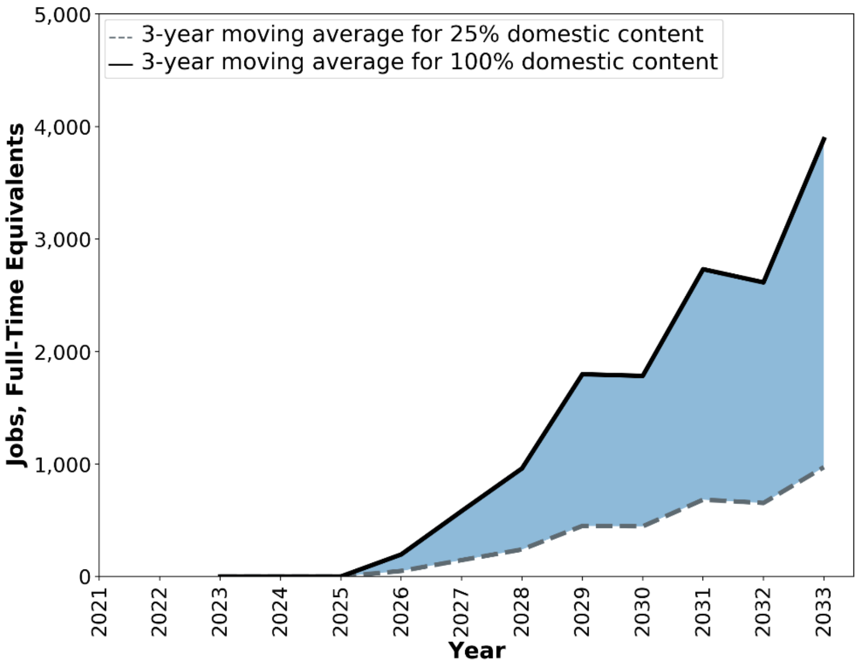


Figure B26. Baseline scenario – number of jobs (FTEs) for tower demand based on 25% and 100% domestic content scenarios

6.1.3.1.3 Rotor blades

The average number of jobs from 2026 and 2030 required to fabricate and assemble all rotor blade components is between 200 and 800 jobs (FTEs) for the baseline scenario, which achieves 30 GW of offshore wind energy by 2030. The maximum job potential before 2030 occurs in 2028 when between 300 and 1,300 jobs would be supported under this demand scenario. Figure B27 shows the job estimates over time for the entire manufacturing and supply chain for the rotor blade component. Those job estimates comprise the direct and indirect impacts activating all tiers of the supply chain at 25% and 100% domestic content assumptions. Figure B27 shows that, as fixed-bottom deployment shifts to floating deployment in the mid-2030s, a higher percentage of the overall workforce will transition to manufacturing floating wind components.

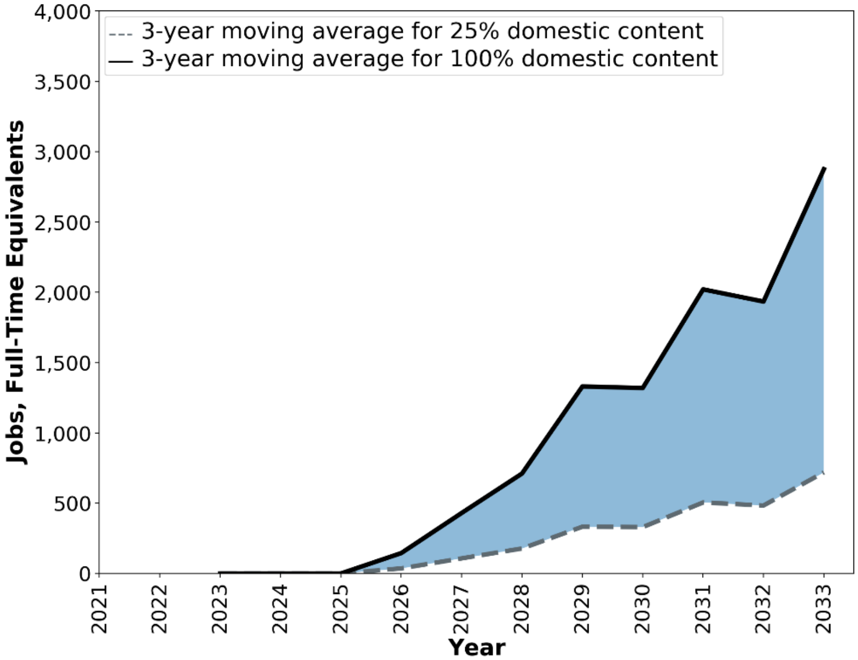


Figure B27. Baseline scenario – number of jobs (FTEs) for rotor blade demand based on 25% and 100% domestic content scenarios

6.1.3.2 Semisubmersibles

The average number of jobs from 2026 and 2030 required to fabricate all semisubmersible components is between 2,100 and 8,500 jobs (FTEs) for the baseline scenario, which achieves 30 GW of offshore wind energy by 2030. The maximum job potential before 2030 occurs in 2029 when between 3,600 and 14,300 jobs would be supported under this demand scenario. Figure B28 shows the job estimates over time for the entire manufacturing and supply chain for the semisubmersible component. Those job estimates comprise the direct and indirect impacts activating all tiers of the supply chain at 25% and 100% domestic content assumptions. Figure B28 shows that, as fixed-bottom deployment shifts to floating deployment in the mid-2030s, a higher percentage of the overall workforce will transition to manufacturing floating wind components.

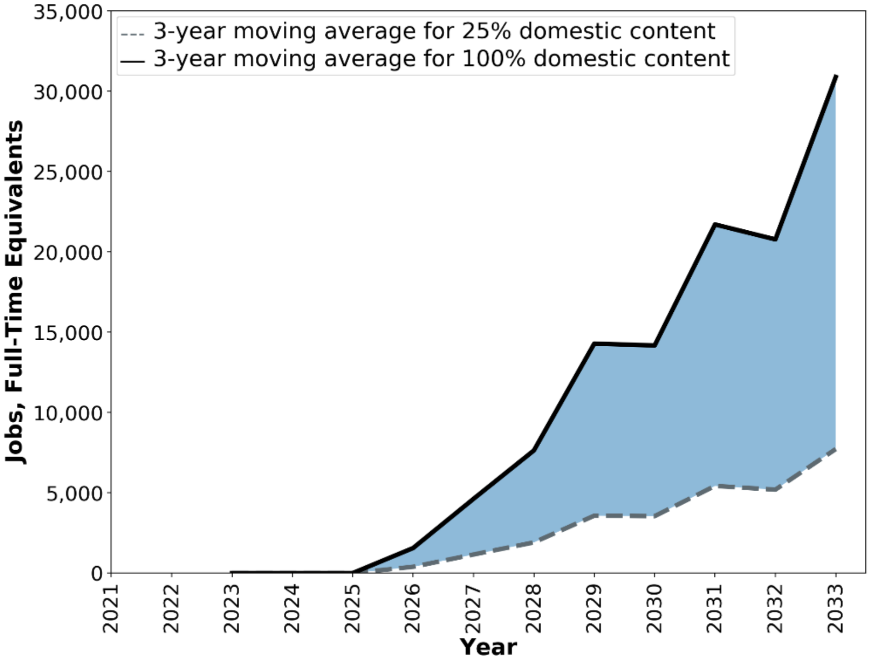


Figure B28. Baseline scenario – number of jobs (FTEs) for semisubmersible demand based on 25% and 100% domestic content scenarios

6.1.3.3 Offshore substations

6.1.3.3.1 Offshore substation topside

The average number of jobs from 2026 and 2030 required to fabricate and assemble all substation components is less than 15 FTEs for the baseline scenario, which achieves 30 GW of offshore wind energy by 2030. The maximum job potential before 2030 occurs in 2030 when between 15 and 60 jobs would be supported under this demand scenario. Substation topsides produce a low number of FTEs because only 1 or 2 of these components are required for each project, resulting in a relatively short manufacturing timeframe and limited annual throughput. The FTE estimate therefore represents multiple workers working over a time period shorter than one year to fabricate and assemble the topsides; for example, 50 people working 8 hours per day for one month would represent 12,000 labor hours or 5.8 FTEs. Figure B29 shows the job estimates over time for the entire manufacturing and supply chain for the offshore substation topside component. Those job estimates comprise the direct and indirect impacts activating all tiers of the supply chain at 25% and 100% domestic content assumptions. Figure B29 shows that, as fixed-bottom deployment shifts to floating deployment in the mid-2030s, a higher percentage of the overall workforce will transition to manufacturing floating wind components.

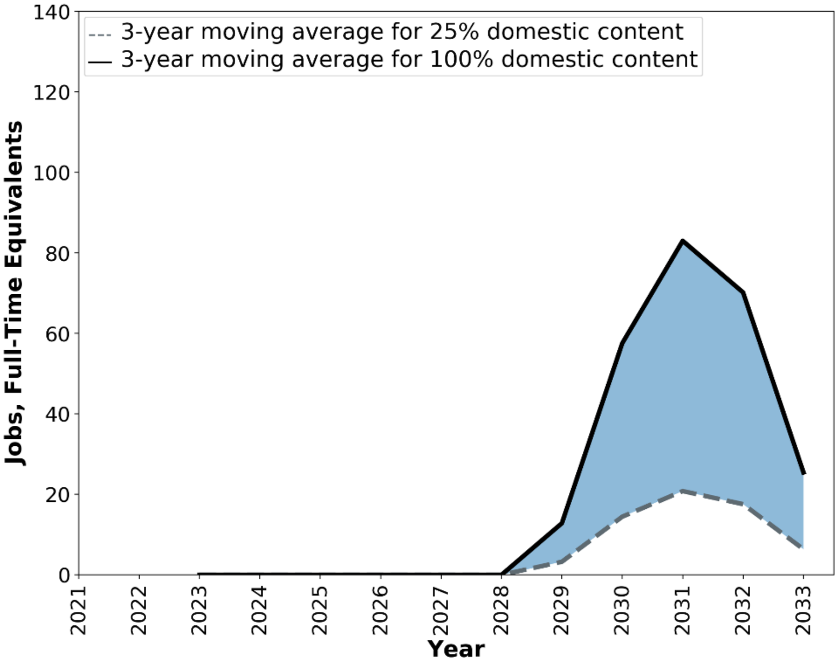


Figure B29. Baseline scenario – number of jobs (FTEs) for offshore substation topside demand based on 25% and 100% domestic content scenarios

6.1.3.3.2 Semisubmersibles (for substation)

The average number of jobs from 2026 and 2030 required to fabricate and assemble all semisubmersible substructure components for offshore substations is between 70 and 300 (FTEs) for the baseline scenario, which achieves 30 GW of offshore wind energy by 2030. The maximum job potential before 2030 occurs in 2030 when between 100 and 500 jobs would be supported under this demand scenario. Figure B30 shows the job estimates over time for the entire manufacturing and supply chain for the jacket substructure for the offshore substation component. Those job estimates comprise the direct and indirect impacts activating all tiers of the supply chain at 25% and 100% domestic content assumptions. Figure B30 shows that, as fixed-bottom deployment shifts to floating deployment in the mid-2030s, a higher percentage of the overall workforce will transition to manufacturing floating wind components.

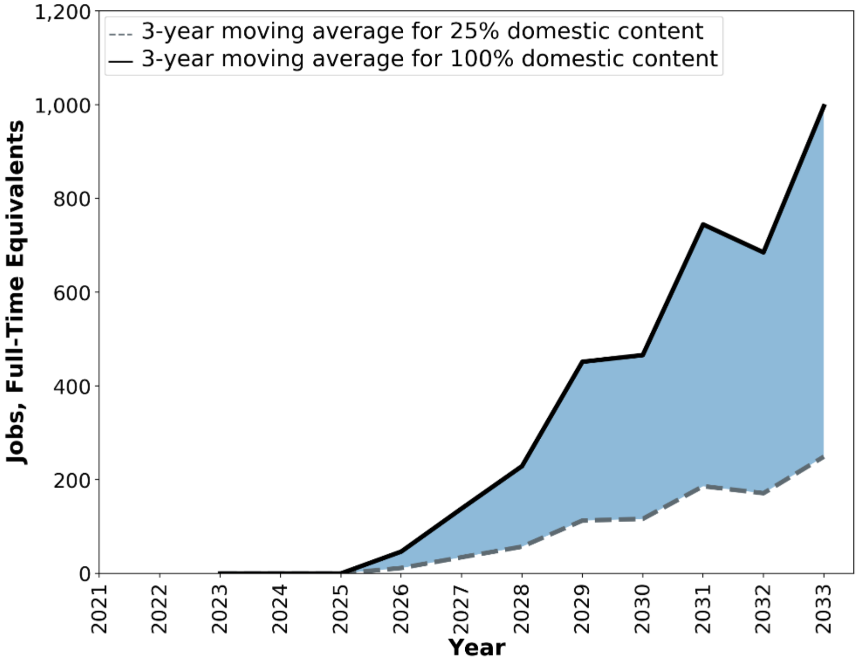


Figure B30. Baseline scenario – number of jobs (FTEs) for semisubmersible demand (for offshore substations) based on 25% and 100% domestic content scenarios

6.1.3.4 Dynamic Cables

6.1.3.4.1 Dynamic array cable

The average number of jobs from 2026 and 2030 required to fabricate all dynamic array cable components is between 100 and 400 jobs (FTEs) for the baseline scenario, which achieves 30 GW of offshore wind energy by 2030. The maximum job potential before 2030 occurs in 2029 when between 200 and 700 jobs would be supported under this demand scenario. Figure B31 shows the job estimates over time for the entire manufacturing and supply chain for the array cable component. Those job estimates comprise the direct and indirect impacts activating all tiers of the supply chain at 25% and 100% domestic content assumptions. Figure B31 shows that, as fixed-bottom deployment shifts to floating deployment in the mid-2030s, a higher percentage of the overall workforce will transition to manufacturing floating wind components.

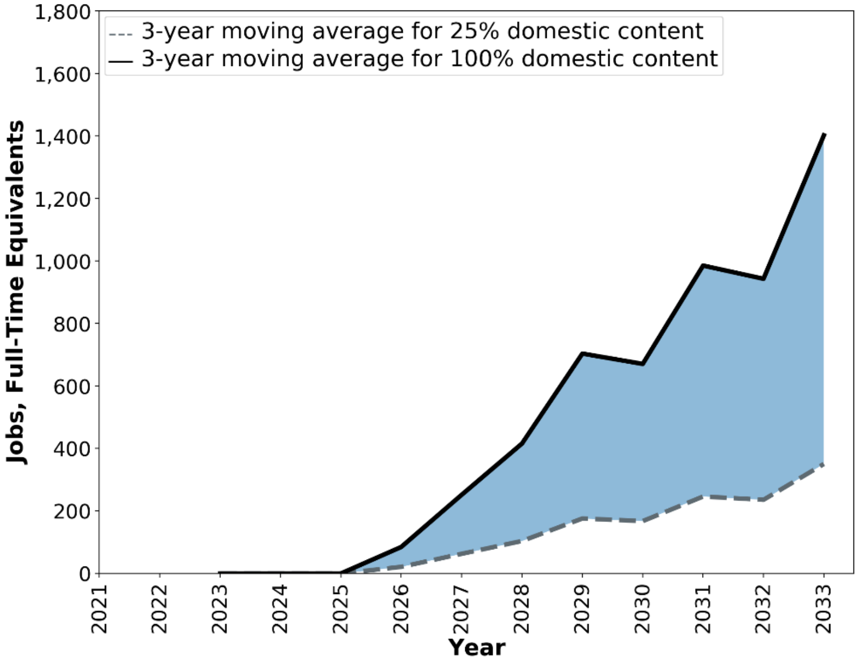


Figure B31. Baseline scenario – number of jobs (FTEs) for array cable demand based on 25% and 100% domestic content scenarios

6.1.3.4.2 Dynamic export cable

The average number of jobs from 2026 and 2030 required to fabricate all dynamic export cable components is between 200 and 800 jobs (FTEs) for the baseline scenario, which achieves 30 GW of offshore wind energy by 2030. The maximum job potential before 2030 occurs in 2029 when between 300 and 1,400 jobs would be supported under this demand scenario. Figure B32 shows the job estimates over time for the entire manufacturing and supply chain of export cables. Those job estimates comprise the direct and indirect impacts activating all tiers of the supply chain at 25% and 100% domestic content assumptions. Figure B32 shows that, as fixed-bottom deployment shifts to floating deployment in the mid-2030s, a higher percentage of the overall workforce will transition to manufacturing floating wind components.

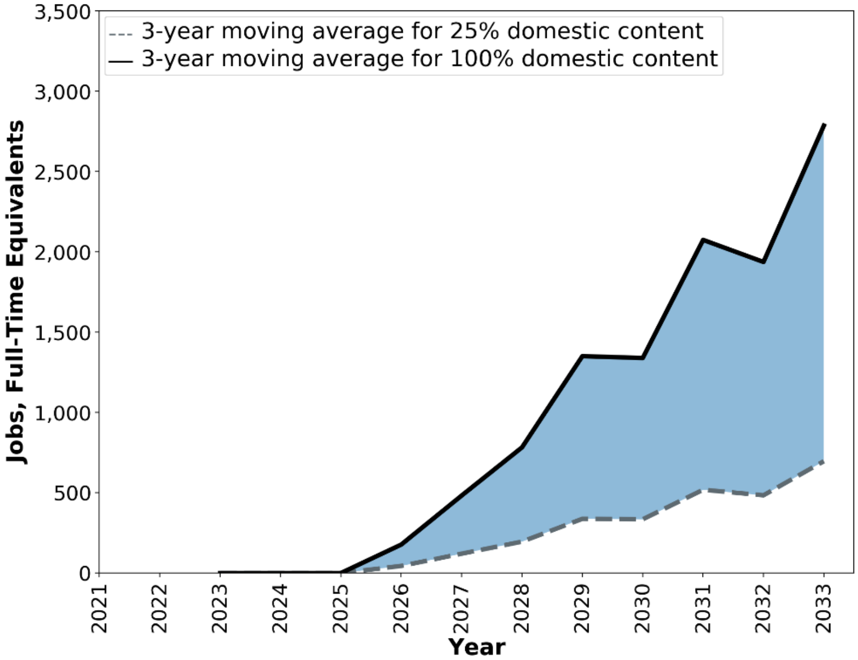


Figure B32. Baseline scenario – number of jobs (FTEs) for export cable demand based on 25% and 100% domestic content scenarios

Appendix C. European Supply Chains

In this section, we provide a brief summary of the European suppliers that will support the initial phase of offshore wind energy development in the United States. Table 5 from Section 2.4.2 (reprinted below [Table C1] for convenience) provides an outlook of the planned deployment in Europe through 2030.

Table C1. Offshore Wind Energy Outlook in Europe From 2021 to 2030 (Wind Europe 2021)

Year	European Union (EU) Cumulative Capacity (gigawatts [GW])	EU Planned Capacity (megawatts [MW])	EU Planned Installations (# of Wind Turbines)
2020	25	0	0
2021	28.7	3,650	468
2022	33.8	5,106	560
2023	38.0	4,204	432
2024	43.7	5,788	508
2025	53.5	9,719	845
2026	65.3	11,795	873
2027	77.1	11,795	873
2028	88.9	11,795	873
2029	100.6	11,795	873
2030	112.4	11,795	873

The substantial demand (nearly 12 gigawatts [GW] per year in the second half of the decade) will be primarily sourced from existing supply chains in Europe. This limited sourcing creates a potential bottleneck as domestic projects seek to obtain components from the same suppliers.

Turbine Original Equipment Manufacturers

In Europe, the offshore wind turbine market is dominated by three original equipment manufacturers (OEMs):

- Siemens Gamesa Renewable Energy (SGRE)
- GE Renewables Energy
- Vestas.

Figure C1 shows the relative market share of each manufacturer. SGRE has approximately 52% of offshore wind energy installations in Europe (1,058 wind turbines with an average power rating of 8.7 megawatts [MW]), Vestas has 19.5% (396 turbines with an average power rating of 8.7 MW), and GE has 10.8% (220 turbines with an average power rating of 11.3 MW). Together, the three manufacturers currently comprise over 99% of projects that have announced wind turbine agreements).

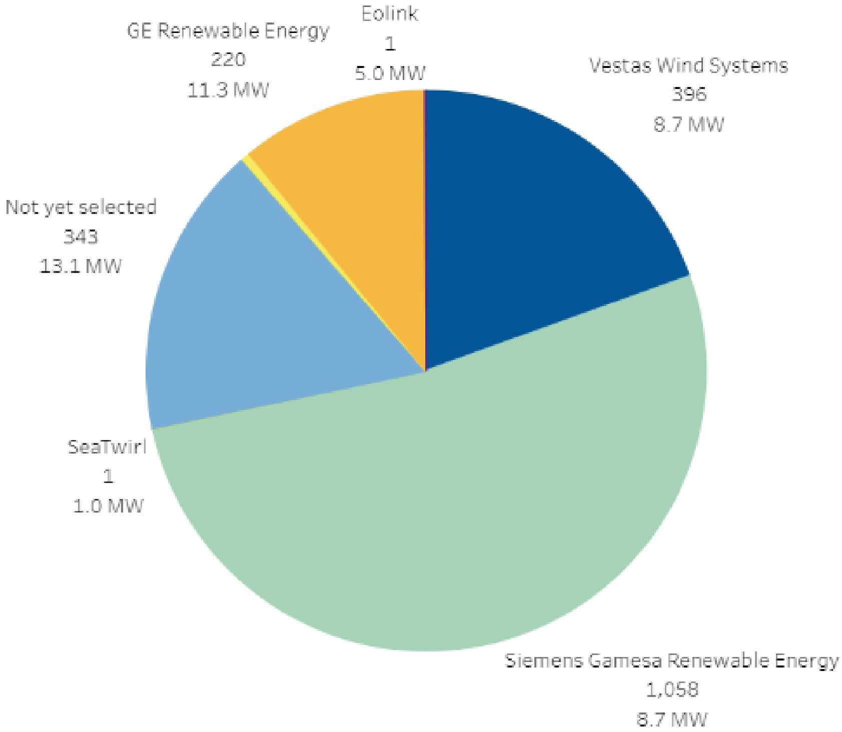


Figure C1. Market share of offshore wind turbine OEMs in Europe from 2021 to 2024. ***Image courtesy of WindEurope (2021)***

The nacelles, blades, and towers of a wind turbine are generally produced in different facilities. Most of the production infrastructure of the three OEMs is currently located in northern Europe (e.g., Denmark, Germany, France, United Kingdom, and the Netherlands), where most of the current demand is also located.

The existing manufacturing capabilities of the OEMs, which include expanded facilities under construction, are sized to supply ordered wind turbines, predominantly for projects in Europe and for some of the first projects in the United States and Taiwan. However, the majority of wind turbine supply contracts have not yet been awarded for the projects to be built in 2024 and later. With Europe's planned increase of yearly installations, the OEMs will likely need to build additional production facilities. The construction of such facilities typically takes about 2 to 3 years and is determined based on awarded contracts. Consequently, the overall wind turbine production capabilities are likely to grow significantly until 2030 to meet the European demand, regardless of the U.S. market.

Wind turbines for the first U.S. offshore wind energy projects are planned to be manufactured in Europe; however, the construction of wind turbine factories in the United States is being considered by the turbine OEMs. Decisions from OEMs will be based on whether a consistent pipeline of projects is foreseen.

The three major offshore wind turbine OEMs also manufacture land-based wind turbines. However, offshore wind turbines are usually produced in dedicated facilities, and are therefore not significantly impacted by the land-based wind turbine production workload.

Generally, nacelles, blades, and towers are produced in different factories. Although the nacelles are assembled in an OEM's own facilities, the towers are often subcontracted.

Rotor Blades

All three of the major offshore wind turbine OEMs in Europe (SGRE, Vestas, and GE) manufacture some or all of their rotor blades in-house and have purchased or invested in blade manufacturing companies. SGRE has blade manufacturing facilities in Spain, Portugal, Morocco, and Denmark, where they operate the world's largest rotor blade test facility. Vestas historically has manufactured its own rotor blades but also subcontracts with TPI Composites, a U.S.-based blade manufacturer with facilities in Iowa, Mexico, Turkey, India, and China. GE purchased Denmark-based LM, which has been a major supplier of offshore wind turbine blades to GE as well as other OEMs.

Foundations

Fixed-bottom foundations in Europe include three main types: monopile, jacket, and gravity-based. The relative mix of foundation types is anticipated to remain similar to its current status, as shown in Table C2.

Table C2. Ratio of Foundation Types To Be Installed in Europe Through 2024

Foundation Type	Proportion
Monopiles	65%
Jackets	25%
Gravity -based	5%
Other/unknown including floating foundations	5%

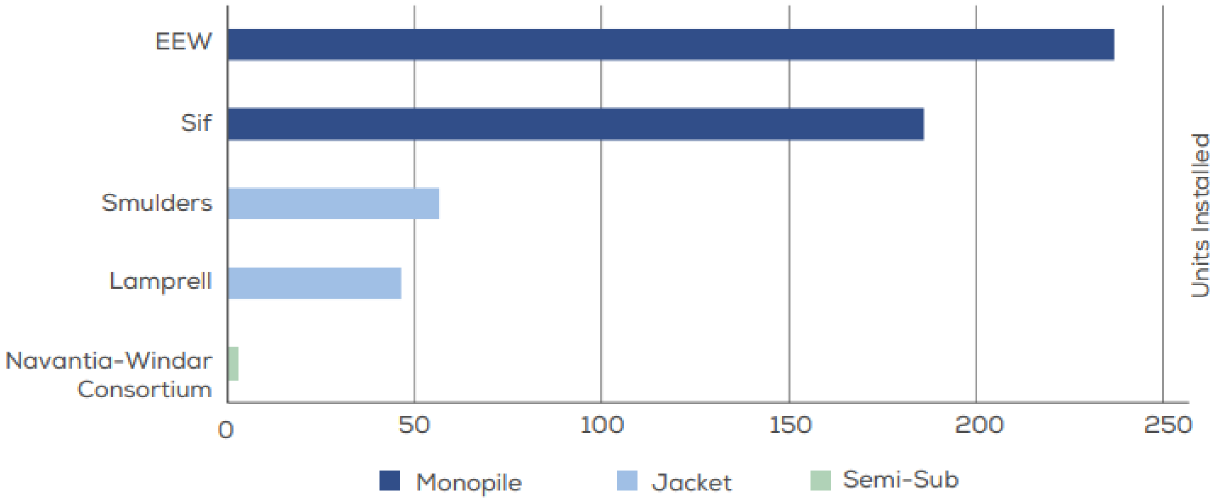
Using the proportions in Table C1, the forecast demand for each foundation type is presented in Table C2, which shows the European demand forecast for offshore substations as well. The values are based on actual project plans when available. For the offshore substation, the baseline assumption is that, on average, one offshore substation will be necessary for every 800 MW. This assumption may be conservative due to the development of higher-capacity high-voltage direct current (HVDC) offshore substations in the coming years.

The acceleration of floating offshore wind development in Europe by the end of the decade will correspondingly increase the demand for floating foundations, representing a portion of the "other" foundations in Table C2.

Table C3. Demand Forecast for Wind Turbine Foundations in Europe Through 2030

Year	Monopiles	Jackets	Gravity-Based Foundations	Unknown/Other	Substations
2021	374	88	0	6	5
2022	340	171	35	14	7
2023	232	121	35	44	6
2024	329	132	24	22	8
2025	548	220	41	37	13
2026	566	227	42	38	15
2027	566	227	42	38	15
2028	566	227	42	38	15
2029	566	227	42	38	15
2030	566	227	42	38	15

As most of the installed foundations are likely to be monopiles, the two largest foundation suppliers are unsurprisingly monopile manufacturers, as shown in Figure C2. Most jacket foundations are supplied by Smulders or Lamprell. Gravity-based foundations (GBFs), to the extent they are used in U.S. projects, will be manufactured domestically. For floating projects, a primary European supplier of semisubmersible foundations is the Navantia-Windar Consortium.



Source: WindEurope

Figure C2. Foundations and substructures installed in 2020. ***Image courtesy of WindEurope (2021)***

Monopiles and Transition Pieces

Two monopile manufacturers share the majority of the market: SIF, in the Netherlands, and EEW, in Germany. The monopile manufacturing facilities require specific steel plate rolling equipment capable of rolling plate thicknesses exceeding 15 centimeters (6 inches), extensive storage area, and easy access to a port quay for loading the components on the transport or installation vessels. While these and other European manufacturers will supply monopiles to some U.S. projects, U.S. Wind has announced plans to fabricate steel monopiles for three projects totaling 2.4 GW at Sparrows Point in Baltimore, Maryland, repurposing part of a former Bethlehem Steel mill. EEW and Ørsted have also begun construction on a monopile facility at the Paulsboro Marine Terminal in New Jersey.

Jackets

The jacket market, although smaller than that for monopiles, has more potential suppliers. In addition to dedicated jacket manufacturers, some shipyards and offshore platform manufacturers have adapted their infrastructure to also produce jackets. Some of the main European jacket suppliers include:

- Bladt (Denmark)
- Smulders (Belgium)
- Eiffage Métal (United Kingdom, France)
- Navantia (Spain)
- Rosetti (Italy)
- ST3 Offshore (Poland).

Compared to monopile fabrication, the infrastructure and equipment needed to produce jackets is less specialized, and most shipyards can be adapted to produce them. The U.S. oil and gas industry has considerable experience fabricating jackets for offshore oil rigs that can be leveraged to supply substructure for offshore wind energy projects.

Gravity-Based Foundations

GBFs are generally fabricated at construction sites established specifically for the project, close to the installation site with easy access to a load-out quay. The construction is generally handled by civil works contractors.

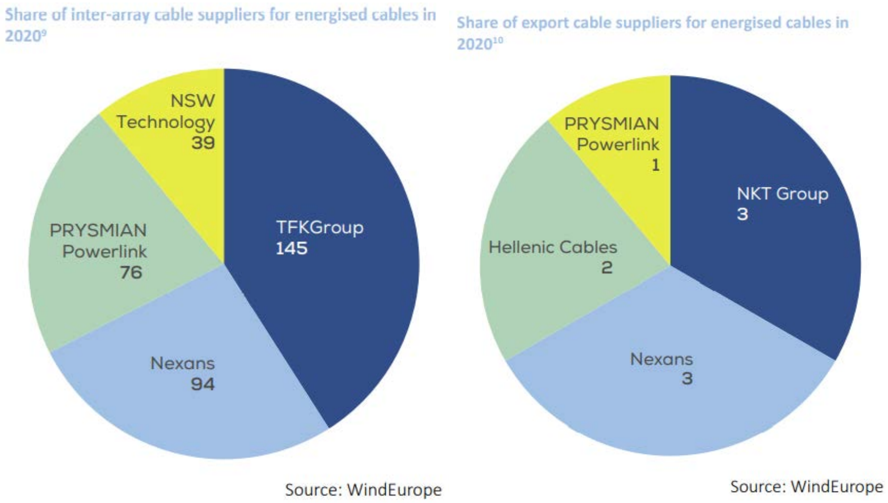
The required infrastructure to manufacture a GBF is relatively light in comparison with that for other foundation types—lighter cranes, no welding workshops, and no painting cells—but because of the volume of GBF structures themselves, and the time required for fabrication, these types of foundations require a very large construction area.

Because of the volume and weight of GBFs, it is very unlikely that these types of foundations for U.S. projects will be built outside of the country.

Subsea Cables

The interarray and export cable market is dominated by six manufacturers in Europe:

- Nexans (France)
- Prysmian Group (Italy)
- NSW Technology (part of Prysmian Group)
- NKT Group (Germany)
- TKF Group (Netherlands)
- Hellenic Cables (Greece).



Share of inter-array cable suppliers for energised cables in 2020[9]

Share of export cable suppliers for energised cables in 2020[10]

Source: WindEurope

Source: WindEurope

Figure C3. Market share of interarray (left) and export (right) subsea cable manufacturers in 2020. ***Image courtesy of WindEurope (2021)***

The demand for subsea power cables is expected to grow quickly in coming years, due to the offshore wind energy development in Europe, the United States, and Asia. The production facilities of the leading manufacturers are predominantly located in Europe and generally dedicated to subsea power cables. Nexans, however, has recently added offshore wind cable manufacturing to its facility in South Carolina, and plans to produce up to 1,000 kilometers of export cables by 2027 for projects Ørsted is constructing. For the Park City Wind project, developer Vineyard Wind, LLC has contracted with Kerite to manufacture interarray cables at their facility in Seymour, Connecticut. Certain other production facilities producing subsea umbilical or smaller power cables for the oil and gas industry can also be adapted to produce interarray and export cables, but that requires significant investment and equipment upgrades. Over time, however, domestic supply of interarray and export cables is expected to grow to meet the growing demand.

Offshore Substation Topsides

Construction of the offshore substation topsides requires specialized construction infrastructure and expertise. Those topsides are mostly made of stiffened steel plates and beam structures and equipped with high-voltage equipment and auxiliary systems. For this reason, several shipyards and oil and gas platform manufacturers have adapted their infrastructure to manufacture these topsides.

Some of the main suppliers of high-voltage alternating current (HVAC) substations in Europe are:

- Engie Solutions (Belgium)
- Bladt (Denmark)
- Chantiers de l’Atlantique (France)
- Navantia (Spain)
- Rosetti (Italy).

On average, each of the previously mentioned manufacturers can produce between 2 and 3 topsides per year.

The construction of HVDC substations poses different challenges. Because of significantly larger volume and weight of the topsides compared to HVAC, as well as a higher level of system complexity, HVAC platform suppliers may not be able to supply HVDC topsides. Some of the HVDC platforms installed in Europe have been built by other shipyards with the ability to handle such dimensions. The limited number of construction facilities able to build these structures may become a bottleneck if HVDC transmission becomes more frequently used and if the topside dimensions remain large.

Appendix D. Component Glossary

Table D1 provides a short definition of the components in the hierarchy maps listed in Section 5.3. A few common items that are not specific to offshore wind energy, such as lighting fixtures, gates, and handrails, are not included.

Table D1. Component Terms and Definitions

Term	Definition
4G/LTE system	4G/LTE systems are a type of wireless broadband communication for mobile devices and data terminals.
AC filter	An alternating current (AC) filter supplies reactive power to the converter station and absorbs harmonic currents generated by the high-voltage direct current (HVDC) converter.
Aerial cableways/cable laying/ stringing equipment	Aerial cableways, cable laying, and stringing equipment are accessories that are used to install cables within an offshore wind turbine.
Anemometry equipment (sensors)	An anemometer is a device used for measuring wind speed and direction.
Armor (jacket/outer sheath)	Armor is a subcomponent of a cable that is used as protection against external impacts that could cause cable failures.
Automatic dependent surveillance system	An automatic dependent surveillance system is air safety technology that emits the location of offshore wind turbines.
Automatic identification system	An automatic identification system is a tracking system for ships that displays vessels and other ocean structures that are in the nearby vicinity.
Auxiliary transformer	Auxiliary transformers are backup transformers that are available in case the primary transformer fails.
Ballast	Ballast is heavy material, like gravel or sand, that is used in a gravity-based foundation to improve stability.
Balsa wood/foam core	Balsa wood and foam cores are internal blade components that are used to increase the durability of the structure.
Battery cabinet	Battery cabinets are storage systems designed to hold spare batteries.
Bedplate	A bedplate is a cast iron component that acts as the main structural support for an offshore wind turbine’s drivetrain and other nacelle components.
Bend restrictors	A bend restrictor is a cable accessory that limits the bending of a cable.
Bend stiffeners	Bend stiffeners are cable accessories that provide additional support and are typically used when there is a requirement to control the minimum bend radius of a cable.
Bird deterrent system	Bird deterrent systems are sounds, lights, and/or markings that repel birds away from offshore wind turbines.
Blade adhesives and coatings	Blade adhesives and coatings are the materials used to bind blade components together and protect the composite structure of a wind turbine blade.
Blade root	The blade root is the base of a wind turbine blade that fits into the hub.
Blade skins	Wind turbine blades are typically manufactured in two shells called “skins” that are then assembled to form a single blade.

Term	Definition
	Blade skins are a combination of different core materials including epoxy and resin.
Boat landing system	A boat landing system is an access component that is located on the substation foundation at sea level. Fabricated with steel, boat landing systems include ladders and guards and are used by technicians to access the platform of a substation.
Brakes	Operational components that are part of the nacelle drivetrain, brakes bring the wind turbine to a stop in an emergency and hold the rotor in that position.
Bus coupler	A bus coupler is a substation component that connects a conductor or group of conductors without any interruptions to power supplies.
Cable joints/fittings (high and low voltage)	Cable joints are connections that allow two sections of cable to be spliced together.
Cable trays	Cable trays are a cable accessory that are used for cable management in an offshore wind turbine.
Cables (fiber optic)	Fiber-optic cables provide offshore wind projects with the ability to monitor and communicate changes to project conditions.
Cable (from earthing auxiliary transformers to neutral earthing resistors)	Part of the substation, this cable connects the earthing auxiliary transformer to the neutral earthing resistor that provides a neutral grounding point for connection.
Cable (from J-tube to high-voltage and medium-voltage gas-insulated switchgear)	Part of the substation, this cable carries the load generated from the project to the high-voltage and medium-voltage gas-insulated switchgear.
Cable (power offtake)	Part of the nacelle drivetrain, power offtake cables are internal components that carry the load generated by the wind turbine.
Cable (shunt reactor to high-voltage gas-insulated switchgear)	Part of the substation, this cable connects the shunt reactor to the high-voltage gas-insulated switchgear.
Cable (upland to substation)	Upland to substation cables are cables that begin onshore and carry the load generated from the project to the onshore substation.
Cables and wiring lugs, trays, and ties	Cables and wiring lugs, trays, and ties are cable accessories that are used for cable management and organization in an offshore wind turbine.
Cables or gas-insulated ducting from high-voltage to medium-voltage transformers	Components that act as a connection between high-voltage and medium-voltage transformers.
Capacitors	Capacitors are onshore electrical components that correct the power factor and minimize voltage fluctuations.
Circuit breakers	Used in offshore and onshore substations, circuit breakers protect against faults in transformers and cables.
Clamps	Cable accessories that are used to secure and route cables.
Clean water and topside cleaning systems	Clean water and topside cleaning systems can be reverse-osmosis systems for changing seawater to freshwater, or general water storage if alternative freshwater delivery is utilized.
Closed-circuit television system	Closed-circuit television systems are a form of video surveillance.
Communication mast	A communication mast is a ground-based or rooftop structure for antennas that support communication abilities.
Concrete mattress	A concrete mattress is a form of scouring protection that is used to reduce scour impact from exposed cables.

Term	Definition
Conductor core	Made from copper or aluminum, conductor cores include the parts of the cable that transport the electricity generated by offshore wind.
Conduit	A conduit is a housing, such as a pipe or tunnel, through which electrical wires can pass.
Control equipment hardware and software	Part of the control system for various components within an offshore wind energy project, control equipment hardware and software are the codes and physical devices that allow operators to interface with the controlled elements of an offshore wind energy project.
Control panel	A control panel is the interactive housing that allows operators to interface with the controlled elements of an offshore wind energy project.
Control system (electrical)	A control system includes multiple components that allow operators to interface with the controlled elements of an offshore wind energy project.
Controls hardware and software	Part of the control system for various components within an offshore wind energy project, control equipment hardware and software are the codes and physical devices that allow operators to interface with the controlled elements of an offshore wind energy project.
Cooling equipment (auxiliary)	Cooling equipment includes the fans, ductwork, and any other HVAC equipment designed to cool the internal components of a wind turbine.
Copper winding	Part of the nacelle drivetrain for a direct-drive system, copper windings are subcomponents of the generator.
Core insulation	Core insulation prevents the different wires within a cable from coming into contact with each other while extending the lifetime of the wire by providing a layer of protection against environmental impacts from water and heat.
Core protection	Core protection is a layer of filler material that extends the lifetime of a cable by providing a layer of protection within the cable that protects against environmental and anthropogenic impacts.
Cranes (crawler/hydraulic/overhead)	Cranes are heavy-duty equipment used for lifting and hoisting. Crawler cranes are mobile systems that operate on tracks. Hydraulic cranes have hydraulic lifting systems and can be used for heavy loads. Overhead cranes, also known as bridge cranes, operate using two elevated tracks that are connected by a moveable bridge.
Cranes (davit)	Davit cranes are large exterior cranes that are installed on the external working platform of an offshore wind turbine.
Cranes (internal service/auxiliar	Internal service/auxiliary cranes are heavy-duty equipment used for lifting and hoisting.
Damping liquid (tuned damper)	Damping liquid is part of the tuned damper, which reduces vibrations created by the operation of an offshore wind turbine.
Data acquisition equipment (SCADA)	Supervisory Control And Data Acquisition (SCADA) equipment is used to operate wind turbines, and collect operating data including wind conditions, power production, and turbine faults, alarms, and downtime. Information gathered by data acquisition equipment can alert operators to impending component failures.

Term	Definition
Diesel bunkering	Diesel bunkering is equipment including tanks that are used when bunkering (supplying) fuel that is used to power generators and other infrastructure on the substation.
Disconnectors/load switches and accessories	Electrical equipment that can isolate equipment and break currents when operating high-voltage substation components.
Distributed temperature sensing system	A distributed temperature sensing system monitors temperature over long distances.
Doors/frames	Doors and frames are personnel access components that are part of offshore wind turbine towers.
Duct bank	A duct bank is an onshore electrical component that provides a protected pathway for onshore export cables.
Earthing switch	An earthing switch is a safety device that grounds a switchgear when a circuit is removed.
Earthing/grounding system	Earthing/grounding systems are electrical components that protect people and equipment from power system failures by providing a low-resistance pathway for undesired fault currents.
Electric Panel	An electric panel comprises steel boxes that house circuit breakers for offshore and onshore substations.
Elevator	An elevator is lifting equipment that provides access to the nacelle of an offshore turbine from the base of the tower.
Emergency/safety equipment signage	Emergency equipment signs label the equipment that may be needed during fires, falls, or other accidents.
Emergency escape lighting	Emergency escape lighting is used to illuminate essential pathways to expedite personnel exits during emergencies.
Emergency shelter	An emergency shelter is a designated space, typically an extra container, that contains offshore survival kits, evacuation/rescue equipment, first-aid equipment, basic plumbing equipment, lighting, heating, and power outlets.
Evacuation equipment/emergency refuge	Evacuation equipment includes inflatable rafts, life jackets, flares, and other equipment that is housed in an emergency refuge that is designated space, typically an extra container, that contains offshore survival kits, evacuation/rescue equipment, first-aid equipment, basic plumbing equipment, lighting, heating, and power outlets.
External access system	An external access system is made of a steel framework, nonslip decking, as well as the external platforms, guardrails, and lights needed to allow a technician access to the offshore wind turbine tower from the foundation.
Fall arresters	Fall arresters are the equipment used to safely stop an individual as they are falling.
Fiber distribution system	Fiber distribution systems, also called fiber distribution panels, house, organize, manage, and protect fiber-optic cable, splices, terminations, and connectors.
Filler	Cable filler is the material used to fill the spaces between the cores of a cable.
Fire/gas detection/protection systems	The system and equipment used to detect fire or gas, alert personnel, and suppress or slow the spread of fire.
First aid/advanced medical/eye- washing kits	Medical supplies and equipment used to administer first aid to technicians.

Term	Definition
Flanges (steel/metal)	A flange is a large-diameter component used to connect foundations to the tower, substations to the tower, tower sections to tower sections, and the tower to the nacelle.
Freshwater tank	Freshwater tanks are used to store potable water.
Gearbox	A gearbox is used to increase rotational speeds to the level needed to transform mechanical power into electricity.
Gears (gearbox)	Gears are an integral part of the gearbox and vary in size, type, and number depending on the gearbox design.
Generator cooling system	A generator cooling system includes the fans, ductwork, and any other high-voltage alternating current (HVAC) equipment designed to cool the generator.
Generator shaft (gearbox)	The generator shaft is a high-speed shaft that is connected to the gearbox and generator. It carries the increased rotational speeds from the gearbox to the generator.
Gas-insulated switchgear interface plugs	These interface plugs allow the gas-insulated switchgear to interface with the cable system.
Gas-insulated switchgear terminators	These terminators allow the gas-insulated switchgear to interface with the transformer.
Grating and decking	Grating and decking are secondary steel components that are used as flooring for internal and external platforms.
Grey water system	Grey water systems are used to manage gently used wastewater from sinks, showers, and other low wastewater uses.
Hang off	A cable hang-off system is a cable accessory that secures medium- and high-voltage power cables that run through the foundation and tower of an offshore wind energy project.
Headroom hoists/ high-voltage gas-insulated switchgear handling system	Lifting equipment used to maneuver and position gas-insulated switchgear during operations, maintenance, and replacement.
Heat tracing system	A heat tracing system is a safety element of an offshore wind substation that can identify elevated temperatures that could be indicative of a larger issue.
Helicopter crash equipment	Helicopter crash equipment is the required crash rescue, evacuation, and first-aid equipment that is located near a substation’s helipad.
Helipad	Topside space designated for helicopter landings that can occur during emergency response or other activities.
High-speed intermediate carrier (Gearbox)	High-speed intermediate carriers are a bearing-based gearbox component.
Human-machine interface/engineering workstation	A human-machine interface is a user dashboard that connects a technician to various substation systems. Information gathered by an human-machine-interface dashboard can alert operators to impending component failures.
Hub casting	Hub castings are the primary housing for blades, pitch bearings, and the main shaft of an offshore wind turbine.
HVAC (electrical system)	A high-voltage alternating current power system is a type of cable system used for offshore wind energy projects.
HVAC building management system	Building management systems are computer-based systems that monitor and control heating, ventilation, and air conditioning.
HVAC ductwork	HVAC ductwork carries heated, cooled, or otherwise ventilated air throughout an offshore substation.
HVAC switchboards	An HVAC switchboard is a component of a high-voltage electrical distribution system that divides an electrical power feed into

Term	Definition
	branch circuits while providing a protective circuit breaker for each circuit in a common enclosure.
HVAC system	HVAC systems are the heating, cooling, and ventilation systems that are used on an offshore wind substation.
Hydraulic actuator	Part of the hydraulic pitch system, a hydraulic actuator is a cylinder or fluid motor that exerts force to change blade pitch during the operation of an offshore wind turbine.
Hydraulic pitch power pack	The power unit located in the nacelle that supplies power to the hydraulic pitch system.
Insulation	Insulation is an internal component of a cable that is made of a nonconductive material and shields the current from the insulated wire from contacting other conductors.
Interior and exterior anodes	Typically made from aluminum, anodes are corrosion-protection components designed to maintain the structural integrity of offshore wind foundations and transition pieces.
Internal electrical support	Internal electrical support includes the accessories needed to supply electrical function from the foundation to the tower.
Joints/fittings	Joints/fittings are the metal-to-metal connection including welds that are used in the fabrication of tower, foundations, and other components.
J-tube	J-tubes are metal tubes that run the length of a foundation and provide the necessary protection of cables as they transition from the wind turbine to seabed.
Junction boxes	Electrical junction boxes house and protect electrical connections, thereby keeping them isolated from the elements.
Kickplates	A kickplate is part of the staircase that creates a boundary between each step/tread.
Ladders	Ladders are used in the wind turbine tower to provide personnel with access from the base of the tower to the nacelle.
Light-emitting diode lighting/turbine markings	Light-emitting-diode lighting/wind turbine markings are visual identification components that are used for exterior detection of individual offshore wind turbines.
Lifting aids (tackles/winches)	Lifting aids are part of a type of lift system that features two or more pulleys and is usually used to lift heavy loads.
Light distribution system	Light distribution systems are used to achieve the desired spread/distribution of light from multiple fixtures.
Lighting control and socket outlet system	Lighting control and socket outlet systems are part of the larger lighting and electric system that provides access to power and lighting.
Lightning protection	Part of an offshore wind turbine blade and substation, lightning protection is used to prevent damage from the effects of a lightning strike.
Limit switch	Limit switches are presence-sensing devices that activate when an object makes physical contact with the actuator.
Local area network	A local area network is a group of computers or devices that are connected through a communications line or wireless connection.
Low-speed intermediate carrier (gearbox)	A low-speed intermediate carrier is a bearing-based gearbox component.
Low-voltage cabinet	Low-voltage cabinets are enclosures used to house relays for various electronic systems.
Low-voltage wiring (lighting system)	Low-voltage wiring is wiring with a capacity of less than 50 volts.

Term	Definition
Main bearing	Part of the nacelle drivetrain, a main bearing is part of the subassembly that transfers the low-speed rotation of the wind turbine blade to the gearbox.
Main low-voltage switchboards	Main low-voltage switchboards are a component of a low-voltage electrical distribution system that divides an electrical power feed into branch circuits while providing a protective circuit breaker for each circuit in a common enclosure.
Main shaft	Part of the nacelle drivetrain, a main shaft is part of the subassembly that transfers the low-speed rotation of the wind turbine blade to the gearbox.
Manifold blocks	Part of a hydraulic pitch system, manifold blocks direct the flow of hydraulic fluid linking valves, pumps, and actuators.
Monitoring equipment hardware and software	Part of the onshore electrical components for an offshore wind energy project, monitoring equipment hardware and software are the codes and physical devices that allow operators to interface with the power coming onshore from an offshore wind project.
Nacelle cover	Typically made from fiberglass, a nacelle cover is an enclosure that protects nacelle components from outside elements.
Navigation and aviation aids	Navigational aids are markers, signals, or devices that assist aircraft approaching an offshore wind energy project.
Nodes (K, X, Y)	Nodes are standardized joints that are used to connect the struts of an offshore wind turbine jacket foundation.
Obstruction lights	Warning lights that are located on the top of an offshore wind turbine to provide a visual warning for nighttime aviators who may be flying near an offshore wind energy project.
Oil/water pumps	Oil/water pumps are used to circulate water or oil through a designated system within an offshore wind substation.
Oil/water separator	Oil/water separators are components used to separate water from oil.
Oil breather valves (gearbox)	Oil breather valves are a type of relief valve designed for tank protection.
Oily water tank	Part of an oil water separator, an oily water tank holds oil and water mixtures that are waiting to be separated.
Onshore cable racking	Onshore cable racking is used to organize and avoid twisting of optical cables and communications wiring.
Open and closed drain systems	Open and closed drain systems are used to collect and transport wastewater throughout the offshore wind substation.
Outdoor terminators	Outdoor terminators are devices that are used to electrically terminate coaxial ports.
Outer polyethylene (PE) sheath	Outer polyethylene sheaths are protective coverings mainly used for mechanical strengthening and anticorrosion.
Overvoltage protection system	Overvoltage protection systems are used to shut down the power supply or output when the voltage exceeds a preset level.
Passive fire protection (fire and blast walls, doors, floor, and ceiling)	Passive fire protection, such as fire and blast walls, doors, floor, and ceiling, are specially designed components that slow the spread of fire and allow personnel to escape.
Permanent magnet	Part of the nacelle drivetrain, a permanent magnet is made of heavy rare-earth metal and is used in direct-drive machine generators as an alternative to a gearbox.

Term	Definition
Pile sleeves	Pile sleeves are part of the pre or postpiled connections that are used to secure a jacket foundation to the seabed.
Piles	Piles are steel components that are driven through the base of a jacket foundation to secure it to the seabed.
Pinion (gearbox)	A pinion is a type of gear that is used in the gearbox of an offshore wind turbine.
Pitch/blade bearings	Pitch/blade bearings are the bearings used to connect the blade to the hub.
Pitch accumulator	A pitch accumulator is a component of the pitch system that is used to feather the pitch of the blade and as an auxiliary power storage device that can be used in case of electrical failures.
Pitch controller	Pitch controllers monitor and adjust the blade angle of an offshore wind turbine.
Pitch cylinder	A pitch cylinder is a component of the pitch system that is used to feather the pitch of the blade.
Pitch motor	A pitch motor drives the pitch system that is used to adjust the blade angle of an offshore wind turbine.
Planetary carrier (gearbox)	Part of the gearbox, a planetary carrier is a housing for the planetary gears.
Pole rotor	Part of the generator, a pole rotor is a magnetic rotor component.
Power converter (power offtake)	A power converter adjusts generator frequency and voltage to the grid.
Private radio communication system	A private radio communication system is a portable radio (walkie talkie) used so multiple individuals within a certain proximity can communicate.
Protective coating/primers/paints	Protective coating/primers/paints are part of the corrosion protection for offshore wind turbine components.
Public address and general alarm system	A public address and general alarm system is a communication system that features a general alarm and public address broadcasting to alert technicians of emergencies.
Rescue equipment/descenders/hub rescue	Rescue equipment for exterior scenarios at elevated heights.
Reserve diesel generator	A reserve diesel generator is a backup system that can be used when the primary diesel generator fails.
Roller bearings (gearbox)	Rolling bearings support rotating machine elements and transfer loads between machine components.
Rotary union	A rotary union transfers fluid under pressure from a stationary inlet to a rotating outlet.
Rotor/intermediate frame	A rotor frame is a support structure that is used in a direct-drive generator.
Rotor shaft	Rotor shafts turn due to the rotation of the blades and transfer the resulting torque to the generator.
Satellite system	Part of the telecom system for an offshore substation, satellite systems are used for global positioning system and other forms of telemetry.
Scour protection/rocks/rip rap	Scour protection, rocks, and/or rip rap are used to avoid erosion and maintain the structural integrity of foundations.
Seawater utility pumps	Pumps used to circulate seawater away from essential systems within an offshore wind substation.
Semiconductive screening	Semiconductive screening covers the conductor, thereby improving the distribution of the electric field on its surface.

Term	Definition
Semiconductive taping	Semiconductive taping is mylar-backed tape that is used to wrap bundled wires within a cable.
Shaft coupling	Shaft coupling is a mechanical component that connects the drive shaft of a gearbox to the generator.
Shear web	A shear web is a structural component that connects the two halves of an offshore wind turbine blade.
Sheath (jacket/outer sheath)	A sheath is an outer cover that protects the conductor within a cable.
Shunt reactor	Shunt reactors are electrical components that stabilize voltage during load differences in high-voltage power transmission systems.
Shunt reactor coolers	Shunt reactor coolers are fans that circulate air to cool the shunt reactor.
Slip rings	A slip ring is an electromechanical component that allows the transmission of power and electrical signals from a stationary to a rotating structure.
Software: transformer monitoring system	Transformer monitoring systems are designed to monitor and diagnose transformer operating conditions in a substation.
Spar cap	Spar caps are a structural support component that runs the length of a wind turbine blade.
Spinner molding	A spinner molding is the protective covering for the hub of an offshore wind turbine and is designed to protect key hub components.
Spinner support frame	A spinner support frame is the mounting device used to attach a spinner molding to the hub.
Static VAR compensator	Static VAR compensators provide reactive power to HVAC transmission systems.
Stator frame	A stator frame is a stationary device in the generator of a direct-drive wind turbine to which the windings are attached.
Steel building	Steel buildings are part of the topside of an offshore wind substation that houses many substation subassemblies and subcomponents.
Steel plate	Steel plates are large slabs that are bent and welded to form towers, foundations, and parts of transition pieces.
Storage and transfer system	Storage and transfer systems are used to hold bulk fuel for diesel generators.
Structural fasteners: bolts/studs/ nuts/washers	Used throughout a wind turbine, structural fasteners are customized components that vary in size depending on use.
Structure (concrete, rebar)	Structure is assembled by combining concrete and rebar, which is used to fabricate the skirt and shaft of gravity-based foundations.
Struts (legs, feet/mudmats and braces)	Struts, including legs, feet, mudmats, and braces, are the steel components that are assembled and welded together to fabricate the main structure of a jacket foundation.
Sump tank	A containment system, sump tanks are used to isolate excess water that can accumulate on an offshore substation.
Sump tank pump	Sump tank pumps are used to remove the water that is accumulated in the sump tank.
Supervisory control equipment	Supervisory control equipment monitors the movement of electricity from an offshore wind energy project through the offshore substation to the onshore substation.

Term	Definition
Support structure (tuned damper)	A tuned damper is a component that reduces vibrations created by the operation of an offshore wind turbine.
Surge arrestors	A surge arrester protects electrical equipment from overvoltage.
Swelling tape	Swelling tape stops water migration along the axis of the cable if the cable is cut.
Switchgear	Electrical switchgear include a centralized collection of circuit breakers, disconnectors, fuses, and switches that are used to protect, control, and isolate electrical equipment. Switchgears can be air- or gas-insulated. Gas-insulated switchgears are more compact and can be used in areas with space constraints.
Telecommunication hardware/software	Part of the telecommunication system for an offshore substation, hardware and software are the codes and physical devices that allow operators to communicate.
Torque arm (gearbox)	The torque arm prevents counterrotation of gearbox components during operation.
Transformer	Transformers are used to convert the voltage to a higher value to effectively transmit the energy generated at an offshore substation to the onshore transmission and distribution grid.
Transformer coolers	Transformer coolers are air-cooled or water-cooled systems used to reduce the temperature of an oil-filled transformer.
Transformer oil spill tank	Transformer oil spill tanks are secondary storage systems designed to capture oil from a transformer if operations result in a spill or leak.
Transition piece section	Located between a tower and a foundation, a transition piece includes a flange that connects these components while providing a housing for secondary steel.
Transition vault	A transition vault is an onshore electrical component that houses the transition from subsea export cables to onshore electrical cables.
Trunnion mount (gearbox)	Trunnion mounts are gearbox components that minimize movement due to torque variations and provide an accessible way to remote and service the drivetrain.
Uninterruptable power supply (auxiliary)	An uninterruptible power supply provides backup power that can be used when a power source fails or if voltage drops to an unacceptable level.
Very high frequency radio telephone system (aviation)	Very high frequency communication systems are commonly used for maintaining contact between the ground and aircraft.
Voice over internet protocol telephone system	A voice over internet protocol telephone system facilitates voice calls using a broadband internet connection instead of an analog phone line.
Waterproofing	Waterproofing for cables allows components to be completely submerged and to function at varying depths.
Weather station system	A weather station system comprises the instruments and equipment used to measure atmospheric conditions to provide information for weather forecasts and study the weather and climate.
Wireless local area network	A wireless local area network uses high-frequency radio waves to create a wireless distribution method for two or more devices.
Work platform: external	External working platforms are used to support access to the transition piece and wind tower.

Term	Definition
Work platform: internal	Internal work platforms are used to support equipment and provide personnel access for installation and maintenance purposes.
Wind turbine generator supervisory control and data acquisition	Supervisory control and data acquisition is a fundamental tool to monitor and control several parameters of an offshore wind energy project.
Yaw bearing	Part of a yaw system, yaw bearings support a wind turbine's ability to align its rotor to the wind.
Yaw brakes	Part of a yaw system, yaw brakes stop a wind turbine once it has aligned its rotor to the wind.
Yaw motor/drive	The yaw drive is a motor-and-gearbox assembly used to rotate the nacelle around the tower.