Large Castings for Wind Turbines

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

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1 Background

Wind energy deployment in the United States is likely to increase significantly in the next decade to meet national goals for clean electricity generation and mitigating climate change. Supply chains for wind turbine components and materials will need to grow as well. Expanding supply chains may provide opportunities for U.S. manufacturers, if they are able to anticipate the changing needs of the wind energy industry. Land-based wind already has a substantial presence in the country, with approximately 136 gigawatts (GW) installed by the end of 2021, including 13.4 GW of new capacity in 2021 (Wiser et al. 2022). Meeting clean energy goals will likely require a severalfold increase in annual capacity installations. Domestic offshore wind energy is currently only present in the form of small pilot projects; however, there are 40 GW of offshore wind capacity in the leasing, permitting, and construction phases (Musial et al. 2022). Supporting this growing market will require additional supply chains to deliver components that are larger than typical land-based wind components and located in coastal regions—far from the Great Plains where current wind industry suppliers are concentrated.

Wind turbines in the United States are produced from a combination of domestic and foreign components. The share of domestic production varies between components; for example, about 70% of towers are sourced domestically, whereas only 36% of generators come from U.S. manufacturers (Baranowski et al. 2022). All large castings are currently imported; however, innovative manufacturing techniques could potentially enable the development of U.S. supply chains for these components. The environmental impacts of current casting and forging processes make it challenging to permit this type of manufacturing facility in the U.S., but novel techniques with reduced emissions would face lower barriers to entry.

The primary large cast-iron components in wind turbines are the bedplate (also called the support frame) and the rotor hub. Figure 1 illustrates how these components are connected to the wind turbine drivetrain. The bedplate is a load-bearing structural element that forms the base of the nacelle, which sits at the top of the tower and houses the generator, main shaft, and electronics. The rotor hub is in front of the nacelle, where it connects the main shaft of the drivetrain to the three rotor blades. Both the hub and nacelle are enclosed in exterior shells made of fiberglass, which improve the aerodynamics, protect workers, and provide shelter from the weather.

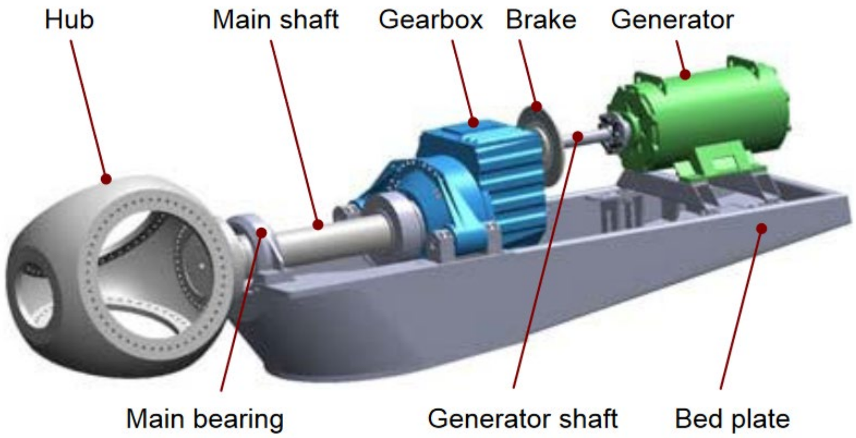

Figure 1. Schematic representation of a typical wind turbine drivetrain: three-bladed upwind rotor with gearbox and generator. ***Image created by the National Renewable Energy Laboratory (NREL)***

Rotor Hub

A complete hub assembly comprises the hub, pitch system, and spinner cover. The pitch system controls the orientation of each blade using hydraulic or electric actuators. Blades are joined to the hub via pitch bearings, which are made from high-alloy steel. Fiberglass is typically used for the spinner cover to create a lightweight, protective enclosure. The cast iron hub structure needs to be strong enough to support the weight of the rotor blades (more than 30 metric tons (t) for land-based wind turbines, and over 100 t for offshore wind turbines). Hub castings for the current generation of land-based wind turbines with rated power around 3 megawatts (MW) contain between 7 and 14 t of cast iron. Typical dimensions are a diameter of 3 to 4 meters (m) and a length of 4 m to 6 m. Offshore wind turbines rated at 8 MW or more require larger hubs, with 40–50 metric tons of cast iron and diameters close to 8 m. Future land-based and offshore wind turbines are expected to be larger than current designs.

Bedplate

Designs for wind turbine bedplates vary widely. The exterior profile can be boxy and rectangular or more curvilinear. The bedplate may consist of a single cast-iron piece, or it may be divided into a cast-iron front section that connects to the tower and supports the weight of the rotor and a steel rear section that supports the nacelle (BVG Associates 2019). This analysis focuses on cast-iron bedplates (more common for land-based wind turbines) and the cast-iron portion of multi-part bedplates (primarily offshore). Key design drivers for the bedplate are the drivetrain configuration (geared or direct drive), stiffness, and the weight and position of major components in the nacelle and rotor (Guo et al. 2015). The width of the bedplate is similar to the tower-top diameter and narrower than the maximum nacelle width of approximately 4 m for land-based wind turbines or 8 m for offshore wind turbines. Bedplates for current land-based wind turbines contain 10 to 20 t of cast iron, with current offshore wind turbine bedplates using more than 30 t of cast iron with additional structural steel.

A summary of typical dimensions for cast-iron hubs and bedplates in the current generation of wind turbines are provided in Table 1. Turbine sizes have grown significantly over the past few decades and this growth is likely to continue, so the size and weight of cast-iron components is also likely to become larger.

Table 1. Typical Dimensions and Cast-Iron Content of Current Wind Turbine Components

Technology	Component	Dimensions	Cast-Iron Mass
Land-based (3 MW)	Hub	3-4 m diameter; 4-6 m length	7-14 t
	Bedplate	Up to 4 m	10-20 t
Offshore (8 MW)	Hub	Approx. 8 m sphere	40-50 t
	Bedplate	Up to 8 m	>30 t

2 Methodology

To estimate future demand for wind turbine hubs and bedplates, we combine projections of annual capacity additions and technology evolution. Annual land-based and offshore wind capacity additions were modeled by Denholm et al. (2022) under four different scenarios that meet the target of 100% clean electricity (net-zero greenhouse gas emissions) in 2035. After 2035, the scenarios aim to achieve net-zero emissions across all sectors. These scenarios use the National Renewable Energy Laboratory's (NREL's) Regional Energy Deployment System (ReEDS) model to select least-cost options for electricity generation that account for differences in resource availability and electricity demand across regions and over time. We consider an additional scenario for offshore wind deployment to 2035, which incorporates state targets and development plans from offshore wind lease areas to arrive at a bottom-up estimate of annual capacity additions (Shields et al. 2022). Average annual capacity additions from 2025 to 2035 and 2036 to 2050 across all of these scenarios are shown in Figure 2. For context, Figure 2 also shows the range of actual annual capacity additions between 2018 and 2021 (Musial et al. 2022; Wiser et al. 2022).

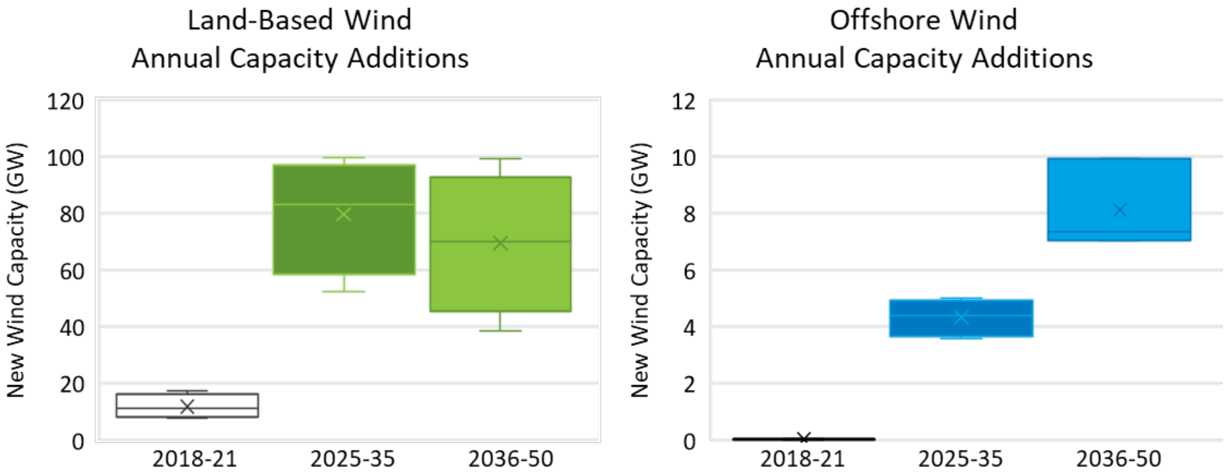

Figure 2. Range of annual land-based and offshore wind energy capacity additions between 2025 and 2050 compared with recent annual deployments. Data sources include Wiser et al. (2022), Musial et al. (2022), Denholm et al. (2022), and Shields et al. (2022).

In these box-and-whisker plots, the central horizontal line is the median and the mean is marked with an 'x'. The shaded box represents the middle two quartiles, and the whiskers extend to the upper and lower quartiles.

We use the Renewable Energy Materials Properties Database (REMPD) (Cooperman et al. 2023) to relate the annual capacity additions to the number of hubs and bedplates required each year, and the associated amount of cast iron that would be required to produce them using conventional methods. The REMPD contains information about the quantity and types of materials used in current wind power plants. It also assesses future material needs based on technology configurations from NREL's Annual Technology Baseline (NREL 2021). The rated capacity of land-based wind turbines is modeled to increase from an average of 2.8 MW in 2020 to 4.0 MW in 2030 (using a conservative estimate) or 7.0 MW in 2030 (assuming more aggressive growth). Offshore wind turbines are modeled to grow from an initial capacity of 8

MW to 12 MW or 18 MW in 2030. The total number of wind turbines installed in a year is calculated by dividing the projected annual capacity addition by the individual turbine capacity in each year. Each turbine requires one hub and one bedplate. Component weights are modeled using scaling factors from the REMPD. The REMPD reports quantities of cast iron in the hub and nacelle based on published literature and data from wind turbine manufacturers. For future scenarios, component masses are scaled based on turbine characteristics including rated power, blade length, and hub height. Mass scaling for the hub is based on Fingersh et al. (2006), whereas the nacelle mass scaling was customized for the REMPD. Across the range of wind turbines considered in this analysis, the mass of cast iron in the nacelle and bedplate depends most strongly on the rated power and is nearly constant per megawatt. This scaling does not assume that manufacturers will shift from fully cast-iron bedplates to iron and steel structures as rated power increases, which would reduce the required quantity of cast iron while increasing the demand for steel.

3 Results and Discussion

Figure 3 shows the number of hubs and bedplates required to support recent land-based wind deployment and anticipated future levels of deployment. The average annual demand in 2025-2035 is roughly triple the current annual demand. Between 2036 and 2050, the number of hubs and bedplates is projected to go down to approximately 10,000 per year. The amount of cast iron contained in these components rises from the current level of 100 million kilograms per year to between 500 and 700 million kilograms per year throughout the study period. This analysis is predicated on the assumption that there are no major changes to the design or manufacture of cast-iron components, so the amount of cast iron grows in tandem with the annual capacity additions. The number of units declines more sharply between 2036 and 2050 because the individual components are expected to become larger.

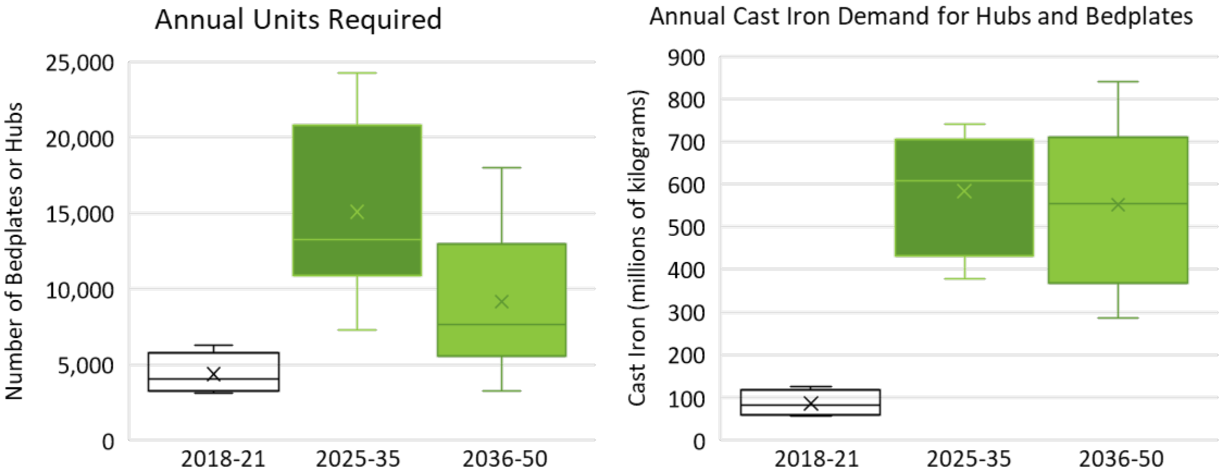

Figure 3. Range of current and projected future annual demand for hubs and bedplates and associated cast-iron content for land-based wind energy

Figure 4 shows projected growth in demand for hubs, bedplates, and cast iron for offshore wind energy. No large cast-iron components have been produced in the United States for offshore wind turbines to date. Between 2025 and 2035, demand reaches approximately 300 units per year, growing to around 400 units per year through 2050. Annual material demand increases more steeply, from approximately 30 million kilograms per year in 2025-2030 to nearly 60 million kilograms per year through 2050. Although the demand for cast iron grows more quickly for offshore wind than land-based wind, the total material requirement is much lower at approximately 10% of the total for land-based wind, due to lower overall levels of resulting demand in these specific scenarios. The large dimensions of offshore wind components, which are 2-4 times the size of equivalent components for land-based wind turbines, is a key challenge for manufacturing and transporting these parts.

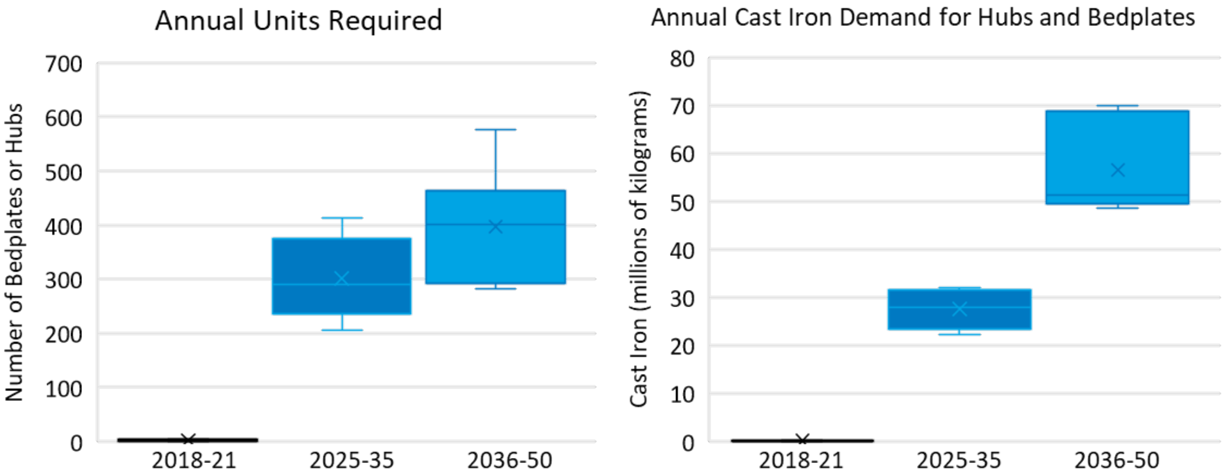

Figure 4. Range of current and projected future annual demand for hubs and bedplates and associated cast-iron content for offshore wind energy

Domestic manufacturing of wind energy components is incentivized by federal and state policies that promote local content; however, the value of these incentives for manufacturers of large castings would need to be analyzed for specific policies. Currently, large castings are not produced domestically. Costs for labor and compliance with environmental regulations contribute to regional differences in the cost of castings, which require a skilled workforce and an energy-intensive production process. Although some U.S. manufacturers produce cast-iron products at smaller scales, they have not invested in expanding the capacity of their facilities to produce castings as large as those required for offshore wind and the largest land-based wind turbines.

Innovative approaches for manufacturing hubs and bedplates could provide opportunities for domestic manufacturers to gain market share. Examples of these opportunities include approaches such as robotic grinding and finishing to reduce the number of labor hours per component, or the use of cleaner energy sources and alternative processes to reduce emissions during manufacturing. Emissions and costs associated with transportation can be lower for domestically manufactured components, especially as components become larger and heavier.

4 Conclusions

The demand for wind turbine hubs and bedplates is estimated to increase at least fivefold in the next decade to meet the United States' clean energy goals. As many as 20,000 individual hubs or bedplates, each spanning 4-8 m across, could be installed per year. These large castings are currently imported; however, innovative manufacturing techniques could provide opportunities for domestic producers. There are also significant challenges for domestic manufacturing, including the time and investment required to permit and construct new facilities.

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