U.S. DEPARTMENT OF ENERGY

# Wind Energy

## Supply Chain Deep Dive Assessment

U.S. Department of Energy Response to Executive Order 14017, “America’s Supply Chains”

February 24, 2022

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# About the Supply Chain Review for the Energy Sector Industrial Base

The report "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition" lays out the challenges and opportunities faced by the United States in the energy supply chain as well as the federal government plans to address these challenges and opportunities. It is accompanied by several issue-specific deep dive assessments, including this one, in response to Executive Order 14017 "America's Supply Chains," which directs the Secretary of Energy to submit a report on supply chains for the energy sector industrial base. The Executive Order is helping the federal government to build more secure and diverse U.S. supply chains, including energy supply chains.

To combat the climate crisis and avoid the most severe impacts of climate change, the U.S. is committed to achieving a 50 to 52 percent reduction from 2005 levels in economy-wide net greenhouse gas pollution by 2030, creating a carbon pollution-free power sector by 2035, and achieving net zero emissions economy-wide by no later than 2050. The U.S. Department of Energy (DOE) recognizes that a secure, resilient supply chain will be critical in harnessing emissions outcomes and capturing the economic opportunity inherent in the energy sector transition. Potential vulnerabilities and risks to the energy sector industrial base must be addressed throughout every stage of this transition.

The DOE energy supply chain strategy report summarizes the key elements of the energy supply chain as well as the strategies the U.S. government is starting to employ to address them. Additionally, it describes recommendations for Congressional action. DOE has identified technologies and crosscutting topics for analysis in the one-year time frame set by the Executive Order. Along with the policy strategy report, DOE is releasing 11 deep dive assessment documents, including this one, covering the following technology sectors:

- Carbon capture materials,
- Electric grid including transformers and high voltage direct current (HVDC),
- Energy storage,
- Fuel cells and electrolyzers,
- Hydropower including pumped storage hydropower (PSH),
- Neodymium magnets,
- Nuclear energy,
- Platinum group metals and other catalysts,
- Semiconductors,
- Solar photovoltaics (PV), and
- Wind.

DOE is also releasing two deep dive assessments on the following crosscutting topics:

- Commercialization and competitiveness, and
- Cybersecurity and digital components.

More information can be found at www.energy.gov/policy/supplychains.

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# List of Acronyms and Abbreviations

| | |
|---|---|
| CES | clean electricity standard |
| GW | gigawatt |
| IEA | International Energy Agency |
| IRENA | International Renewable Energy Agency |
| ITC | investment tax credit |
| MW | megawatt |
| NREL | National Renewable Energy Laboratory |
| PTC | Production Tax Credit |
| STEM | science, technology, engineering, and mathematics |

# Executive Summary

On January 27, 2021, the Biden Administration issued Executive Order 14008 ("Executive Order on Tackling the Climate Crisis at Home and Abroad" 2021), which established a target of achieving 100% carbon pollution-free electricity by 2035 and net zero greenhouse gas emissions economy-wide by no later than 2050 (The White House 2021c). Achieving these goals is expected to require deploying several clean energy technologies at a rapidly increasing scale. A subsequent Executive Order 14017 on America's Supply Chains directs the Secretary of Energy to submit a supply chain overview report for the Energy Sector Industrial Base. A cross-DOE team led by the Office of Policy was tasked with reviewing key technology supply chains and determining actionable policy steps to enable the United States to meet its domestic demand for these critical technologies within five years while also considering environmental justice and impacts on underserved communities (The White House 2021a).

To inform the DOE team's supply chain review, researchers at the National Renewable Energy Laboratory (NREL) conducted research and analyses that characterize supply chain strengths, weaknesses, opportunities, and threats within the wind industry, including both land-based and offshore wind. The team also conducted interviews with industry stakeholders and subject matter experts. This report documents these findings and provides a foundation for addressing the observed vulnerabilities and enhancing U.S. wind supply chain competitiveness.

Research into the U.S. wind supply chain reveals several vulnerabilities. These vulnerabilities manifest differently for offshore and land-based wind given their current domestic supply chain status (i.e., absent or nascent for offshore wind, significant and mature for land-based wind), but several common themes emerge. Research conducted to date reveals strong consistency regarding the following most crucial supply chain vulnerabilities for the United States to address:

- A lack of demand certainty in the wind energy project pipeline provides limited motivation for new supply chain investments; near-term domestic manufacturing capacity may even contract due to forecast reductions in annual installations in 2022 and 2023.
- Low labor costs from overseas competitors threaten U.S. supplier competitiveness, especially for labor-intensive operations such as blade manufacturing.
- Logistics networks for land-based wind turbine components are increasingly strained due to the increasing size of components; offshore wind component logistics require specialized infrastructure, particularly ports and vessels, that do not yet exist in the United States. The operation of foreign-flagged vessels for installation of offshore wind turbines in United States waters is limited by the Jones Act.
- Technology evolution, including increasingly larger wind turbine components, drives the need for facility upgrades and retooling and compounds difficult transportation hurdles—lack of demand certainty complicates such upgrades; innovative solutions such as modularity could erode U.S. competitiveness by facilitating transportation of components from lower-cost global manufacturing regions.
- Shortages of rare earth magnets and fundamental commodity price risks could disrupt supply chain activities, erode U.S. competitiveness, and jeopardize deployment ambitions. Offshore wind projects would be most impacted by rare earth magnet shortages, but all wind applications are impacted by commodity price risk.
- Expected new workforce demand to serve the Administration's goals is likely in the hundreds of thousands. Additional education and training programs are expected to be necessary; scenarios range from several hundred new programs to more than 1,000. Re-training workers for offshore wind facilities, construction, and servicing is critical.

Opportunities for private sector collaboration include the following:

- Increasing the skilled workforce through wind-specific training and development. Cooperation between wind energy component manufacturers, wind developers, community colleges, and labor unions can address key educational and training requirements for the wind industry.
- Developing port facilities and vessels to support the offshore wind industry. Collaboration with the private sector can bring wind component manufacturing facilities to ports, support redevelopment of existing ports, and leverage existing shipbuilding capabilities to produce Jones Act-compliant vessels for wind turbine installation and maintenance.
- Developing alternatives to rare earth permanent magnet generators (such as superconducting systems). Collaboration with private industry will be required to commercialize alternatives.
- Developing and commercializing additive manufacturing of large iron and steel castings and forgings, such as rotor hubs and nacelle bedplates. These components are not currently produced in the United States at the sizes required due to the cost and environmental impact of associated foundries. Additive manufacturing of these components and associated tooling represents a significant leadership opportunity for the United States--for the iron and steel industry to meet growing global demand in wind and other energy technologies such as nuclear and hydropower, and to reduce the environmental impact associated with current processes.
- Reversing the decline in blade manufacturing facilities in the United States. As mentioned, domestic blade manufacturing faces challenges from increasing blade size and overseas competitors with low labor costs. Development of new blade designs and novel approaches to manufacturing will require collaboration with the private sector to ensure that these innovations enable new investment in domestic facilities.
- Scaling up and commercializing wind industry recycling. Collaboration should be possible with turbine OEMs—including Vestas (Vestas n.d.), GE (GE Renewable Energy 2020; 2021) and Siemens Gamesa (Siemens Gamesa 2021)—who have announced efforts to increase recycling of wind turbine blades.

***Find the policy strategies to address the vulnerabilities and opportunities covered in this deep dive assessment, as well as assessments on other energy topics, in the Department of Energy 1-year supply chain report: "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition."***

***For more information, visit www.energy.gov/policy/supplychains.***

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# 1 Introduction

Wind energy—which includes the land-based, offshore, and distributed sectors—is expected to be a cornerstone for achieving U.S. clean electricity generation objectives, including 100% clean electricity by 2035 (The White House 2021c). The Biden Administration has also proposed an offshore wind goal of 30 gigawatts (GW) by 2030 (The White House 2021b). Meeting this offshore wind target will, in 2030, generate enough power to meet the demand of more than 10 million American homes and avoid 78 million metric tons of $CO_2$ emissions (The White House 2021b). Without new policies, expert forecasts for the domestic market include expected capacity additions ranging from 13 GW to 16 GW in 2021, a downturn in 2022 and 2023, and a possible addition of 11 to 13 GW per year in 2024 and 2025. At these levels for ongoing wind deployment, decarbonization targets will likely not be achieved. Yet, land-based and offshore wind can potentially be deployed at even greater scale throughout the United States, especially as the technology progresses (Wiser et al. 2021; Musial et al. 2021), making it a key player in transforming the energy sector.

In 2019, wind power provided 5% of the world's electricity output, 96% of which came from land-based wind. In Europe, the share of electricity generated was as high as 12.4%, with Denmark reporting the highest share at nearly 50% ("DNV's Energy Transition Outlook 2021" 2021; Wiser et al. 2021). In 2020, the global wind industry installed 93 GW of new capacity, exceeding the 2019 single year total by nearly 50%. As of March 2021, global installed wind energy capacity reached 743 GW, helping to avoid more than 1.1 billion tons of $CO_2$ emissions (Joyce Lee and Feng Zhao 2021).

In line with global industry trends and supported by the federal Production Tax Credit (PTC) and state renewable portfolio standards, in 2020 U.S. wind power capacity also grew at a record pace, with 16.8 GW of new capacity added and $24.6 billion invested. Cumulative wind capacity grew to 121,985 megawatts (MW) (Wiser et al. 2021) and reflects a 5-year average wind installation of ~10 GW per year. In 2019 and 2020, project developers installed more wind power capacity in the United States than any other utility-scale generating technology (U.S. Energy Information Administration 2021). Also in 2020, the 12-MW Coastal Virginia Offshore Wind pilot project began generating power as the first offshore wind installation in federal waters (Musial et al. 2021). Finally, 3,087 MW of existing wind plants were partially repowered in 2020 to higher production capacity, mostly by upgrading rotors and major nacelle components of existing turbines (Wiser et al. 2021).

In 2020, the United States ranked second in the world for annual and cumulative wind power capacity additions, behind China. Although the United States ranks lower than many other countries in terms of wind energy as a share of total generation, at 8.3%, wind energy currently provides more than 10% of electricity in 16 states and more than 30% in Iowa, Kansas, Oklahoma, South Dakota, and North Dakota (Wiser et al. 2021). With the support of federal tax incentives, wind power purchase agreement prices are "below the projected cost of burning natural gas in existing gas-fired combined cycle units" (Wiser et al. 2021).

Installation of wind generating capacity in the United States would need to accelerate to meet the Administration's clean energy and $CO_2$ emissions targets. Wind power could potentially serve 35% or more of U.S. electricity demand, representing the largest or near-largest U.S. electricity generation source. The U.S. Long-Term Strategy for reaching net zero greenhouse gas emissions by 2050 calls for new wind deployment at the level of 25 to 30 GW per year (United States Department of State and United States Executive Office of the President 2021). As shown in Figure 1, scenarios aligned with the Long-Term Strategy project that wind deployment in 2035 would reach a cumulative total of between 480 and 680 GW, with deployment of up to 1,150 GW by 2050. Achieving these deployment levels would require average installations of 25 to 30 GW per year over the next few decades. Similar levels of wind capacity additions are estimated by the Solar Futures Study "Decarbonization" and "Decarbonization with Electrification" scenarios, which model a 95% reduction in carbon dioxide emissions from 2005 levels by 2035 and a 100% reduction by 2050 (Ardani et al. 2021). In these scenarios, most new wind turbines would be land-based, although offshore wind is expected to play an increasing role, as evidenced in part by the Biden Administration's target of 30 GW by 2030.

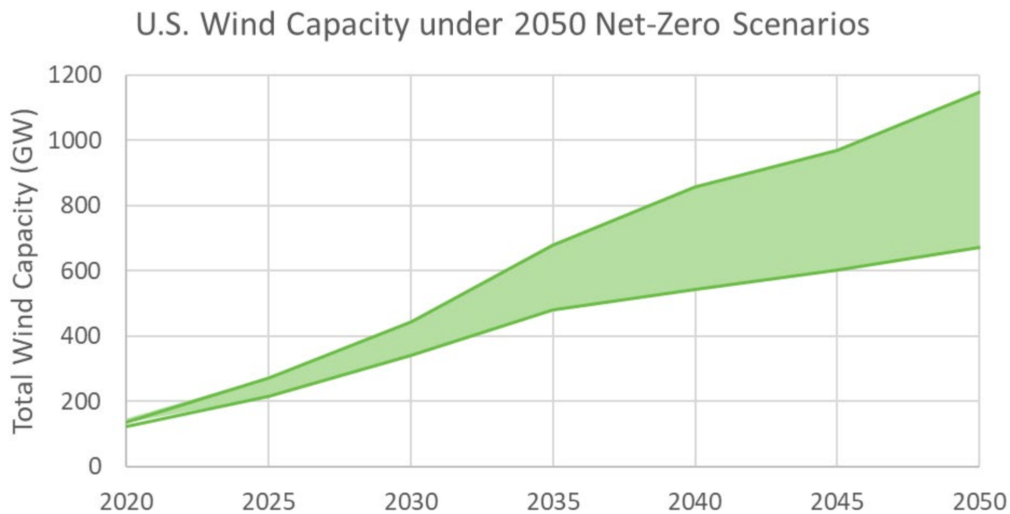


**Figure 1. Range of potential U.S. wind generating capacity under one set of decarbonization scenarios. Source: *The Long-Term Strategy of the United States, Pathways to Net-Zero Greenhouse Gas Emissions by 2050,* United States Department of State and United States Executive Office of the President 2021**

Globally, scenarios aligned with the goal of limiting global warming to between 1.5°C and 2°C project significant increases in wind generating capacity. Wind capacity projections from several scenarios are depicted in Figure 2. The International Energy Agency (IEA) Net Zero Emissions scenario targets net-zero $CO_2$ emissions from the global energy sector by 2050, consistent with limiting the global temperature rise to 1.5°C with a 50% probability (IEA 2021a). The Net Zero Emissions scenario projects that global wind generating capacity will reach 3,100 GW in 2030 and 8,300 GW in 2050. The International Renewable Energy Agency (IRENA) Transforming Energy scenario models a 70% reduction in carbon emissions from today's levels by 2050, with an expected temperature rise "well below" 2°C. The Transforming Energy scenario projects 2,500 GW of wind capacity in 2030 and 6,000 GW in 2050 (IRENA 2020). A separate scenario from IRENA that aims for no more than 1.5°C temperature increase projects more than 8,100 GW of wind capacity by 2050 (IRENA 2021). Two scenarios from the Institute for Sustainable Futures at the University of Technology Sydney consider electricity generation consistent with limiting the temperature rise to 1.5°C and 2°C, arriving at wind generation capacities in 2050 of 7,800 GW and 7,900 GW, respectively (Teske et al. 2019). BloombergNEF's New Energy Outlook examines three scenarios that reach net-zero emissions in 2050. All three scenarios project increased use of renewable energy generation and battery storage, combined with green hydrogen in the "green" scenario, carbon capture and storage in the "gray" scenario, and nuclear power in the "red" scenario. Wind capacity projections range from 4,800 to 13,300 GW in 2035 and 7,000 to 25,000 GW in 2050 across the three scenarios (BloombergNEF 2021a).

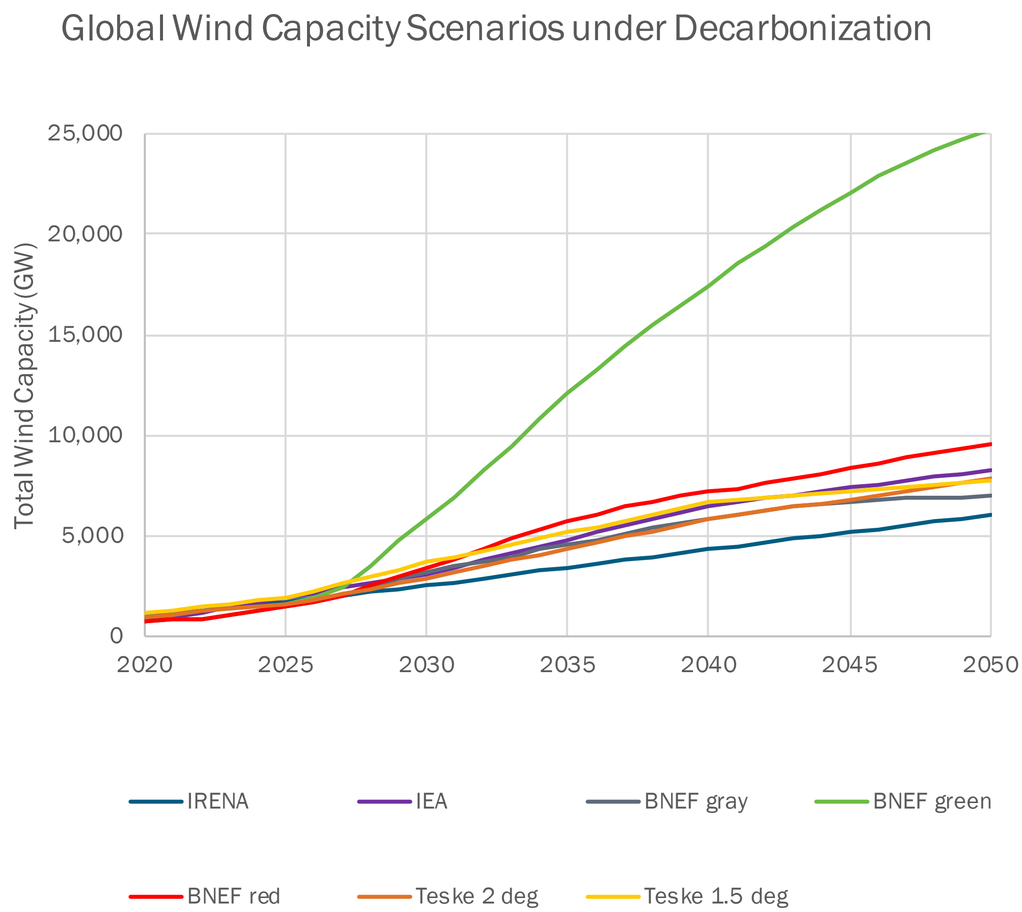


**Figure 2. Potential global wind capacity under scenarios limiting global warming to 1.5-2°C. IRENA "Transforming Energy" scenario, IEA "Net Zero by 2050" scenario, BNEF "Red" (renewable and nuclear electricity), "Gray" (renewable electricity + carbon capture and storage), and "Green" (renewable electricity and hydrogen) scenarios, Institute for Sustainable Futures (Teske et al.) 1.5°C and 2°C scenarios. Sources: IRENA 2020, IEA 2021a, BloombergNEF 2021, Teske et al. 2019.**

Achieving the level of wind capacity projected by deep decarbonization scenarios would require supply chains capable of delivering enough wind power plant components. In the United States, annual installations of land-based wind turbines have averaged approximately 10 GW, or 4,000 turbines per year, over the past 5 years (American Clean Power 2021). The land-based wind capacity growth shown in Figure 1 is equivalent to 22 to 26 GW per year through 2035, or 5,000 to 6,000 turbines per year.[1] Meeting the 30 GW by 2030 target for offshore wind is expected to require more than 2,000 offshore wind turbines (Lantz et al. 2021).

Analysts recently estimated that a typical land-based U.S. wind project sources 57% of its components (dollar value) from domestic sources (Goldie-Scot, Zindler, and Lezcano 2021). The domestic supply chain for the offshore wind segment in the United States is nascent. Raw and processed materials needed by the wind

[1] Estimation of the number of land-based wind turbines assumes an average turbine capacity of 4 MW in 2020-2030 and 5 MW in 2030-2035.

industry are currently produced by a range of global sources (many of which are not U.S. allies), available quantities of these materials are in high demand, and the available supply is competing with other uses and demands. To achieve decarbonization objectives, a massive increase of total wind manufacturing and supply chain capacity by the United States and its allies will be required, along with a) supporting domestic rail, truck, and vessels transportation; b) installation equipment and cranes; and c) a trained workforce. Finally, as wind energy technology continues to advance, turbine sizes are projected to continue increasing. Existing manufacturing facilities may face challenges building and testing the next generation of wind technology. Larger and heavier components result in additional transportation challenges.

This report examines the challenges and opportunities facing the U.S. land-based and offshore wind energy supply chains with an aim to providing stakeholders and policymakers an understanding of where interventions to support domestic wind supply could be most fruitful. As a sector-specific assessment, it does not consider in-depth important, broader economic considerations associated with these vulnerabilities and opportunities (such as the net effects of offshoring of labor-intensive manufacturing on the U.S. economy, or on the cost of achieving decarbonization objectives). Section 2 provides an overview of supply chain mapping, including a discussion of components, subcomponents, processed materials, raw materials, recycling, digital products, and the wind industry workforce. Section 2 also offers a discussion of the strengths and weaknesses inherent in the U.S. wind industry supply chain, key global players and U.S. competitiveness, and policies and incentives implemented by leading nations. Section 3 provides an overview of the supply chain risk assessment: current, anticipated over the next decade, and most crucial to address. In Section 4, we discuss U.S. opportunities and challenges for offshore and land-based wind and opportunities for private sector collaboration.

# 2 Supply Chain Mapping

The domestic supply chain for land-based wind energy has remained reasonably stable over the past 5 years, with production capacity between 7 GW and 10 GW for blades and towers and between 10 GW and 15 GW for nacelle assembly (Figure 3).

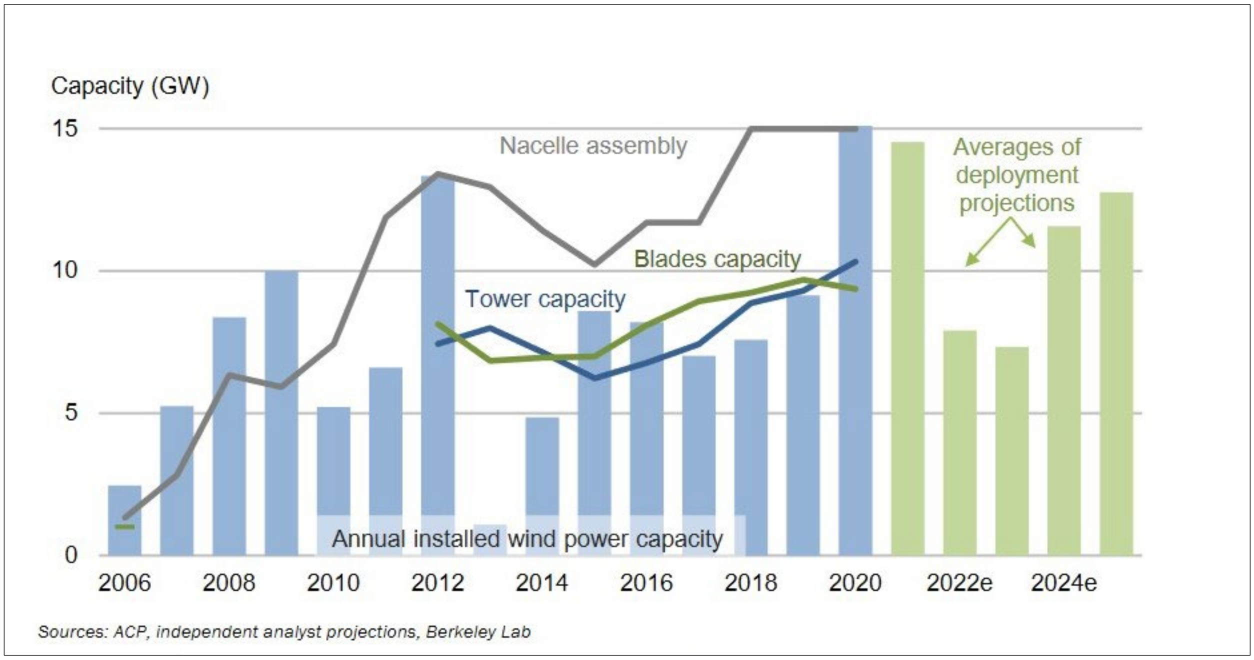


**Figure 3. Domestic wind manufacturing capability vs. U.S. wind power capacity installations. Sources: American Clean Power, independent analyst projections, Berkeley Lab**

In addition to the domestic supply chain, the United States imports wind plant components from around the world. Imports include complete turbines, major components, and subcomponents, with the top countries of origin in 2016–2020 shown in Figure 4.

There has been limited deployment of offshore wind in the United States through 2021, and the domestic supply chain for the offshore wind segment in the United States is nascent. International supply chains have already developed for major components, installation vessels, and engineering expertise. The U.S. offshore wind industry can leverage these sources to accelerate U.S. offshore wind near-term deployments, but it also has an opportunity to build domestic supply chain capacity that can lower project risk and costs and provide local economic benefits (Musial et al. 2021). As well, offshore wind plants will require vessels that can handle components for the next generation of offshore wind turbines with capacities of 15 MW or more. Components for offshore wind are larger than for land-based turbines and more difficult to move over land, which poses a challenge for existing U.S. wind manufacturers that are concentrated close to the Great Plains. Coastal locations can also ease some of the logistical challenges of importing large components, eroding some of the advantage that domestic manufacturers have due to their proximity to inland sites.

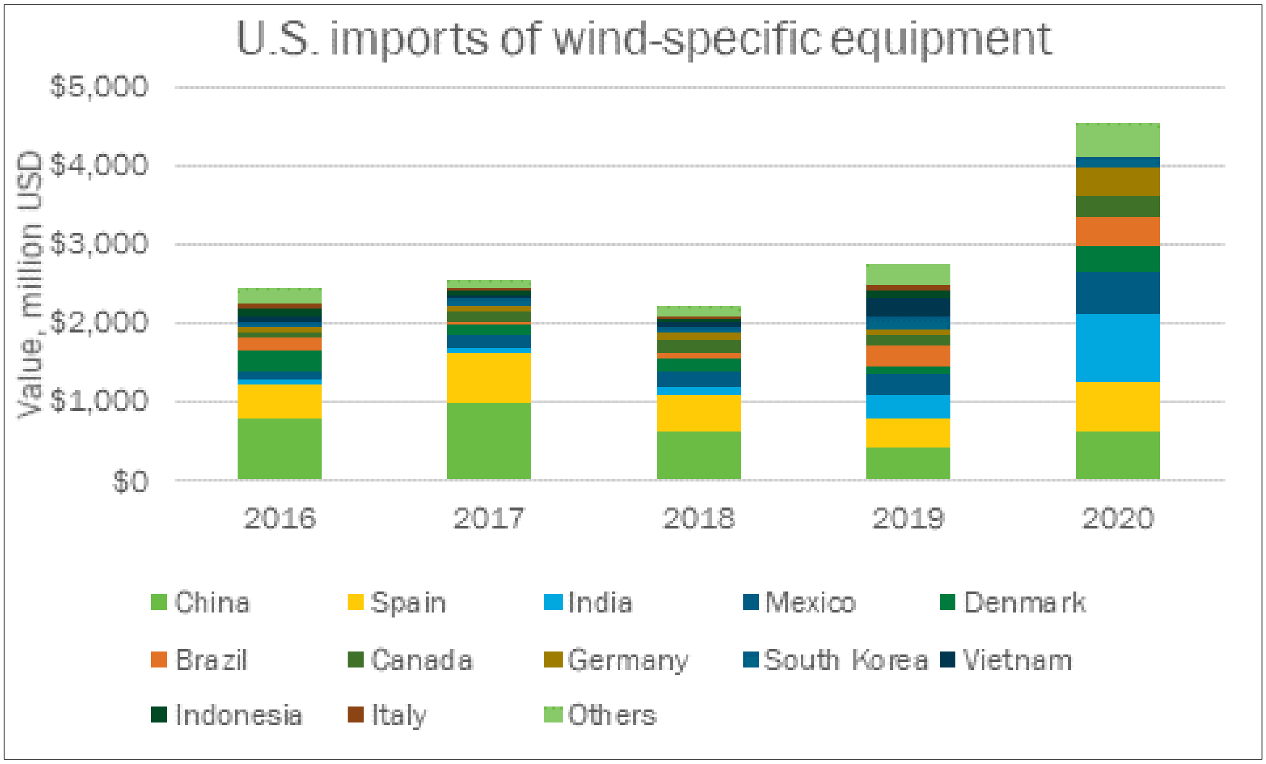


**Figure 4. U.S. imports of wind-specific equipment, 2016-2020. Sources: BNEF, Berkeley Lab**

This section provides an overview of the U.S. land-based and offshore wind energy supply chain, including segments, strengths and weaknesses, U.S. competitiveness and global players, and national policies and incentives implemented by leading nations to support their industries.

## 2.1 Supply Chain Segments

We examined the following wind industry supply chain segments: components, sub-components, processed materials, raw materials, wind industry recycling, digital products, and workforce, for both land-based and offshore wind. See Figure 5 for a schematic diagram that details the relationships of these supply chain elements. We discuss logistics and installation in Section 3.1.

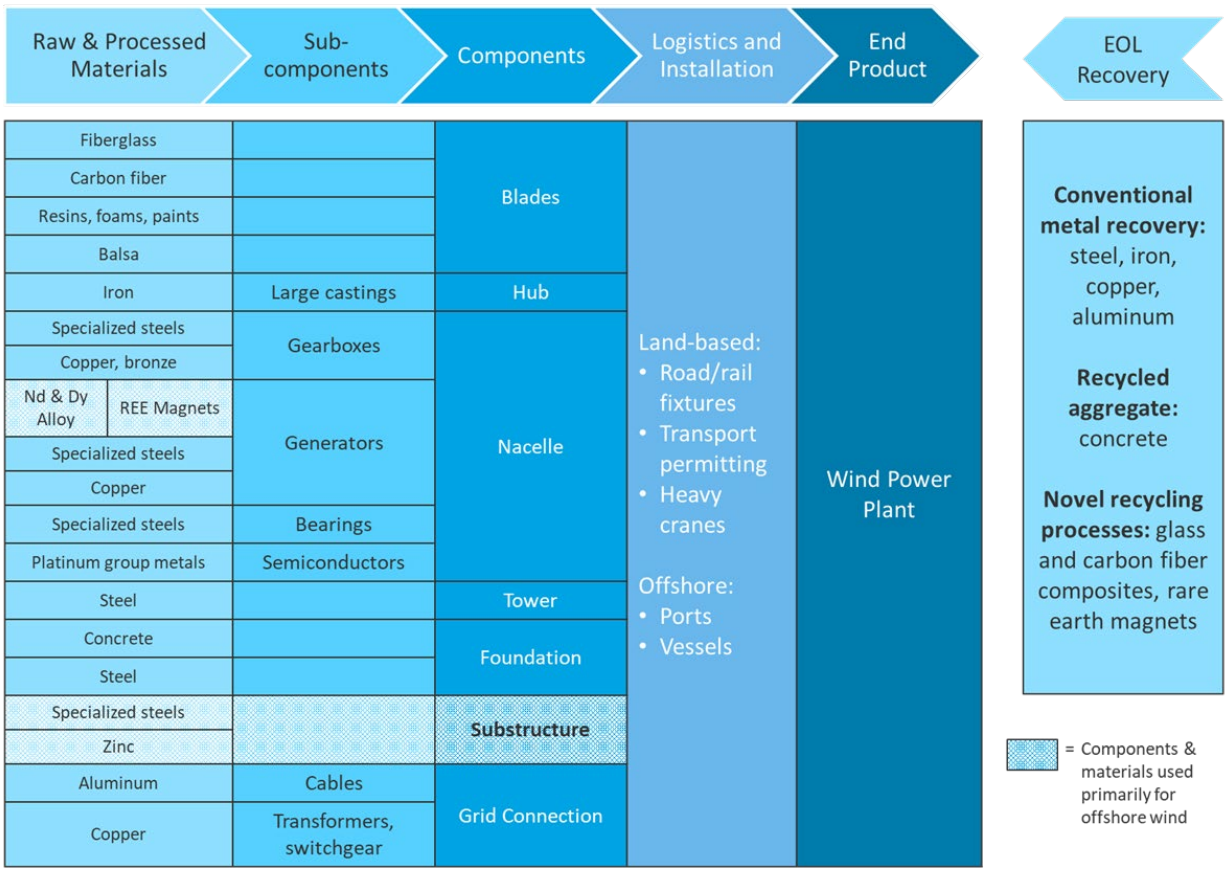


**Figure 5. Schematic relationship of supply chain elements in land-based and offshore wind power plants**

### 2.1.1 Components

Wind power plants have five primary components for assembly and manufacturing: towers, rotors/blades, nacelle/drivetrain, foundations, and grid interconnection equipment. Domestic content is relatively strong for larger components of land-based wind plants, such as towers and blades (Figure 6), though domestic content in blades has declined in recent years. Although there is no domestic offshore wind supply chain capacity in 2021, apart from some manufacturing of applicable electrical equipment and cabling, several manufacturers have announced the intent to begin production at U.S. facilities in the coming years (Table 1). The domestic supply chain in 2020 was capable of producing 10-15 GW/year for each primary land-based turbine component (towers, blades, and nacelles) (Wiser et al. 2021). BloombergNEF estimated that a typical onshore wind project in the U.S. sources 57% of its components (by dollar value) domestically (Goldie-Scot, Zindler, and Wang 2021).

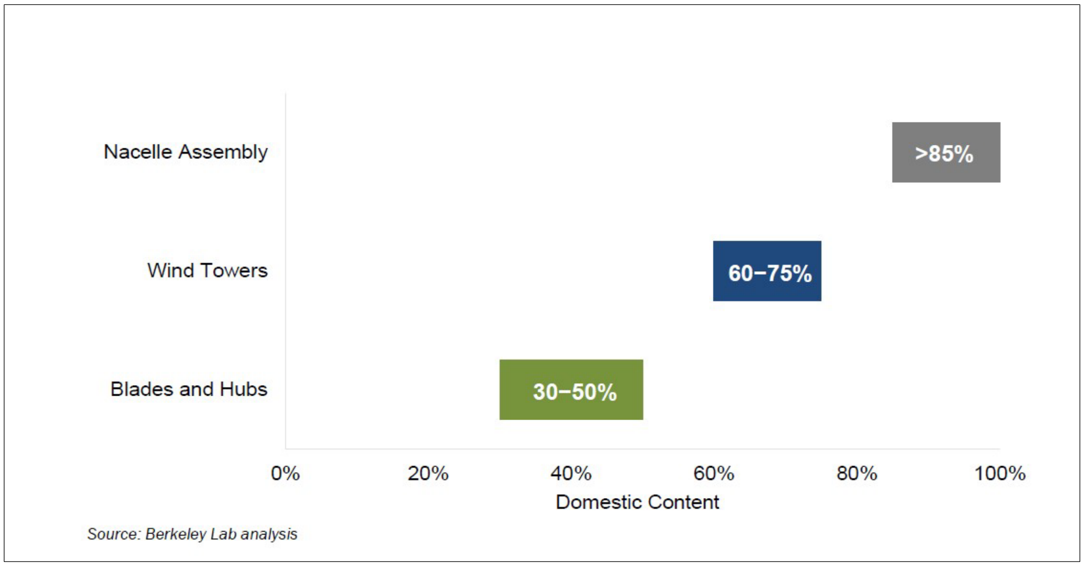


**Figure 6. Domestic manufacturing content in 2020 was relatively strong for nacelle assembly, towers, and blades. Source: Berkeley Lab**

- **Towers:** Most towers are made from steel, although there are some examples of concrete and hybrid concrete/steel towers. Domestic tower manufacturing capacity reached 10 GW in 2020 (Wiser et al. 2021). Approximately 30% of towers are imported, supplementing domestic production. There is significant year-to-year variation in sourcing of imported towers with Indonesia (27%), Canada (20%), and Spain (18%) supplying the largest quantities between 2015–2019 (Goldie-Scot, Zindler, and Wang 2021).
- **Blades:** Standard wind turbine rotors consist of three blades and a hub. Rotor diameters have been increasing steadily from 30 m in 1998 to nearly 125 m in 2020 (Wiser et al. 2021). Blade manufacturing facilities that were set up to produce smaller blades for an earlier generation of wind turbines may be difficult to reconfigure for larger blades. Domestic blade manufacturing capacity was approximately 10 GW in 2019; subsequently three blade production facilities have closed, reducing domestic capacity to approximately 6 GW. Siemens Gamesa has announced plans to open a blade production facility for offshore wind in Virginia (Siemens Gamesa Renewable Energy 2021). The main sources of imported blades and hubs in 2019 were China (20%), Brazil (14%), Mexico (14%), India (14%), and Spain (11%) (Goldie-Scot, Zindler, and Wang 2021).
- **Nacelles:** The nacelle houses the drivetrain, including the generator and gearbox (in geared drivetrains), as well other subcomponents including the yaw system and power electronics. Domestic nacelle assembly, wherein domestic and imported components are assembled into complete nacelles on U.S. soil, represented more than 85% of the U.S. market in 2020 with a total capacity of approximately 15 GW. Imports of nacelles are combined with other components in trade data from the U.S. Department of Commerce. The primary suppliers of wind-powered generating sets and parts, including nacelles, were India (26%), Denmark (15%), Germany (15%), Brazil (10%), and Spain (8%) in 2020 (Wiser et al. 2021).
- **Foundations:** Land-based foundations are typically constructed of concrete with steel or iron reinforcement. Concrete is supplied locally from domestic sources. For fixed-bottom offshore turbine installations through 2035, approximately 65% of U.S. offshore turbines planned for the Atlantic coast are likely to use monopile foundations, 25% are likely to be supported by jacket foundations, and the remaining 10% of turbines are likely to be gravity-based or some other foundation design (e.g., tripod). Most offshore foundation designs consist primarily of steel, except for gravity-based foundations that can be constructed of concrete supplemented with rocks or sand as ballast.

- **Grid interconnection cabling and equipment:** Cables that link individual wind turbines to substations and deliver electricity to the grid have copper or aluminum conductors. Aluminum is more commonly used for overhead cables, whereas copper is more common in underground and subsea cables (IEA 2021b). Subsea cables require additional protection against the marine environment, with external layers manufactured from specialized plastics and lead alloys. Collector substations include components such as switchgear and transformers that are sourced from domestic and foreign manufacturers.

To date, domestic offshore wind manufacturing is limited to the grid interconnection cabling and equipment category. However, public announcements for new facilities across the other primary component areas have occurred and are listed in Table 1.

**Table 1. U.S. Offshore Wind Supply Chain Announcements. Source: Shields et al. 2022**

| Component | Location | Investors | Investment | Status |
|---|---|---|---|---|
| **Blades** | Portsmouth Marine Terminal (VA) | Siemens Gamesa | $200 million | Announced |
| **Nacelles (assembly only)** | New Jersey Wind Port (NJ) | Vestas, Atlantic Shores | Not announced | Announced |
| | Paulsboro Marine Terminal (NJ) | GE, Orsted | Not announced | Announced |
| **Towers** | Port of Albany (NY) | Marmen Welcon, Equinor | $350 million | Announced |
| **Monopiles** | Paulsboro Marine Terminal (NJ) | EEW, Orsted | $250 million | Under construction |
| | Sparrows Point (MD) | US Wind | $150 million | Announced |
| **Transition pieces** | Port of Albany (NY) | Marmen Welcon, Smulders | $60 million | Announced |
| **Gravity-based foundations** | Port of Coeymans (NY) | Cobra, Esteyco, Equinor | Not announced | Announced |
| **Export cables** | Nexans high voltage cable facility (SC) | Nexans | $200 million | Operational |
| **Array cables** | Kerite (CT) | Kerite, Marmon Group, Vineyard Wind | $4 million | Operational |
| | Tradepoint Atlantic (MD) | Eversource, Orsted | $150 million | Announced |

| Component | Location | Investors | Investment | Status |
|---|---|---|---|---|
| **Offshore substations** | Ingleside (TX) | Kiewit, Eversource, Orsted | Not announced | Operational |

### 2.1.2 Subcomponents

Wind subcomponents are manufactured by a mix of domestic producers and producers in allied and non-allied nations; current domestic capacities are heavily or exclusively focused on land-based wind equipment.

- **Generators:** Domestically produced generators represent 36% of the U.S. wind market by value. Imports of generators and generator parts primarily came from Vietnam (32%), Spain (31%), Serbia (12%), and Germany (9%) in 2019 and 2020 (Goldie-Scot, Zindler, and Wang 2021; Wiser et al. 2021). Manufacturers often produce a range of generating equipment including motors, thermal generators, and electrical equipment in addition to wind turbine generators. Rare earth permanent magnet generators, which have higher upfront costs than induction generators and are common in offshore wind turbines but represent a minimal share of generators for land-based wind turbines in the U.S. market, are not produced domestically. As turbines increase in size, they are more likely to incorporate permanent magnet generators and for the highest capacity turbines, to incorporate superconducting generators. Some manufacturers (e.g., GE) are also pursuing novel superconducting wind generator designs, which do not depend on rare earth magnets and have a smaller footprint and lower mass. Although a few domestic superconducting companies (e.g., AMSC, Commonwealth Fusion Systems, GE) have expressed interest in the superconducting generator wind industry, it is unknown if these new, emerging designed generators would be manufactured in the United States. A detailed assessment of the supply chain for rare earth magnets is beyond the scope of this report but can be found in DOE's Rare Earth Magnets Supply Chain Deep Dive Assessment. For more information, visit www.energy.gov/policy/supplychains.
- **Gearboxes:** The domestic content of gearboxes is 10% by value. Gearboxes require precision manufacturing and are comparatively easy to ship, so production is concentrated in a few locations: nearly half of factories are in China, followed by Germany, Spain, Italy, and the United States (Goldie-Scot, Zindler, and Wang 2021). The outlook for gearbox manufacturers depends on broader design decisions within the nacelle: fewer gearboxes will be required if direct drive systems gain market share, whereas adoption of medium-speed or hybrid drives could increase gearbox manufacturers' role in assembling complete powertrains (Barla 2021a). It may seem logical to conclude that moving to direct drive machines would result in more U.S. content by value. However, as noted above, most direct drive machines use permanent magnet generators that are not produced domestically; therefore, the opposite is likely to be true. To help inform a future outlook, it may be helpful to examine drivetrains of the most current land-based and offshore wind turbines; for example, all Vestas wind turbines and the overwhelming majority of other land-based wind turbines use gearboxes, most with doubly fed induction generators, but some of the larger new ones use permanent magnet generators. The GE Haliade-X and SGRE offshore wind turbines utilize direct drive permanent magnet generators, likely manufactured overseas.
- **Bearings:** The domestic content of bearings is 75% by value. Manufacturers of precision bearings supply many different sectors (the automotive sector, for example), and the wind industry does not drive the market. Large-diameter bearings required for wind turbines are primarily made by German, Swedish, Japanese, and U.S. manufacturers (Goldie-Scot, Zindler, and Wang 2021). Bearings with diameters greater than 4 m (yaw bearings) and 6 m (pitch bearings) for offshore wind turbines are not produced domestically and current market conditions have not motivated U.S. manufacturers to develop capacity to produce bearings at these sizes (Shields et al. 2022).

- **Large castings:** Large castings include the rotor hub and the nacelle bedplate (also called the support frame). There is limited capability to manufacture large castings in the U.S. and no serial production (Fullenkamp and Holody 2014).
- **Forged rings and shafts:** Forged rings and shafts are used in several components, including the main generator shaft, tower flanges, and forged rings for the yaw, pitch, and main bearings. Domestic production capacity exists for the mining, transportation, and oil and gas sectors. Forged rings for wind turbines have been produced in the United States, but this industry segment has lost market share to foreign producers (Fullenkamp and Holody 2014).
- **Semiconductors:** Semiconductors are widely used in wind turbines as components of sensors, controllers, power electronics, and communications equipment. A global shortage of semiconductors currently exists, worsened in part by the COVID-19 pandemic. A bigger issue is the general U.S. dependence on foreign-made semiconductors. The U.S. share of global semiconductor production has declined from 37% in 1990 to 12% currently (Varas et al., as cited in The White House 2021d). Most advanced semiconductor fabrication production capacity is concentrated in East Asia. Thanks in part to Chinese government investments, more than half of the planned new fabrication facilities for the next several years are projected to be in China (Congressional Research Service 2020). A White House supply chain review identified eight cross-cutting risks related to semiconductor supply chains: fragile supply chains; malicious supply chain disruptions; use of obsolete semiconductors and related challenges for continued profitability of companies in the supply chain; customer concentration and geopolitical factors; electronics production network effects; human capital gaps; intellectual property theft; and challenges in capturing the benefits of innovation and aligning private and public interests (The White House 2021d). Obstacles to constructing and operating domestic fabrication facilities include high capital costs (estimates to build range from $7 billion to $20 billion), requirements for continuing factory improvements, rapid obsolescence of chips as designs improve, and high R&D costs (Congressional Research Service 2020). These issues are covered in depth in DOE's Semiconductor Supply Chain Deep Dive Assessment. For more information, visit www.energy.gov/policy/supplychains.

### 2.1.3 Processed Materials

Wind turbines require a wide range of processed materials. This section highlights a few of the materials that make significant contributions by mass or function.

- **Concrete**: Concrete represents the most significant material input by mass, accounting for close to 70% of a wind power plant (Garrett and Rønde 2013; Razdan and Garrett 2017a; 2017b; 2017c; 2017d; 2017e; 2018a; 2018b; 2019b; 2019a; 2019c). The demand for concrete to build wind power plants is small relative to other industries and even with significant growth in wind installations globally, the demand by 2050 is projected to represent no more than 3% of supply (Carrara et al. 2020). The domestic supply chain can meet demand from the wind industry. Greenhouse gas emissions associated with concrete production (primarily from cement) are significant, and researchers are investigating methods to decarbonize concrete production through carbon capture, mineralization, or the use of alternative cementitious materials, which include fiberglass from end-of-life wind turbine blades as well as other materials such as fly ash. The adoption of concrete towers and/or gravity-based (offshore) foundations could increase the concrete content of wind power plants.
- **Steel**: Steel is the largest component of a wind turbine by mass, representing approximately 73% of the total (Garrett and Rønde 2013; Razdan and Garrett 2017a; 2017b; 2017c; 2017d; 2017e; 2018a; 2018b; 2019b; 2019a; 2019c). Relative to other industries, the demand for steel to produce wind turbines is not large: the projected annual demand for steel in wind turbines between 2030 and 2050 is 2% to 3% of the global supply (Carrara et al. 2020). Steel commodity prices are driven by demand from various industries, and increased steel prices can affect wind turbine prices. High prices for U.S. steel could affect the level of domestic content in the supply chain. Emissions associated with steel production are

significant, leading to interest in "green" steel (e.g., electrification of production processes, use of green hydrogen, or carbon capture and sequestration (Blank 2019)). Volvo announced production of the world's first fossil-fuel-free steel in August ("Volvo Group and SSAB to Collaborate on the World's First Vehicles of Fossil-Free Steel" 2021). There is significant domestic production of steel, with imports representing 12% of U.S. consumption in 2019 and 2020 (USGS 2021). There is limited domestic production of specialty steels such as electrical steel.

- **Fiber-reinforced composites:** Glass or carbon fiber composites are the primary materials used in wind turbine blades, and fiberglass is also used for the nacelle cover. Composite materials make up 6% to 7% of the mass of a typical turbine (Garrett and Rønde 2013; Razdan and Garrett 2017a; 2017b; 2017c; 2017d; 2017e; 2018a; 2018b; 2019b; 2019a; 2019c). Carbon fiber is more expensive than fiberglass and is used mainly in the spar cap, where its superior strength-to-weight ratio provides the most benefit. Blade manufacturers' adoption of carbon fiber for the blade root and flanges in addition to the spar cap may increase as blades become longer, with analysts projecting that demand for carbon fiber for wind turbines will triple by 2027 (Barla 2021a). Fiber-reinforced composites are used in various sectors including aerospace, automotive, and marine applications in addition to wind energy. The global wind industry accounts for approximately 10% of demand for fiberglass and 24% of demand for carbon fiber (BloombergNEF 2019). Domestic fiberglass production capacity in 2020 represented 10% of the global capacity for all industries, and domestic carbon fiber capacity was 28% of the global total ((BloombergNEF 2020b; 2020a).
- **Polymers:** Polymer materials are used in various wind turbine subcomponents, including as resin in composites, coatings on blades and towers, cable exteriors, in foam core for some blades, and in auxiliary equipment. Polymers represent approximately 3% of a typical wind turbine by mass, excluding composite materials (Garrett and Rønde 2013; Razdan and Garrett 2017a; 2017b; 2017c; 2017d; 2017e; 2018a; 2018b; 2019b; 2019a; 2019c). The primary source of polymer materials is petrochemical feedstocks, although production of polymers from bio-based feedstocks has been demonstrated. Approximately 10% of global petrochemical production capacity is located in the United States (BloombergNEF 2021b).
- **Rare earth magnets:** As mentioned earlier, rare earth permanent magnet generators are not produced domestically. More than 60% of 2019 rare earth production was in China, and analysts forecast that demand for rare earths in wind turbine manufacturing will triple by 2029 (Goldie-Scot, Zindler, and Wang 2021). See Section 2.1.4 for more discussion of rare earth elements in wind turbines.

### 2.1.4 Raw Materials

The demand for some raw materials required for wind turbine manufacturing can be met with domestic production, either completely (e.g., concrete source materials) or partially (e.g., iron/boron; copper, aluminum, other metals needed for lightning protection systems; tantalum/gallium/platinum group metals used in semiconductors/processors; niobium/manganese used in hardened steel). Some materials currently cannot be sourced domestically, most notably rare earth elements, some steel alloying elements, and balsa wood.

- **Rare-earth elements (e.g., neodymium, dysprosium)**: While rare earth elements are required for magnets used in permanent magnet generators, they are not mined in the United States in sufficient quantities to meet the demand for offshore wind drivetrains and other uses. Global production is concentrated in China, with all processing of heavy rare earth elements—including dysprosium and terbium—taking place there (AMO 2020). Global demand for rare earth elements in wind turbines in 2050 could exceed the current level of supply for all uses by up to 3.5x (terbium) or 1.6x (neodymium) (Carrara et al. 2020). Increasing production of specific elements is challenging because rare earths are typically found blended together in low concentrations and require extensive processing to concentrate and separate the individual elements. If demand for other rare earth elements does not increase at the same rate, there may be little economic motivation to increase production of the elements needed for wind turbine drivetrains. Wind-related demand for rare earths can be mitigated by the selection of drivetrains that do not use permanent magnets (e.g., electrically excited synchronous generators, superconducting generators, or high-speed geared designs) or hybrid designs that use smaller permanent magnets.

- **Steel alloying elements**: The production of steel alloys used in wind turbines requires elements including chromium, molybdenum, manganese, nickel, and niobium that are produced in limited quantities or not at all in the United States.
- **Balsa wood:** This material sourced from near the Equator is still widely used for blades as a lightweight core material. Some companies have investigated using foam, PTE, or PVC core instead, but using these materials introduces sustainability issues.

### 2.1.5 Wind Industry Recycling

Some wind project components can be completely recycled (e.g., metals, concrete, electronics components), some have limited recycling options (e.g., fiberglass/carbon fiber in wind turbine blades), and some (e.g., rare earth elements) are not typically recycled today. New facilities and processes are under development with the aim of lowering the cost and increasing the volume of recycling for materials including glass and carbon fiber composites and rare earth elements.

Between 80% (Delaney et al. 2021) and 90% (García Sánchez, Pehlken, and Lewandowski 2014) of a wind turbine's mass consists of materials that are already widely recycled, including aluminum, steel, copper, and iron used in the turbine tower, climbing equipment, and nacelle components. The resale value of and high demand for the metal in the turbines encourage recycling the materials into new products, which contributes to the larger circular economy.

Fiber-reinforced composites, which make up approximately 6% of a wind turbine by mass, represent the largest fraction of material that is not readily recyclable (Cooperman, Eberle, and Lantz 2021). Nearly all utility-scale wind turbine blades are currently manufactured using epoxy resin, a hardening material that binds glass or carbon fiber to create a strong, lightweight, and durable composite product—which makes recycling difficult and not always economical. Mechanical, thermal, and chemical recycling processes for recycling composite wind turbine blades have been demonstrated in laboratories and are at various stages of scaling up to commercial implementation. Turbine OEMs including Vestas (Vestas n.d.), GE (GE Renewable Energy 2020; 2021) and Siemens Gamesa (Siemens Gamesa 2021) have announced efforts to increase recycling of wind turbine blades.

The increasing number of wind turbine blades removed from service and the pursuit of cost-effective recyclability drive current renewable energy research that will help make wind energy a full participant in the circular economy. DOE is working to quantify blade waste as well as pursue R&D and commercialization to enable cost-effective recycling of existing composite blades and advanced manufacturing techniques for better recyclability of future blades ("Wind Energy Technologies Multi-Year Program Plan: Fiscal Years 2021—2025" 2020). Examples of this research include:

- DOE's NREL established a potentially groundbreaking approach to manufacturing wind turbine blades based on thermoplastic resins that can be recycled when they are removed from service (National Renewable Energy Laboratory n.d.).
- DOE's NREL is also leading a project examining how the use of three-dimensional (3D) printing, advanced materials, and advanced design procedures could improve the structural design of a wind turbine blade. Direct printing enables new solutions that might utilize domestically sourced recyclable materials (National Renewable Energy Laboratory 2021).

- DOE's Wind Energy Technologies Office provided funding to the University of Tennessee to help develop a method of reclaiming fiberglass from retired wind turbine blades. The recovered fiberglass will be used to manufacture new composite products for the automotive, consumer, marine, and aerospace industries (U.S. Department of Energy 2021).

Rare earth elements are used in permanent magnet generators, where they make up 0.1-0.2% of the total mass of the wind turbine. The current global market share of wind turbines using permanent magnet generators is approximately 32% of land-based wind turbines and 76% of offshore wind turbines (Carrara et al. 2020). Currently, less than 1% of rare earth elements used worldwide are recycled at end of life (Jowitt et al. 2018). Rare earth elements used in consumer products (e.g., hard disk drives) are challenging to separate from end-of-life waste streams because they represent a small mass fraction of the total product; however, the large permanent magnets used in wind turbine generators may be easier to separate at end of life for recycling or reuse (Yang et al. 2017). The availability of rare earth permanent magnets from wind turbines for recycling is limited by their long (20+ year) service lifetime, which means that end-of-life turbines will not be a significant supply of rare earth elements through 2030 (Rademaker, Kleijn, and Yang 2013). Although there are currently no commercially successful processes for rare earth element recycling, ongoing research and commercial start-ups are investigating several potential processes [Ames CMI, UPenn Schelter group, Urban Mining Company, Rare Earth Salts].

### 2.1.6 Wind Digital Products

Wind digital products are the computing and electronics systems and include wind controls systems (e.g., wind control management systems, wind grid management systems, etc.) and wind cybersecurity systems. These systems primarily encompass semiconductors, processors, and computer storage/memory systems, all of which are primarily manufactured overseas and subject to the respective global supply chain risks and vulnerabilities. See Section 2.1.2 for an overview of vulnerabilities related to foreign semiconductor industry dominance.

### 2.1.7 Workforce

In 2020, wind-related job totals in the United States increased by 1.8% to 116,800 full-time workers (DOE 2021b). These figures include jobs in construction (~42,300) and manufacturing (~23,900) ("U.S. Energy & Employment Jobs Report (USEER)" 2021). Ramping up the domestic supply chain will require training and development across all elements: components manufacturing and assembly, subcomponents manufacturing, processed materials production, and raw materials mining and refining.

The current wind-related workforce is concentrated in the land-based wind supply chain. Increased wind deployment will require expansion of the domestic supply chain to maintain or increase the level of domestic content in land-based wind plants, while offshore wind will require new supply chains to support a nascent industry. A recent assessment of the workforce needs for offshore wind component manufacturing and supply chain in the U.S. estimates that this sector will support between 10,500 and 42,500 full-time equivalent jobs annually, depending on how quickly manufacturing plants are built in the United States and how quickly the supply chain matures. Based on component demand over time, the peak workforce demand occurs in 2026 with a requirement of between 18,000 jobs (if 25% of components are produced domestically) and 72,000 jobs (if 100% of components are produced domestically). This maximum job demand is an indication of the highest workforce level that the United States offshore wind industry may need to have trained or hired depending on domestic content each year. The actual number of jobs would likely land within this range as the domestic supply chain grows to support the offshore wind project pipeline. In addition, there is the potential for a significant ramp up in jobs between 2021 and 2022 if the industry meets its manufacturing plant announcement goals and partners with suppliers to fabricate and assemble components for initial offshore wind projects. The high demand for a trained workforce in the early 2020s suggests that there is an immediate need for training in the appropriate job categories (Matt Shields, Frank Oteri, and Jeremy Stefek, n.d.).

Nacelle production has the potential to create the highest demand for jobs in the offshore wind sector, particularly through the fabrication and assembly of costly and labor-intensive subcomponents such as generators, gearboxes, and power converters. Fabrication of monopiles, towers, and rotor blades provide the next highest opportunities for job creation. For land-based wind turbines, historically most of the equipment internal to the nacelle has been imported and then assembled into the nacelles in the United States (U.S. Department of Energy 2019). BloombergNEF estimates that in 2020, the United States had 12 GW of nacelle manufacturing capacity (Goldie-Scot, Zindler, and Wang 2021).

The wind industry comprises a diverse workforce, requiring 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 oversee the plant-level workers and include 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 typically are supervisor and technician roles that ensure the plant is operating by performing preventative and corrective maintenance.

State-level requirements through project labor agreements have signaled the need for the offshore wind industry to support domestic workforce and training programs. Community colleges and labor unions are often well placed 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 in the context of project labor agreements will help facilitate development of workforce in specific opportunities such as manufacturing facilities (Matt Shields, Frank Oteri, and Jeremy Stefek, n.d.).

## 2.2 Resilience of Current U.S. Wind Industry Supply Chain

The following summary provides **a snapshot** of the current U.S. wind industry supply chain. More detailed discussion can be found in the following sections: U.S. production capabilities (Section 2.1 and Section 3) and workforce (Section 2.1.7).

### 2.2.1 Strengths

U.S. wind industry strengths include:

- The capability to manufacture and assemble many land-based turbine components, including towers, foundations, nacelle assembly, specific nacelle and blade subcomponents, certain processed materials including steel
- Domestic availability of raw materials
- Capacity to recycle wind components/materials (except blades)
- A robust global supply chain for most components and materials, which can absorb short-term shocks in U.S. wind energy demand.

The United States also has innovation potential to expand U.S. supply chain production via advancements in advanced manufacturing methods, new materials advancements, and new turbine/plant designs.

#### 2.2.2 Weaknesses and Vulnerabilities

U.S. wind industry weaknesses and vulnerabilities include:

- A lack of demand certainty in the wind energy project pipeline provides limited motivation for new supply chain investments; near-term domestic manufacturing capacity may even contract due to forecast reductions in annual installations in 2022 and 2023.
- There is a lack of domestic supply chain capacity in a few components and materials (specifically semiconductors, rare earth elements, carbon fiber, metal castings, and specific nacelle components), especially for offshore wind.
- Shortages of rare-earth magnets and fundamental commodity price risks could disrupt supply chain activities, erode U.S. competitiveness, and jeopardize deployment ambitions.
- There is a need to scale up and commercialize wind turbine recycling, especially for blades (glass and carbon fibers).
- Overseas competitors with low labor costs threaten U.S. supplier competitiveness, especially for labor-intensive operations such as blade manufacturing.
- Expected new workforce demand to serve the Administration's goals is likely in the hundreds of thousands. Additional education and training programs are expected to be necessary; scenarios range from several hundred new programs to more than 1,000.
- Retooling existing manufacturing facilities as turbine size increases will be required.
- Technology evolution, including increasingly larger wind turbine components, drives the need for facility upgrades and retooling and compounds difficult transportation hurdles.

Innovation potential could address weaknesses by designing alternatives that do not require non-allied sourcing, especially in regard to using rare earth elements, responsibly producing carbon fiber with international labor and safety standards and advancing U.S. wind blade recycling technologies. At the same time and all else equal, innovation in modularizing large wind industry components could impact U.S. competitiveness by reducing or eliminating transportation barriers that limit the economic viability of importing some components from foreign sources. See Section 3 for a complete discussion of supply chain risk assessment.

## 2.3 Key Global Players and U.S. Competitiveness

#### 2.3.1 Land-Based Wind

The United States is one of only five countries that can produce all major components contained in a wind turbine. The other four countries are China, India, Spain, and Germany. The United States commissioned more than 9 GW of wind capacity in 2019 but imported less than 400 MW in wind turbine generating sets (assembled nacelles, blades, hubs, and associated electronics) that year. Nonetheless, although the United States has the capability to manufacture certain volumes of each major component, it relies on other nations for supplies of specific subcomponents, as well as processed and raw materials, that are not domestically available.

Three primary OEMs serve U.S. markets: GE, Siemens Gamesa Renewable Energy, and Vestas. All have significant operations and manufacturing capacity in the United States. Nordex Acciona also supplies a significant number of turbines to the United States, with little domestic manufacturing presence. China has many OEMs, but almost all of their products go to the Chinese market (an exception is Goldwind, with a small U.S. market share) (Barla 2021b).

The United States is currently competitive in production of towers, foundations, nacelle assembly, specific nacelle and blade subcomponents, certain processed materials including steel, certain raw materials, and U.S. recycling capacity.

U.S.-manufactured towers are seeing some pressure from low-cost imports from Asian markets (Indonesia, South Korea, Vietnam, India).[2] The cost of steel is a major driver of the cost of the tower, but around 20% of the cost is labor (i.e., rolling, welding, assembling are labor-intensive processes) (Indra Mukherjee, Samantha Bobo 2021; Fullenkamp and Holody 2014). The United States is also currently losing competitiveness for U.S. blade production; new blade factories are located in Mexico and Europe (Indra Mukherjee, Samantha Bobo 2021). India continues to attract foreign investments in the wind industry supply chain due to factors including trade tensions with China, low manufacturing costs, and lower labor costs than China (Barla 2021a).

### 2.3.2 Offshore Wind

The United States is not competitive for producing offshore wind components such as large forgings and castings and large steel plates for monopile foundation production.[3] Another competitive challenge for the United States is access to vessels. Coastwise qualified installation vessels are under construction; for example, Dominion Energy is constructing one at a shipyard in Texas that should be available to support the U.S. offshore wind industry by 2023 (Dominion Energy 2020). Offshore wind supply chain hubs are located in Europe, Taiwan, and China. European developers are lending their experience and capital to U.S. development, partnering with U.S.-based companies or oil and gas players to secure leases and build these projects. Some analysts point to a knowledge transfer from Europe to North America with a similar potential to transfer manufacturing capability (Indra Mukherjee, Samantha Bobo Woodworth 2021). However, because large offshore wind components must be transported by water, offshore wind projects can be supplied by mature European supply chains, resulting in barriers to establishing a domestic supply chain (Musial et al. 2021). States are proving to be drivers for domestic manufacturing; a willingness to invest in these facilities can be partially attributed to the local content requirements imposed by individual states as part of the power offtake agreements (Shields et al. 2022).

## 2.4 Policies and Incentives Implemented by Leading Nations

Leading nations have implemented national policies and incentives to support their domestic industries, intellectual property, etc., and these policies can affect the U.S. domestic supply chain and related decisions. The following provides a few examples:

- The government of China has several protective policies in place; for example, it provides seed money to support high-tech companies such as semiconductor manufacturers. The association of European Union steelmakers has urged stronger enforcement of trade remedy laws against China trade, claiming that "the Chinese government has created cost advantages for Chinese firms through subsidies, preferential loans, debt forgiveness, and by lowering the level of labor rights and labor and environmental standards" (Capital Trade Incorporated n.d.). In recent years, the Chinese government has limited exports of rare earth elements to the United States and increased tariffs (Lu, Sophie 2020).
- "Dumping" is defined as a foreign company selling a product in another nation at less than its fair value. Members of the World Trade Organization adhere to rules surrounding this practice. In January 2020,

[2] Note that the United States has antidumping and countervailing duties orders in place on utility-scale wind towers imported from China, Vietnam, Canada, Indonesia, Korea, India, Spain, and Malaysia.
[3] Large forgings and castings for land-based wind turbines are also not currently competitive in the U.S.

the Department of Commerce announced results of its antidumping duty investigations of imports of fabricated structural steel from Canada, China, and Mexico, and its countervailing duty investigations of fabricated structural steel imports from China and Mexico. The Department confirmed dumping (U.S. Department of Commerce n.d.). Steel dumping affects tower and metal castings. Many nations, including the United States, utilize antidumping/countervailing duties and other tariffs to protect their domestic investments in manufacturing against unfair foreign competition.

- The European Union "Fit for 55" package of proposed legislation includes renewable energy requirements and a carbon border adjustment mechanism to protect European Union manufacturing capacity (Council of the EU and the European Council 2021).

# 3 Supply Chain Risk Assessment

Section 3.1 explores current vulnerabilities and risks, divided into land-based and offshore sectors where applicable. Section 3.2 explores anticipated vulnerabilities and risks over the next decade. Section 3.3 concludes with a summary of the most crucial vulnerabilities for the United States to address.

Several wind energy supply chain research efforts are currently underway at NREL on behalf of DOE. In support of NREL's upcoming 30 GW by 2030: A Supply Chain Roadmap for Offshore Wind in the United States report, researchers have interviewed internal and external subject matter experts, OEMs, and offshore wind turbine component manufacturers. The aggregated results of these interviews are also incorporated into this analysis.

## 3.1 Current Vulnerabilities and Risks

**Lack of certainty in the forward wind project pipeline due to policy instability threatens both the current U.S. supply chain and its ability to expand rapidly.** Supply chain investments—including additional production lines, re-tooling, new facilities, and qualifying new suppliers—are dependent on expected capital recovery over the amortized life of the capital expenditure. Investments needed to serve the Administration's goals are contingent on a certainty level that meets investors' risk threshold for new capital expenditures.

*Land-based wind unique risks:* Historically, frequent changes and even lapses of the PTC[4] have resulted in volatility in demand for new wind projects, with consequent risk for suppliers. Despite recent short-term extensions of the PTC and ITC, wind OEMs state that they currently anticipate a supply chain contraction in 2022-2023 as a result of current PTC deadlines. Current policy proposals to extend the PTC could even exacerbate this risk in the near term by reducing the urgency to deploy projects now.

*Offshore wind unique risks:* Although the federal ITC helps buy down the cost of offshore wind, demand for

[4] Established in 1992, the Production Tax Credit (PTC) is a federal incentive, found in Section 45 of the U.S. tax code (United States Environmental Protection Agency 2021) for alternative energy investments that has spurred demand for wind turbines. The PTC provides a tax credit of 1¢–2¢ per kilowatt-hour for the first 10 years of electricity generation for utility-scale wind. The alternative Investment Tax Credit (ITC), identified in the Internal Revenue Service Code 48 (Congressional Research Service 2021), provides a credit for 12%–30% of investment costs at the start of the project and is especially significant for the offshore and distributed wind sectors because such projects are more capital-intensive and benefit from the up-front tax benefits (U.S. Department of Energy 2020). In December 2020, Congress passed extensions of the PTC and ITC for 1 year (U.S. Energy Information Administration 2021b). Additionally, Congress established a 30% ITC for any offshore wind project that begins construction by December 31, 2025 or began construction before January 1, 2017 (Congressional Research Service 2021).

offshore wind has been driven by state-by-state policy commitments, with competing state-level content requirements. This fragmentation may not provide the requisite certainty to support supply chain investment at the pace and scale required to meet state and federal goals without heavy dependence on foreign suppliers.

**Overseas competitors' low labor costs threaten labor-intensive domestic supply chain operations, particularly blade manufacturing.** Suppliers report that low labor costs in competing markets are rendering domestic manufacturing of blades uncompetitive with foreign markets. Further, they report that skilled labor for these operations is in short supply and that attrition is high.

*Land-based wind unique risks:* OEMs report that reductions in labor content of up to 50% or more may be required for U.S.-manufactured blades to remain competitive with blades manufactured abroad. OEM representatives also cite a shortage of skilled transportation workers who can operate the machinery and vehicles needed to safely transport components to project sites.

*Offshore wind unique risks:* Overseas competitors' low labor costs could impact whether OEMs choose to domestically source labor-intensive components like blades and towers or choose to expand component production in these markets with lower-cost labor. This could result in near-term and long-term decreased potential for domestic workforce and domestic content levels related to offshore wind component manufacturing in the United States. Labor costs could also impact the demand for Jones Act-compliant offshore wind vessels for installation and maintenance.

**The size of wind components is pushing the limits of domestic logistics.** Safely transporting large components from production sites and ports to inland and offshore project sites requires extremely exacting logistics and is increasingly burdened by fragmentation in state and local permitting. Offshore wind turbine components (blades, towers, foundations, and nacelles) are especially large and require transport by water, which makes the use of mature European supply chains to supply U.S. projects relatively competitive and poses barriers to developing domestic manufacturing.

*Land-based wind unique risks:* While the sheer size of wind components provides some protection from offshoring, current blades, towers, and nacelles are becoming too large to efficiently transport over existing road and rail networks. Transportation routes, permits, and escorts to project sites must be planned and secured; both administrative and physical bottlenecks are common. This increases cost, limits potential throughput, and is driving technological change such as modularization (see below), which could erode the competitiveness of U.S. component manufacturing. Turbine components, particularly blades, are also becoming too large to be produced in current domestic facilities and expanding production in foreign facilities already capable of producing the largest components may prove more attractive than investing in new domestic production.

*Offshore wind unique risks:* Because large components must be transported by water in any case, offshore wind projects can be readily supplied by mature European supply chains, resulting in barriers to establishing a domestic supply chain. As well, global demand for a limited supply of wind turbine installation vessels is high; only three are capable of installing a 12-MW-plus turbine in >50-m water depths, and this demand is a major cause of project risk and motivates additional vessel construction. U.S. vessel supply is complicated by increased risk and cost associated with the requirements of the Jones Act. As of August 2021, one Jones Act-compliant wind turbine installation vessel is being constructed in the United States and plans for a second were announced to support the domestic offshore wind energy industry (Musial et al. 2021). Additionally, Jones-

Act-compliant feeder vessels may be used to transport large components from ports to wind power plants for installation by either Jones-Act or non-Jones-Act installation vessels that remain on-site.

**Consolidation of supply of key components outside the United States presents barriers to a vertically integrated domestic supply chain.** Some wind energy components, subassemblies, and subcomponents require established supply chain structures or specialized manufacturing experience, facilities, or equipment that do not exist in the United States and may only be available from a limited number of global suppliers.

*Land-based wind unique risks:* Large castings critical to wind turbine hubs and nacelle internals are not manufactured in the United States due to the environmental impact of the foundries that produce them; the number of foundries that can produce these components is limited globally. Investment in additive and advanced manufacturing may mitigate these risks but commercialization of these technologies is likely years into the future.

*Offshore wind unique risks:* In addition to issues with castings mentioned above, the complexity of the manufacturing process, size of the components, and existing clusters of subcomponent suppliers limit the ability of existing U.S. manufacturers to have the experience, facilities, and equipment necessary to assemble or fabricate many essential offshore wind components. Bearings, hubs, flanges, and steel plate are subcomponents that have similar requirements. For example, expert interviews indicate that no U.S. supplier can currently produce steel plate to the dimensions required for offshore monopile foundation fabrication. The supply of generators, gearboxes, microchips, and substations also currently depends on experienced foreign manufacturers. These companies typically rely on their own existing supply chain structures, which may make it easier to expand existing facilities rather than establish new U.S. facilities.

**Tariffs and other barriers to foreign trade can impact the supply chain.** Although many trade policy actions are conducted pursuant to specific authorities and designed to remedy injury to domestic industry and respond to unfair or unreasonable foreign trade practices, tariffs on wind turbine components and raw materials and wind tower imports affect both the land-based and offshore wind supply chains. Analysis indicates that imposing tariffs of 25% on blades, gearboxes, and generators would delay cost parity with new natural gas power plants by 3 years (Goldie-Scot, Zindler, and Lezcano 2021).[5]

Supply hubs are emerging in India and Mexico. These markets can provide an alternative to trade with nations more heavily impacted by tariffs.

**Critical materials and subcomponents are in high demand across multiple industries and can be sourced from a limited number of suppliers.** In some cases, high-vulnerability production risks exist due to reliance on foreign suppliers (some of which may not be U.S. allies) with geographic concentration. Single-source providers or processors can leave the United States vulnerable to ongoing or future supply chain breakdowns related to pandemics, climate change, and other workforce disruptions and potentially jeopardize U.S. deployment goals.

Limited or vulnerable supply of specific raw materials and subcomponents affects land-based and offshore wind projects. As discussed in Section 2.1, critical materials and subcomponents that are sourced from a

[5] It should be noted that anti-dumping/countervailing duties and other tariffs can be beneficial to the U.S. domestic supply chain by protecting domestic investments in manufacturing against unfair foreign competition, including illegal dumping and foreign subsidies.

limited number of suppliers, many of which are not domestic, include rare earth elements, gearboxes, large castings, forged rings and shafts, semiconductors, fiber-reinforced composites, polymers, steel alloying elements, and balsa wood.

## 3.2 Anticipated Vulnerabilities and Risks over the Next Decade

**Balancing of global supply chain utilization to rapidly meet increased near-term demand against domestic supply chain buildout to maximize U.S. content in the long term is likely to be difficult.** The Administration's ambitions to rapidly accelerate deployment and maximize U.S. economic return on investment could potentially conflict, introducing uncertainty and delaying actions that are necessary to serve both objectives. Domestic demand peaks are currently accommodated by the excess capacity of the global supply chain, typically by increasing wind turbine component imports. In the near term, global supply capacity may be the quickest means to serve the Administration's deployment goals; however, over the long term, domestic assets may be the best means to ensure the sustained high deployment levels needed to serve the Administration's goals. Maximizing deployment and U.S. benefits will require an intentional optimization strategy and tactics.

*Land-based wind unique risks:* New demand in multiple markets around the world could create the potential for supplier competition that can increase project costs and impact domestic goals. At the same time, the Administration's goals require urgent and significant deployment increases even as manufacturing facilities may take years to upgrade or site and build new facilities. Existing facilities need re-investment for state-of-the-art technology, and substantial new capacity is presumed to be critical to serve the Administration's goals.

*Offshore wind unique risks:* Over the past year, ambitious offshore wind deployment targets in the United States, Europe, and other parts of the world have created concerns related to the current manufacturing capacity of the global offshore wind supply chain and how it will be able to respond to increased global and domestic demand. Domestically, investment is needed across all facets of the supply chain including not only factories, but also port facilities for staging and construction, as well as vessels that can install and maintain offshore wind power plants in the United States.

**Anticipated scale increases to meet the Administration's goals will compound existing vulnerabilities.** Expected future demand to meet the Administration's goals could require deployment at levels of 25 GW to 30 GW per year or more (United States Department of State and United States Executive Office of the President 2021); this equates to two to three times the average of the past five years (2016-2020) and would significantly exacerbate current vulnerabilities. The scale challenges are significant for both land-based and offshore wind applications.

*Land-based wind unique risks:* New facilities designed to produce state-of-the-art technology of today will be required in existing and future market regions. New manufacturing methods and technologies could bolster the economic positioning of U.S. manufacturing but need continued R&D to be commercialized. Current strains on critical materials including rare earth elements, other specialized materials such as balsa wood, as well as price pressures on commodities more generally, will be impacted by the anticipated increase in demand.

*Offshore wind unique risks:* Manufacturing capacity for offshore wind is largely non-existent in the United States today. Investments in Tier 1 components (blades, towers, foundations, nacelle assembly) are needed as well as investments throughout the supply chain and inclusive of ports, vessels, and other supporting industries. A mature U.S. supply chain will help reduce project risk and costs and provide local economic benefits to support the existing deployment pipeline; however, the timeline for developing these capabilities and infrastructure is not clear, which introduces uncertainty into the planning process for individual projects and may encourage developers to rely on international sources.

**Expected new workforce demand to serve the Administration's goals is likely in the hundreds of thousands; U.S. labor costs could put U.S. suppliers at a relative cost disadvantage.** Additional education and training programs are expected to be necessary; scenarios range from several hundred new programs to more than 1,000.

*Land-based wind unique risks:* Workers will be needed to support manufacturing, construction, operations, and even decommissioning and repowering. Wind industry skillsets are unique and not readily transferred from other industries. Moreover, construction and operations needs may be located in remote locations far from existing skilled workforce locations. According to blade OEMs, a 50% reduction in labor content may be needed to remain competitive with foreign suppliers.

*Offshore wind unique risks:* While proximate to major population centers, the offshore wind industry supply chain also entails significant novel and unique skillsets. Re-training workers for offshore wind facilities, construction, and servicing is critical. Developing a cost-competitive workforce relative to global manufacturing alternatives is also a risk. Water transport makes labor-intensive components relatively easy to supply from abroad.

**Modular components developed to reduce transportation burdens and barriers may erode the economic basis for U.S. manufacturing, especially in labor-intensive applications such as blade manufacturing.** Component transport is a significant current supply chain challenge. As innovators seek to address this challenge through modularity, it may create opportunities to utilize lower-cost global manufacturing locations to serve U.S. and global demand. The speed of change complicates investment decisions (e.g., step changes in turbine size could render even new facilities obsolete).

*Land-based wind unique risks:* This issue is of particularly acute risk to land-based wind manufacturing due to the need to ship components from ports or facilities to project sites.

*Offshore wind unique risks:* While this is arguably less of a concern for offshore components, which are often manufactured in locations where they can easily be transferred to ships for transport to project site, innovations motivated by land-based wind such as segmented blades or other large components and applied to offshore wind could drive the same risk, eroding the economic motivation for U.S. manufacturing.

## 3.3 Most Crucial Vulnerabilities for the United States to Address

Research conducted to date reveals strong consistency regarding the following most crucial vulnerabilities for the U.S. to address:

- A lack of demand certainty in the wind energy project pipeline provides limited motivation for new supply chain investments; near-term domestic manufacturing capacity may even contract due to forecast reductions in annual installations in 2022 and 2023.
- Low labor costs from overseas competitors threaten U.S. supplier competitiveness, especially for labor-intensive operations such as blade manufacturing.
- Logistics networks for land-based wind turbine components are increasingly strained due to the increasing size of components; offshore wind component logistics require specialized infrastructure, particularly ports and vessels, that do not yet exist in the United States.

- Technology evolution, including increasingly larger wind turbine components, drives the need for facility upgrades and retooling and compounds difficult transportation hurdles; innovative solutions such as modularity could erode U.S. competitiveness by facilitating transportation of components from lower-cost global manufacturing regions.
- Shortages of rare-earth magnets and fundamental commodity price risks could disrupt supply chain activities, erode U.S. competitiveness, and jeopardize deployment ambitions. Offshore wind projects would be most impacted by rare-earth magnet shortages, but all wind applications would be impacted by commodity price risk.
- Expected new workforce demand to serve the Administration's goals is likely in the hundreds of thousands. Additional education and training programs are expected to be necessary; scenarios range from several hundred new programs to more than 1,000. Re-training workers for offshore wind facilities, construction, and servicing is critical.

# 4 U.S. Opportunities and Challenges

Primary component production (e.g., towers, blades, nacelles, foundations, electrical equipment) represents one of the most significant U.S. supply chain opportunities for wind energy. Although the opportunities are somewhat distinct for offshore and land-based wind, it is the scale of the required investment across both sectors that is perhaps the single largest opportunity and challenge.

The Administration's national **offshore wind** target represents an opportunity for the United States to establish a new domestic industry, with a possible average of $942 million to $3,800 million per year injected into the U.S. economy. Specific gross domestic product impacts depend on the level of domestic content, with greater expansion of the supply chain leading to larger effects on the economy. Investing in a domestic offshore wind supply chain also allows an opportunity to reduce risk and logistical complexities associated with sourcing components internationally (Shields et al. 2022).

Taking advantage of these opportunities for offshore wind would require mobilization of significant investment to establish the domestic supply chain for offshore wind turbine components (blades, nacelles, and towers for wind turbines with capacities of 10 MW and larger) and offshore substructures and to leverage existing businesses to provide subcomponents. Moreover, developing the necessary port and vessel infrastructure to support this nascent industry is critical. Developing a skilled workforce for the manufacturing, construction, and transportation sectors will also be needed.

Opportunities for **land-based wind** include economic development and jobs, as well as a reduced reliance on importing resources from European or Asian markets. Taking advantage of these opportunities would also require a massive expansion of manufacturing to scale to meet the Administration's objectives and developing new transportation and assembly solutions to ease logistics as turbine sizes increase.

Further detail on opportunities (Section 4.1) and challenges (Section 4.2) is provided in the following sections.

## 4.1 Opportunities

### 4.1.1 Establish Offshore Wind Tier 1 Supply Chain

Tier 1 components are the finished, major products that are purchased by an offshore wind project developer (i.e., towers, blades, nacelles, substructures, and grid interconnection equipment). There is no domestic offshore wind supply chain capacity in 2021 for towers, blades, nacelles, and substructures; however, several manufacturers have announced the intent to begin production at U.S. facilities in the coming years (Table 1), offering an opportunity for many new participants to enter the supply chain.[6]

The **nacelle** component has the largest theoretical potential for jobs out of all components in the offshore wind industry. In domestic nacelle assembly, domestic and imported components are assembled into complete nacelles on U.S. soil. Additional jobs would be supported through the fabrication and assembly of the many internal sub-components (e.g., generators, gearboxes, power converters), which all require and activate their individual supply chains for parts and materials.

Production of **blades** is an opportunity for transfer of skills and experience from the land-based wind market; however, blades for offshore wind turbines will likely need to be produced in sites with ocean access. The relative ease of transport from coastal locations could enable domestic facilities to export to other markets, but conversely it can also reduce the cost of imported blades. One manufacturer has announced that it will invest in a new blade production facility for offshore wind turbines in Virginia (Siemens Gamesa Renewable Energy 2021).

Another significant opportunity for jobs is related to metal fabrication of **towers** and **substructures** such as monopiles, transition pieces, and jacket foundations. Offshore wind turbine towers are typically fabricated at a single location in three flanged sections. A single offshore wind turbine tower can consist of up to 45 individually rolled plates of steel, so manufacturers will need to have the 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 (Shields et al. 2022).

There is already some domestic manufacturing of electrical equipment and cables. Between 2023 and 2030, offshore wind buildout requires an annual average of 980 miles of **electrical cable** (Lantz et al. 2021). Although these cabling and related electrical equipment needs are not a relatively large opportunity, they could be meaningful for existing domestic suppliers of electrical cables and equipment.

### 4.1.2 Maintain and Expand Land-Based Wind Tier 1 Supply Chain

Domestic content is relatively strong for larger components of land-based wind plants such as **nacelle assembly**, **towers**, and **blades**; however, domestic content in blades has declined in recent years. Three blade production facilities have recently closed, reducing domestic blade manufacturing capacity by close to 40%. Preventing blade and other component production facilities from moving offshore is a primary opportunity. At the same time, there is an opportunity to scale up the land-based wind component supply chain to support increased demand anticipated under the Administration's clean energy goals.

Many blade manufacturing facilities that were set up to produce smaller blades for an earlier generation of wind turbines may be difficult to reconfigure for larger blades. R&D investment in retooling and expanding manufacturing facilities and domestic production could help prevent future investment in foreign facilities already capable of producing the largest components. R&D investment could support the development of new polymers and resins and demonstration of blades constructed from these materials (Derek Berry 2021), as well as modularization, customization, and onsite manufacturing modes to ease transport requirements. Current R&D work conducted at DOE's NREL examines how the use of 3D printing, advanced materials, and advanced design procedures could improve the structural design of a wind turbine blade (National Renewable

[6] The status of offshore wind Tier 1 components is assessed in Section 2.1. and summarized in Table 1.

Energy Laboratory 2021). Direct printing enables new solutions that might utilize domestically sourced recyclable materials.

Approximately 30% of **towers** are imported, supplementing domestic production (Goldie-Scot, Zindler, and Wang 2021), and there is an opportunity to manufacture a greater percentage in the United States and reap the resulting economic benefits.

### 4.1.3 Develop Offshore Wind Logistics and Infrastructure

The U.S. offshore wind industry can leverage established international supply chains for installation vessels to accelerate U.S. offshore wind near-term deployments, but it also has an opportunity to build domestic capacity that can lower project risk and costs and provide local economic benefits (Musial et al. 2021). Only three wind turbine installation vessels in the world are capable of installing 12-MW or larger turbines in >50-m water depths; meeting the Administration's ambitious offshore wind goals will require additional vessels. Between 2023 and 2030, offshore wind buildout to meet the 30 GW by 2030 scenario will require annual averages of four to six turbine installation vessels operating in U.S. waters. As many as nine turbine installation vessels could be required to support U.S. offshore wind construction and operation from 2041 to 2050 (Lantz et al. 2021). Building vessels in the United States would create new domestic employment, address the logistics challenge of the Jones Act, and would help developers of U.S. offshore wind projects avoid bottlenecks and associated risks to the Administration's 30 GW by 2030 target (Shields et al. 2022).

The nascent offshore wind industry will also require ports that are capable of supporting installation, operations, and maintenance. Between 2023 and 2030, offshore wind buildout to meet the 30 GW by 2030 scenario will require a minimum of $375 million–$500 million in port upgrades beyond current plans. Extending the scenario to 110 GW of offshore capacity in 2050 could require minimum port upgrades as high as $3.1 billion from 2041 to 2050 (Lantz et al. 2021). With most large offshore wind components expected to be transported by water, there are opportunities to bring new manufacturing facilities to ports, illustrated by the list of announced facilities in Table 1. To handle large offshore wind components, most existing East Coast ports would need to increase the load-bearing capacity of their quayside and laydown areas and may need to dredge berths to greater depths to accommodate the largest wind turbine installation vessels (Shields et al. 2022). All of these activities would contribute jobs and related economic development to the U.S. economy.

### 4.1.4 Expand Domestic Manufacturing of Composite Materials

Glass or carbon **fiber-reinforced composites** are the primary materials used in wind turbine blades, and fiberglass is also used for the nacelle cover. Analysts project that demand for carbon fiber for wind turbines will triple by 2027 (Barla 2021a). There is some domestic manufacturing of both glass and carbon fiber-reinforced composites. Continued growth in domestic capabilities could benefit from synergies with research and development activities into novel composite materials or advanced manufacturing techniques for wind energy applications.

### 4.1.5 Improve Competitiveness Through R&D

Wind technology R&D could increase the competitiveness of the U.S. supply chain for **offshore and land-based** components, subcomponents, and processed and raw materials. Investing in R&D would offer U.S. suppliers insights and experience in the emerging state-of-the-art, fostering their ability to prepare and plan for scaling. Such research would also result in domestic intellectual property development, accelerate clean energy deployment, and fundamentally alter U.S. competitiveness at home and in the global wind energy market. In areas, such as large castings and forgings, R&D would have benefits beyond wind—for example, both hydropower and nuclear energy require large castings that cannot currently be produced in the United States. Federal RD&D investment in wind technology could be particularly beneficial in areas such as alternative manufacturing methods or production facilities for materials and components from single-source providers or processors. This would reduce or eliminate the risk of single points of failure in the U.S. wind energy supply. Specific areas where supplemental federal RD&D investment in wind technology could be particularly beneficial include:

- Automation and other advancements in blade manufacturing to reduce the quantity and increase the productivity of labor content
- Modularization, customization, and onsite manufacturing to ease transport requirements
- Advancements in additive manufacturing for components such as hubs and nacelle bedplates to replace traditional large casting and forging methods, which have significant environmental impacts and take place predominantly in foreign foundries
- Development of alternative manufacturing methods or production facilities for materials and components from single-source providers or processors to avoid leaving the nation vulnerable to ongoing or future supply chain breakdowns
- Development of alternative designs to decrease or eliminate dependencies on rare earth elements and other critical and strategic minerals and materials
- Development of new polymers and resins and demonstration of new blade designs constructed from these materials.

## 4.2 Challenges

### 4.2.1 Pivoting Existing Applicable Suppliers to Offshore Wind Tier 1 Needs

Apart from the sheer scale of investment in component production and fabrication to advance from a nascent industry to the supplier for a major global market, several tactical challenges deserve consideration. One challenge to consider includes the capacity of existing domestic suppliers to pivot to the offshore wind industry; this potential is not well understood at present, but manufacturing lines for primary wind turbine components are not typically able to transition from land-based to offshore turbines due to differences in size and scale between these turbine types. The land-based wind supply chain is not located in the Northeast, where most near-term offshore opportunities exist. In addition, local content requirements currently employed by states to encourage in-state supply chain development are often not designed to incentivize collaborative solutions that involve multiple states. This can lead to compartmentalized and suboptimal development of the supply chain (Shields et al. 2022).

### 4.2.2 Establishing Training Programs to Support an Expanded Workforce

Finding and training workers with a wide range of specialized skills for building and maintaining wind energy facilities is a critical challenge. Wind-related job totals in the United States reached 116,800 full-time workers in 2020 (Wiser et al. 2021). Increasing annual land-based wind deployment by a factor of two or more will require training and development for a range of professions including design, installation, operations and maintenance, component and subcomponent manufacturing and assembly, and materials production. Projections for the next ten years indicate that offshore wind could support between 10,500 and 42,500 domestic full-time equivalent jobs (Shields et al. 2022). These require diverse skillsets including machining, welding, design, engineering, and management, as well as working at heights and in marine environments. Additional education and training programs are expected to be necessary to prepare or retrain workers with the needed skills; scenarios range from several hundred new programs to more than a thousand.

### 4.2.3 Improving Land-Based Wind Logistics

As discussed throughout this report, the size of wind components is pushing the limits of domestic logistics for land-based wind projects. Current blades, towers, and nacelles are becoming too large to efficiently transport over existing road and rail networks, and moving components is further challenged by highly fragmented state and local permitting requirements. Innovation based solutions along with policy and regulatory solutions could reduce the challenges presented by overland transport of these components.

### 4.2.4 Fostering U.S. Competitiveness in Subcomponent Manufacturing

Subcomponents are often produced by suppliers who specialize in a specific technique or material with applications across various industries. As wind turbines have evolved (notably, by becoming larger) the requirements for some subcomponents are diverging from other sectors (e.g., automotive); however, individual suppliers may not have the resources to invest in developing new capacity to support the wind industry alone.

Wind subcomponents for land-based wind are manufactured by a mix of domestic producers and producers in allied and non-allied nations. As supply chains for U.S. offshore wind are being established, it is possible that domestic suppliers for land-based wind—or relevant industries such as aerospace and shipbuilding—can leverage their existing capabilities to support this new sector. If domestic supply chains do not emerge, offshore wind developers would rely on international supply chains for specialized subcomponents. Greater domestic manufacturing of **generators, gearboxes, bearings,** and **semiconductors** would result in jobs and economic development. Investing in semiconductor manufacturing could serve to secure multiple additional supply chains that depend on this subcomponent, including smartphones, autonomous electric vehicles, 5G, and artificial intelligence (Antonio Varas, Raj Varadarajan, Jimmy Goodrich, Falan Yinug 2021).

**Forged rings and shafts** are used in several components, including the main generator shaft, tower flanges, and forged rings for the yaw, pitch, and main bearings. Forged rings for wind turbines have been produced in the United States, but this industry segment has lost market share to foreign producers (Fullenkamp and Holody 2014). Currently, there is no domestic production of bearings with diameters greater than 4 m (yaw bearings) and 6 m (pitch bearings) for offshore wind turbines (Shields et al. 2022).

**Large castings** include the rotor hub and the nacelle bedplate (also called the support frame). There is limited manufacturing capability and no serial production of large castings in the United States due to the environmental impact of the foundries that produce them (Fullenkamp and Holody 2014). Given the macro-economic and regulatory challenges that have pushed manufacturing of these subcomponents out of the U.S., a key challenge to bringing new capacity in this part of the supply chain to the U.S. is innovating new methods for producing large castings. R&D investment in additive and advanced manufacturing may help to mitigate these risks, but commercialization of these technologies is likely to be years in the future.

### 4.2.5 Addressing Processed Materials Challenges

Key challenges for processed materials used in wind turbines include ensuring a robust supply chain from domestic and allied sources, lowering costs, and reducing the environmental burden of materials production. Research, development, and deployment of novel production methods for key materials could address each of these challenges.

**Steel:** Steel represents approximately three-quarters of a wind turbine's total mass and is also the primary material in most offshore wind substructures. Wind turbine prices are sensitive to steel commodity prices, which are driven by demand from various industries. There is significant domestic production of steel, with imports representing 12% of U.S. consumption in 2019 and 2020 (USGS 2021). Deviations in prices for U.S. steel compared with global averages could affect the level of domestic content in the supply chain. Certain specialty steels used in wind turbines, such as grain-oriented electrical steel, have limited domestic production. Emissions associated with steel production are significant, which presents a challenge for increasing steel productions in regions with more stringent emissions controls. This challenge could be addressed by "green" steel (e.g., electrification of production processes and use of renewably-sourced hydrogen (Blank 2019)).

**Rare earth magnets:** The majority of offshore wind turbines and a small percentage of land-based wind turbines use permanent magnet generators. While rare earth elements are required for permanent magnet generators, they are not mined in the United States in sufficient quantities to meet the demand for offshore wind drivetrains and other uses. Analysts forecast that demand for rare earths in wind turbine manufacturing will triple by 2029 (Goldie-Scot, Zindler, and Wang 2021). If demand for other rare earth elements does not increase at the same rate, there may be little economic motivation to increase production of the elements needed for wind turbines. Although there have been efforts to establish domestic rare earth mining operations, there is also a lack of facilities that can process these materials into permanent magnets that are large enough for wind turbine generators. As a result, permanent magnets are primarily produced in China (AMO 2020).

In 2019, the U.S. Department of Commerce published a report outlining a federal strategy to ensure supplies of critical minerals, including rare earths. Recommendations to address vulnerabilities include increasing domestic exploration, production, recycling, reprocessing, industry incentives, and R&D investments (U.S. Department of Commerce 2019). More recently, in September 2021, the Commerce Department initiated an investigation to determine the effects on U.S. national security from imports of Neodymium-iron-boron (NdFeB) permanent magnets, which are used in wind turbines as well as, for example, fighter aircraft and missile guidance systems (U.S. Department of Commerce 2021). See Section 2.1.4 for more discussion of rare earth elements in wind turbines.

**Concrete:** Domestic supply chains are able to meet demand for concrete in wind plants, but greenhouse gas emissions associated with concrete production (primarily from cement) are significant. Researchers are investigating methods to produce "green" concrete based on alternative cementitious materials, which include fiberglass from end-of-life wind turbine blades as well as other materials such as fly ash.

**Semiconductors:** As discussed in Section 3.1.2, U.S. dependence on foreign-made semiconductors is a big issue, not just for the wind energy industry. The Congressional Research Service published a report in 2020 that listed the following possible solutions to addressing this domestic supply chain vulnerability: investments in R&D, including through the use of public-private partnerships; grants and tax benefits for establishing domestic production capacity; support for investments in science, technology, engineering, and mathematics (STEM) education and skills training related to semiconductor design and fabrication; investments in the development of manufacturing machinery; and investments in semiconductor industry infrastructure (Congressional Research Service 2020).

## 4.3 Opportunities for Private Sector Collaboration

Private sector collaboration can take various forms. Conceptual themes that would support private sector collaboration include public private partnerships and financing for facility or infrastructure investment. The following are examples of specific opportunities for private sector collaboration:

- **Increasing the skilled workforce through wind-specific training and development.** Cooperation between wind energy component manufacturers, wind developers, community colleges, and labor unions can address key educational and training requirements for the wind industry.

- **Developing port facilities and vessels to support the offshore wind industry.** Collaboration with the private sector can bring wind component manufacturing facilities to ports, support redevelopment of existing ports, and leverage existing shipbuilding capabilities to produce Jones Act-compliant vessels for wind turbine installation and maintenance.
- **Developing alternatives to rare earth permanent magnet generators (such as superconducting magnets).** Collaboration with private industry will be required to commercialize alternatives.
- **Developing and commercializing additive manufacturing of large iron and steel castings and forgings, such as rotor hubs and nacelle bedplates.** These components are not currently produced in the United States due to the cost and environmental impact of associated foundries. Additive manufacturing of these components represents a significant leadership opportunity for the United States--for the iron and steel industry to meet growing global demand in wind and other energy technologies such as nuclear and hydropower, and to reduce the environmental impact associated with current processes.
- **Reversing the decline in blade manufacturing facilities in the United States.** As mentioned, domestic blade manufacturing faces challenges from increasing blade size and overseas competitors' low labor costs. Development of new blade designs and approaches to manufacturing will require collaboration with the private sector to ensure that these innovations enable new investment in domestic facilities.
- **Scaling up and commercializing wind industry recycling.** Collaboration should be possible with turbine OEMs—including Vestas (Vestas n.d.), GE (GE Renewable Energy 2020; 2021) and Siemens Gamesa (Siemens Gamesa 2021)—who have announced efforts to increase recycling of wind turbine blades.

# 5 Conclusions

Wind energy—which includes the land-based, offshore, and distributed sectors—is a cornerstone for achieving U.S. clean electricity generation objectives that include deep decarbonization and 100% clean electricity by 2035. However, several vulnerabilities exist both today and in the context of expanding to reach the Administration's decarbonization goals. Research and subject matter expert interviews reveal the following supply chain vulnerabilities for the United States:

**Current vulnerabilities:**

- Lack of certainty in the forward wind project pipeline due to policy instability threatens both the current U.S. supply chain and its ability to expand rapidly.
- Overseas competitors' low labor costs threaten labor-intensive domestic supply chain operations, particularly blade manufacturing.
- The size of wind components is pushing the limits of domestic logistics. Offshore wind component logistics require specialized infrastructure, particularly ports and vessels, that do not yet exist in the United States. The operation of foreign-flagged vessels for installation of offshore wind turbines in United States waters is limited by the Jones Act.
- Consolidation of supply of key components outside the United States presents barriers to a vertically integrated domestic supply chain.
- Tariffs and other barriers to foreign trade can impact the supply chain. Analysis indicates that raising tariffs on wind turbine components by 25% would delay cost parity with new natural gas power plants by 3 years. See Section 3.1 for a more in-depth discussion.

- Critical materials and subcomponents are in high demand across multiple industries and can be sourced from a limited number of suppliers.

**Anticipated vulnerabilities and risks over the next decade:**

- Balancing of global supply chain utilization to rapidly meet increased near-term demand with domestic supply chain buildout to maximize U.S. content in the long term will require intentional thought and action.
- Anticipated scale increases to meet the Administration's goals will compound existing vulnerabilities.
- Expected new workforce demand to serve the Administration's goals is likely in the hundreds of thousands; low labor costs in competing markets could put U.S. suppliers at a relative cost disadvantage.
- Even as the workforce is scaled to meet incremental demand, new technologies may render existing facilities and skillsets obsolete potentially before capital expenditures are recovered and workers can be retrained.
- Specifically, modular components, developed to reduce transportation burdens and barriers, may erode the economic basis for U.S. manufacturing, especially in labor-intensive applications such as blade manufacturing.

**Most crucial vulnerabilities for the United States to address:**

- A lack of demand certainty in the wind energy project pipeline provides limited motivation for new investments; near-term domestic manufacturing capacity may even contract due to forecast reductions in annual installations in 2022 and 2023.
- Overseas competitors' low labor costs threaten U.S. supplier competitiveness, especially for labor-intensive operations such as blade manufacturing.
- Logistics networks for land-based wind turbine components are increasingly strained due to the increasing size of components; offshore wind component logistics require specialized infrastructure, particularly ports and vessels, that do not yet exist in the United States. The operation of foreign-flagged vessels for installation of offshore wind turbines in United States waters is limited by the Jones Act.
- Technology evolution, including increasingly larger wind turbine components, drives the need for facility upgrades and retooling and compounds difficult transportation hurdles—lack of demand certainty complicates such upgrades; innovative solutions such as modularity could further erode U.S. competitiveness by facilitating transportation of components from lower-cost global manufacturing regions.
- Critical materials shortages and fundamental commodity price risks could disrupt supply chain activities, erode U.S. competitiveness, and jeopardize deployment ambitions. Offshore wind projects would be most likely impacted by critical materials shortages, but all wind applications would be impacted by commodity price risk.

  Expected new workforce demand to serve the Administration's goals is likely in the hundreds of thousands. Additional education and training programs are expected to be necessary; scenarios range from several hundred new programs to more than 1,000. Re-training workers for offshore wind facilities, construction, and servicing is critical.

Recommended policy actions to address the vulnerabilities and opportunities covered in this report may be found in the Department of Energy 1-year supply chain review policy strategies report, "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition." For more information, visit www.energy.gov/policy/supplychains.

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