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List of Acronyms

ATB	Annual Technology Baseline
DOE	U.S. Department of Energy
GW	gigawatt
kg	kilogram
m	meter
MW	megawatt
NREL	National Renewable Energy Laboratory
PVC	polyvinyl chloride
REMPD	Renewable Energy Materials Properties Database
t	metric tons (tonnes)
USGS	United States Geological Survey

Executive Summary

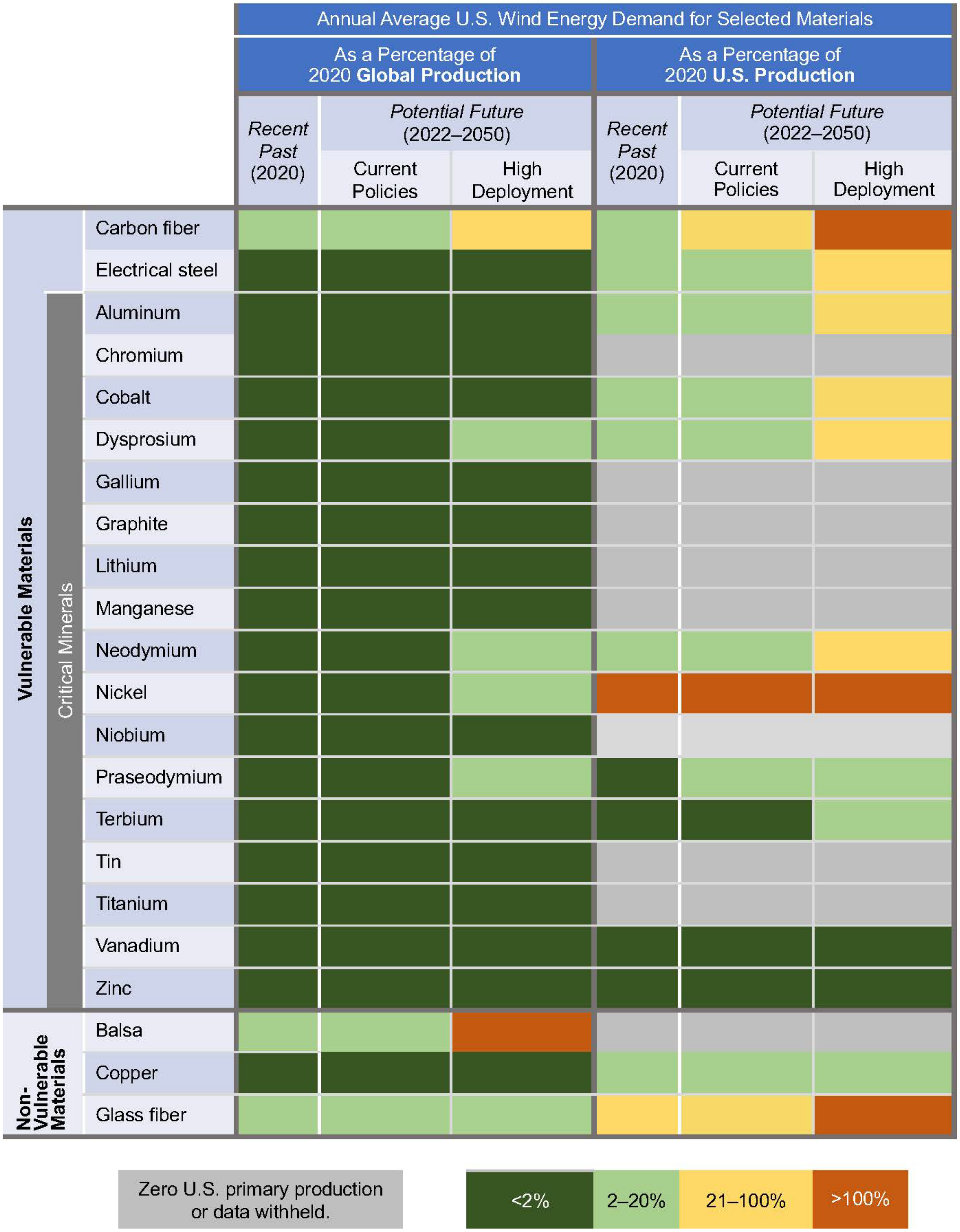
Wind energy is one of the fastest-growing sources of renewable energy. The Biden administration's decarbonization goals (i.e., carbon-pollution-free electricity by 2035 and net-zero economy by 2050) will require at least a threefold increase in the U.S. wind energy deployment rate from current average levels of 10 gigawatts/year (United States Department of State and the United States Executive Office of the President 2021). Increased deployment of wind energy technologies will influence the demand for raw and processed materials that are required to manufacture and operate wind power plants and could therefore impact national resource use and physical materials availability, including critical materials.

Prior research has performed cross-technology assessments of critical material requirements for renewable energy technologies under low-carbon and clean energy futures, explored material requirements and supply chain constraints for specific types of clean energy technologies, and evaluated how deploying these technologies might influence the demand for certain critical materials (e.g., critical minerals). However, no studies have yet developed detailed estimates for material needs associated with U.S. land-based and offshore wind deployment under plausible high-deployment scenarios that would be needed to achieve decarbonization goals.

In this report, the authors explore how material needs for wind energy might change under two U.S. wind deployment scenarios: Current Policies and High Deployment. The Current Policies scenario represents a business-as-usual level of wind energy deployment, and the High Deployment scenario includes high levels of wind energy deployment consistent with achieving the goal of 100% clean electricity by 2035 and net-zero emissions economywide by 2050. We use the Renewable Energy Materials Properties Database (REMPD) to project the amount and types of materials that will be needed for wind energy deployment in the United States under each scenario from 2020 through 2050. We then analyze potential U.S. vulnerabilities linked to physical materials availability and provide some initial recommendations about new technologies that could mitigate resource constraints for wind energy technologies.

We find that the projected annual U.S. demand for materials to construct wind power plants from 2020 through 2050 is anticipated to be less than 2% of global production in 2020 for most materials. Key exceptions include balsa, carbon fiber, glass fiber, nickel, and the rare-earth elements dysprosium and neodymium (Figure ES-1). Our results show that demand for balsa and carbon fiber for U.S. wind energy could reach or exceed current levels of global production in the High Deployment scenario. In addition, there will likely be continued demand for carbon fiber from other countries and sectors that are not considered in this study. Thus, increased domestic or foreign production of carbon fiber will likely be required to achieve U.S. decarbonization goals. Annual production of balsa depends on the amount of land that can be devoted to growing balsa in suitable climate regions. If demand for balsa in wind energy applications begins to exceed production, other materials such as polymer foams may substituted. Demand for glass fiber, nickel, and rare earth elements for U.S. wind energy in the High Deployment scenario peaks from 2038 to 2044 and approaches, respectively, 88%, 35%, and 50% of 2020 global production of these materials. Although these amounts are within current production levels, if production does not increase there may be more competition for access to these materials because of accelerating wind energy deployment worldwide.

We also consider the scale of demand for materials to support U.S. wind energy deployment in relation to domestic production. The amount of nickel used in U.S. deployment of wind energy technologies is already larger than the amount produced domestically. Several critical minerals used for wind energy including gallium, natural graphite, tin, and some elements used in steel alloys (e.g., chromium, manganese, niobium, and titanium) are not mined in the United States. Multiple strategies can be applied to secure supply or limit demand for these materials, including diversifying import sources to minimize supply chain risk, increasing reuse and recycling, modifying wind turbine designs to reduce material demand, substituting alternative materials where possible, and developing domestic sources if they exist. These strategies are also relevant to materials for which demand from wind energy after 2030 is projected to represent a significant share (greater than 20%) of current domestic production, including cobalt, praseodymium, copper, and aluminum.



			Annual Average U.S. Wind Energy Demand for Selected Materials					
			As a Percentage of 2020 **Global Production**			As a Percentage of 2020 **U.S. Production**		
			Recent Past (2020)	*Potential Future* (2022–2050) Current Policies	*Potential Future* (2022–2050) High Deployment	*Recent Past* (2020)	*Potential Future* (2022–2050) Current Policies	*Potential Future* (2022–2050) High Deployment
Vulnerable Materials		Carbon fiber	2–20%	2–20%	21–100%	2–20%	21–100%	>100%
		Electrical steel	<2%	<2%	<2%	2–20%	2–20%	21–100%
	Critical Minerals	Aluminum	<2%	<2%	<2%	2–20%	2–20%	21–100%
		Chromium	<2%	<2%	<2%	Zero U.S. primary production or data withheld.	Zero U.S. primary production or data withheld.	Zero U.S. primary production or data withheld.
		Cobalt	<2%	<2%	<2%	2–20%	2–20%	21–100%
		Dysprosium	<2%	<2%	2–20%	2–20%	2–20%	21–100%
		Gallium	<2%	<2%	<2%	Zero U.S. primary production or data withheld.	Zero U.S. primary production or data withheld.	Zero U.S. primary production or data withheld.
		Graphite	<2%	<2%	<2%	Zero U.S. primary production or data withheld.	Zero U.S. primary production or data withheld.	Zero U.S. primary production or data withheld.
		Lithium	<2%	<2%	<2%	Zero U.S. primary production or data withheld.	Zero U.S. primary production or data withheld.	Zero U.S. primary production or data withheld.
		Manganese	<2%	<2%	<2%	Zero U.S. primary production or data withheld.	Zero U.S. primary production or data withheld.	Zero U.S. primary production or data withheld.
		Neodymium	<2%	<2%	2–20%	2–20%	2–20%	21–100%
		Nickel	<2%	<2%	2–20%	>100%	>100%	>100%
		Niobium	<2%	<2%	<2%	Zero U.S. primary production or data withheld.	Zero U.S. primary production or data withheld.	Zero U.S. primary production or data withheld.
		Praseodymium	<2%	<2%	2–20%	<2%	2–20%	2–20%
		Terbium	<2%	<2%	<2%	<2%	<2%	2–20%
		Tin	<2%	<2%	<2%	Zero U.S. primary production or data withheld.	Zero U.S. primary production or data withheld.	Zero U.S. primary production or data withheld.
		Titanium	<2%	<2%	<2%	Zero U.S. primary production or data withheld.	Zero U.S. primary production or data withheld.	Zero U.S. primary production or data withheld.
		Vanadium	<2%	<2%	<2%	<2%	<2%	<2%
		Zinc	<2%	<2%	<2%	<2%	<2%	<2%
Non-Vulnerable Materials		Balsa	2–20%	2–20%	>100%	Zero U.S. primary production or data withheld.	Zero U.S. primary production or data withheld.	Zero U.S. primary production or data withheld.
		Copper	<2%	<2%	<2%	2–20%	2–20%	2–20%
		Glass fiber	2–20%	2–20%	2–20%	21–100%	21–100%	>100%

Zero U.S. primary production or data withheld.

<2% | 2–20% | 21–100% | >100%

Figure ES-1. Annual U.S. wind energy demand for selected materials as compared to global and U.S. production in 2020

Although the material demand projections presented in this study provide some insight into which materials may pose challenges for wind energy development, there is scope for additional work to better understand likely constraints and possible solutions. The current work assumes relatively limited changes in wind power plant design and related material requirements. Future work could explore potential impacts of technology innovations on material requirements and incorporate feedback between supply chain constraints and wind plant design to identify technology evolution pathways that avoid material supply bottlenecks.

This study considers only current production and known reserves of wind energy materials. Therefore, a more complete investigation of future material supply chains could identify additional supply risks (for example, due to changes in demand from other countries and industries, or declining mine production) and opportunities for new or expanded production sources. Further research could extend the REMPD to include additional supply chain risk metrics (e.g., likelihood of foreign supply disruption, dependency of U.S. manufacturers on foreign suppliers, and ability of U.S. manufacturers to withstand a supply disruption) and perform a more detailed analysis of supply risks. Other avenues for future work include expanding the REMPD by adding information on wind energy externalities (e.g., emissions from manufacturing and transportation), incorporating other renewable energy technologies (e.g., geothermal plants, marine and hydrokinetic plants, hydrogen electrolyzers, or battery energy storage systems) into the database, and performing a cross-technology analysis of material requirements.

Table of Contents

List of Figures

List of Tables

1 Background

Renewable energy deployment is increasing globally. In the United States, generation from utility-scale wind and solar increased by 11% and 20%, respectively, from 2020 to 2021 (Lawrence Livermore National Laboratory 2021). This growth is expected to continue and may need to increase to achieve domestic objectives for clean energy.[1] For example, the United States' long-term strategy to reach net-zero greenhouse gas emissions by 2050 identifies a need for annual wind energy deployment of 25 to 30 gigawatts (GW) per year, which is approximately three times recent annual average deployment levels (United States Department of State and the United States Executive Office of the President 2021).

Increased deployment of clean energy technologies will affect the demand for raw and processed materials that are required to manufacture and operate these technologies, thus impacting resource use and physical materials availability. Certain materials that play an important role in the economy and are at risk of supply disruption have been designated as critical (or vulnerable) materials in various regions, including the United States (National Research Council 2008; Achzet and Helbig 2013; Graedel and Reck 2016; Hofmann et al. 2018; Schrijvers et al. 2020).[2] The availability of these critical materials may be further limited as global resource use increases as a result of population growth and economic development (United Nations Environment Program [UNEP] 2016).

Prior research has identified critical material requirements for a broad set of clean energy technologies and examined how increased deployment of these technologies might influence the demand for certain critical materials (e.g., critical minerals) (American Physical Society Panel on Public Affairs and Materials Research Society 2011; Atwater et al. 2011; Bauer et al. 2010; Fraunhofer Institute for Systems and Innovation Research ISI et al. 2013; International Energy Agency [IEA] 2021; Junne et al. 2020; World Bank Group 2017). Several prior studies focused on international or European demand for energy materials (Fraunhofer Institute for Systems and Innovation Research ISI et al. 2013; IEA 2021; Junne et al. 2020; World Bank Group 2017). Two others provided a broad assessment of availability and risks without detailed quantification of the projected material needs for U.S. energy technologies (American Physical Society Panel on Public Affairs and Materials Research Society 2011; Atwater et al. 2011). And, at least one study, the U.S. Department of Energy's (DOE's) *Critical Minerals and Materials Strategy* (Bauer et al. 2010), performed a more detailed analysis of the supply and demand of critical materials in the context of U.S. clean energy technologies and estimated future demand for four specific components: permanent magnets in wind turbines and electric vehicles, advanced batteries in electric vehicles, thin-film semiconductors in solar photovoltaic power systems, and phosphors in high-efficiency lighting systems.

In addition to these cross-technology assessments of critical material requirements, prior work also analyzed material requirements and supply chain constraints for individual types of clean energy technologies (Ardani et al. 2021; Baars et al. 2021; Cao et al. 2019; Carrara et al. 2020;

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[1] Refer to Appendix A for more details about the Biden administration's clean energy goals, including the Hydrogen Shot.

[2] See Appendix B for a brief history of critical materials research.

Dunn et al. 2021; Nassar et al. 2016; DOE 2022; Wilburn 2011; J. Yang et al. 2020). For example, global and regional estimates of the materials needed to fulfill current and future wind energy deployment have been provided in several studies (Cao et al. 2019; Carrara et al. 2020; IEA 2021; Nassar et al. 2016; Wilburn 2011; J. Yang et al. 2020). These studies vary in their estimates of material types and quantities required per megawatt (MW) of installed capacity; some of this variation stems from differences in material requirements between wind turbines of different sizes or configurations. For example, the generator type determines whether the wind turbine requires rare-earth permanent magnets, and the level of rare-earth element demand linked to wind energy deployment has been estimated in various studies (Alves Dias et al. 2020; Fishman and Graedel 2019; Fraunhofer Institute for Systems and Innovation Research ISI et al. 2013; Habib et al. 2014; Hoenderdaal et al. 2013; Li et al. 2020; Ren et al. 2021). In addition, comparative studies have quantified material impacts from alternative wind turbine configurations and wind blades (Cooperman et al. 2021; Carrara et al. 2020; Guezuraga et al. 2012; Ozoemena et al. 2018; Schreiber et al. 2019). At least one study has also evaluated critical material requirements for solar photovoltaic systems in the context of potential high-deployment scenarios in the United States (Ardani et al. 2021).

However, no studies have yet estimated detailed material requirements of U.S. land-based and offshore wind energy technologies under plausible high-deployment scenarios, such as the carbon-pollution-free power sector by 2035 and net-zero economy by 2050 that would be required to achieve the Biden administration’s federal sustainability goals (The White House 2021). Because many wind energy materials are sourced and processed globally, U.S. energy security and economic health are vulnerable to disruptions in the supply of these materials outside our borders. Thus, it is important to develop a more detailed understanding of how U.S. demand for wind energy materials might change under various deployment scenarios.

1.1 Motivation and Goals

Building on the Energy Act of 2020’s guidance to establish a physical materials property database for wind energy (Consolidated Appropriations Act 2021), this report provides a detailed analysis of wind material requirements at the scales required to achieve the Biden administration’s objectives. Here, we explore how material requirements for wind energy might change under two scenarios, analyze potential U.S. vulnerabilities linked to physical materials availability, and provide some initial recommendations about new technologies that could mitigate resource constraints for wind energy technologies. We use a newly developed tool for estimating material requirements associated with renewable energy technologies—the Renewable Energy Materials Properties Database (REMPD) (NREL 2023)—to project the amount and types of materials that will be needed for wind energy deployment in the United States from 2020 through 2050. The analysis performed here incorporates variability in wind turbine designs and technological improvements and includes a review of the geographical origin of wind turbine materials and availability. These results could help inform better planning to mitigate potential material supply risks for wind energy deployment.

The goals of this report are to: (1) improve understanding of the constraints and vulnerabilities that exist for physical materials availability and manufacturing supply chains under two wind energy deployment scenarios, and (2) identify how new technologies could mitigate resource constraints. We describe our methodology in Section 2, summarize results for material requirements to 2050 in Section 3, provide an overview of opportunities for innovation to alter material requirements for future wind power plants in Section 4, and summarize our conclusions in Section 5. We perform our analysis at a high level for all materials used in wind energy technologies and examine a subset of vulnerable materials (defined in Section 1.2) in greater detail.

1.2 Definition of Vulnerable Materials

Within this report, the term "vulnerable materials" encompasses all materials used in wind power plants that are at risk of supply chain disruption, including critical minerals. The Energy Act of 2020 defines a critical mineral as:

> *"Any mineral, element, substance, or material designated as critical under subsection (c) except fuel minerals; water, ice, or snow; common varieties of sand, gravel, stone, pumice, cinders, and clay."*

The Energy Act of 2020 (2020) also defines how the Secretary of the Interior, acting through the Director of the United States Geological Survey (USGS), should establish a list of critical minerals, to be revised at least every 3 years. These minerals should meet the following criteria:

- They are essential to the economic or national security of the United States
- Their supply chain is vulnerable to disruption (e.g., due to military conflict, foreign political risks, or sudden demand growth)
- They serve an essential function in the manufacturing of a product (e.g., energy technology, defense, electronics); the absence of which would have significant consequences for the economic or national security of the United States.

A more detailed description of the assessment methodology for material criticality used by the USGS is provided by Nassar and Fortier (2021). In its most recently published list, the USGS identified 50 critical minerals (USGS 2022).

Table 1 lists the vulnerable materials considered here along with the reason for their designation and role in wind energy technologies. The list includes 2 vulnerable materials and 17 critical minerals (the 33 other minerals on the 2022 USGS list play little to no role in wind energy generation facilities[3]). The two vulnerable materials that are not on the USGS list of critical minerals are carbon fiber and electrical steel. Carbon fiber is used to provide structural strength for wind turbine blades, and electrical steel is used in power generators in the nacelle and in transformers. The constituents of carbon fiber and electrical steel are largely not critical by themselves (e.g., electrical steel comprises iron, silicon, carbon, and some aluminum). However, the global capacity for manufacturing these materials is limited. For example, the manufacturing process for electrical steel is metallurgically specialized, and the technical details of the process are highly guarded in the industry. The United States currently relies on Canada and Mexico to

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[3] The 33 minerals included in the 2022 United States Geological Survey list of critical minerals that play a minor or no role in wind energy technologies are antimony, arsenic, barite, beryllium, bismuth, cerium, cesium, erbium, europium, fluorspar, gadolinium, germanium, hafnium, holmium, indium, iridium, lanthanum, lutetium, magnesium, palladium, platinum, rhodium, rubidium, ruthenium, samarium, scandium, tantalum, tellurium, thulium, tungsten, ytterbium, yttrium, zirconium.

augment its domestic production of electrical steel. As a result, carbon fiber and electrical steel are at high risk for supply chain disruption and are thus included in our list of vulnerable materials.

Table 1. Vulnerable Materials and Their Role in Wind Energy Technologies

Type of Material(s)	Reason for Vulnerable Material Designation	Primary Role in Wind Energy Technologies
Carbon fiber	High risk of supply chain disruption	Structural elements in wind turbine blades
Electrical steel	High risk of supply chain disruption	Power generators, transformers
Aluminum	2022 USGS critical mineral	Power cables, nacelle/tower internal equipment
Chromium, cobalt, manganese, nickel, niobium, titanium, vanadium	2022 USGS critical mineral	Steel alloying elements
Graphite, lithium, nickel	2022 USGS critical mineral	Batteries
Dysprosium, neodymium, praseodymium, terbium	2022 USGS critical mineral	Rare-earth permanent magnets
Gallium	2022 USGS critical mineral	Wide bandgap semiconductors for power electronics
Tin	2022 USGS critical mineral	Bronze
Zinc	2022 USGS critical mineral	Anticorrosion coatings (galvanization)

2 Methodology To Assess Material Quantities

In this report, we use the REMPD (NREL 2023) to assess the types and quantities of materials required to construct wind energy technologies. We also compare material demands for wind energy requirements to available materials and provide some initial insights about how new technologies could potentially mitigate resource constraints.

2.1 Overview of the REMPD

The REMPD is a relational database developed using the open-source database server PostgreSQL (PostgreSQL Global Development 2022). A publicly available version of the database can be found at: https://apps.openei.org/REMPD/. A summary of the REMPD including capabilities, definitions, and metrics used in the database are provided in Cooperman et al. (2023). For ease of reference, we provide a high-level overview of the database here and reproduce two figures from Cooperman et al. (2023) (refer to that report for more details). We also provide more information about the REMPD's scenario analysis capabilities, including the system boundary for scenario analysis.

2.1.1 Data Taxonomy

The REMPD uses a six-tiered approach to collect and organize data on the material requirements and properties associated with renewable energy technologies. The database currently includes data for both wind and solar energy technologies. In this report, we describe the database taxonomy in the context of wind energy technologies as that is the focus of our analysis. However, the database does provide additional data on solar technologies (refer to Cooperman et al. [2023] for more details).

The top tier of the REMPD data taxonomy comprises all components and materials required to construct all facilities in the selected category (e.g., all wind power plants in the United States). The next level captures finished components, such as the wind turbine, substation, and electrical cables. Each component is associated with relevant subassemblies and subcomponents (e.g., the pitch drive in a wind turbine is a subcomponent of the hub subassembly). The next tier includes the finished materials, or primary processed materials, such as steel, that are required to manufacture the component, subassembly, and/or subcomponent. The lowest tier provides the raw materials, which also include some secondary processed materials (e.g., glass) that are required to manufacture the finished materials. This taxonomy allows the database to capture all material requirements for energy technologies and break down the material requirements by component, which allows users to explore where materials are used within each technology and help identify opportunities for reducing material requirements.

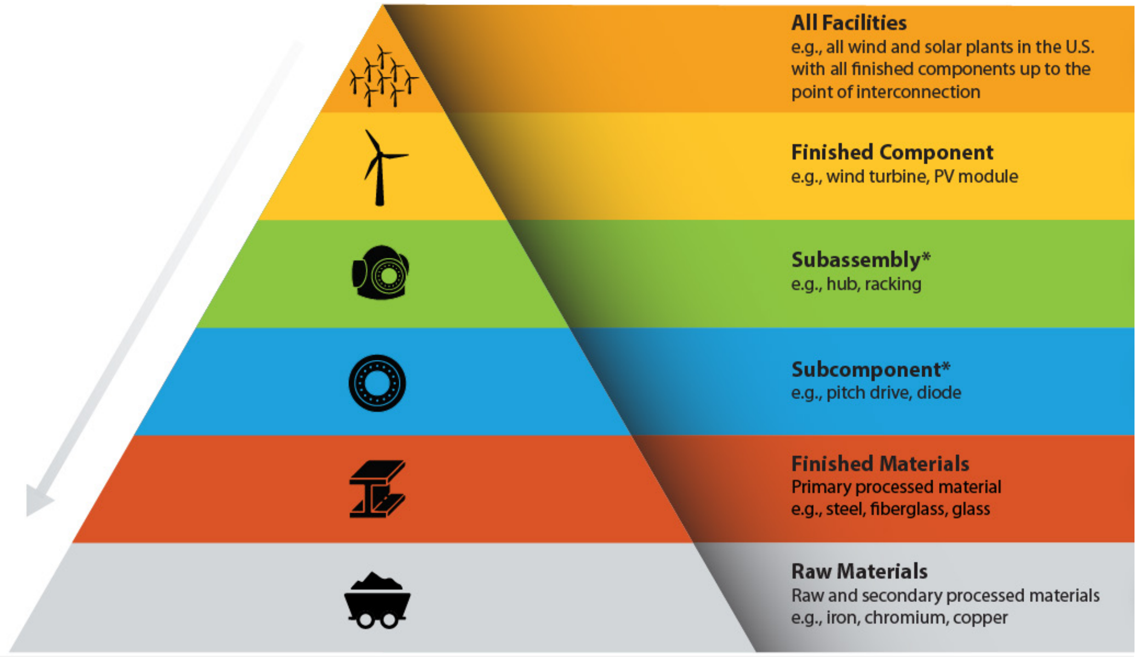

Figure 1. Taxonomy used to organize data in the REMPD. Asterisks note that not all components in the database have data at the subassembly and subcomponent levels. These two tiers are populated based on available data (i.e., whether the materials needed for each component can be disaggregated to the subassembly and/or subcomponent levels, or if they are instead reported at a higher level, such as the finished component level). These data could be added to the database in the future. *Illustration by Nicole Leon, National Renewable Energy Laboratory (NREL).*

In some cases, due to data constraints and the desire for the database to focus primarily on material quantities, the REMPD does not have all data at the subassembly or subcomponent levels. However, in all cases, the REMPD does include data for the finished and raw materials associated with each finished component. For example, substation data are only broken down by material type and are not subdivided at the subassembly or subcomponent levels; wind turbine data are subdivided into multiple subassemblies and subcomponents.

2.1.2 *Wind Energy System Components*

Figure 2 illustrates the wind energy system components that are included in the REMPD and used in the analysis performed here. The five types of components are:

1. Wind turbines, which comprise four subassemblies: the hub, blades, nacelle, and tower
2. Foundation (for land-based wind systems) or substructure (for offshore wind systems)
3. Array and export cables
4. Site access roads (for land-based systems)
5. Substations.

We include all material requirements for the wind turbine (i.e., the nacelle/drivetrain, generator, tower, blades, and hub) and all balance-of-system materials needed to the point of interconnection (i.e., land-based foundation or offshore substructure, electrical cables, substations, and other site parts [e.g., roads for land-based wind power plants]). We exclude material requirements for capital equipment associated with transporting and installing the components as well as materials needed for operating, maintaining, and decommissioning the wind plant (e.g., we do not include the materials needed to construct cranes or other construction equipment and we do not include the fuel required to transport the materials to and from facilities throughout the wind plant life cycle).

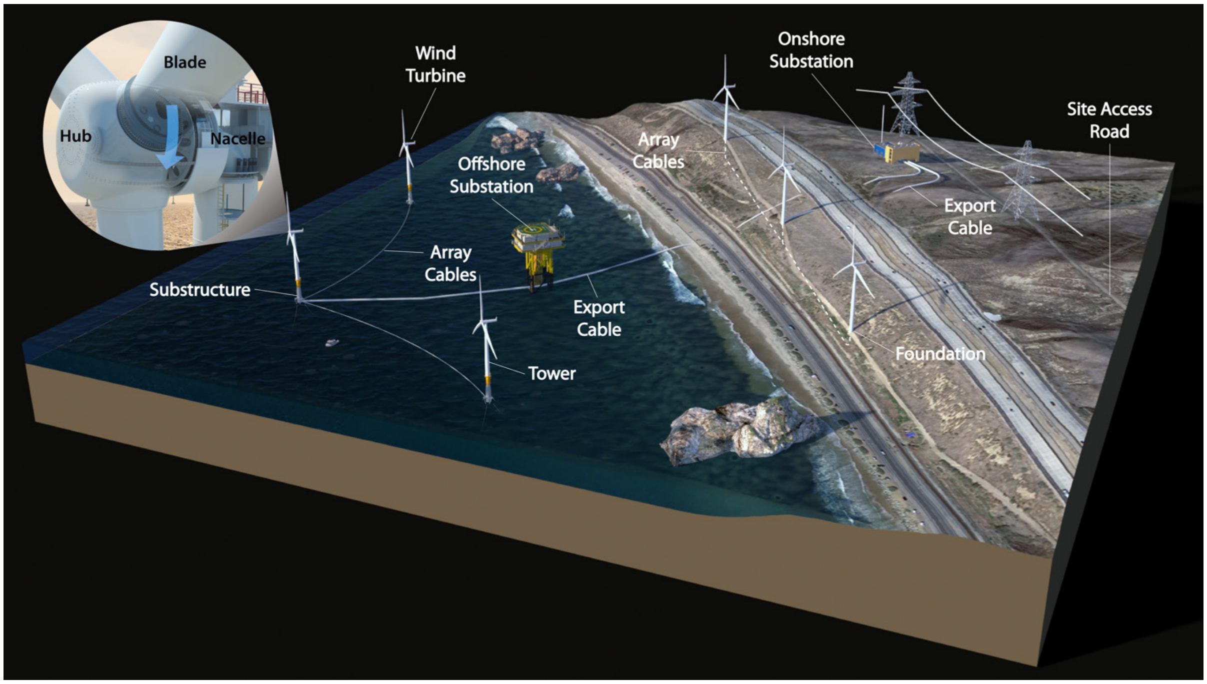

Figure 2. System components included in our analysis of wind energy material requirements. ***Illustration by Joshua Bauer, NREL***

2.1.3 System Boundary for Scenario Analysis

Materials for wind energy technologies come from diverse, global supply chains. These supply chains will continue to evolve in the future as materials selection and availability change. The system boundary used in the REMPD allows the database to capture two types of materials—raw and finished materials—at two levels: the foreground system and background system (Figure 3). Finished materials include primary processed materials (e.g., steel), which are required to manufacture the component, subassembly, or subcomponent. Raw materials include materials that are required to manufacture the finished materials (e.g., critical minerals and some secondary processed materials [e.g., glass]). The foreground system captures processes and materials that are under direct control or decisive influence of renewable energy manufacturers and developers, such as the quantity and type of rare-earth elements used in permanent magnets. Inputs to the foreground system include both raw and processed materials because manufacturers may exert control over materials selection at both levels. Foreground material quantities come from original equipment manufacturers and published literature. The background system includes the upstream processes that are required to extract and process raw materials and manufacture processed materials used in the foreground system). The REMPD system boundary excludes materials used for processes after manufacturing, such as transportation, installation, operations and maintenance, or decommissioning.

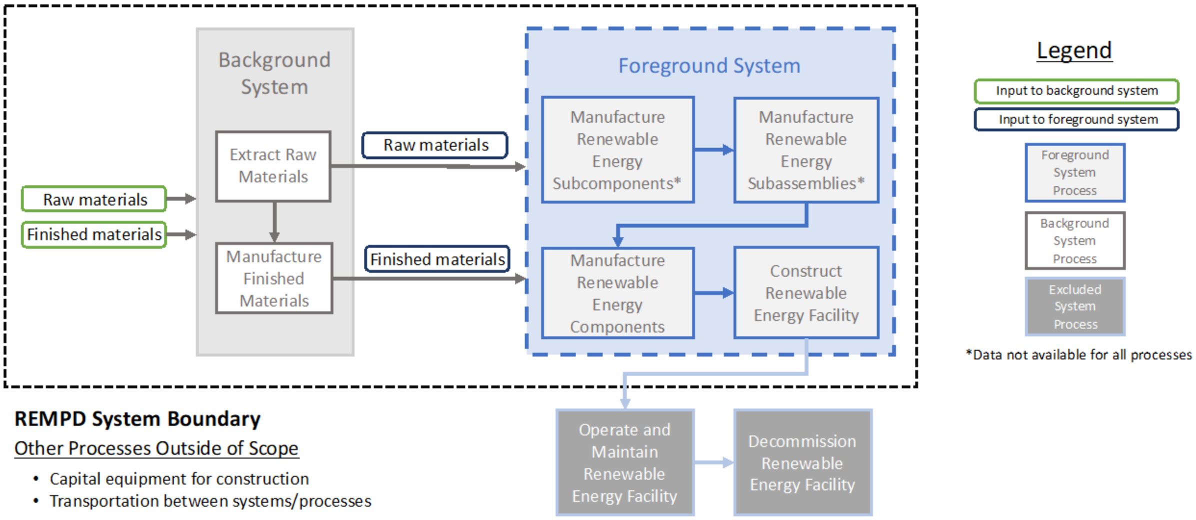

Figure 3. System boundary used in the REMPD. ***Illustration by Annika Eberle, NREL***

To identify and characterize the material quantities in the background system, we employ tools from life cycle assessment. Life cycle assessment allows researchers to model the inputs (e.g., materials and fossil-fuel consumption) and outputs (air pollutant emissions, discharges to water) of a product or process's life cycle from resource extraction through manufacturing, use, and disposal. In the REMPD, we use life cycle inventories generated for life cycle assessment to estimate the background material for the foreground system.[4] As an example, the foreground material steel is used in wind system towers, land-based foundations, and offshore wind substructures. Using existing life cycle inventories, the specific background material requirements for steel are characterized, which include iron, manganese, nickel, titanium, and chromium, among others. This approach positions future work on the REMPD to calculate other types of resource requirements and impacts (e.g., global warming potential, emissions to water, energy consumption) using the background material data available in the REMPD.

2.1.4 Scenario Analysis Capabilities

We leverage the REMPD's scenario analysis capabilities (illustrated in Figure 4) to evaluate material quantities and assess and compare material properties (e.g., availability). Performing scenario analysis using the REMPD involves defining a scenario (a combination of three inputs: a capacity projection, a plant configuration, and a technology configuration) and specifying scaling relationships that allow a user to vary material quantities based on plant configurations and capacity projections. The REMPD then connects that scenario definition to the required renewable energy components, subassemblies, and subcomponents and identifies the required foreground and background materials associated with them. The REMPD uses this information, along with the scaling relationships, to evaluate material quantities. It also joins the required

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[4] Refer to Appendix C for a list of sources used for the life cycle inventory data.

materials with their associated material properties. For any given scenario, a researcher can calculate the amount of all materials needed to construct a single wind turbine, wind plant, or all wind power plants in the United States. Likewise, once a vulnerable material is identified, all scenarios relying on the material can be identified. The relationships defined in the REMPD allow researchers to discover vulnerabilities in the supply chain by connecting materials to countries of origin and national availability, among other characteristics.

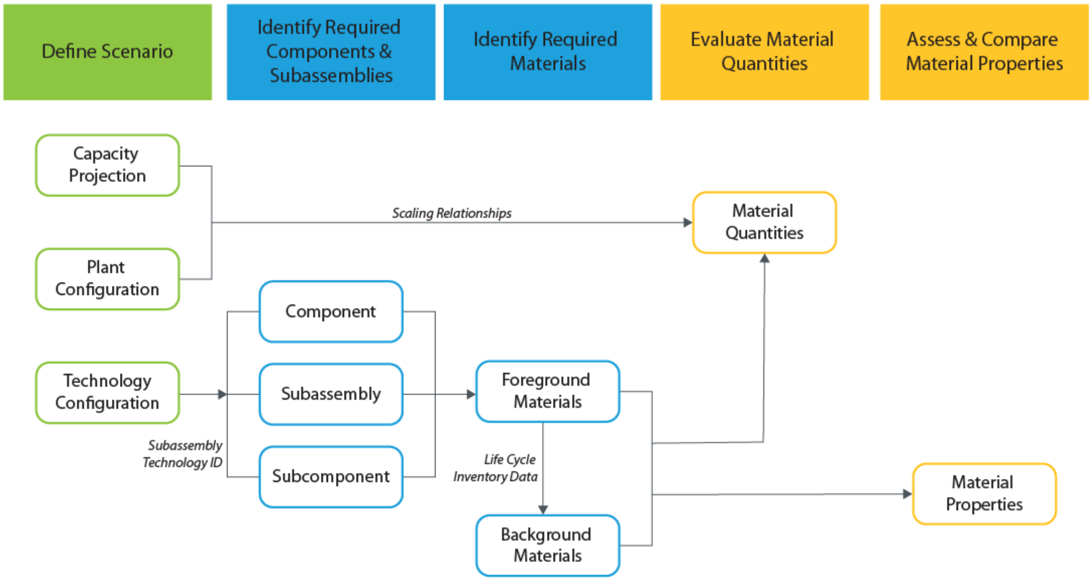

Figure 4. Simplified flow of analysis performed using the REMPD. *Illustration by Nicole Leon, NREL*

The technology configuration in a scenario definition is used to identify the required components, subassemblies, and subcomponents. These entities are associated with known foreground material requirements, which are linked to background materials via life cycle inventory data. The capacity projection and plant configuration in the scenario definition is combined with the foreground and background material requirements to compute the total material quantities for all facilities. The foreground and background materials are also linked to material properties (such as countries of origin).

2.2 Scenario Definitions

In this report, we explore how the material requirements for wind energy technologies might change under two future wind deployment scenarios: Current Policies and High Deployment. Using the REMPD, we define our analysis scenarios using a combination of three factors:

1. **Capacity projection**, which defines the annual amount of capacity (in MW) that is anticipated each year over the period of interest.
2. **Plant configuration**, which describes the quantitative properties (e.g., the wind turbine rating, wind plant capacity, rotor diameter, and hub height) associated with each type of facility (e.g., offshore versus land-based wind), which can vary over time.

3. **Technology configuration**, which identifies the market share for each type of technology that is used within each facility and allows for the exploration of technology innovations (e.g., superconducting direct-drive generators).

Table 2 summarizes how we define each of these three factors for our two analysis scenarios.[5] The Current Policies scenario represents a medium level of wind energy deployment, consistent with median estimates of technology costs and electric-sector policies as of September 2022 (including the Inflation Reduction Act [IRA]), with limited changes in plant configurations (e.g., wind turbine size) and no significant technology innovations beyond conventional technology. The High Deployment scenario includes high levels of wind energy deployment that are aligned with the Biden administration's decarbonization goals and incorporates significant changes in wind plant configurations (e.g., large-scale increases in turbine size), but with limited materials-related innovations applied.

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[5] Refer to Section 3.1.1 through 3.1.3 for more details about each factor.

Table 2. Scenario Definitions for Material Quantities and Availability Analysis

	Current Policies Scenario	High Deployment Scenario
Generic description	Limited changes to plant configurations and medium levels of deployment, with no significant materials-related technology innovations.	Significant technology innovations enable large-scale increases in wind turbine size and high levels of deployment, with limited materials-related technology innovations.
Capacity projection[a]	Mid-Case scenario from National Renewable Energy Laboratory's (NREL's) "Standard Scenarios" (Gagnon et al. 2022), which represents a medium level of wind energy deployment, as required to satisfy electricity demand. The scenario assumes no new decarbonization policies and no deployment of nascent technologies.	All Options scenario from Denholm et al. (2022), which achieves 100% clean electricity by 2035 and puts the United States on a path to net-zero emissions economywide by 2050.
Plant configuration[c]	Linear interpolation of wind turbine and plant characteristics from the 2022 Annual Technology Baseline[d] (ATB) Base scenario (year 2020) to the Conservative scenario (year 2030) and linear extrapolation of 2020–2030 scaling trends through 2050 (up to a maximum hub height of 200 meters (m), rotor diameter of 331 m, and turbine rating of 25 MW for offshore wind and a maximum hub height of 140 m for land-based wind).	Linear interpolation of wind turbine and plant characteristics from the 2022 ATB[d] Base scenario (year 2020) to the Advanced scenario (year 2030) and linear extrapolation of 2020–2030 scaling trends through 2050 (up to a maximum hub height of 200 m, rotor diameter of 331 m, and turbine rating of 25 MW for offshore wind and a maximum hub height of 140 m, rotor diameter of 210 m, and turbine rating of 8 MW for land-based wind).
Technology configuration[e]	Low materials-related technology innovation (Low Innovation technology configuration), which represents current technology (e.g., thermoset blades).	Moderate materials-related technology innovation (Moderate Innovation technology configuration), including segmented blades and carbon-fiber spar caps for land-based systems, advanced steel towers (spiral welding) for 25% of land-based systems, and hybrid tower systems for 25% of land-based systems.

a. Refer to Section 3.1.1 and Figure 5 for more details. Note that Congress passed the Inflation Reduction Act (IRA) after this analysis was performed. As a result, the wind capacity projections used here do not reflect any increased deployment of wind power that may result from the implementation of the IRA.
c. Refer to Section 3.1.2, Table 3, and Table 4 for more details.
d. The ATB provides a consistent set of cost and performance data for energy analysis (refer to National Renewable Energy Laboratory [2022] for details).
e. Refer to Section 3.1.3 and Table 5 for more details.

To capture changes in material intensity that might occur as wind plants and turbines increase in size, the REMPD multiplies the fractional contribution of materials by type (e.g., % concrete, % steel, % carbon fiber) by a scaling relationship related to the plant configuration (e.g., the plant size, number of turbines, rotor diameter). Appendix D provides more details about the scaling relationships used in this analysis.

Using our two analysis scenarios, we can assess what bottlenecks might arise in wind-energy-related materials under current technology assumptions with limited material evolution. Future work could leverage the REMPD to explore how technology innovations could further reduce material usage through high-performing materials, alternate materials (with large supply chains), and/or alternate design approaches (e.g., 100% bio-derived blade).

2.2.1 Capacity Projections

To estimate the future demand for wind energy materials, we consider two different deployment trajectories. The Current Policies scenario uses the Mid-Case deployment projection with no nascent technologies from National Renewable Energy Laboratory's (NREL's) 2022 Standard Scenarios (Gagnon et al. 2022). The High Deployment scenario uses the All Options deployment projection that achieves 100% clean electricity by 2035 and puts the United States on a path to achieve net-zero emissions economywide by 2050 (Denholm et al. 2022). The deployment projections used here were generated using the Regional Energy Deployment System (ReEDS) capacity expansion model (Ho et al. 2021) using the following assumptions[6]:

- **Electricity demand**. The Current Policies scenario assumes moderate growth (close to 1% per year) in electricity demand in response to provisions in the IRA that incentivize electrification of, for example, vehicles and heating. The High Deployment scenario assumes accelerated demand for electrification, with demand growing at a rate of 3.4% per year.
- **Policy**. The Current Policies scenario assumes no change to policies affecting the electric sector beyond September 2022. It incorporates estimated cost impacts due to tax credits that were implemented in the IRA. The High Deployment scenario is designed to meet the Biden administration's goal of 100% clean electricity by 2035. By combining carbon capture and the electrification of sectors that currently rely on fossil fuels, this scenario enables net-zero emissions by 2050.
- **Retirements**. Deployment projections account for power plant retirements when determining the electricity demand in each year. Wind power plants are assumed to have a service life of 30 years.

The wind capacity projections under each scenario are shown in Figure 5. These projections include utility-scale land-based and offshore wind power plants. Land-based wind capacity represents the majority of the projected installations: 85% of the cumulative capacity in 2050 in the Current Policies scenario, and 91% in the High Deployment scenario. Average annual capacity additions for all utility-scale wind energy between 2022 and 2036 are approximately 21 GW/year in the Current Policies scenario and 68 GW/year in the High Deployment scenario. These additions represent significant growth for annual United States wind energy deployment, which averaged below 10 GW per year from 2016 to 2020 (Wiser et al. 2021). In the Current Policies scenario, annual wind energy installations decrease to approximately 10 GW per year from 2038 through 2050. In contrast, annual wind energy installations in the High Deployment scenario increase to an average of 84 GW per year from 2038 through 2050.

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[6] Refer to Gagnon et al. (2022) and Denholm et al. (2022) for more details.

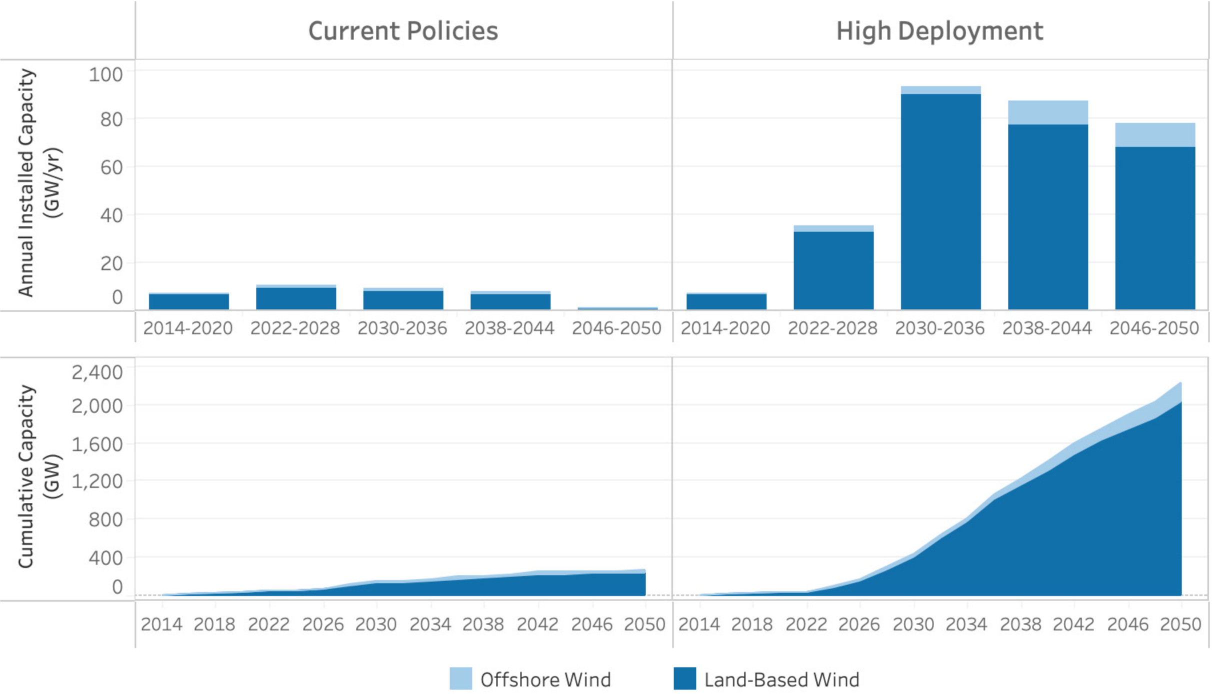

Figure 5. Wind-energy-generating capacity projections for the Current Policies and High Deployment scenarios

2.2.2 Plant Configuration

As described in Section 2.1, the REMPD considers all wind system components that are used in typical utility-scale land-based and offshore wind power plants. These system boundaries remain consistent across the Current Policies and High Deployment scenarios. The basic wind plant system architecture includes three blades joined to a hub that is connected to the nacelle, which contains the drivetrain, generator, power electronics, and auxiliary equipment, and is mounted on a tower.[7] The hub, blades, nacelle, and tower comprise the wind turbine, which is supported by a foundation (on land) or substructure (offshore). Offshore substructures may be rigidly fixed to the seafloor (e.g., monopile or lattice structures), or floating structures may be held in place by mooring lines and anchors. The balance-of-plant components include electrical cables connecting each wind turbine to one or more substations, and site roads (on land).

Wind turbine sizes have grown significantly over the past several decades, and this growth is expected to continue (Musial et al. 2021; Wiser et al. 2021). Material requirements for wind energy systems depend on several factors, including the rated capacity of turbines and power plants, the size of individual components (notably the rotor diameter and tower height), and the selection of materials or technology type for subcomponents where multiple alternatives have gained market share. The plant configuration in the REMPD allows users to define the size and height of the turbines and other parameters associated with a wind plant configuration. The technology configuration (discussed in the next section) allows users to define other factors that

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[7] Refer to Figure 2 for a representation of the components included in this analysis.

affect material requirements (e.g., the type of generator that is used) and are prescribed within each analysis scenario.

In our analysis, wind plants are assumed to have wind turbines with dimensions and characteristics as specified in Table 3 and Table 4 (NREL 2022). We develop these plant configurations based on NREL's 2022 Annual Technology Baseline (ATB) (NREL 2022). To define the configurations over time, we linearly interpolate between the configuration defined by the 2022 ATB Base scenario, which represents current wind energy technology, and two future scenarios: 2022 ATB Conservative and 2022 ATB Advanced. The results of these interpolations are summarized in Table 3 for our Current Policies scenario and Table 4 for our High Deployment scenario. As shown in Table 3 and Table 4, land-based wind technology in 2020 involves a 202-MW wind plant comprising seventy-two 2.8-MW wind turbines. Offshore wind technology in 2020 involves a 1-GW plant with one hundred and twenty-five 8-MW wind turbines. The 2020 technology configurations are the same across both our analysis scenarios. However, from 2020 to 2050, the plant configurations for the Current Policies and High Deployment scenarios differ. From 2020 to 2030, turbine and plant characteristics are linearly interpolated from the ATB 2022's Base scenario data in 2020 to the ATB 2022's Conservative data in 2030 for our Current Policies scenario (or from the ATB's 2022 Base scenario in 2020 to the ATB's 2022 Advanced scenario data in 2030 for our High Deployment scenario). From 2030 to 2050, we assume a linear extrapolation of 2020-2030 trends through 2050 (up to a maximum hub height of 200 meters (m), rotor diameter of 331 m, and turbine rating of 25 MW and a maximum hub height of 140 m, rotor diameter of 210 m, and turbine rating of 8 MW for land-based wind).

Table 3. Plant Configuration for the Current Policies Scenario Explored Here (Derived Using NREL's ATB [NREL 2022][*])

	Land-Based Wind			Offshore Wind		
	2020	2030	2050	2020	2030	2050
Plant capacity	202 MW	200 MW	205 MW	1,000 MW	1,008 MW	1,000 MW
Turbine rating	2.8 MW	4 MW	6.4 MW	8 MW	12 MW	20 MW
No. of turbines	72	50	32	125	84	50
Hub height	90 m	110 m	140 m	102 m	136 m	200 m
Rotor diameter	125 m	150 m	200 m	159 m	214 m	324 m
Specific power	228 watts (W)/square meter (m^2)	226 W/m^2	204 W/m^2	403 W/m^2	334 W/m^2	243 W/m^2
Plant lifetime	30 years	30 years	30 years	30 years	30 years	30 years

[*] Values were calculated using a linear interpolation of wind turbine and plant characteristics from the Base scenario (year 2020) to the Conservative scenario (year 2030) using ATB 2022 data (NREL 2022) and a linear extrapolation of 2020-2030 trends through 2050 (up to a maximum hub height of 200 m, rotor diameter of 331 m, and turbine rating of 25 MW for offshore wind and a maximum hub height of 140 m for land-based wind).

Table 4. Plant Configuration for the High Deployment Scenario Explored Here (Derived Using NREL's ATB [NREL 2022][*])

	Land-Based Wind			Offshore Wind		
	2020	2030	2050	2020	2030	2050
Plant capacity	202 MW	203 MW	200 MW	1,000 MW	1,008 MW	1,000 MW
Turbine rating	2.8 MW	7 MW	8 MW	8 MW	18 MW	25 MW
No. of turbines	72	29	25	125	56	40
Hub height	90 m	135 m	140 m	102 m	161 m	200 m
Rotor diameter	125 m	200 m	210 m	159 m	263 m	331 m
Specific power	228 W/m^2	223 W/m^2	230 W/m^2	403 W/m^2	331 W/m^2	291 W/m^2
Plant lifetime	30 years	30 years	30 years	30 years	30 years	30 years

[*] Values were calculated using a linear interpolation of wind turbine and plant characteristics from the Base scenario (2020) to the Advanced scenario (2030) using ATB 2022 data (NREL 2022) and a linear extrapolation of 2020-2030 trends through 2050 (up to a maximum hub height of 200 m, rotor diameter of 331 m, and turbine rating of 25 MW for offshore wind and a maximum hub height of 140 m, rotor diameter of 210 m, and turbine rating of 8 MW for land-based wind).

2.2.3 Technology Configuration

We use the technology configuration in the REMPD to incorporate technology changes over time. These technology configurations are developed by assigning market shares for alternative materials and subcomponent technologies based on available data, projections, and expert opinion. There are a variety of technology innovations that could modify the material requirements for wind energy technologies.[8] In this analysis, we use two technology configurations: 1) Low Innovation, which is based on current technology, and 2) Moderate Innovation, which includes three materials-related technology innovations. Both configurations are summarized in Table 5.[9]

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[8] Refer to Table 10 for a list of potential innovations that might impact each wind energy component.

[9] Refer to Section 2.2.3.1 and 2.2.3.2, respectively, for more details about each configuration.

Table 5. Technology Configurations for Material Quantities and Availability Analysis

	Low Innovation (Used in Our Current Policies Scenario)	Moderate Innovation (Used in Our High Deployment Scenario)
Land-Based Wind		
Foundation	Concrete spread foot	Concrete spread foot
Tower	Transportable tubular steel can	50% transportable tubular steel can 25% spiral-welded steel 25% hybrid steel and concrete
Generator	100% high-speed geared	100% high-speed geared
Blades	Fiberglass/thermoset shell Fiberglass/thermoset spar cap 50% balsa core 50% foam core	Segmented blade tip Fiberglass/thermoset shell Carbon fiber/thermoset spar cap 50% balsa core 50% foam core
Offshore Wind		
Substructure	Steel monopile	80% steel monopile 15% steel jacket 2% concrete gravity base 3% steel semisubmersible
Tower	Tubular steel can	Tubular steel can
Generator	100% permanent-magnet synchronous generator	100% permanent-magnet synchronous generator
Blades	Fiberglass/thermoset shell Carbon fiber/thermoset spar cap 50% balsa core 50% foam core	Fiberglass/thermoset shell Carbon fiber/thermoset spar cap 50% balsa core 50% foam core

2.2.3.1 *Low Innovation*

As shown in Table 5, under the Low Innovation technology configuration, we assume that land-based and offshore wind plants rely on current technology with no materials-related technology innovations over time. For example, land-based wind towers and foundations use conventional designs: a spread-foot foundation made from concrete and steel rebar, and a transportable tubular steel tower. The blade material quantities assume that fiberglass is used throughout the blade, with a conventional thermoset resin. The blade core material is assumed to be 50% balsa wood and 50% foam. When assessing material properties, we assume polyvinyl chloride (PVC) foam is used in the core, although other polymers such as polyethylene terephthalate may be substituted. Materials used in the nacelle vary depending on the type of generator. Worldwide, nearly 30% of wind turbines use permanent-magnet synchronous generators, whereas 70% use high-speed geared generators, and around 2% use electrically excited synchronous generators (European Commission et al. 2020b). In the United States, the share of permanent-magnet synchronous generators is lower at approximately 2%, with most wind turbines using high-speed geared generators. In the Low Innovation technology configuration, we assume 100% of land-based systems use high-speed geared generators.

For offshore wind technology, the Low Innovation technology configuration assumes fixed-bottom steel monopile foundations with tubular steel towers. Given the limited number of offshore wind turbines currently in U.S. waters, the generator type is drawn from data provided by original equipment manufacturers, which assume offshore turbines will be constructed largely using permanent-magnet synchronous generators. Fiberglass is used for the blade shell, with carbon fiber used for the spar caps. Like land-based wind turbines, 50% of blades are assumed to use balsa wood while the remainder use PVC foam cores.

2.2.3.2 Moderate Innovation

The Moderate Innovation technology configuration includes spiral-welded towers, hybrid towers, and segmented blades with carbon-fiber spar caps. Spiral-welded towers enable on-site manufacturing of larger (taller) towers that would be difficult to transport using traditional tubular steel can towers. Hybrid towers are constructed using a hybrid of concrete and steel to help enable taller towers for land-based systems. In the Moderate Innovation technology configuration, we assume 25% of land-based systems will use hybrid towers. We also assume that 25% of land-based towers will be spiral welded. The remaining 50% of land-based towers and all offshore towers are assumed to be assembled from conventional transportable tubular steel "can" segments. In the Moderate Innovation technology configuration, we assume 100% of future land-based systems will use segmented blades. Segmented blades incorporate carbon spar caps and segmentation to enable the transport of longer blades for land-based systems (refer to Appendix D.7 for more details). No other technology innovations (e.g., changes in generator types or other technology changes) are included in the Moderate Innovation technology configuration.

3 Projected Material Needs for U.S. Wind Energy Systems

There are more than 200 unique foreground system materials and more than 1,700 unique background system material flows in the proprietary version of the REMPD.[10] To improve the interpretability of this analysis, we group these materials into seven major categories:

1. Concrete
2. Road aggregate (crushed rock, stones, and gravel)
3. Steel (including electrical steel)
4. Composites and polymers (including carbon fiber in carbon-fiber-reinforced polymers)
5. Cast iron
6. Other metals and alloys (including 16 critical minerals)
7. Other materials (including graphite).

We use these categories to discuss the results of our analysis and perform a more detailed analysis on 19 vulnerable materials (defined in Table 1). The vulnerable materials that we explore fall into different material categories (e.g., electrical steel is included with other types of steel in the "Steel" category and most critical minerals are included in the "Other metals and alloys" category).

In this section, we summarize material intensities of current and potential future wind energy technologies, discuss the projected material needs for U.S. wind energy systems over time, compare projected needs for all materials to the amount of material that is currently produced, and compare vulnerable material needs to projected availability.

3.1 Material Intensities of Current and Potential Future Wind Energy Technologies

Figure 6 illustrates the total material intensities of current and potential future[11] wind energy technologies and how the material requirements break down by material category. For example, current land-based wind power plants require about 1,200 metric tonnes (t) of material per megawatt, comprised (by mass) of approximately 53% road aggregate, 34% concrete, 9% steel, 2% composites and polymers, 1% cast iron, 1% other metals and alloys, and less than 1% other materials. Future land-based wind plants may contain a larger proportion of concrete due to bigger foundations required for larger and taller turbines and more concrete in hybrid towers. These changes could shift the material breakdown of the future land-based wind plants by mass to 46% concrete, 39% road aggregate, 10% steel, 3% composites and polymers, 1% cast iron, 1% other metals and alloys, and the remainder other materials. Offshore wind plants currently require about 300 t of material per megawatt, comprised (by mass) of 87% steel, 5% other metals and alloys, 4% composites and polymers, 3% cast iron, and 1% other materials. Shifts in material

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[10] Refer to Section 2.1.3 and Figure 3 for a definition of the foreground and background systems.

[11] Potential future technology is represented using results from the High Deployment scenario in the year 2050 (see Table 2 for more details about the High Deployment scenario definition).

requirements for land-based wind in the High Deployment scenario are due to the technology configuration changes and moderate materials-related technology that are assumed in this scenario; the High Deployment scenario does not predict major changes to the material requirements for future offshore wind plants. Concrete is used in the High Deployment scenario for some offshore wind substructures; it represents a large fraction of the material use in those facilities but only 3% of the average material intensity because concrete gravity-base substructures make up only 2% of predicted installations.

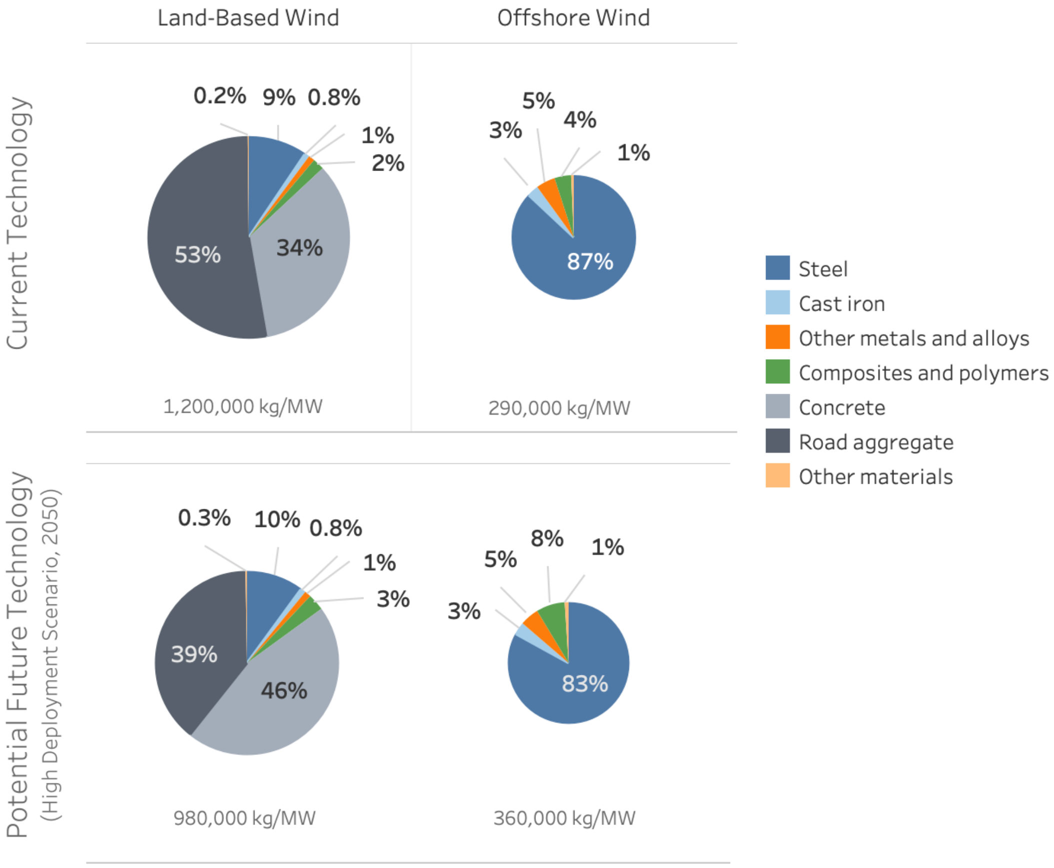

Figure 6. Material intensities of current and potential future wind energy technologies

Table 6 and Table 7, respectively, provide more details about the average material intensities of current and future wind energy technologies shown in Figure 6. The tables break down the material intensities by facility, component, subassembly, and material type. For example, a current land-based wind turbine tower requires approximately 66 t of steel, 2.7 t of other metals and alloys, 0.1 t of composites and polymers, and 0.2 t of other materials per megawatt of installed capacity (Table 6). Current offshore towers require about 31 t of steel, 1.4 t of other metals and alloys, 0.1 t of composites and polymers, and 0.2 t of other materials per megawatt of installed capacity. The material intensity of future offshore towers in the High Deployment scenario increases slightly but the relative contribution of each material remains similar (Table 7). However, future land-based towers could require 15 t of concrete in addition to 52 t of steel, 2.2 t of other metals and alloys, 0.1 t of composites and polymers, and 0.2 t of other materials per megawatt of installed capacity due to the adoption of hybrid steel-concrete towers.

Array and export cables for land-based systems mostly comprise composites and polymers, along with other metals and alloys (mostly aluminum). Offshore array and export cables also contain lead and galvanized steel. Foundations in land-based wind plants comprise mostly concrete with a small amount of steel reinforcement, and substructures in offshore systems are built almost entirely from steel. Roads are only used in land-based systems and are comprised of aggregate. Offshore substations use steel as the primary structural material; electrical equipment within the substation uses more steel (including electrical steel), along with other metals and alloys (e.g., copper) and a small fraction of composites and polymers and other materials. Land-based substations use these materials along with concrete and cast iron.

Table 6. Average Material Intensity of Current Wind Energy Technologies (2020)

			Average Material Intensity (metric tonnes [t]/megawatt [MW]) of Current Wind Energy Technologies by Material Category						
	Component	Subassembly	Steel	Cast iron	Other metals and alloys	Composites and polymers	Concrete	Road aggregate	Other materials
Land-Based Wind	Array and export cables	Total*			3.6	4.4			
	Foundation	Total*	20.8		1.0	<0.01	398.1		<0.01
	Roads	Total*						613.0	
	Substation	Total*	1.0	<0.01	0.2	0.1	0.6		0.2
	Turbine	Blades	0.3		<0.01	15.8			1.1
		Hub	4.8	2.5	0.2	0.1			<0.01
		Nacelle	17.0	6.3	3.8	1.0			0.3
		Tower	66.0		2.7	0.1			0.2
Offshore Wind	Array and export cables	Array cable	0.6		2.6	0.7			0.2
		Export cable	<0.01		0.5	0.5			0.1
		Onshore cable			<0.01	<0.01			
	Substructure	Monopile	144.5		4.9				
		Transition piece	51.5		1.8				
	Substation	Substation equipment	0.3		0.1	<0.01			0.2
		Support structure	7.0		0.2				
	Turbine	Blades	0.3		<0.01	10.4			0.9
		Hub	3.0	0.9	0.2	<0.01			<0.01
		Nacelle	11.5	7.8	2.6	0.7			0.4
		Tower	30.9		1.4	0.1			0.2

* Only total component data are available for these components; these data are not broken down by subassembly.

Table 7. Average Material Intensity of Potential Future Wind Energy Technologies (As Defined Based on Technology Projections and Expert Input Used in the High Deployment Scenario, 2050)

	Component	Subassembly	Material Intensity (t/MW) of Potential Future Wind Energy Technologies by Material Category						
			Steel	Cast iron	Other metals and alloys	Composites and polymers	Concrete	Road aggregate	Other materials
Land-Based Wind	Array and export cables	Total*			3.6	4.4			
	Foundation	Total*	22.8		1.1	<0.01	434.4		<0.01
	Roads	Total*						383.9	
	Substation	Total*	1.0	<0.01	0.2	0.1	0.6		0.2
	Turbine	Blades	0.8		0.1	22.9			1.7
		Hub	4.8	2.5	0.2	0.1			<0.01
		Nacelle	16.7	6.2	3.8	1.0			0.3
		Tower	52.8		2.2	0.1	15.2		0.2
Offshore Wind	Array and export cables	Array cable	0.6		2.6	0.7			0.2
		Export cable	<0.01		0.5	0.5			0.1
		Onshore cable			<0.01	<0.01			
	Substructure	Pile/jacket/floater	218.1		7.4				
		Gravity base			<0.01		11.5	2.3	<0.01
	Substation	Substation equipment	0.3		0.1				0.2
		Support structure	7.0		0.2				
	Turbine	Blades	0.5		<0.01	19.2			1.7
		Hub	4.9	1.5	0.3	<0.01			<0.01
		Nacelle	11.4	7.7	2.6	0.7			0.4
		Tower	50.9		2.4	0.2			0.4

* Only total component data are available for these components; these data are not broken down by subassembly and instead provide a total value equal to the material requirements for all subassemblies associated with the component.

3.1.1 Variation in Material Intensities for Vulnerable Materials

Figure 7 shows how the material intensities for vulnerable materials could differ between current and potential future wind energy technologies (see Tables E-1 and E-2 for the underlying data used to develop this figure).

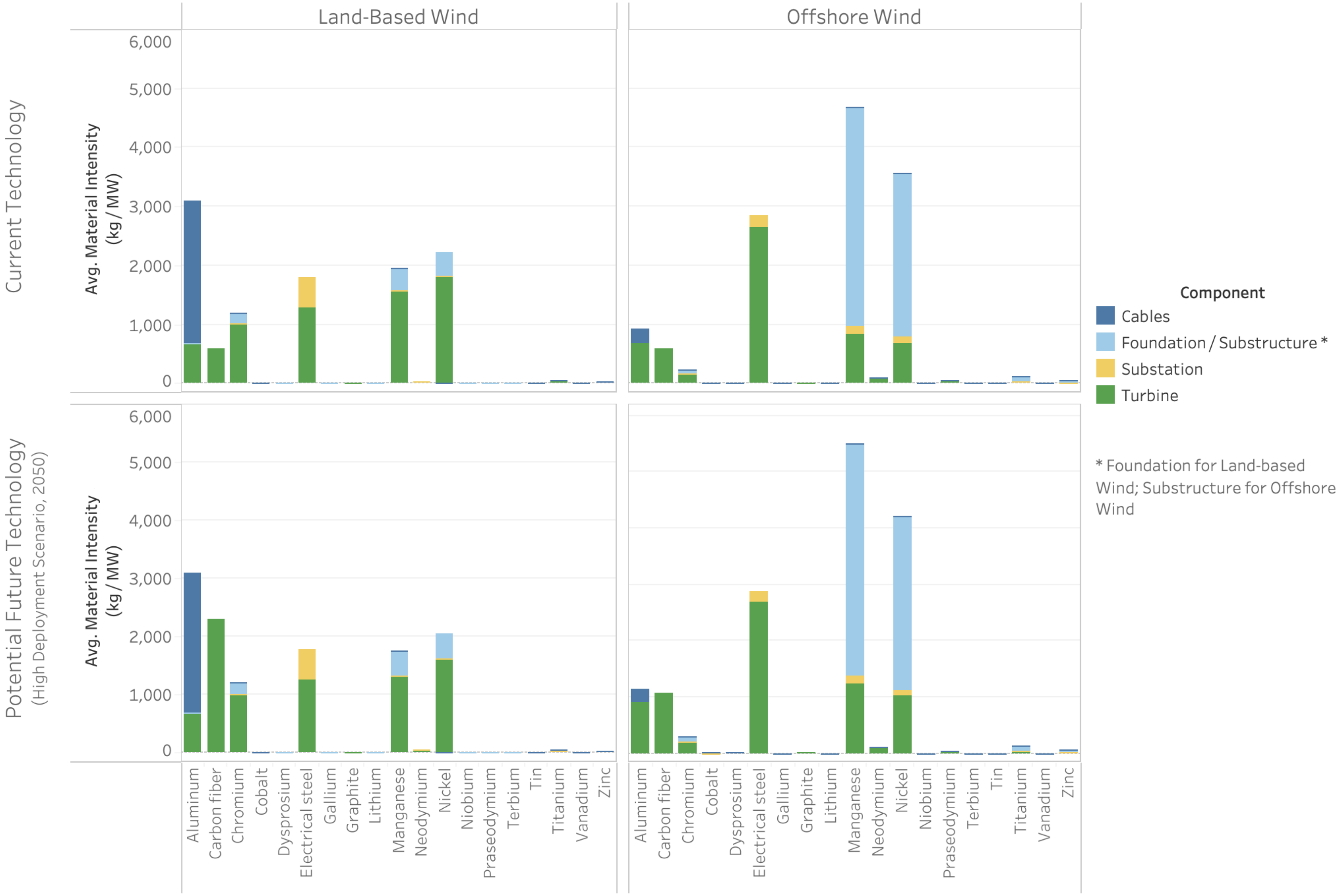

Figure 7. Average material intensities for vulnerable materials as determined using the Current Policies and High Deployment scenarios

For current and potential future technology in both land-based and offshore wind systems, the vulnerable materials with the highest average material intensities are aluminum, carbon fiber, chromium, electrical steel, manganese, and nickel. Aluminum is mostly used in the cables, tower, and nacelle. Carbon fiber is used solely in the wind turbine blades. Chromium is primarily used in the nacelle and foundation in land-based wind plants and in the nacelle and hub in offshore wind plants. Electrical steel is used mostly in the nacelle and substation. Manganese and nickel are primarily used in the tower and foundation (land-based) or substructure (offshore).

As shown in Figure 7, the average material intensities for vulnerable materials used in land-based wind plants do not change much for current versus potential future technology, except for carbon fiber. The material intensity for carbon fiber is higher for potential future technology because blade lengths are expected to increase more quickly than rated power, and the High Deployment scenario assumes the use of segmented blades, which are expected to require more carbon fiber. For offshore wind, longer blades and lower specific power also contribute to an increase in the average material intensity for carbon fiber. Material intensities of chromium, manganese, and nickel all increase for offshore wind because these vulnerable materials are used in steel manufacturing and more steel is required per megawatt to build larger turbines with taller towers and substructures in the High Deployment scenario.

3.2 Projected U.S. Wind Energy Demand for Materials

Figure 8 illustrates the projected U.S. wind energy demand for our seven categories of wind energy materials as estimated using the assumptions outlined in the Current Policies and High Deployment scenarios (see Table 2 for more details about how we defined these scenarios). Figure 9 shows the projected U.S. wind energy demand for a subset of these materials, specifically vulnerable materials. In both Figure 8 and Figure 9, average annual material requirements generally follow capacity projection trends (see Figure 5). Material requirements are primarily driven by land-based wind capacity additions, which are more than seven times higher than offshore wind. Land-based wind plants are also more material-intensive than offshore facilities because they require large quantities of concrete to construct foundations and aggregate for roads.[12] As a result, the total material requirements for land-based wind energy technologies are 25 to 35 times greater than for offshore wind.

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[12] See Section 3.1, including Figure 6, Table 6, and Table 7 for more details on the differences in material intensities between land-based and offshore wind energy technologies.

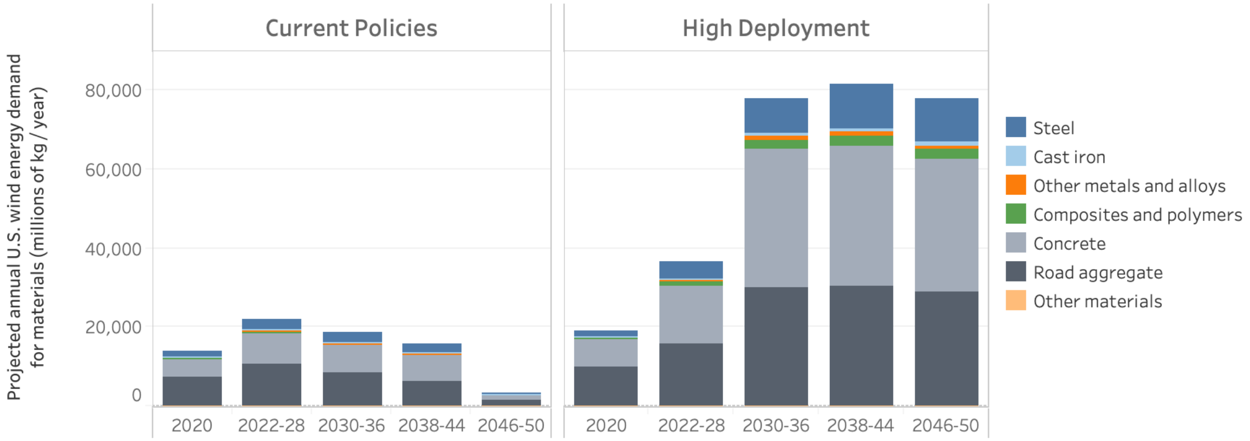

Figure 8. Average quantity per year of all materials required for land-based and offshore wind technologies as determined using the Current Policies and High Deployment scenarios

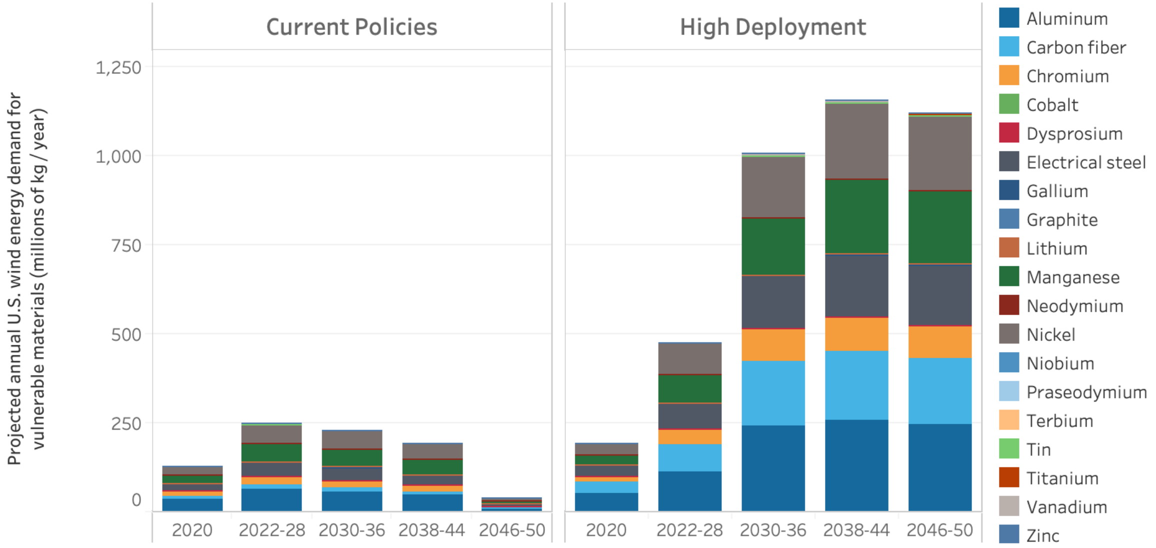

Figure 9. Average quantity per year of vulnerable materials required for land-based and offshore wind technologies as determined using the Current Policies and High Deployment scenarios

3.2.1 Projected Changes in Material Intensity Over Time

The trends in material quantities shown in Figure 8 are further explained by examining the change in material intensity of each technology over time (Figure 10). As shown in Figure 10, land-based wind plants require a total of 1,000-1,200 t of material per megawatt compared to 300-350 t of material per megawatt for offshore wind.[13] Land-based wind energy projects show the most change in material intensity over time. This variation is primarily driven by road aggregate requirements, which decrease over time because fewer miles of roads are needed per unit of capacity to access larger wind turbines. In addition, the amount of concrete required per megawatt for land-based foundations generally increases as the rotor size and hub height increase. There is also a slight increase in the material intensity of offshore wind over time in both scenarios due to greater material requirements for taller towers.

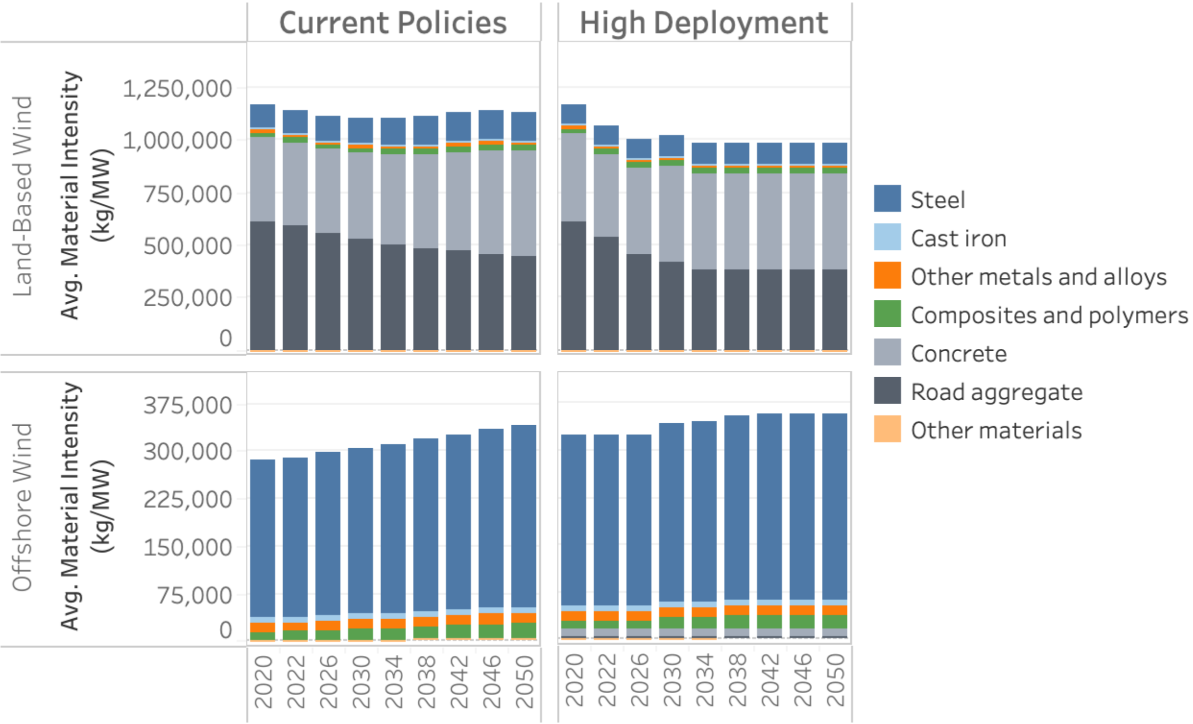

Figure 10. Annual material intensity for land-based and offshore wind in the Current Policies and High Deployment scenarios

3.3 Projected U.S. Wind Energy Demand for Materials Compared to Current Production

To put the projected material needs for U.S. wind energy technologies into context, we compared the U.S. wind energy demand for nonvulnerable materials in each analysis scenario to global and U.S. production of each material in 2020 (Figure 11).

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[13] See Figure 6, Table 6, and Table 7 for more details about the differences in material requirements and the breakdown of material quantities by material type, facility, component, and subassembly.

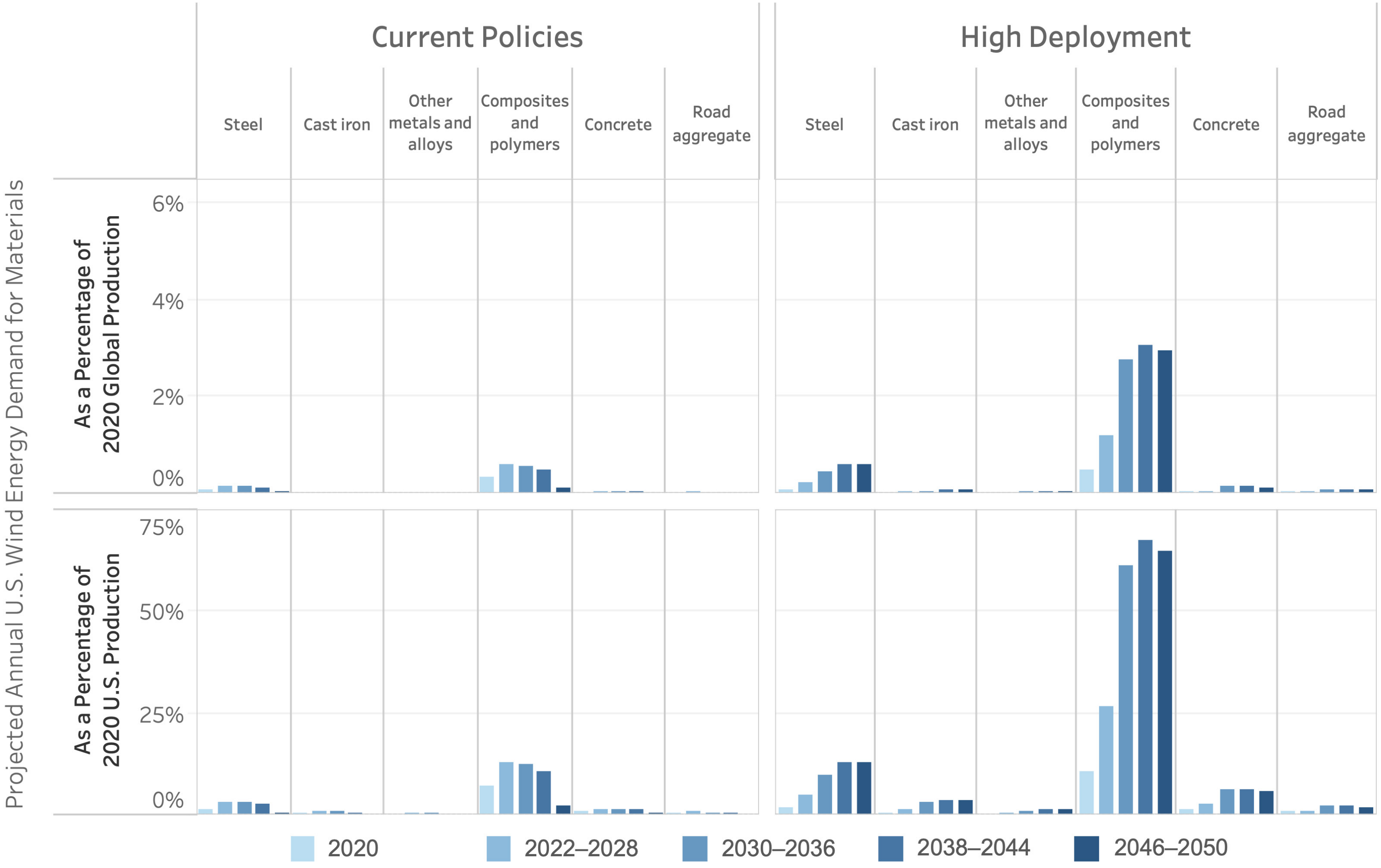

Figure 11. Projected annual U.S. wind energy demand for nonvulnerable materials, as estimated in the Current Policies and High Deployment scenarios as a percentage of 2020 production

Results are presented for global (top row) and United States (bottom row) production.

Future availability of these materials depends on many factors, including the mineral resources, cost of extraction, and global level of demand from various industries. Current production levels provide an initial data point from which to estimate production in future years.

In both scenarios, the quantity of nonvulnerable materials needed to satisfy U.S. wind energy demand comprise less than 4% of the 2020 global production (top row of Figure 11). The quantities of cast iron, other nonvulnerable metals and alloys, and road aggregate needed to satisfy U.S. wind energy demand through 2050 also comprise less than 5% of the total annual U.S. production of these materials in both scenarios (assuming future average U.S. production levels remain the same as in 2020; bottom row of Figure 11).

However, the projected annual U.S. wind energy demand for composites and polymers, steel, and concrete could exceed 5% of 2020 U.S. production of these materials (bottom row of Figure 11). Under the Current Policies scenario, demand for steel and concrete remains below 5% of current U.S. production, whereas demand for composites and polymers from 2022 through 2036 represents approximately 12% of the total amount of these materials produced in the United States in 2020. In the High Deployment scenario, demand for composites and polymers, steel, and other metals and alloys is even higher. From 2038 to 2044, U.S. wind energy demand for composites and polymers, steel, and concrete could consume 67%, 13%, and 6% of the amount of U.S. production of these materials in 2020, respectively. Thus, it is important to consider how to mitigate potential supply risks for these nonvulnerable materials—especially composites and polymers—to enable high levels of wind energy deployment.

Demand for specific materials (e.g., vulnerable materials such as carbon fiber, nickel, and dysprosium) may comprise an even higher portion of U.S. production. For vulnerable materials, we performed a more detailed analysis and examined how the material needs for wind energy technologies in each scenario compare to U.S. production, global production, U.S. reserves, and global reserves (Table 8, Figure 12, Figure 13, and Figure 14). Table 8 provides the production and reserve values for each vulnerable material and additional information about the significant uses of these vulnerable materials along with a breakdown of material quantities by country of origin. Figures 12-14 illustrate how the material requirements compare to production and reserves. The distribution of countries supplying raw materials to the United States varies in many instances from global production levels, reflecting trade ties between individual companies or nations. Comparisons against global production provide a high-level overview of how the magnitudes of total global production compare to material needs for wind energy technologies.

Table 8. Uses, Sources, Production, Reserves, and Projected Wind Material Needs for Vulnerable Materials

Material	Other Significant Uses[a]	Country of Origin		Total Global Production (millions of kilograms [kg] in 2020)	Total Global Reserves (millions of kg)	Ranges of Projected Material Needs for U.S. Wind Energy Technologies (millions of kg)	
		Global Production	*U.S. Import Sources (2016–2019)*			*Current Technology (Current Policies Scenario, 2020)*	*Potential Future Technology (High Deployment Scenario, 2050)*
Carbon fiber	Transportation (aerospace, automotive, marine), consumer goods (pressure vessels, sports equipment)	United States (28%) Japan (13%) China (13%) Turkey (12%) Hungary (5%) Taiwan (5%) Others (24%)	Data not available	192	N/A	7–28	240–260
Electrical steel	Machinery and appliances (transformers, motors, inductors)	South Korea (14%) China (14%) Japan (12%) Germany (11%) Russia (10%) Others (39%)	Japan (21%) Korea (21%) France (13%) Austria (11%) China (6%) Others (28%)	20,000	N/A	18–63	190–570
Critical Minerals							
Aluminum	Transportation (aviation and automotive), consumer goods, packaging, construction, electrical, machinery and appliances	China (57%) Russia (6%) India (5%) Canada (5%) Others (27%)	Canada (50%) United Arab Emirates (10%) Russia (9%) China (5%) Others (26%)	65,200	32,000,000	34–49	300–420
Chromium	Steel (stainless and heat-resisting steel), other steel alloys	South Africa (36%) Turkey (22%) Kazakhstan (19%) India (7%) Finland (6%) Others (10%)	South Africa (39%) Kazakhstan (8%) Mexico (6%) Russia (6%) Others (41%)	37,000	570,000	14–47	110–390
Cobalt	Alloys (superalloys, other alloys), chemicals, steel	Congo (73%) Russia (5%) Others (22%)	Norway (20%) Canada (14%) Japan (13%) Finland (10%) Others (43%)	165	7,600	0.03–0.07	0.3–0.6

Material	Other Significant Uses[a]	Country of Origin		Total Global Production (millions of kilograms [kg] in 2020)	Total Global Reserves (millions of kg)	Ranges of Projected Material Needs for U.S. Wind Energy Technologies (millions of kg)	
		Global Production	*U.S. Import Sources (2016–2019)*			*Current Technology (Current Policies Scenario, 2020)*	*Potential Future Technology (High Deployment Scenario, 2050)*
Dysprosium[b]	Magnets, ceramics and glass, battery alloys, catalysts	China (58%) United States (16%) Burma (13%) Australia (9%) Others (4%)	China (80%) Estonia (5%) Japan (4%) Malaysia (4%) Others (7%)	2.4	44	0.02–0.09	0.3–0.8
Gallium	Electronics (integrated circuits, optoelectronic devices)	China (97%) Others (3%)	China (55%) United Kingdom (11%) Germany (10%) Others (24%)	0.33	100	0.0006–0.002	0.005–0.01
Graphite (natural)	Metal products (bearings, brake lining, lubricants), rubber	China (79%) Brazil (7%) Others (14%)	China (33%) Mexico (23%) Canada (17%) India (9%) Others (18%)	970	320,000	0.04–0.2	0.3–1.1
Lithium	Batteries, ceramics and glass, lubricating greases	Australia (48%) Chile (26%) China (16%) Argentina (7%) Others (3%)	Argentina (55%) Chile (36%) China (5%) Others (4%)	83	22,000	0.008–0.04	0.06–0.22
Manganese	Steel	South Africa (34%) Australia (18%) Gabon (18%) China (7%) Others (23%)	Gabon (20%) South Africa (19%) Australia (15%) Georgia (10%) Others (36%)	19,000	1,500,000	22–35	220–410
Neodymium[b]	Magnets, ceramics and glass, battery alloys, catalysts	China (58%) United States (16%) Burma (13%) Australia (9%) Others (4%)	China (80%) Estonia (5%) Japan (4%) Malaysia (4%) Others (7%)	40.8	1,200	0.5–1.9	6–18

Material	Other Significant Uses[a]	Country of Origin		Total Global Production (millions of kilograms [kg] in 2020)	Total Global Reserves (millions of kg)	Ranges of Projected Material Needs for U.S. Wind Energy Technologies (millions of kg)	
		Global Production	*U.S. Import Sources (2016–2019)*			*Current Technology (Current Policies Scenario, 2020)*	*Potential Future Technology (High Deployment Scenario, 2050)*
Nickel	Steel (stainless and heat-resisting steel), superalloys, batteries	Indonesia (31%) Philippines (13%) Russia (11%) New Caledonia (8%) Australia (7%) Canada (7%) China (5%) Others (18%)	Canada (42%) Norway (10%) Finland (9%) Russia (8%) Other (31%)	2,500	95,000	26–56	240–550
Niobium	Steel, superalloys	Brazil (90%) Canada (10%)	Brazil (66%) Canada (22%) Others (12%)	65	18,000	0.004–0.005	0.03–0.06
Praseodymium[b]	Magnets, ceramics and glass, battery alloys, catalysts	China (58%) United States (16%) Burma (13%) Australia (9%) Others (4%)	China (80%) Estonia (5%) Japan (4%) Malaysia (4%) Others (7%)	14.4	370	0.006–0.01	0.8–1.5
Terbium[b]	Magnets, ceramics and glass, battery alloys, catalysts	China (58%) United States (16%) Burma (13%) Australia (9%) Others (4%)	China (80%) Estonia (5%) Japan (4%) Malaysia (4%) Others (7%)	0.5	10	<0.0001	0.006–0.012
Tin	Alloys, coatings (tinplate), chemicals, metal products (solder)	China (32%) Indonesia (20%) Burma (11%) Peru (8%) Congo (7%) Bolivia (6%) Brazil (6%) Others (10%)	Indonesia (24%) Malaysia (21%) Peru (20%) Bolivia (17%) Other (18%) Scrap: Canada (99%)	260	4,900	0.002–0.004	0.02–0.05

Material	**Other Significant Uses**[a]	**Country of Origin**		**Total Global Production (millions of kilograms [kg] in 2020)**	**Total Global Reserves (millions of kg)**	**Ranges of Projected Material Needs for U.S. Wind Energy Technologies (millions of kg)**	
		Global Production	*U.S. Import Sources (2016–2019)*			*Current Technology (Current Policies Scenario, 2020)*	*Potential Future Technology (High Deployment Scenario, 2050)*
Titanium	Steel, superalloys	China (53%) Japan (21%) Russia (13%) Kazakhstan (7%) Others (6%)	Japan (90%) Kazakhstan (7%) Others (3%)	230	750,000	0.6–0.9	6–10
Vanadium	Steel, other alloys, catalysts	China (67%) Russia (19%) South Africa (8%) Brazil (6%)	Canada (26%) China (14%) Brazil (10%) South Africa (9%) Others (41%)	105	24,000	<0.0001	<0.0001
Zinc	Coatings (galvanization), rubber, chemicals, paint, agriculture	China (34%) Australia (11%) Mexico (5%) Peru (11%) United States (6%) India (6%) Others (27%)	Peru (98%) Others (2%)	12,000	250,000	0.4–1.3	3–11

a. Other significant uses than wind energy technologies. Data are primarily drawn from the USGS *Metals and minerals: U.S. Geological Survey Minerals Yearbooks* (most recent available, 2018-2022) and are supplemented with data from the National Ready Mixed Concrete Association (https://www.nrmca.org/), the UN Comtrade Database (https://comtrade.un.org/data/), BloombergNEF (2020), and Carrara et al. (2020).

b. The source and other significant uses information reported for dysprosium, neodymium, praseodymium, and terbium correspond to data for all rare-earth compounds and metals (they are not specific to each of the individual elements) because these data are not available at the level of individual elements.

As shown in Figure 12 and Figure 13, the projected annual U.S. wind energy demand for vulnerable materials is anticipated to require less than 10% of global 2020 production for all materials in the Current Policies scenario. However, in the High Deployment scenario, U.S. wind energy demand for carbon fiber could reach 101% of 2020 global production (Figure 12) and demand for neodymium could reach 12% of 2020 global production from 2038 to 2044 (Figure 13); U.S. wind energy demand for all other materials is below 10% of global production in the High Deployment scenario.

From a domestic perspective, U.S. wind energy demand for nickel, electrical steel, and carbon fiber could require up to 317%, 18%, and 25% of 2020 levels of U.S. production of these materials between 2022 and 2028 in the Current Policies scenario. In the High Deployment scenario, demand for wind energy materials is highest after 2030. From 2030 to 2045, U.S. wind energy demand for nickel, electrical steel, and carbon fiber could approach, respectively, 1,200%, 75%, and 400% of 2020 levels of U.S. production in the High Deployment scenario.

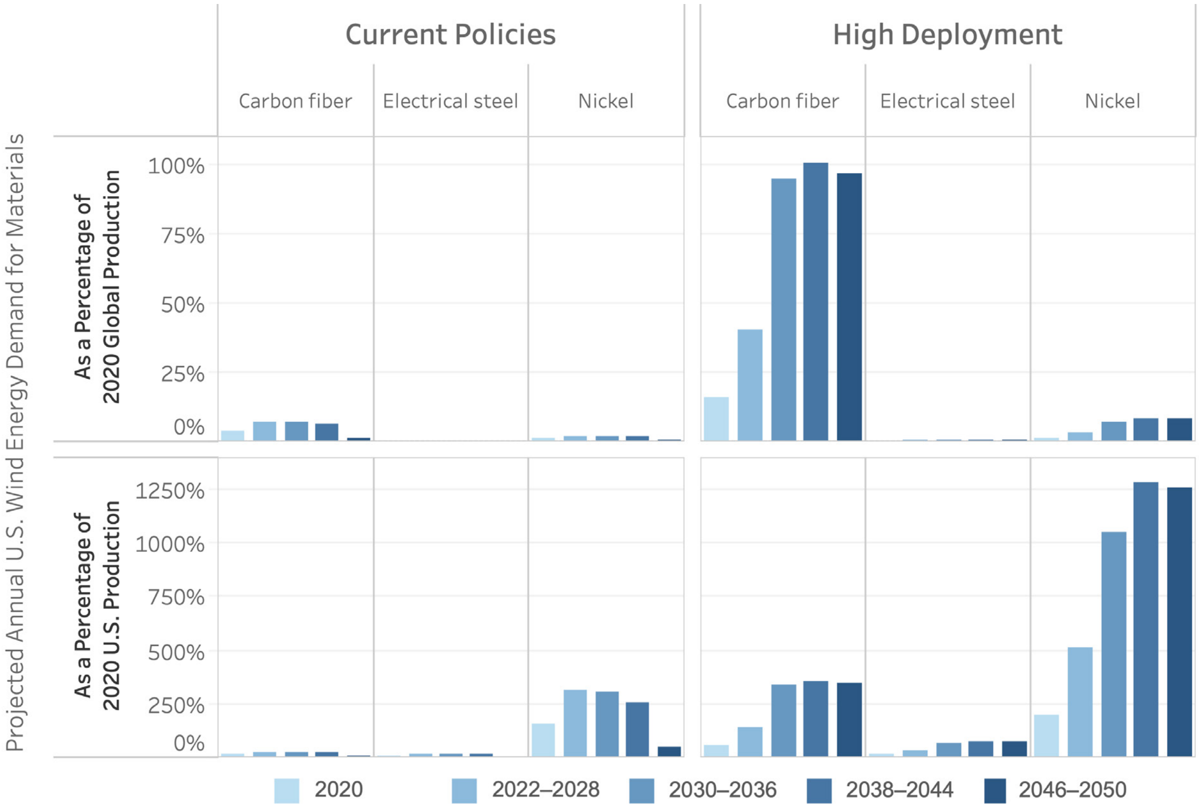

Figure 12. Projected U.S. wind energy demand for carbon fiber, electrical steel, and nickel, as estimated in the Current Policies and High Deployment scenarios as a percentage of 2020 production.

Results are presented for global (top row) and United States (bottom row) production.

Figure 13 illustrates the projected annual U.S. wind energy demand as a percentage of production in 2020 for a subset of vulnerable materials excluding carbon fiber, electrical steel, and nickel. Demand for these materials is compared with global production in the top portion of

Figure 13 and U.S. production in the bottom portion of the figure.[14] Here, we can see that U.S. wind energy demand for this subset of vulnerable materials comprises less than 12% of 2020 global production in both the Current Policies and High Deployment scenarios. However, in the High Deployment scenario, demand for neodymium and dysprosium reaches 69% and 55%, respectively, of 2020 U.S. production from 2038 to 2044; demand for praseodymium, cobalt, and aluminum also rises to 20%-35% of 2020 domestic production levels.

Overall, these results indicate that current domestic production levels of carbon fiber and nickel may be lower than the amount required to achieve high levels of wind energy deployment in the United States consistent with a net-zero economy. Additionally, U.S. wind energy demand for rare-earth elements (i.e., dysprosium and neodymium) and electrical steel may comprise a large portion of domestic production (if production does not increase beyond 2020 levels). And, globally, production of carbon fiber would need to increase to meet demand for wind energy. Demand from other sectors of the economy may further limit availability of certain materials. For instance, demand from electric vehicles could further constrain carbon fiber, neodymium, and praseodymium supplies. A strategy to avoid supply issues could be to diversify imports: when considering global production, U.S. wind energy demand for vulnerable materials never exceeds 10% of global production (in either scenario) except for neodymium and carbon fiber in the High Deployment scenario.

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[14] Demand for chromium, gallium, graphite, lithium, manganese, niobium, tin, and titanium are not compared with domestic production because lithium and titanium production data were withheld from publication and the other materials are not mined domestically (USGS 2021).

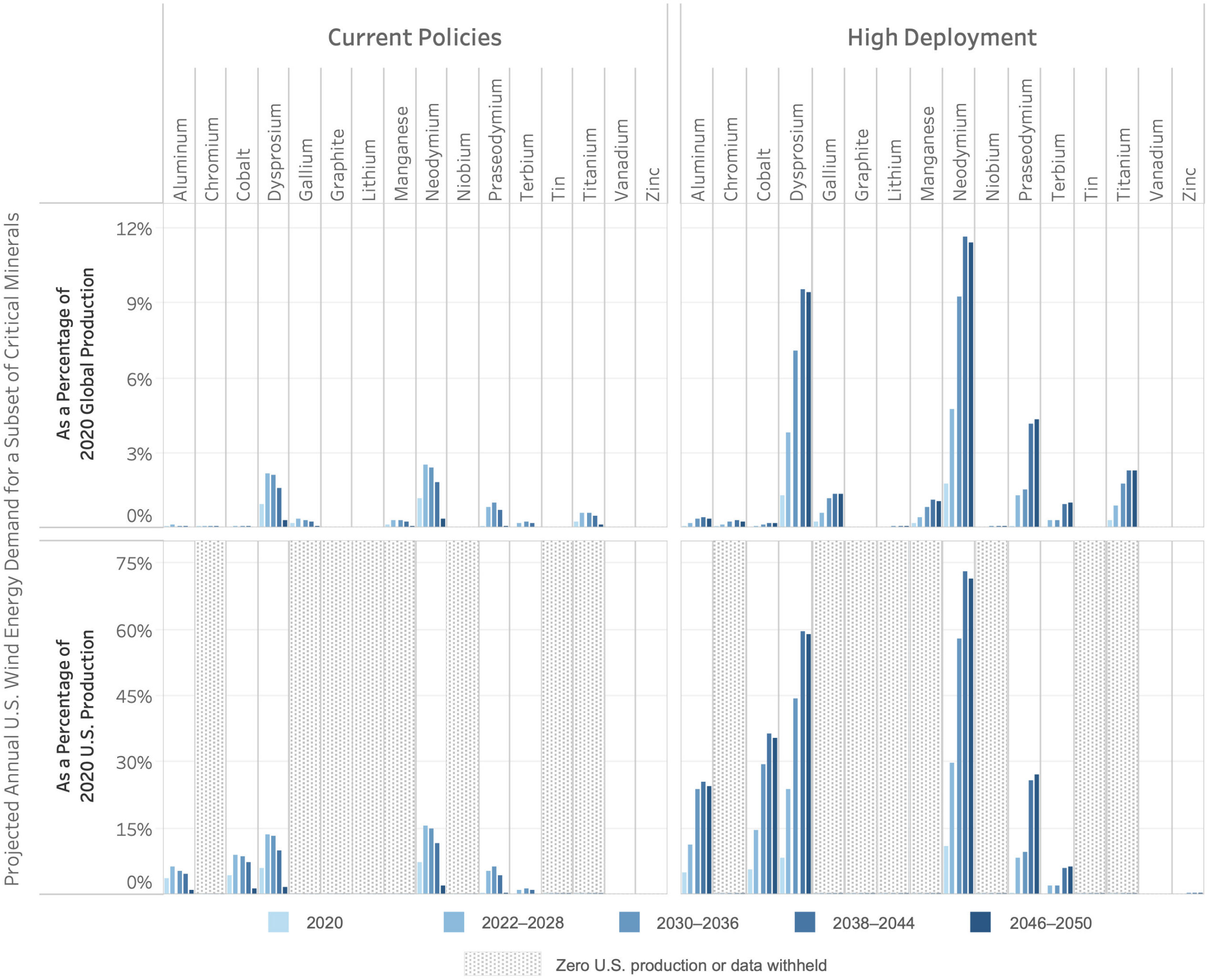

Figure 13. Projected U.S. wind energy demand for a subset of vulnerable materials (excluding nickel, carbon fiber, and electrical steel), as estimated in the Current Policies and High Deployment scenarios as a percentage of 2020 production.

Results are presented for global (top row) and United States (bottom row) production. In 2020, gallium, graphite, manganese, and niobium were not produced in the United States; the United States had no primary production of tin or chromium; and the amount of lithium and titanium production were withheld to protect confidential company data (USGS 2021).

3.4 Material Needs for Wind Energy Technologies Compared to Projected Availability

Projected availability of materials depends on many factors, including mineral resources, cost of extraction, and global level of demand from various industries. Current estimates of reserves provide an initial data point from which to estimate projected availability of materials in future years. Reserves are not estimated for electrical steel and carbon fiber, because the concept of reserves does not apply to these highly processed materials in the same way as for critical minerals.

Figure 14 shows how annual U.S. wind energy demand for critical minerals compares to U.S. and global reserves for each material in the Current Policies and High Deployment scenarios. None of the critical mineral needs for U.S. wind energy technologies are expected to exceed 0.5% of global reserves. Most critical mineral requirements are below 2% of U.S. reserves in both the Current Policies and High Deployment scenarios; the three exceptions are nickel, dysprosium, and chromium. In the High Deployment scenario, annual U.S. wind energy demand for nickel, chromium, and dysprosium could reach 63%, 16%, and 11% of U.S. reserves for each material, respectively, from 2038 to 2044.

Overall, Figure 12, 13, and 14 show that global production and reserves are sufficient to meet the U.S. wind energy demand for all vulnerable materials except carbon fiber. The projected demand for carbon fiber, particularly in the High Deployment scenario, will require large increases in both domestic and global supply. In addition, domestic production or imports of nickel will have to increase significantly to meet the material requirements in the High Deployment scenario particularly after 2030. Depending on competing uses, production of electrical steel, cobalt, and rare-earth elements (dysprosium and praseodymium) may also need to increase.

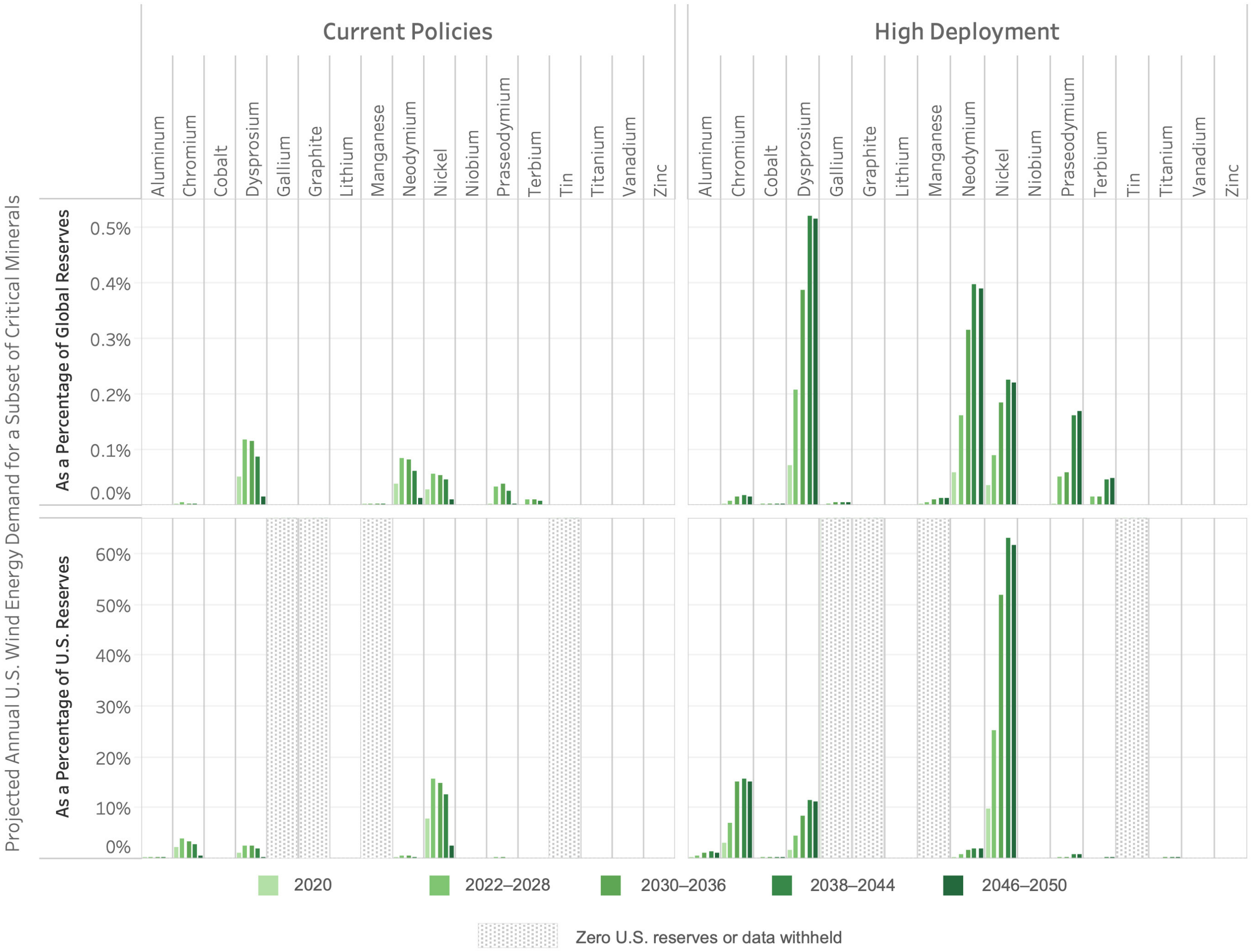

Figure 14. Projected U.S. wind energy demand for critical minerals, as estimated in the Current Policies and High Deployment scenarios as a percentage of reserves.

Results are presented for global (top row) and United States (bottom row) reserves (the United States does not have known, economically recoverable reserves of gallium, graphite, manganese, or tin (USGS 2021).

3.5 High-Level Overview of Material Supply Challenges for U.S. Wind Energy

To assess potential material supply challenges for U.S. wind energy, we examined the potential future U.S. wind energy demand for each material in 2050 as a percentage of U.S. and global production in 2020 (illustrations of these results are shown for vulnerable materials in Figure 12 and Figure 13). In this section, we further discuss challenges for both vulnerable and nonvulnerable materials that could exceed 20% of U.S. or global production in 2050. Our results indicate that there are six types of vulnerable materials that exceed this threshold: carbon fiber, electrical steel, aluminum, cobalt, rare-earth elements (i.e., dysprosium, neodymium, and praseodymium), and nickel (Figure 15). (It is important to note that we do not compare demand for chromium, gallium, graphite, lithium, manganese, niobium, tin, and titanium with domestic production because lithium and titanium production data were withheld from publication and the other materials are not mined domestically (USGS 2021); however, in both of our analysis scenarios, U.S. wind energy demand for all of these materials is below 2% of 2020 global production.) There are also three types of nonvulnerable materials that could pose supply challenges: balsa, copper, and glass fiber. We provide a high-level overview of the challenges in this section and discuss potential opportunities for reducing material requirements more generally in the next section.

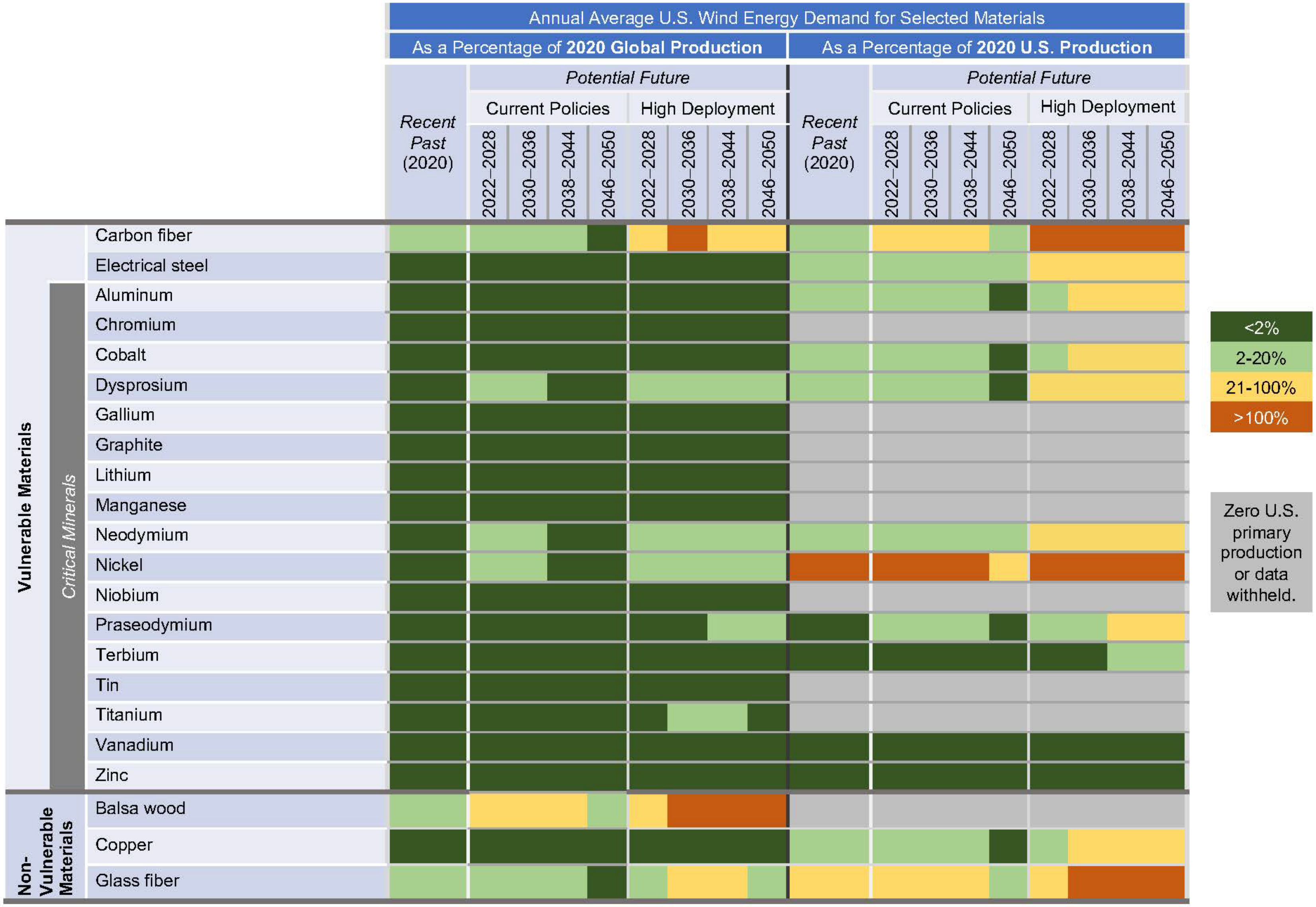

Figure 15. Annual U.S. wind energy demand over time for selected materials as compared to global and U.S. production in 2020

3.5.1 Vulnerable Materials

3.5.1.1 Nickel

As shown in Table 8, nickel is primarily used in the production of stainless and heat-resisting steels. It is also used to produce other steel alloys, superalloys, other nickel alloys, electroplating, chemicals, batteries, catalysts, ceramics, and coinage. Within a wind plant, nickel is mostly used as an alloy for chromium steel and low-alloyed steel and is therefore accounted for within the background system of the REMPD.[15] The wind energy components that use the most of these types of steel (and therefore the most nickel) are the wind turbine tower, the land-based foundation or offshore substructure, and the wind turbine nacelle.

In 2020, Indonesia produced the most nickel (accounting for 30% of global nickel mine production) and U.S. mine production accounted for less than 1% of global nickel production. If future U.S. production levels remain the same as 2020 levels, the two scenarios analyzed here indicate that future U.S. deployment of wind energy technologies could require 97%–1,600% of current U.S. production of nickel and 5%–63% of U.S. reserves of nickel (see Table 9, Figure 12, and Figure 14). Although the estimated world reserves of nickel are more than sufficient to satisfy U.S. wind energy demand for nickel, current U.S. production will not be sufficient to satisfy the nickel needed for U.S. wind energy deployment. In addition, in the first 3 months of 2022, nickel prices increased by more than 60%, a surge that indicates the possibility of future market volatility and supply disruption. As a result, to enable increased U.S. wind energy deployment, it will be important for the U.S. to secure supply of nickel, which could include expanding domestic production and recycling of nickel, identifying alternatives its use in steel manufacturing, identifying alternatives to steel in wind turbine applications (e.g., through the increased use of concrete in hybrid towers), and diversifying imports.

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[15] Refer to Section 2.1.3 for more details about the foreground and background system definitions in the REMPD.

Table 9. Challenges and Opportunities for U.S. Wind Energy Demand of Selected Materials[a]

	Material	**Potential Future U.S. Wind Energy Demand for Selected Materials in 2050**				**Challenges and Opportunities for U.S. Wind Energy**
		As a Percentage of U.S. Production in 2020 (%)		As a Percentage of Global Production in 2020 (%)		
		Current Policies	*High Deployment*	*Current Policies*	*High Deployment*	
Vulnerable Materials	Nickel	97	1,600	1	11	• Global production should be sufficient to satisfy future U.S. wind energy demand for nickel, but it could exceed domestic production levels (if production remains unchanged from 2020 levels) • Expanding domestic production and diversifying imports for nickel could help secure domestic supply • Increasing recycling of nickel, identifying alternatives for nickel in steel manufacturing, and identifying alternatives to steel in wind energy applications could help reduce material requirements
	Carbon fiber	9	440	3	120	• Future wind energy demand for carbon fiber could exceed domestic and global production levels (if production remains unchanged from 2020 levels) • It will be important for the United States to expand domestic production and diversify imports for carbon fiber • Material substitution, recycling, and end-of-life extension could help reduce wind energy material demand for carbon fiber
	Rare-earth elements *Dysprosium:* *Neodymium:* *Praseodymium:*	 3.0 3.8 0.2	 75 91 34	 0.49 0.61 0.03	 12 15 5	• Domestic and global production should be sufficient to satisfy future U.S. wind energy demand for rare-earth elements • Depending on competing uses, it may be important for the United States to expand domestic production and diversify imports of rare-earth elements • Material substitution, technology substitution, and recycling could also help reduce wind energy material demand for rare-earth elements
	Electrical steel	5	94	0.06	1	• Global production should be sufficient to satisfy future U.S. wind energy demand for electrical steel, but it could approach domestic production levels (if production remains unchanged from 2020 levels) • Material substitutions and recycling may not always be viable options for electrical steel • Expanding domestic production and diversifying imports of electrical steel could help secure domestic supply
	Cobalt	3	45	0.01	0.2	• Domestic and global production should be sufficient to satisfy future U.S. wind energy demand for cobalt • Depending on competing uses, it may be important for the United States to expand domestic production and diversify imports of cobalt

	Material	**Potential Future U.S. Wind Energy Demand for Selected Materials in 2050**				**Challenges and Opportunities for U.S. Wind Energy**
		As a Percentage of U.S. Production in 2020 (%)		As a Percentage of Global Production in 2020 (%)		
		Current Policies	*High Deployment*	*Current Policies*	*High Deployment*	
						- Identifying alternatives for cobalt in steel manufacturing and alternatives to steel in wind energy applications could help reduce wind energy material needs for cobalt
Vulnerable Materials	Aluminum	2	31	0.03	0.5	- Domestic and global production should be sufficient to satisfy future U.S. wind energy demand for aluminum - Depending on competing uses, it may be important for the United States to expand domestic production and diversify imports of aluminum - Increasing aluminum recycling and identifying alternatives in wind energy applications could help reduce wind energy material needs for aluminum
Nonvulnerable Materials	Balsa	N/A	N/A	14	520	- Future U.S. wind energy demand for balsa could exceed global production levels (if production remains unchanged from 2020 levels) - Material substitution and end-of-life extension could help reduce wind energy material demand for balsa
	Glass fiber	17	280	2	27	- Global production should be sufficient to satisfy future U.S. wind energy demand for glass fiber, but it could exceed domestic production levels (if production remains unchanged from 2020 levels) - Alternative blade designs, recycling methods, and end-of-life extension could help reduce wind energy material demand for glass fiber
	Copper	2	30	0.06	1	- Domestic and global production should be sufficient to satisfy future U.S. wind energy demand for copper - Depending on competing uses, it may be important for the United States to expand domestic production and diversify imports of copper - Increasing copper recycling and identifying alternatives in wind energy applications could help reduce wind energy material needs for copper

a. The materials presented here were selected based on whether the potential future U.S. wind energy demand for them could exceed 20% of U.S. or global production in 2050 under the Current Policies and High Deployment scenarios considered here. Materials not listed here comprise less than 20% of annual U.S. and global production in 2050 (e.g., U.S. wind energy demand for tin is estimated to be less than 0.1% of U.S. and global production in 2050 [if production levels do not change from 2020 levels]).

3.5.1.2 Carbon Fiber

Carbon fiber is stiff, strong, lightweight, and has good fatigue resistance. It is used in high-strength applications, including the manufacture of wind blades. Outside of the wind industry, it is primarily used in industrial applications for automobiles and pressure vessels. It is also used to manufacture aircraft and produce sports equipment (e.g., bicycles, golf equipment, racquets, and marine applications). Although there are substitutes for carbon fiber (e.g., glass fiber), the performance characteristics of these alternatives are generally lower than that of carbon fiber and therefore design modifications (e.g., increased weight) are often necessary to accommodate such a substitution.

In 2020, 76% of the world's carbon fiber was produced by six countries: the United States, Japan, China, Taiwan, and Hungary, with the United States producing more than 25% (refer to Table 8 for more details). The remaining 24% of global production in 2020 came from other countries that produce less than 5% of the global total. Under the High Deployment scenario, U.S. wind energy material needs for carbon fiber could exceed current global production from 2038 to 2044 (Figure 12). Thus, if the United States does not reduce the material requirements for carbon fibers in wind blades (e.g., through recycling, material substitution, or lifetime extension, which are further discussed in Section 4) or increase domestic manufacturing of carbon fiber, it risks relying on other countries to supply a substantial portion of the carbon fiber needed for U.S. wind energy applications under high wind deployment scenarios.

3.5.1.3 Rare-Earth Elements

Rare-earth elements are contained in mineral deposits such as bastnaesite and monazite, and the quality of a mineral deposit is judged on its percentage of total rare-earth oxides or grade (deposits with grades above 5% are considered viable (Alves Dias et al. 2020). Because rare-earth elements are mined together, USGS does not provide individualized information for each element in its mineral commodity summaries (USGS 2021). Data are also scarce, for instance, regarding Chinese rare-earth element reserves (Alves Dias et al. 2020). However, some studies provide some methods to determine production, reserves, and consumption of each rare-earth element, as well as estimates (Alves Dias et al. 2020; Du and Graedel 2011; Hoenderdaal et al. 2013).

The United States is currently the second largest producer of rare-earth elements after China, with U.S. production totaling 16% of global production compared to China's 58% (USGS 2021). However, most ore extracted from U.S. sources is exported for processing and U.S. consumption of rare-earth elements relies heavily on imports (China provides 80% of U.S. rare-earth element imports). Although recycling rare-earth element technologies exist, secondary production has not yet matured, and all commercial-scale U.S. consumption of rare-earth elements comes from primary sources. While the U.S. rare-earth element reserves represent about 1% of global reserves, rare-earth element resources are abundant in North America (e.g., Canada and the United States are estimated to be home to about 15 million tonnes and 2.4 million tonnes of rare-earth element resources, respectively). The main rare-earth element deposits currently exploited in the United States reside in Mountain Pass, California; they are of high grade (around 8%) but do not contain much dysprosium or terbium (Du and Graedel, 2011). As a result, the U.S. shares of global production for those elements are below 3%, whereas the U.S. shares of global production for neodymium and praseodymium are both 6%.

Rare-earth elements are used to produce magnets, ceramics and glass, battery alloys, and catalysts. Within wind power plants, rare-earth elements are primarily used for power generators in the nacelle and the quantity and type of rare-earth element needed depends on the type of generator used. For example, direct-drive permanent-magnet synchronous generators require 180 kilograms (kg)/MW of neodymium, 17 kg/MW of dysprosium, and 7 kg/MW of terbium, whereas gearbox double-fed induction generators only require 12 kg/MW of neodymium, 2 kg/MW of dysprosium, and 0 kg/MW of terbium (European Comission et al. 2020b). Based on the technology configurations and scenario definitions used in this study[16], if future U.S. production levels remain the same as 2020 levels, future U.S. deployment of wind energy technologies could consume 4%–91% of domestic neodymium production and 3%–75% of domestic dysprosium production in 2050. As discussed in greater detail in Section 4, material substitution, technology substitution, and recycling are three viable options for reducing the wind energy demand for rare-earth elements (e.g., a direct-drive generator can be made with a magnet constructed from copper windings, superconducting generators could be used instead of permanent-magnet generators and recycling could enable material recovery).[17] Depending on competing uses, it may be important for the United States to expand domestic production, develop ore processing capabilities, and diversify imports for rare-earth elements, particularly for dysprosium and neodymium.

3.5.1.4 Electrical steel

Electrical steels (also known as silicon steels, relay steels, and transformer steels) contain iron, silicon, carbon, and some aluminum—thus the constituents are largely not critical by themselves. However, the manufacturing pathway for electrical steels is metallurgically specialized and the technical expertise for manufacturing electrical steels is highly guarded in industry (U.S. Department of Commerce, Bureau of Industry and Security 2021). As a result, the production of electrical steels is vulnerable to supply chain disruptions.

Electrical steels are primarily used to manufacture transformers, motors, and inductors. There are two types of electrical steels: grain-oriented electrical steel (GOES) and nongrain-oriented electrical steel (NOES). Compared to NOES, GOES conducts a magnetic field with a higher degree of efficiency in the direction of rolling and GOES is therefore more efficient at transforming mechanical energy to electrical energy (U.S. Department of Commerce, Bureau of Industry and Security 2021). Due to the highly specialized and advanced manufacturing processes that are required to create its uniformly oriented grain structures, GOES is more challenging to produce than NOES. As a result of its improved properties for transforming energy, GOES is primarily used in medium- and large-sized transformers, whereas NOES is generally used in electric motors, generators, and smaller transformers.

In terms of total electrical steel production (combined production of GOES and NOES), South Korea and China are the two largest exporters of electrical steel (each accounting for 14% of global exports), followed by Japan, Germany, and Russia. The United States comprises just more than 1% of total global exports for all types of electrical steel and relies on Japan, Korea, France, Austria, and China for imports. With respect to GOES, the United States currently consumes

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[16] Refer to Section 2.2 for details about the scenario definitions, including the technology configurations.
[17] Refer to Section 4 for more details.

about 220,000 t of GOES per year and imports accounted for 21%–37% of U.S. consumption of GOES (by mass) from 2015 to 2019. According to an investigation conducted by the U.S. Department of Commerce, AK Steel, Inc. (a subsidiary of Cleveland Cliffs Inc.) is the only domestic producer of GOES and the company "is unable to meet the domestic demand for the full range of GOES products" (U.S. Department of Commerce, Bureau of Industry and Security 2021).

Within the wind energy industry, electrical steels are used for power generators in the nacelle and for transformers. If future U.S. production levels remain the same as 2020 levels, the High Deployment scenario analyzed here indicates that U.S. deployment of wind energy technologies in 2050 could require up to 94% of 2020 U.S. production of electrical steel. Due to the specialized manufacturing and functions of electrical steel, material substitutions and recycling may not always be viable options for this material. Thus, it will be important for the United States to secure supply of electrical steels by expanding domestic production and diversifying imports.

3.5.1.5 Cobalt

Cobalt is primarily used to produce electrodes in lithium-ion batteries. It is also used to produce other chemicals, superalloys, ceramics, steels, and other alloys. The estimated cobalt resource in the United States is about 1 million tonnes, whereas the world terrestrial resources are about 25 million tonnes. Most cobalt is produced as a byproduct of nickel and copper mines. In 2021, the United States produced about 700 t of cobalt, most of which comes from the nickel-copper Eagle Mine in Michigan. The rest of the cobalt used in the United States comes from imports and scrap materials (USGS 2022). Globally, about 70% of cobalt is mined in the Congo and more than 65% of refined cobalt is processed in China.

Within the wind industry, cobalt is used as an alloy for chromium steel and low-alloyed steel and is therefore accounted for within the background system of the REMPD.[18] The wind energy components that use the most of these types of steel (and therefore the most cobalt) are the wind turbine tower, land-based foundation or offshore substructure, and wind turbine nacelle. If future global production levels remain the same as 2020 levels, the two scenarios analyzed here indicate that global production should be sufficient to satisfy U.S. wind energy demand for cobalt. However, U.S. deployment of wind energy technologies in 2050 could comprise close to 45% of U.S. production of cobalt. As a result, depending on competing uses for cobalt, it may be important for the United States to secure domestic supply of cobalt, which could include expanding domestic production, identifying alternatives for cobalt in steel manufacturing, identifying alternatives to steel in wind turbine applications (e.g., through the increased use of concrete in hybrid towers), and diversifying imports.

3.5.1.6 Aluminum

Aluminum is a relatively lightweight metal—about one-third the weight of steel or copper—with excellent corrosion resistance, strength, and durability. It is used in a wide variety of applications, including the manufacturing of airplanes and automobiles, packaging (e.g., cans

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[18] Refer to Section 2.1.3 for more details about the foreground and background system definitions in the REMPD.

and foil), consumer goods such as cooking utensils, construction (e.g., windows and doors), electrical transmission lines, machinery, and appliances. Primary (or virgin) aluminum is manufactured through the electrolysis of alumina, which is refined from bauxite, and the global resources of bauxite are estimated “to be between 55 billion and 75 billion tons and are sufficient to meet world demand for metal well into the future” (USGS 2022). Aluminum can also be recovered from new scrap (manufacturing) and old scrap (discarded aluminum products).

In 2020, China was the world’s leading producer of primary aluminum, accounting for 57% of world production (about 37 million tons), followed by Russia (6%), India (5%), Canada (5%), and the United Arab Emirates (4%). In 2020, the United States recovered about 3 million tons of aluminum from scrap, which was equivalent to about 75% of apparent U.S. consumption. The United States. also produced about 1 million tons of primary aluminum in 2020.

Within a wind power plant, aluminum is mostly used in the cables, tower, and nacelle. Our analysis indicates that domestic and global production should be sufficient to satisfy future U.S. wind energy demand for aluminum. However, depending on competing uses for aluminum (e.g., aviation and automotive industries), it may be important for the United States to expand domestic production and diversify imports of aluminum. In addition, increasing aluminum recycling and identifying alternatives in wind energy applications could help reduce wind energy material needs for aluminum.

3.5.2 Nonvulnerable Materials

3.5.2.1 Balsa

Balsa is a lightweight hardwood that is used in a variety of commercial applications, including insulation, packaging, structural reinforcement, and marine applications (e.g., surfboards and boats). Within the wind industry, balsa is used in wind turbine blades to provide increased stiffness through the insertion of relatively light core structure between stiff fiber-reinforced plastic or carbon-reinforced plastic skins.

Ecuador is the top exporter of balsa globally, accounting for about 80% of the world’s total balsa exports in 2020, followed by Peru (10% of global exports in 2020) and Brazil (5% of global exports in 2020). If future production levels remain the same as 2020 levels, the High Deployment scenario indicates that U.S. wind energy demand for balsa in 2050 could exceed five times the current level of global production. Material substitution—for example, increasing the use of PVC foam, using fiber-reinforced polymers, or developing alternative bio-based fibers for blade cores—and end-of-life extension could potentially reduce wind energy material demand for balsa.

3.5.2.2 Glass Fiber

Glass fiber is made by heating and drawing silica-based glass into thin strands. The most common type of glass fiber is E-glass, which has low electrical conductivity compared to other types of glass fiber materials (Fitzer et al. 2000). Glass fibers are usually processed into textile glass fabrics (e.g., via weaving, knitting, and braiding) or embedded in a polymer matrix (e.g., epoxy, vinyl ester, polyester) to produce a composite material known as glass-fiber reinforced polymer, which is known for its high strength and low weight. Textile glass fabrics are used to produce circuit boards and thermal insulation for use in the electronics industry and glass fiber-reinforced polymers are often used in structural applications within the construction, transportation, and industrial sectors (Fitzer et al. 2000). Within a wind plant, glass fibers are used within the fiber-reinforced polymers in wind turbine blades.

In 2020, China produced more than 50% of the world's glass fiber, followed by the United States (10%) and Malaysia (9%). If future global production levels remain the same as 2020 levels, the two scenarios analyzed here indicate that global production should be sufficient to satisfy U.S. wind energy demand for glass fiber. However, future U.S. deployment of wind energy technologies could use 20%–300% of 2020 U.S. production of glass fiber annually. Thus, to secure domestic supply of glass fiber for U.S. wind industry applications, it may be important for the country to increase production beyond 2020 levels. Although there are some composite recycling processes (e.g., mechanical recycling, thermal recycling, and chemical recycling) that can be used to recover some of the original glass fiber material, these processes often degrade the quality of the fibers to the extent that they can only be used in applications with less stringent design requirements than are required for wind blades. Alternative wind blade designs (e.g., using thermoplastic resins that can be heated and remolded) could allow for increased recycling of glass fibers within the wind industry. In addition, extending the lifetime of wind blades could also help reduce the quantity of glass fiber that is required for wind blades. However, further research is needed to develop and improve these circular economy approaches for glass fibers.

3.5.2.3 Copper

Copper has excellent electrical conductivity, along with high strength, hardness, and ductility. It is also a good conductor of heat (it conducts heat about 30 times better than stainless steel and 1.5 times better than aluminum). Due to these properties, the metal is largely used in electrical applications, including power transmission and generation, building wiring, telecommunication, electronics, and electronic products.

China is the world's leading producer of refined copper and produced about 10 million tons of refined copper (or 40% of the world's total copper refinery production) in 2020. Refined copper is also produced by Chile, Japan, Congo, Russia, and the United States, each producing 9%, 6%, 4%, 4%, and 4% of the world's refined copper production, respectively, with other countries each producing less than 3%. The recoverable copper content of U.S. mine production was around 1.2 million tons in 2020. Most of the refined copper produced in the United States. comes from primary refinery production of copper from ore; the amount of copper recovered from old and new scrap in the country is only equivalent to about 10% of the apparent U.S. consumption of copper (USGS 2022).

Within a wind power plant, copper is used in the array and export cables, foundation, substation, and turbine. Based on the Current Policies and High Deployment scenarios, domestic and global production should be sufficient to satisfy future U.S. wind energy demand for copper. However, depending on competing uses, it may be important for the United States to expand domestic production and diversity imports. Increasing copper recycling and identifying alternatives in wind energy applications could help reduce wind energy material needs for copper.

4 Opportunities To Reduce Material Requirements

There are many opportunities for innovation to change material requirements for wind energy. Table 10 summarizes innovations that could be relevant to each component and subassembly within a wind power plant. We do not examine their impact and simply provide a high-level overview of how three categories of material innovations could influence wind energy materials. These categories are material substitution, weight reduction, and other circular economy approaches (including recycling).

Table 10. Innovations That Could Modify Material Requirements for Wind Energy Technologies

Component, Subassembly	Innovations That Could Modify Material Requirements
Wind turbine, blade	• Material substitution ○ Bio-based resins and biofibers ○ Recyclable resin systems (e.g., thermoplastic resin) • Weight reduction ○ Carbon-fiber spar caps • Other circular economy approaches ○ Composite recycling ○ Lifetime extension
Turbine, nacelle	• Material substitution ○ Superconducting direct-drive generators ○ Other generators that use fewer rare-earth elements • Weight reduction ○ High-voltage direct-current generators ○ Replacing steel with cast iron in the rotor shaft and main bearing • Other circular economy approaches ○ Lifetime extension ○ Reuse of permanent magnets in generators ○ Recycling of rare-earth elements
Turbine, tower	• Material substitution ○ Alternative materials (e.g., wood, aluminum, concrete, composites), including hybrid designs with steel • Weight reduction ○ Higher-strength steel ○ Increased tower diameter (would likely require other technology innovations such as spiral welding) • Other circular economy approaches ○ Lifetime extension via partial repowering ○ Increased recycling • Other technology innovations ○ Land-based: on-site manufacturing (e.g., spiral welding)

Component, Subassembly	Innovations That Could Modify Material Requirements
Array and export cables and other electrical equipment, all subassemblies	• Material substitution ○ High deployment conductor materials (e.g., graphene) ○ Alternatives to sulfur hexafluoride gas in electrical equipment • Other circular economy approaches ○ Dry transformers • Other technology innovations ○ Optimized transmission planning (e.g., high-voltage direct-current backbones) ○ Increasing cable rating
Turbine, land-based foundation or offshore substructure	• Material substitutions ○ Hybrid materials (e.g., steel and concrete) ○ Land-based: steel pile foundation • Weight reduction ○ Offshore: high-alloy steel ○ Offshore: lattice structures such as jacket designs ○ Land-based: ribbed or annular concrete foundation • Other circular economy approaches ○ Lifetime extension via partial repowering • Other technology innovations ○ Controls to reduce design loads ○ Land-based: additive manufacturing ○ Offshore: floating substructures ○ Offshore: innovation in post-tensioning for substructure/anchors/tower ○ Offshore: sustainable geopolymers to replace Portland cement ○ Offshore: shared mooring and anchors ○ Offshore: micropile anchors
Substation, all subassemblies	• Other technology innovations ○ Land-based: increasing plant size ○ Land-based: gas-insulated switchgear and transformers ○ Offshore: modular substations that share turbine platform

4.1 Material Substitution

When a material has limited availability, manufacturers may be able to reduce reliance on it by substituting it with another material. The substitution of one material for another can take various forms. In some cases, it is possible to directly substitute one element for another with similar properties. For example, aluminum, cadmium, or plastic-based coatings can replace zinc coatings in some applications (Tolcin 2022). Other substitutions can occur between different technologies that perform the same function (Smith and Eggert 2016). Material substitution is an effective method to reduce dependence on vulnerable materials, but it may increase the mass of other materials required, thereby increasing the total system mass.

Rare-earth elements are vulnerable materials that could be substituted—partially or completely—in wind turbine generators. The sharp rise in rare-earth-element prices in 2011 spurred alternatives to permanent-magnet synchronous generators. Some technologies already existed; for example, induction generators that do not require a permanent magnet. Wind turbines without permanent-magnet generators may use a geared drive with an electromagnetic generator (this remains the dominant configuration for land-based wind turbines) or a direct-drive generator with a magnet made from copper windings (this configuration, known as an electrically excited synchronous generator, eliminates rare-earth magnets but adds weight). Recently, medium-speed generators that use a smaller quantity of rare-earth permanent magnets have begun to be adopted. Although the demand for rare-earth magnets still exists, reducing the size of the magnets allows more generators to be produced from the same quantity of rare-earth elements. Superconducting generators have also been proposed as an alternative to designs using permanent magnets (Pavel et al. 2017).

The dominant role of steel in wind turbine towers and offshore substructures could also be altered by material substitution. Hybrid towers that replace steel with concrete in the lower sections of the structure were included in the High Deployment scenario (see Table 2). Other alternative materials that have been proposed for wind turbine towers include wood, aluminum, or fiberglass composites with a concrete or foam core (Watson et al. 2019). For offshore wind energy, concrete, gravity-base foundations have been used in some European projects. Concrete is also a possible alternative to steel for floating substructures; one example is the "damping pool" barge design demonstrated in Japan and France (BW Ideol n.d.). Reducing steel requirements would also decrease the wind energy demand for the critical minerals that are used in steel alloying (e.g., nickel).

4.2 Weight Reduction

Material requirements can be reduced by lowering the overall mass of wind energy systems. Reducing weight can have both direct and indirect effects on material use; for example, reducing the weight of the nacelle can lessen loads on the tower, which can then be made lighter as well. Often, weight reduction is achieved by using lightweight, high-performance materials. In some cases, switching to lightweight materials involves increasing the use of critical minerals; for example, adding nickel, molybdenum, and copper to cast iron can reduce the weight of large castings used in the nacelle (International Molybdenum Association 2011). Opportunities for reducing the weight of specific components include:

- **Blades**. Carbon-fiber spar caps enable a weight reduction of approximately 25% compared to fiberglass (Ennis et al. 2019)
- **Tower**. Increasing the diameter of the tower base can decrease the total mass; however, large-diameter towers may require additional innovations such as spiral welding to avoid transportation constraints (Lantz et al. 2019)
- **Generator**. High-voltage direct-current generators could help reduce the weight of electrical equipment compared with alternating-current generators (Watson et al. 2019)
- **Drivetrain**. Replacing steel with cast iron in the rotor shaft and main bearing seat could enable hollow designs with lower mass (Kirsch and Kyling 2021)

- **Substructure**. Lattice structures such as jacket designs could reduce mass requirements for fixed-bottom substructures in water depths of 40 m or more (Damiani et al. 2016).

4.3 Other Circular Economy Approaches

Material requirements for wind energy can also be affected by material handling at end of life. Some approaches that could be used to encourage the development of a more circular economy for wind energy materials include the following:

- **Lifetime extension**. Lifetime extension refers to the continued use of wind turbines and other plant components beyond their design lifetimes. Additional maintenance, monitoring, or refurbishment may be necessary to support the extended operational period, but the overall material requirements are less than would be needed for replacement with new equipment. The impact of life cycle extension on vulnerable material consumption for wind turbine generators was illustrated by Veers, Sethuraman, and Keller (2020), who obtained a 15% decrease in rare-earth element demand when increasing the assumed lifetime from 20 to 25 years. Extending the lifetime of the tower, land-based foundation, or offshore substructure while replacing the nacelle and rotor also reduces material requirements.
- **Reuse**. The large permanent magnets used in wind turbines are relatively straightforward to separate from other materials in the nacelle (compared to other permanent-magnet applications like hard disk drives), which presents an opportunity to reuse the magnets in new turbines after refurbishment, reducing the requirement for virgin rare-earth elements (Yang et al. 2017). The stock of used magnets available for reuse lags installation by 2-3 decades, so there is limited potential for reuse to contribute to reduction in material demand for near-term growth in wind energy.
- **Recycling.** Recycling already makes a significant contribution to the U.S. supply of some metals, with approximately half of the aluminum, iron, steel, and nickel used in the country coming from secondary sources. Recycling also supplies approximately one-third of copper, chromium, and tin in the United States, and nearly 20% of zinc (Sangine 2022). The scope for increasing recycled content varies by material and depends on the ratio between in-use stocks and material demand as well as the end-of-life recycling rate. For example, there may be room for growth in the recycled content of copper, which has an estimated recycling rate close to 50%, but there is less opportunity to increase lead recycling, which has already reached more than 90% (UNEP 2011). Iron and steel make up the largest portion of wind turbine and offshore substructure mass; globally, these materials are estimated to have an end-of-life recycling rate between 70% and 90% (UNEP 2011). Rare-earth elements are recycled at much lower rates; however, researchers are engaged in developing more effective methods for recycling and material recovery (Jowitt et al. 2018; Lorenz and Bertau 2019; Rademaker et al. 2013).[19] Recycling of wind turbine blade materials is also an active area of research (Deeney et al. 2021; Fonte and Xydis 2021; Sommer and Walther 2021).

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[19] Refer to Appendix F for a summary of rare-earth element processing methods and recycling opportunities.

5 Conclusion

This report describes how we used the REMPD to determine the quantity of materials that might be needed to satisfy two deployment scenarios for U.S. wind energy. For the two scenarios, the database helped us better understand the constraints and vulnerabilities linked to the availability of physical materials.

5.1 Summary of Approach and Results

Here, we evaluated the types and quantities of materials that are needed to manufacture and construct wind energy plants under two deployment scenarios: Current Policies and High Deployment. We defined these two scenarios using a capacity projection, plant configuration, and technology configuration and used the REMPD to determine the wind energy components and computed the total raw and process material requirements (including both foreground and background systems). A moderate wind energy capacity projection, plant configuration, and technology configuration (based on the Standard Scenarios 2022 Mid-case with no new decarbonization policies, limited changes to current plant configurations [e.g., wind turbine size], and no technology innovations) are assumed in the Current Policies scenario. The High Deployment scenario assumes high levels of wind energy deployment (aligned with the Biden administration's goal of carbon-free electricity by 2035 and net-zero economy by 2050) and incorporates significant changes in wind power plant configurations and limited materials-related innovations. The REMPD provided the annual quantity of materials required for each scenario along with material properties (e.g., availability and significant use).

To improve the interpretability of the results, we grouped materials into seven major categories: concrete, road aggregate, steel, composites and polymers, cast iron, other metals and alloys, and other materials. We also performed a more detailed analysis of 19 vulnerable materials, which include 17 critical minerals, along with carbon fiber and electrical steel.[20] Our major findings include:

- In both scenarios, the projected annual U.S. wind energy demand for vulnerable and nonvulnerable materials through 2050 is anticipated to require less than 10% of 2020 global production for all materials except nickel, dysprosium, neodymium, glass fiber, carbon fiber, and balsa. In the High Deployment scenario, from 2030 to 2036, annual average U.S. wind energy demand for nickel, dysprosium, neodymium, glass fiber, carbon fiber, and balsa could account for 8%, 8%, 11%, 23%, 111%, and 268%, respectively, of 2020 global production of those materials.

- In addition, if future U.S. production remains the same as 2020 levels, the material needs for U.S. wind energy could approach or exceed the domestic production of nickel, electrical steel, carbon fiber, and glass fiber. Wind energy facilities also use materials for which there is currently no primary production in the United States, including balsa, chromium, gallium, graphite, manganese, niobium, and tin.

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[20] Refer to Table 1 for a list of vulnerable materials included in our analysis.

- Other materials for which demand from wind energy is projected to be high relative to current U.S. production include neodymium, dysprosium, and cobalt.

Overall, we find that U.S. wind energy demand for nickel, balsa, electrical steel, glass fiber, carbon fiber, neodymium, dysprosium, and cobalt could pose challenges under high wind deployment. As a result, it will be important for the United States to secure supply of these materials by increasing domestic production, diversifying imports for these materials, identifying alternative materials, or modifying designs to improve reuse and recycling.

5.2 Opportunities and Vulnerabilities

Using the Current Policies and High Deployment scenarios, we identified several vulnerabilities. Although current global supply chains should be able to meet the U.S. wind energy demand for most materials in both scenarios, it might prove to be more challenging for nickel, balsa, electrical steel, glass fiber, carbon fiber, rare-earth elements (i.e., neodymium and dysprosium), and cobalt. However, there are a variety of opportunities for reducing wind energy requirements for these materials (e.g., increasing domestic production, diversifying import sources, making material substitutions, and increasing other circular economy pathways such as alternative designs and recycling). Our key findings include:

- Nickel and cobalt are primarily used in chromium steel and low-alloyed steel within the wind turbine tower, the land-based foundation or offshore substructure, and the wind turbine nacelle. With more than half of U.S. steel production already coming from scrap, the wind energy industry could benefit from technological solutions that reduce steel requirements. A hybrid wind tower—which uses a large quantity of concrete in the tower and less steel—is one such solution. In addition, the United States could consider identifying alternatives for cobalt and nickel in steel manufacturing, increasing domestic production, and diversifying imports.

- Balsa, carbon fiber, and glass fiber are all used within wind turbine blades. Although the United States is currently one of the top three producers of composite materials, production will need to increase globally to meet increasing demand from the wind industry and other sectors. If the United States does not increase domestic production of these materials, it risks relying on other countries to supply a substantial portion of the carbon fiber needed for U.S. wind energy applications under high wind deployment scenarios. Lifetime extension and alternative wind blade designs (e.g., foam instead of balsa cores and thermoplastic rather than thermoset resins) could help reduce virgin material requirements for balsa, glass fiber, and carbon fiber. Increased recycling of wind blade composites could also help mitigate material demand for carbon and glass fibers within the wind industry. However, further research is needed to develop and improve circular economy approaches for these materials.

- Electrical steel is used for power generators in the nacelle and for transformers. Due to the specialized manufacturing and functions of electrical steel, material substitution and recycling may not always be viable options. Thus, expanding domestic production and diversifying import sources are likely to be important strategies to ensure a stable supply of electrical steel.

- Rare-earth elements are primarily used within the wind turbine generator. Although some rare-earth ores are mined in the United States, nearly all refining and processing into rare-earth metals occurs in China, causing high supply risks. In the long term, increased domestic production or imports from other countries such as Canada (home to the biggest known rare-earth-element resources) could mitigate this risk. However, in the short term, hybrid generators (with smaller permanent magnets), alternative magnet materials, rare-earth-element recycling, or the reuse of old permanent magnets could be viable solutions.

5.3 Broader Impacts

As a relational database, the REMPD can be extended; for instance, to include additional information on wind energy externalities (e.g., emissions from transportation, material requirements for transmission, impacts on local communities). In future work, the REMPD could be used to compute the life cycle impacts related to a given scenario as the life cycle inventory data used to connect the foreground and background materials contains all the necessary information.

The database taxonomy (see Figure 1) is also designed to allow other technologies or facilities with components and core materials to be stored and analyzed. For example, the REMPD structure has already been used to answer the requirements outlined in Subsection (5) of Section 3004 of the Energy Act of 2020 (i.e., developing “a comprehensive physical property database of materials for use in solar energy technologies, which shall identify the type, quantity, country of origin, source, significant uses, projected availability, and physical properties of materials used in solar energy technologies”). Other renewable energy technologies could also be added.

Additional research could also enable the REMPD to provide a more detailed analysis of potential supply chain risks. For example, three indicators could be added to the database: likelihood of foreign supply disruption (disruption potential), dependency of U.S. manufacturers on foreign suppliers (trade exposure), and the ability of U.S. manufacturers to withstand a supply disruption (economic vulnerability). Such analysis could also highlight mitigation opportunities and trade dynamics (e.g., the role of neodymium substitution with praseodymium). Another option could be to investigate hurdles to increasing material production in supply chains (e.g., for a given material, current U.S. production capacities could increase supply by 10% but a new plant would need to increase it by 15%).

The estimates of total material requirements for wind energy are highly sensitive to the projected deployment of wind energy in the United States. As updated capacity projections data become available, future work will evaluate how the results reported here might change under alternative deployment assumptions. Evolution of the technology used in wind power plants will also affect material requirements. Future work should continue to modify the wind power plant configurations and wind turbine technology to reflect trends in design and material usage.

References

4C Offshore. 2022. Global Offshore Wind Farm Intelligence (Online Database). February 2022. https://www.4coffshore.com/windfarms/.

ABB. 2010. "XLPE Submarine Cable Systems Attachment to XLPE Land Cable Systems - User´s Guide." https://new.abb.com/docs/default-source/ewea-doc/xlpe-submarine-cable-systems-2gm5007.pdf.

Achzet, Benjamin, and Christoph Helbig. 2013. "How to Evaluate Raw Material Supply Risks—an Overview." *Resources Policy* 38 (4): 435–47. https://doi.org/10.1016/j.resourpol.2013.06.003.

Alsaleh, A., and M. Sattler. 2019. "Comprehensive Life Cycle Assessment of Large Wind Turbines in the US." *Clean Technologies and Environmental Policy* 21 (4): 887–903. https://doi.org/10.1007/s10098-019-01678-0.

Alves Dias, P., S. Bobba, S. Carrara, B. Plazzotta. 2020. *The role of rare earth elements in wind energy and electric mobility*. European Commission, Joint Research Centre. EUR 30488 EN. Publication Office of the European Union, Luxembourg. https://data.europa.eu/doi/10.2760/303258.

American Physical Society Panel on Public Affairs and Materials Research Society. 2011. "Energy Critical Elements: Securing Materials for Emerging Technologies." https://www.aps.org/policy/reports/popa-reports/upload/elementsreport.pdf.

Ardani, K., P. Denholm, T. Mai, R. Margolis, E. O'Shaughnessy, T. Silverman, J. Zuboy. 2021. *Solar Futures Study*. Washington, D.C.: U.S. Department of Energy. https://www.energy.gov/sites/default/files/2021-09/Solar%20Futures%20Study.pdf.

Arvesen, Anders, Rasmus Nikolai Nes, Daniel Huertas-Hernando, and Edgar G. Hertwich. 2014. "Life Cycle Assessment of an Offshore Grid Interconnecting Wind Farms and Customers across the North Sea." *The International Journal of Life Cycle Assessment* 19 (4): 826–37. https://doi.org/10.1007/s11367-014-0709-2.

Atwater, Harry, Neil Fromer, and Val Otten. 2011. "Critical Materials For Sustainable Energy Applications." Pasadena, CA: Resnick Institute, California Institute of Technology. https://authors.library.caltech.edu/32727/1/ri_criticalmaterials_report.pdf.

Baars, J., T. Domenech, R. Bleischwitz, H. E. Melin, and O. Heidrich. 2021. "Circular Economy Strategies for Electric Vehicle Batteries Reduce Reliance on Raw Materials." *Nature Sustainability* 4 (1): 71–79. https://doi.org/10.1038/s41893-020-00607-0.

Bauer, D., D. Diamond, J. Li, D. Sandalow, P. Telleen, and B. Wanner. 2010. "U.S. Department of Energy Critical Materials Strategy." U.S. Department of Energy. https://www.osti.gov/biblio/1000846-department-energy-critical-materials-strategy.

Benke, D., M. Fries, M. Specht, J. Wortmann, M. Pabst, T. Gottschall, I. Radulov, K. Skokov, A. I. Bevan, D. Prosperi, C. O. Tudor, P. Afiuny, M. Zakotnik, O. Gutfleisch. 2020. "Magnetic Refrigeration with Recycled Permanent Magnets and Free Rare-Earth Magnetocaloric La–Fe–Si." *Energy Technol*., 8: 1901025. https://doi.org/10.1002/ente.201901025.

Binnemans, K., P. T. Jones, B. Blanpain, T. Van Gerven, Y. Yang, A. Walton, M. Buchert. 2013. "Recycling of rare earths: a critical review." *J Clean Prod*, 51, pp. 1-22. https://www.sciencedirect.com/science/article/pii/S0959652612006932.

BloombergNEF. 2020. Carbon fiber manufacturing-related data.

Bogart, J., B. Cole, M. Boreen, C. Lippincott, B. Manor, P. Carroll, E. Schelter. 2016. "Accomplishing simple, solubility-based separations of rare earth elements with complexes bearing size-sensitive molecular apertures." *PNAS*, 113 (52) 14887-14892. https://doi.org/10.1073/pnas.1612628113.

BW Ideol. n.d. "Floatgen." Accessed May 6, 2022. https://www.bw-ideol.com/en/floatgen-demonstrator.

Cao, Z., C. O'Sullivan, J. Tan, P. Kalvig, L. Ciacci, W. Chen, J. Kim, G. Liu. 2019. "Resourcing the Fairytale Country with Wind Power: A Dynamic Material Flow Analysis." *Environmental Science & Technology, 53*(19), 11313-11322. doi:10.1021/acs.est.9b03765.

Carrara, S., P. Alves Dias, B. Plazzotta, C. Pavel. 2020b. *Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system*. European Commission, Joint Research Centre, Publication Office of the European Union, Luxembourg. https://data.europa.eu/doi/10.2760/160859.

Connelly, E., M. Penev, A. Milbrandt, B. Roberts, N. Gilroy, M. Melaina. 2020. *Resource Assessment for Hydrogen Production*. https://www.osti.gov/biblio/1660128.

Consolidated Appropriations Act. 2021. https://www.congress.gov/bill/116th-congress/house-bill/133/text

Cooperman, A., A. Eberle, Eric Lantz. 2021. "Wind turbine blade material in the United States: Quantities, costs, and end-of-life options." *Resources, Conservation and Recycling, 168*, 105439. https://doi.org/10.1016/j.resconrec.2021.105439.

Cooperman, A., A. Eberle, D. Hettinger, M. Marquis, B. Smith, R. Tusing, J. Walzberg. 2023. *Renewable Energy Materials Properties Database: Summary*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-82830. nrel.gov/docs/fy23osti/82830.pdf.

Crawford, R. H. 2009. "Life Cycle Energy and Greenhouse Emissions Analysis of Wind Turbines and the Effect of Size on Energy Yield." *Renewable and Sustainable Energy Reviews* 13 (9): 2653–60.

Damiani, R., K. Dykes, G. Scott. 2016. "A comparison study of offshore wind support structures with monopiles and jackets for U.S. waters." *Journal of Physics: Conference Series, 753,* 092003. doi:10.1088/1742-6596/753/9/092003.

Deeney, Peter, Angela J. Nagle, Fergal Gough, Heloisa Lemmertz, Emma L. Delaney, Jennifer M. McKinley, Conor Graham, Paul G. Leahy, Niall P. Dunphy, and Gerard Mullally. 2021. "End-of-Life Alternatives for Wind Turbine Blades: Sustainability Indices Based on the UN Sustainable Development Goals." *Resources, Conservation and Recycling* 171 (August): 105642. https://doi.org/10.1016/j.resconrec.2021.105642.

Denholm, P., P. Brown, W. Cole, T. Mai, B. Sergi, M. Brown, P. Jadun, J. Ho, J. Mayernik, C. McMillan, R. Sreenath. 2022. *Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-81644. nrel.gov/docs/fy22osti/81644.pdf.

Du, X., and T. E. Graedel. 2011. "Global In-Use Stocks of the Rare Earth Elements: A First Estimate." *Environ. Sci. Technol., 45*(9), 4096-4101. doi:10.1021/es102836s.

Dunn, Jessica, Margaret Slattery, Alissa Kendall, Hanjiro Ambrose, and Shuhan Shen. 2021. "Circularity of Lithium-Ion Battery Materials in Electric Vehicles." *Environmental Science & Technology* 55 (8): 5189–98. https://doi.org/10.1021/acs.est.0c07030.

Dysinger, D. K., and J. E. Murphy. 1994. *Electrowinning of neodymium from a molten oxide-fluoride electrolyte. Report of investigations/1994*. Reno, NV: Bureau of Mines. https://www.osti.gov/biblio/7168096.

Eberle, A., J. O. Roberts, A. Key, P. Bhaskar, K. L. Dykes. 2019. *NREL's Balance-of-System Cost Model for Land-Based Wind.* Golden, CO: National Renewable Energy Laboratory (NREL). NREL/TP-6A20-72201. https://www.nrel.gov/docs/fy19osti/72201.pdf.

Elshkaki, A., and T. E. Graedel. 2014. "Dysprosium, the balance problem, and wind power technology." *Applied Energy, 136*, 548-559. https://doi.org/10.1016/j.apenergy.2014.09.064.

———. 2015. "Solar cell metals and their hosts: A tale of oversupply and undersupply." *Applied Energy, 158*, 167-177. https://doi.org/10.1016/j.apenergy.2015.08.066.

Energy Act of 2020. 2020. https://www.energy.senate.gov/services/files/847E2D8F-0CED-407E-9D65-C1589C9E1412.

Ennis, B. L., C. L. Kelley, B. T. Naughton, B. Norris, S. Das, D. Lee, D. Miller. 2019. *Optimized Carbon Fiber Composites in Wind Turbine Blade Design.* (SAND2019-14173). https://www.osti.gov/servlets/purl/1592956.

Erdmann, L., and T. E. Graedel. 2011. "Criticality of Non-Fuel Minerals: A Review of Major Approaches and Analyses." *Environmental Science & Technology* 45 (18): 7620–30. https://doi.org/10.1021/es200563g.

Fingersh, L., M. Hand, and A. Laxson. 2006. *Wind Turbine Design Cost and Scaling Model*. Golden, CO: National Renewable Energy Laboratory (NREL). NREL/TP-500-40566. https://www.nrel.gov/docs/fy07osti/40566.pdf.

Fishman, T. and T. E. Graedel. 2019. "Impact of the establishment of US offshore wind power on neodymium flows." *Nature Sustainability*, 2(4), 332-338. doi:10.1038/s41893-019-0252-z.

Fitzer, E., R. Kleinholz, H. Tiesler, M. H. Stacey, R. De Bruyne, I. Lefever, A. Foley et al. 2000. "Fibers, 5. Synthetic Inorganic." In *Ullmann's Encyclopedia of Industrial Chemistry*. Wiley-VCH Verlag GmbH & Co.

Fonte, Rosario, and George Xydis. 2021. "Wind Turbine Blade Recycling: An Evaluation of the European Market Potential for Recycled Composite Materials." *Journal of Environmental Management* 287 (June): 112269. https://doi.org/10.1016/j.jenvman.2021.112269.

Fraunhofer Institute for Systems and Innovation Research ISI, Institute for Energy and Transport (Joint Research Centre), Oakdene Hollins Ltd, Espinoza Luis Tercero, Ruth Bryson, Adrian Chapman, Evangelos Tzimas, et al. 2013. *Critical metals in the path towards the decarbonisation of the EU energy sector: Assessing rare metals as supply-chain bottlenecks in low-carbon energy technologies*. LU: Publications Office of the European Union. https://data.europa.eu/doi/10.2790/46338.

Gaertner, E., J. Rinker, L. Sethuraman, F. Zahle, B. Anderson, G. Barter, N. Abbas, F. Meng, P. Bortolotti, W. Skrzypinski, G. Scott, R. Feil, H. Bredmose, K. Dykes, M. Shields, C. Allen, and A. Viselli. 2020. *Definition of the IEA 15-Megawatt Offshore Reference Wind*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-75698. https://www.nrel.gov/docs/fy20osti/75698.pdf.

Gagnon, P., M. Brown, Steinberg, D., Brown, P., et al. 2022. *2022 Standard Scenarios Report: A U.S. Electricity Sector Outlook*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-84327 https://www.nrel.gov/docs/fy23osti/84327.pdf.

Graedel, T. E., and Barbara K. Reck. 2016. "Six Years of Criticality Assessments: What Have We Learned So Far?" *Journal of Industrial Ecology* 20 (4): 692–99. https://doi.org/10.1111/jiec.12305.

Guezuraga, Begoña, Rudolf Zauner, and Werner Pölz. 2012. "Life Cycle Assessment of Two Different 2 MW Class Wind Turbines." *Renewable Energy* 37 (1): 37–44. https://doi.org/10.1016/j.renene.2011.05.008.

Habib, K., P. K. Schibye, A. P. Vestbø, O. Dall, H. Wenzel. 2014. "Material Flow Analysis of NdFeB Magnets for Denmark: A Comprehensive Waste Flow Sampling and Analysis Approach." *Environmental Science & Technology 48*(20), 12229–37. https://doi.org/10.1021/es501975y.

Habib, K., K. Parajuly, and H. Wenzel. 2015. "Tracking the Flow of Resources in Electronic Waste - The Case of End-of-Life Computer Hard Disk Drives." *Environmental Science & Technology, 49*(20), 12441-12449. doi:10.1021/acs.est.5b02264.

Harris, I. R., A. Williams, A. Walton, J. Speight. 2011. Magnet Recycling. https://patents.google.com/patent/US8734714B2/en.

Hitachi. 2010. "Hitachi Develops Recycling Technologies for Rare Earth Metals." https://www.hitachi.com/New/cnews/101206.html.

Ho, Jonathan, Jonathon Becker, Maxwell Brown, Patrick Brown, Ilya Chernyakhovskiy, Stuart Cohen, Wesley Cole, et al. 2021. Regional Energy Deployment System (ReEDS) Model Documentation: Version 2020. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-78195. https://www.nrel.gov/docs/fy21osti/78195.pdf.

Hoenderdaal, Sander, Luis Tercero Espinoza, Frank Marscheider-Weidemann, and Wina Graus. 2013. "Can a Dysprosium Shortage Threaten Green Energy Technologies?" *Energy* 49 (January): 344–55. https://doi.org/10.1016/j.energy.2012.10.043.

Hofmann, Margarethe, Heinrich Hofmann, Christian Hagelüken, and Alessandra Hool. 2018. "Critical Raw Materials: A Perspective from the Materials Science Community." *Sustainable Materials and Technologies* 17 (September): e00074. https://doi.org/10.1016/j.susmat.2018.e00074.

Hydrogen Council. 2020. *Path to Hydrogen Competitiveness: A Cost Perspective*. https://hydrogencouncil.com/en/path-to-hydrogen-competitiveness-a-cost-perspective/.

Ikhennicheu, M., M. Lynch, S. Doole, F. Wendt, M. Schwarzhopf, D. Matha, R. D. Vincente, T. Habekost, L. Ramirez, and S. Potestio. 2020. "Review of the State of the Art of Dynamic Cable System Design." Brussels, Belgium: Corewind. https://corewind.eu/wp-content/uploads/files/publications/COREWIND-D3.1-Review-of-the-state-of-the-art-of-dynamic-cable-system-design.pdf.

International Energy Agency. 2021. "The Role of Critical Minerals in Clean Energy Transitions." World Energy Outlook Special Report, Paris. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

International Molybdenum Association. 2011. *Molybdenum in Irons and Steels for Clean and Green Power Generation*. https://www.imoa.info/download_files/alloy-steel/Clean_and_Green_Energy.pdf.

International Renewable Energy Agency. 2020. *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal*. https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf.

Iowa Department of Transportation. 2021. *Densities for Use in Estimating Quantities*. https://iowadot.gov/design/dmanual/01b-04.pdf.

Itoh M., K. Miura, K. I. Machida. 2009. "Novel rare earth recovery process on Nd-FeB magnet scrap by selective chlorination using NH_4Cl." *J Alloys Compd* 477:484–487. https://doi.org/10.1016/j.jallcom.2008.10.036.

Jakobsson, L. K., M.W. Kennedy, R.E. Aune, G. Tranell. 2016. “Recovery of Rare Earth Elements from the Ferrous Fraction of Electronic Waste.” REWAS 2016, Chapter. https://link.springer.com/chapter/10.1007/978-3-319-48768-7_13.

Johnson, N., J. Paquette, P. Bortolotti, N. Mendoza, M. Bolinger, E. Camarena, E. Anderson, and B. Ennis. 2021. Big Adaptive Rotor Phase I Final Report. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-79855. https://www.nrel.gov/docs/fy22osti/79855.pdf.

Jowitt, S. M., T. T. Werner, Z. Weng, G. M. Mudd. 2018. “Recycling of the rare earth elements.” *Current Opinion in Green and Sustainable Chemistry* Volume 13, Pages 1-7, https://doi.org/10.1016/j.cogsc.2018.02.008.

Junne, T., N. Wulff, C. Breyer, and T. Naegler. 2020. “Critical Materials in Global Low-Carbon Energy Scenarios: The Case for Neodymium, Dysprosium, Lithium, and Cobalt.” *Energy* 211. https://doi.org/10.1016/j.energy.2020.118532.

Kinjal G., G. Ouyang, S. Gupta, V. Kunc, M. P. Paranthaman, I. C. Nlebedim. 2019. “Recycling of additively printed rare-earth bonded magnets.” *Waste Management* Volume 90, Pages 94-99, https://doi.org/10.1016/j.wasman.2019.04.040.

Kinjal G., I. C. Nlebedim, V. Kunc, E. Lara-Curzio, R. Fredette, M. P. Paranthaman. 2020. “Additive manufacturing of highly dense anisotropic Nd–Fe–B bonded magnets.” *Scripta Materialia*, Volume 183, 2020, Pages 91-95, https://doi.org/10.1016/j.scriptamat.2020.03.012.

Kirsch, J., and H. Kyling. 2021. “Optimized Cast Components in the Drive Train of Wind Turbines and Inner Ring Creep in the Main Bearing Seat.” *Forschung Im Ingenieurwesen* 85 (2): 199–210. https://doi.org/10.1007/s10010-021-00458-x.

Lantz, E., O. Roberts, J. Nunemaker, E. DeMeo, K. Dykes, G. Scott. 2019. *Increasing Wind Turbine Tower Heights: Opportunities and Challenges*. Golden, CO: National Renewable Energy Laboratory (NREL). NREL/TP-5000-73908. https://www.nrel.gov/docs/fy19osti/73629.pdf.

Lawrence Livermore National Laboratory. 2021. “Americans move to more solar and wind power in 2021.” https://www.llnl.gov/news/americans-move-more-solar-wind-power-2021.

Li, L., A. Tirado, I. Nlebedim, O. Rios, B. Post, V, Kunc, R. R. Lowden, E. Lara-Curzio, et al. 2016. “Big Area Additive Manufacturing of High Performance Bonded NdFeB Magnets.” *Sci Rep* 6, 36212. https://doi.org/10.1038/srep36212.

Li, J., K. Peng, P. Wang, N. Zhang, K. Feng, D. Guan, J. Meng, W. Wei, Q. Yang. 2020. “Critical Rare-Earth Elements Mismatch Global Wind-Power Ambitions.” *One Earth, 3*(1), 116-125. https://doi.org/10.1016/j.oneear.2020.06.009.

Lorenz, T., and M. Bertau. 2019. “Recycling of Rare Earth Elements from FeNdB-Magnets via Solid-State Chlorination.” *Journal of Cleaner Production* 215 (April): 131–43. https://doi.org/10.1016/j.jclepro.2019.01.051.

Lyman, J. W., G. R. Palmer. 1993. "Recycling of Rare Earths and Iron from NdFeB Magnet Scrap." *High Temp Mater Process* 11(1–4):175–187. https://doi.org/10.1515/HTMP.1993.11.1-4.175.

Martínez, E., F. Sanz, S. Pellegrini, E. Jiménez, and J. Blanco. 2009. "Life-Cycle Assessment of a 2-MW Rated Power Wind Turbine: CML Method." *The International Journal of Life Cycle Assessment* 14 (1): 52–63. https://doi.org/10.1007/s11367-008-0033-9.

McQueen, S., J. Stanford, S. Satyapal, E. Miller, N. Stetson, D. Papageorgopoulos, N. Rustagi, A. Vanessa, et al. 2020. *Department of Energy Hydrogen Program Plan*. United States. https://www.osti.gov/biblio/1721803.

Musial, W., P. Spitsen, P. Beiter, P. Duffy, M. Marquis, A. Cooperman, R. Hammond, M. Shields. 2021. *Offshore Wind Market Report: 2021 Edition.* U.S. Department of Energy, Washington, D.C. https://www.energy.gov/sites/default/files/2021-08/Offshore%20Wind%20Market%20Report%202021%20Edition_Final.pdf.

Nassar, N., D. Wilburn, and T. Goonan. 2016. "Byproduct Metal Requirements for U.S. Wind and Solar Photovoltaic Electricity Generation up to the Year 2040 under Various Clean Power Plan Scenarios." *Applied Energy* 183 (December): 1209–26. https://doi.org/10.1016/j.apenergy.2016.08.062.

Nassar, N. T., and S. M. Fortier. 2021. *Methodology and technical input for the 2021 review and revision of the U.S. Critical Minerals List*. U.S. Geological Survey Open-File Report 2021–1045, 31 p., https://doi.org/10.3133/ofr20211045.

National Research Council. 2008. *Minerals, critical minerals, and the US economy*. Washington, DC: National Academies Press.

National Renewable Energy Laboratory. 2022. *2022 Annual Technology Baseline*. https://atb.nrel.gov/.

———. 2023. "Renewable Energy Materials Properties Database." Version 1.0. Washington, D.C.: U.S. Department of Energy. https://apps.openei.org/REMPD/.

Negro, V., J. López-Gutiérrez, M. D. Esteban, P. Alberdi, M. Imaz, and J. Serraclara. 2017. "Monopiles in Offshore Wind: Preliminary Estimate of Main Dimensions." *Ocean Engineering* 133 (March): 253–61. https://doi.org/10.1016/j.oceaneng.2017.02.011.

Ozoemena, M., W. M. Cheung, and R. Hasan. 2018. "Comparative LCA of Technology Improvement Opportunities for a 1.5-MW Wind Turbine in the Context of an Onshore Wind Farm." *Clean Technologies and Environmental Policy* 20 (1): 173–90. https://doi.org/10.1007/s10098-017-1466-2.

Paranthaman, M. P., I. C. Nlebedim, F. Johnson, S. K. McCall. 2016. "Additive Manufacturing of Permanent Magnets." *Material Matters*, 11.4. https://www.sigmaaldrich.com/US/en/technical-documents/technical-article/materials-science-and-engineering/nanoparticle-and-microparticle-synthesis/additive-manufacturing-of-permanent-magnets.

Parker, J. G. and Baroch, C. T. 1971. *Rare-earth elements, yttrium, and thorium. A materials survey.* Bureau of Mines Information Circular, 8476, U.S. Department of Interior, Washington, D.C. https://www.osti.gov/biblio/7111745.

Paulick, H., and Machacek, E. 2017. "The global rare earth element exploration boom: An analysis of resources outside of China and discussion of development perspectives." *Resources Policy, 52*, 134-153. https://doi.org/10.1016/j.resourpol.2017.02.002.

Pavel, C. C., R. Lacal-Arántegui, A. Marmier, D. Schüler, E. Tzimas, M. Buchert, W. Jenseit, D. Blagoeva. 2017. "Substitution strategies for reducing the use of rare earths in wind turbines." *Resources Policy, 52*, 349-357. https://doi.org/10.1016/j.resourpol.2017.04.010.

PostgreSQL Global Development. 2022. "PostgreSQL." PostgreSQL. March 8, 2022. https://www.postgresql.org/.

Prosperi, D., C. O. Tudor, A. I. Bevan, E. De Leon Quiroz, H. Peh, G. Furlan, R. Skomski, D. Suvorov, M. Zakotnik. 2019. "Thermal-stability and microstructure comparison between recycled M2M and conventionally produced sintered neodymium-iron-boron magnets, *Journal of Cleaner Production*, Volume 239, 118091. https://doi.org/10.1016/j.jclepro.2019.118091.

Rademaker, Jelle H., René Kleijn, and Yongxiang Yang. 2013. "Recycling as a Strategy against Rare Earth Element Criticality: A Systemic Evaluation of the Potential Yield of NdFeB Magnet Recycling." *Environmental Science & Technology* 47 (18): 10129–36. https://doi.org/10.1021/es305007w.

Rajaei, M., and J. M. Tinjum. 2013. "Life Cycle Assessment of Energy Balance and Emissions of a Wind Energy Plant." *Geotechnical and Geological Engineering* 31 (6): 1663–70. https://doi.org/10.1007/s10706-013-9637-3.

Ren, K., X. Tang, X., P. Wang, J. Willerström, M. Höök. 2021. "Bridging energy and metal sustainability: Insights from China's wind power development up to 2050." *Energy*, 227, 120524. https://doi.org/10.1016/j.energy.2021.120524.

Riddle, M. E., E. Tatara, C. Olson, B. J. Smith, A. Bennett Irion, B. Harker, D. Pineault, E. Alonso, D. J. Graziano. 2021. Agent-based modeling of supply disruptions in the global rare earths market. *Resources, Conservation and Recycling, 164*, 105193. https://doi.org/10.1016/j.resconrec.2020.105193.

Ruth, M. F., P. Jadun, N. Gilroy, E. Connelly, R. Boardman, A. J. Simon, A. Elgowainy, J. Zuboy. 2020. *The Technical and Economic Potential of the H2@Scale Hydrogen Concept within the United States*. Golden, CO: National Renewable Energy Laboratory (NREL). NREL/TP-6A20-77610. https://www.nrel.gov/docs/fy21osti/77610.pdf.

Saito T., H. Sato, S. Ozawa, J. Yu, T. Motegi. 2003. "The extraction of Nd from waste Nd-Fe-B alloys by the glass slag method." *J Alloys and Compd* 353:189–193. https://doi.org/10.1016/S0925-8388(02)01202-1.

Sangine, E. S. 2022. “Recycling—Metals.” In *2018 Minerals Yearbook*. United States Geological Survey. https://pubs.usgs.gov/myb/vol1/2018/myb1-2018-recycling.pdf

Schreiber, A., J. Marx, and P. Zapp. 2019. “Comparative life cycle assessment of electricity generation by different wind turbine types.” *Journal of Cleaner Production, 233*, 561-572. https://doi.org/10.1016/j.jclepro.2019.06.058.

Schrijvers, D., A. Hool, G. A. Blengini, W.-Q. Chen, J. Dewulf, R. Eggert, et al. 2020. “A review of methods and data to determine raw material criticality.” *Resources, Conservation and Recycling, 155*, 104617. https://doi.org/10.1016/j.resconrec.2019.104617.

Sharma, R. A. 1987. “Neodymium Production Processes.” *Journal of Metals*, Volume 39, pp 33-37. https://doi.org/10.1007/BF03259468.

Shirayama, S., and T. H. Okabe. 2018. “Selective Extraction and Recovery of Nd and Dy from Nd-Fe-B Magnet Scrap by Utilizing Molten $MgCl_2$.” *Metallurgical and Materials Transactions B* 49, 1067-1077. https://doi.org/10.1007/S11663-018-1176-0.

Smith, B. J., and R. G. Eggert. 2016. “Multifaceted Material Substitution: The Case of NdFeB Magnets, 2010–2015.” *JOM 68*(7), 1964–71. https://doi.org/10.1007/s11837-016-1913-2.

Sommer, Valentin, and Grit Walther. 2021. “Recycling and Recovery Infrastructures for Glass and Carbon Fiber Reinforced Plastic Waste from Wind Energy Industry: A European Case Study.” *Waste Management* 121 (February): 265–75. https://doi.org/10.1016/j.wasman.2020.12.021.

Sprecher, Benjamin, Ichiro Daigo, Shinsuke Murakami, Rene Kleijn, Matthijs Vos, and Gert Jan Kramer. 2015. “Framework for Resilience in Material Supply Chains, With a Case Study from the 2010 Rare Earth Crisis.” *Environmental Science & Technology* 49 (11): 6740–50. https://doi.org/10.1021/acs.est.5b00206.

The White House. 2021. “Executive Order on Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability.”https://www.whitehouse.gov/briefing-room/presidential-actions/2021/12/08/executive-order-on-catalyzing-clean-energy-industries-and-jobs-through-federal-sustainability/. Tolcin, Amy. 2022. “Zinc.” In *Mineral Commodity Summaries*, by the United States Geological Survey. https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-zinc.pdf.

Tse, P.-K. 2011. *China’s rare-earth industry*. U.S. Department of the Interior, United States Geological Survey. https://pubs.usgs.gov/of/2011/1042/of2011-1042.pdf.

Uda, T. 2002. “Recovery of Rare Earths from Magnet Sludge by $FeCl_2$.” *Master Trans*, 43:55–62. https://www.jstage.jst.go.jp/article/matertrans/43/1/43_1_55/_pdf.

Ueberschaar, M., J. Geiping, M. Zamzow, S. Flamme, V. S. Rotter. 2017. “Assessment of element-specific recycling efficiency in WEEE pre-processing.” *Resour Conserv Recycl*, 124, pp. 25-41. https://doi.org/10.1016/j.resconrec.2017.04.006.

United Nations Environment Program. 2011. "Towards a green economy: Pathways to sustainable development and poverty eradication." http://www.unep.org/greeneconomy.

———. 2016. "Global Material Flows and Resource Productivity." UNEP International Resource Panel. https://www.resourcepanel.org/reports/global-material-flows-and-resource-productivity-database-link.

U.S. Department of Commerce, Bureau of Industry and Security. 2021. *Publication of a Report on the Effect of Imports of Transformers and Transformer Components on the National Security: An Investigation Conducted Under Section 232 of the Trade Expansion Act of 1962*. 64606 Federal Register, Vol. 86, No. 220. https://www.govinfo.gov/content/pkg/FR-2021-11-18/pdf/2021-24958.pdf.

U.S. Department of Energy. 2021a. "Secretary Granholm Launches Hydrogen Energy Earthshot to Accelerate Breakthroughs Toward a Net-Zero Economy." https://www.energy.gov/articles/secretary-granholm-launches-hydrogen-energy-earthshot-accelerate-breakthroughs-toward-net.

———. 2021b. *Solar Futures Study*. Office of Energy Efficiency and Renewable Energy. https://www.energy.gov/sites/default/files/2021-09/Solar%20Futures%20Study.pdf.

———. 2022. *America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition.* https://www.energy.gov/sites/default/files/2022-02/America%E2%80%99s%20Strategy%20to%20Secure%20the%20Supply%20Chain%20for%20a%20Robust%20Clean%20Energy%20Transition%20FINAL.docx_0.pdf.

U.S. Department of State and the United States Executive Office of the President. 2021. *The Long-Term Strategy of the United States, Pathways to Net-Zero Greenhouse Gas Emissions by 2050*. https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf.

United States Environmental Protection Agency. 2012. "Rare Earth Elements: A Review of Production, Processing, Recycling, and Associated Environmental Issues." Washington, D.C., Report No.: EPA 600/R-12/572. https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=251706&Lab=NRMRL.

United States Geological Survey. 2021. *Mineral Commodity Summaries 2021*. https://pubs.usgs.gov/periodicals/mcs2021/mcs2021.pdf.

———. 2022. "2022 List of Critical Minerals." https://www.usgs.gov/news/national-news-release/us-geological-survey-releases-2022-list-critical-minerals.

Veers, P., L. Sethuraman, and J. Keller. 2020. "Wind-Power Generator Technology Research Aims to Meet Global-Wind Power Ambitions." *Joule 4*(9), 1861–63. https://doi.org/10.1016/j.joule.2020.08.019.

Vestas. 2013. *Life Cycle Assessment of electricity production from an Onshore V90-3.0 MW Wind Plant*. Vestas Wind Systems A/S, Hedeager 44, Aarhus N, 8200, Denmark. https://www.vestas.com/en/sustainability/reports-and-ratings#lcadownload.

———. 2017a. *Life Cycle Assessment of electricity production from an Onshore V136-3.45 MW Wind Plant*. Vestas Wind Systems A/S, Hedeager 42, Aarhus N, 8200, Denmark. https://www.vestas.com/en/sustainability/reports-and-ratings#lcadownload.

———. 2017b. *Life Cycle Assessment of electricity production from an Onshore V126-3.45 MW Wind Plant*. Vestas Wind Systems A/S, Hedeager 42, Aarhus N, 8200, Denmark. https://www.vestas.com/en/sustainability/reports-and-ratings#lcadownload.

———. 2017c. *Life Cycle Assessment of electricity production from an Onshore V117-3.45 MW Wind Plant*. Vestas Wind Systems A/S, Hedeager 42, Aarhus N, 8200, Denmark. https://www.vestas.com/en/sustainability/reports-and-ratings#lcadownload.

———. 2017d. *Life Cycle Assessment of electricity production from an Onshore V112-3.45 MW Wind Plant*, Version 1.1. Vestas Wind Systems A/S, Hedeager 42, Aarhus N, 8200, Denmark. https://www.vestas.com/en/sustainability/reports-and-ratings#lcadownload.

———. 2017e. *Life Cycle Assessment of electricity production from an Onshore V105-3.45 MW Wind Plant*, Version 1.1. Vestas Wind Systems A/S, Hedeager 42, Aarhus N, 8200, Denmark. https://www.vestas.com/en/sustainability/reports-and-ratings#lcadownload.

———. 2018a. *Life Cycle Assessment of electricity production from an Onshore V116-2.0 MW Wind Plant*. Vestas Wind Systems A/S, Hedeager 42, Aarhus N, 8200, Denmark. https://www.vestas.com/en/sustainability/reports-and-ratings#lcadownload.

———. 2018b. *Life Cycle Assessment of electricity production from an Onshore V120-2.0 MW Wind Plant*. Vestas Wind Systems A/S, Hedeager 42, Aarhus N, 8200, Denmark. https://www.vestas.com/en/sustainability/reports-and-ratings#lcadownload.

———. 2019. *Life Cycle Assessment of electricity production from an Onshore V117-4.2 MW Wind Plant*. Vestas Wind Systems A/S, Hedeager 42, Aarhus N, 8200, Denmark. https://www.vestas.com/en/sustainability/reports-and-ratings#lcadownload.

———. 2022a. *Life Cycle Assessment of electricity production from an Onshore V150-4.2 MW Wind Plant*. Vestas Wind Systems A/S, Hedeager 42, Aarhus N, 8200, Denmark. https://www.vestas.com/en/sustainability/reports-and-ratings#lcadownload.

———. 2022b. *Life Cycle Assessment of electricity production from an Onshore V136-4.2 MW Wind Plant*. Vestas Wind Systems A/S, Hedeager 42, Aarhus N, 8200, Denmark. https://www.vestas.com/en/sustainability/reports-and-ratings#lcadownload.

Watari, T., K. Nansai, K. Nakajima. 2020. “Review of critical metal dynamics to 2050 for 48 elements.” *Resources, Conservation and Recycling, 155*, 104669. https://doi.org/10.1016/j.resconrec.2019.104669.

Watson, S., A. Moro, V. Reis, C. Baniotopoulos, S. Barth, G. Bartoli, F. Bauer, et al. 2019. “Future emerging technologies in the wind power sector: A European perspective.” *Renewable and Sustainable Energy Reviews, 113,* 109270. https://doi.org/10.1016/j.rser.2019.109270.

Wellens, S., B. Thijs, and K. Binnemans. 2012. "An environmentally friendlier approach to hydrometallurgy: highly selective separation of cobalt from nickel by solvent extraction with undiluted phosphonium ionic liquids." *Green Chem* 14:1657–1665. https://doi.org/10.1039/C2GC35246J.

Wilburn, David R. 2011. "Wind Energy in the United States and Materials Required for the Land-Based Wind Turbine Industry from 2010 through 2030." *Scientific Investigations Report*. United States Geological Survey. https://pubs.usgs.gov/sir/2011/5036/sir2011-5036.pdf.

Wiser, R., M. Bolinger, B. Hoen, D. Millstein, J. Rand, G. Barbose, N. Darghouth, W. Gorman, S. Jeong, A. Mills, B. Paulos. 2021. *Land-Based Wind Market Report: 2021 Edition.* U.S. Department of Energy, Washington, D.C. https://www.energy.gov/eere/wind/articles/land-based-wind-market-report-2021-edition-released.

World Bank Group. 2017. "The Growing Role of Minerals and Metals for a Low Carbon Future." World Bank, Washington, DC. https://doi.org/10.1596/28312.

Yang, Y., A. Walton, R. Sheridan, K. Guth, R. Gauß, O. Gutfleisch, et al. 2017. "REE Recovery from End-of-Life NdFeB Permanent Magnet Scrap: A Critical Review." *J. Sustain. Metall*. 3, 122–149. https://doi.org/10.1007/s40831-016-0090-4.

Yang, J., L. Zhang, Y. Chang, Y. Hao, G. Liu, Q. Yan, Y. Zhao. 2020. "Understanding the material efficiency of the wind power sector in China: A spatial-temporal assessment." *Resources, Conservation and Recycling*, 155, 104668. https://doi.org/10.1016/j.resconrec.2019.104668.

Zakotnik, M., I. R. Harris, A. J. Williams. 2008. "Possible methods of recycling NdFeB-type sintered magnets using the HD/degassing process." *J Alloys Compd* 450:525–531. https://doi.org/10.1016/j.jallcom.2007.01.134.

Appendix A. Biden Administration Objectives

A.1 Carbon-Free Power Sector by 2035 and Irreversible Path to a Net-Zero Economy by 2050

The "Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050" describes the Biden administration's decarbonization goals for the country and outlines an approach for achieving them (United States Department of State and the United States Executive Office of the President 2021). The primary goal is to achieve net-zero greenhouse gas emissions by no later than 2050. This goal is supported by five key transformations:

1. Decarbonizing electricity (i.e., achieving 100% clean electricity by 2035)
2. Electrifying most of the economy and switching to other clean fuels
3. Cutting energy waste
4. Reducing methane (and other non-carbon-dioxide) emissions
5. Scaling up carbon dioxide removal.

The capacity projection used in the High Deployment scenario in this study is aligned with the goal of achieving a carbon-free power sector by 2035 and supports the goal of putting the United States on an irreversible path to a net-zero economy by 2050. Refer to United States Department of State and the United States Executive Office of the President 2021 for more details about the administration's objectives and strategy.

A.2 Role of Renewable Wind Energy in Hydrogen Shot Goal

Hydrogen is a versatile energy carrier that can be stored in liquid, gas, or as a chemical compound and converted to energy through traditional combustion methods or electrochemical processes via fuel cells (McQueen et al. 2020). If produced from clean energy sources, it will help decarbonize some of the most energy-intensive U.S. sectors: transportation, electricity generation, buildings' heat and power, and manufacturing.

In June 2021, the U.S. Department of Energy (DOE) launched the first Energy Earthshots Initiative—the Hydrogen Shot—which aims to reduce the cost of clean hydrogen (produced without emitting greenhouse gas emissions) by 80% in the next decade (DOE 2021a). This reduction would bring the costs of clean hydrogen from its current \$5/kilogram (kg) to \$1/kg, which would make clean hydrogen competitive with blue hydrogen (produced from fossil fuels with carbon capture and storage) (International Renewable Energy Agency 2020) and help reach the goal of a net-zero economy by 2050.

Reaching the Hydrogen Shot goal requires reducing the cost of electrolyzers and increasing their efficiency as well as inexpensive and abundant access to renewable energy resources (International Renewable Energy Agency 2020). The "Solar Futures Study" estimated that deep decarbonization of the United States supported by hydrogen would almost triple the demand for renewable energy in 2050 (DOE 2021b). Furthermore, according to a National Renewable Energy Laboratory study, wind energy represents the second-highest technical potential—after solar—for hydrogen production from renewable resources (Connelly et al. 2020). Specifically, the technical potential from land-based and offshore wind is 700 million metric tonnes per year— enough to supply the current hydrogen demand and serviceable consumption potential of 10 tonnes and 106 tonnes, respectively (Ruth et al. 2020).

Hence, while contributing to laying a path toward a net-zero economy, the addition of wind power to reach the carbon-free power sector, net-zero economy, and Hydrogen Shot goals also implies that considerable amounts of materials will be needed to manufacture new wind turbines.

Appendix B. Brief History of Critical Materials Research

The term “critical material” was first used by the U.S. government in 1939, when it referred to material stockpiles needed to supply the nation during wartime. Subsequently, these materials came to include those required for civilian and industrial uses in addition to national defense (National Research Council 2008). In 2010–2011, a trade dispute between China and Japan caused prices of rare-earth elements[21] to increase up to tenfold and drew attention to the potential for disruptions in the supply of critical materials, thereby impacting the clean energy transition (Sprecher et al. 2015). Since then, many studies on material criticality have been published, with six articles providing summaries (Achzet and Helbig 2013; Erdmann and Graedel 2011; Graedel and Reck 2016; Habib, Parajuly, and Wenzel 2015; Schrijvers et al. 2020; Watari et al. 2020). For example, Watari et al. (2020) identified 88 studies exploring the projected long-term status of 48 critical materials with respect to their use in 10 emerging technologies.

Following the 2010–2011 China-Japan trade dispute and its ripple effects on the pricing of rare-earth metals, several studies dedicated to the supply and demand of rare-earth metals were published (Du and Graedel 2011; Paulick and Machacek 2017; Tse 2011). Riddle et al. (2021) highlighted that out of the 10 rare-earth metals included in the analysis, dysprosium is the most vulnerable to supply disruption, showing the highest increases in prices. The study also shows that supply disruptions may foster more—and earlier—development of new mining projects outside China, which is in line with the rare-earth metal deposits exploration boom that followed the 2010–2011 trade dispute (Paulick and Machacek 2017). Due to supply restrictions, higher prices of rare-earth metals may trigger reductions in demand for neodymium magnets, threatening wind energy development (especially offshore projects).

Another challenge posed by critical minerals is that they are often byproducts of host metals and, therefore, depend on the demand for the latter (Watari et al. 2020). For example, production of indium, gallium, and dysprosium relies on demand for their respective host metals of zinc, aluminum, and yttrium (Riddle et al. 2021; Watari et al. 2020). Dysprosium oxide production is constrained by the co-production of other rare-earth metals with lesser demand, which suggests that dysprosium production may fall short of demand (Riddle et al. 2021). While constraints from host metal mining may limit the supply of critical materials, removing those constraints may also create issues. Elshkaki and Graedel (2015) estimated that greenhouse gas emissions from mining oversupplies of the host metals zinc and copper to obtain tellurium, indium, and germanium for solar cells might, in some cases, exceed the greenhouse gas emission reductions from replacing coal with solar photovoltaics. The production of dysprosium is likely to increase the production of thorium (Elshkaki and Graedel 2014). This oversupply of thorium may be costly to deal with because of the metal’s radioactivity.

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[21] The rare-earth elements are scandium, yttrium, and the 15 elements of the lanthanide series of chemical elements: lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium.

Appendix C. Data Sources for Life Cycle Inventories

As described in the main text, the authors use tools from life cycle assessment (LCA) to identify and characterize background material quantities. LCA allows researchers to model the inputs (e.g., materials and fossil-fuel consumption) and outputs (air pollutant emissions, discharges to water) of a product or process's life cycle from raw material extraction through manufacturing, use, and disposal. In the Renewable Energy Materials Properties Database (REMPD), we use life cycle inventory data generated for the life cycle assessment to estimate the background material for the foreground system (refer to Section 2.1.3 for a definition of foreground and background systems and Figure 3 for an illustration of the system boundary used in the REMPD). This approach positions future work on the REMPD to calculate other types of resource requirements and impacts (e.g., global warming potential, emissions to water, energy consumption) using the background material data available in the database.

Whenever possible, we sourced life cycle inventory data from publicly available data sources using the material that most closely aligned with each foreground material. When a specific material was unavailable, we used a proxy to model life cycle inputs and outputs. For example, for the unique fiberglass/epoxy materials used in wind turbine blades, our team modeled life cycle assessment results for epoxy and fiberglass separately, and combined the results based on the allocation of materials by mass. Table C-1 lists the database foreground materials modeled in the REMPD along with the associated life cycle assessment proxy material and data source. Our team used U.S. supply chain scopes whenever possible in modeling these results for all materials. If U.S. scopes were unavailable, we used global supply chain assumptions. European supply chain assumptions were used if neither U.S. nor global scopes were available.

Table C-1. Data Sources and Proxy Materials Used for Background Life Cycle Inventory Data

REMPD Material Type	Life Cycle Assessment Proxy Material	Data Source
Road aggregate	aggregate	Gursel, P. and C. Custodio. 2012. Green Concrete LCA Webtool. https://greenconcrete.berkeley.edu/
Aluminum	aluminum	U.S. Life Cycle Inventory Database. 2012. National Renewable Energy Laboratory (NREL). https://www.nrel.gov/lci/
Balsa	veneer hardwood	U.S. Life Cycle Inventory Database. 2012. NREL. https://www.nrel.gov/lci/
Carbon fiber	polyacrylonitrile fibers	European Reference Life Cycle Database of the Joint Research Center - Version 3.2. 2015. European Commission Joint Research Center. https://eplca.jrc.ec.europa.eu/ELCD3/
Cast iron	cast iron	U.S. Life Cycle Inventory Database. 2012. NREL. https://www.nrel.gov/lci/
Casting steel	low-alloyed steel	Frischknecht R., N. Jungbluth, H.-J. Althaus, G. Doka, R. Dones, T. Heck, S. Hellweg, R. Hischier, T. Nemecek, G. Rebitzer, M. Spielmann. 2005. "The ecoinvent database: Overview and methodological framework." *International Journal of Life Cycle Assessment* 10, 3–

REMPD Material Type	Life Cycle Assessment Proxy Material	Data Source
		9. https://link.springer.com/article/10.1065/lca2004.10.181.1
Chromium steel	chromium steel	Frischknecht R., N. Jungbluth, H.-J Althaus, G. Doka, R. Dones, T. Heck, S. Hellweg, R. Hischier, T. Nemecek, G. Rebitzer, M. Spielmann. 2005. “The ecoinvent database: Overview and methodological framework.” *International Journal of Life Cycle Assessment* 10, 3–9. https://link.springer.com/article/10.1065/lca2004.10.181.1
Concrete	concrete	Yang, Y., W. Ingwersen, T. Hawkins, M. Srocka, and D. Meyer. 2017. “USEEIO: a New and Transparent United States Environmentally Extended Input-Output Model.” *Journal of Cleaner Production*. Elsevier Science Ltd, New York, NY, 158:308-318. https://doi.org/10.1016/j.jclepro.2017.04.150
Copper	copper	Yang, Y., W. Ingwersen, T. Hawkins, M. Srocka, and D. Meyer. 2017. “USEEIO: a New and Transparent United States Environmentally Extended Input-Output Model.” *Journal of Cleaner Production*. Elsevier Science Ltd, New York, NY, 158:308-318. https://doi.org/10.1016/j.jclepro.2017.04.150
Electrical steel	low-alloyed electric steel	Frischknecht R., N. Jungbluth, H.-J Althaus, G. Doka, R. Dones, T. Heck, S. Hellweg, R. Hischier, T. Nemecek, G. Rebitzer, M. Spielmann. 2005. “The ecoinvent database: Overview and methodological framework.” *International Journal of Life Cycle Assessment* 10, 3–9. https://link.springer.com/article/10.1065/lca2004.10.181.1
Epoxy	epoxy	Keoleian, G., S. Miller, R. D. Kleine, A. Fang, J. Mosley. 2012. *Life cycle material data update for GREET model*. Report No. CSS12-12. Argonne National Laboratory, Argonne, IL (United States). https://greet.es.anl.gov/publication-greet2-lca-update
Fiberglass_e	fiberglass E	U.S. Life Cycle Inventory Database. 2012. NREL. https://www.nrel.gov/lci/
Galvanized steel	galvanized steel, low alloy	Internal life cycle assessment by NREL for this report.

REMPD Material Type	Life Cycle Assessment Proxy Material	Data Source
Glass-fiber-reinforced polymer	glass-fiber-reinforced plastic	Keoleian, G., S. Miller, R. D. Kleine, A. Fang, J. Mosley. 2012. *Life cycle material data update for GREET model*. Report No. CSS12-12. Argonne National Laboratory, Argonne, IL (United States). https://greet.es.anl.gov/publication-greet2-lca-update
Glass-reinforced plastic	glass-fiber-reinforced plastic	Keoleian, G., S. Miller, R. D. Kleine, A. Fang, J. Mosley. 2012. *Life cycle material data update for GREET model.* Report No. CSS12-12. Argonne National Laboratory, Argonne, IL (United States). https://greet.es.anl.gov/publication-greet2-lca-update
Graphite	graphite	Dunn, J. B., C. James, L. Gaines, K. Gallagher, Q. Dai, J. C. Kelly. 2015. *Material and energy flows in the production of cathode and anode materials for lithium ion batteries* (No. ANL/ESD-14/10 Rev). Argonne National Laboratory, Argonne, IL (United States). https://doi.org/10.2172/1224963
Iron	iron	U.S. Life Cycle Inventory Database. 2012. NREL. https://www.nrel.gov/lci/
Lead	lead	GHGs Regulated Emissions, and Energy use in Transportation 2 Model. 2021. Argonne National Laboratory. https://greet.es.anl.gov/
Low-carbon steel	low-alloyed steel	Frischknecht R., N. Jungbluth, H.-J. Althaus, G. Doka, R. Dones, T. Heck, S. Hellweg, R. Hischier, T. Nemecek, G. Rebitzer, M.Spielmann. 2005. “The ecoinvent database: Overview and methodological framework.” *International Journal of Life Cycle Assessment* 10, 3–9. https://link.springer.com/article/10.1065/lca2004.10.181.1
Magnetic steel	galvanized steel, low alloy	Internal life cycle assessment by NREL for this report.
PET foam	polyethylene terephthalate	U.S. Life Cycle Inventory Database. 2012. NREL. https://www.nrel.gov/lci/
Polyester	polyester	U.S. Life Cycle Inventory Database. 2012. NREL. https://www.nrel.gov/lci/
PVC foam	polyvinyl chloride	U.S. Life Cycle Inventory Database. 2012. NREL. https://www.nrel.gov/lci/
Reinforcing steel	low-alloyed steel	Frischknecht R., N. Jungbluth, A.-J. Althaus, G. Doka, R. Dones, T. Heck, S. Hellweg, R. Hischier, T. Nemecek, G. Rebitzer, M. Spielmann. 2005. “The ecoinvent database: Overview and methodological framework.” *International Journal of Life Cycle Assessment* 10, 3–

REMPD Material Type	Life Cycle Assessment Proxy Material	Data Source
		9. https://link.springer.com/article/10.1065/lca2004.10.181.1
Thermoplastic	HDPE	U.S. Life Cycle Inventory Database. 2012. NREL. https://www.nrel.gov/lci/
Plastic	polyurethane, rigid	Idemat https://www.ecocostsvalue.com/data/download-of-databases/
Silicone	silicone	Frischknecht R., N. Jungbluth, H.-J Althaus, G. Doka, R. Dones, T. Heck, S. Hellweg, R. Hischier, T. Nemecek, G. Rebitzer, M. Spielmann. 2005. "The ecoinvent database: Overview and methodological framework." *International Journal of Life Cycle Assessment* 10, 3–9. https://link.springer.com/article/10.1065/lca2004.10.181.1

Abbreviations: PET = polyethylene terephthalate; PVC = polyvinyl chloride; HDPE = high-density polyethylene.

Appendix D. Scaling Relationships

To capture changes in material intensity that might occur as wind power plants and wind turbines increase in size, the authors multiply the fractional contribution of materials by type (e.g., % concrete, % steel, % carbon fiber) by a scaling relationship related to the plant configuration (e.g., the plant size, number of turbines, rotor diameter). These scaling relationships are summarized in Table D-1. The following sections provide more detail about each scaling relationship.

Table D-1. Scaling Relationships Used To Compute Material Requirements Over Time

Component, Subassembly	Scaling Relationship	Data Source
Roads, all subassemblies	$mass = 12{,}208(N_t - 1) * D_r + 15{,}256{,}640$	Eberle, A., J. O. Roberts, A. Key, P. Bhaskar, K. L. Dykes. 2019. *NREL's Balance-of-System Cost Model for Land-Based Wind*. Golden, CO: NREL. https://www.nrel.gov/docs/fy19osti/72201.pdf.
Foundation, all subassemblies	$mass = 0.67042 * h * \frac{\pi}{4} * {D_r}^2 + 444{,}740$	Linear regression performed for this report
Substructure, all subassemblies	$mass \propto C$	Mass is assumed to scale linearly with turbine capacity
Substation, all subassemblies	$mass \propto P_c$	Mass is assumed to scale linearly with plant size
Array and export cables, all subassemblies	Array cable: $mass \propto P_c$ Export cable: • Offshore: mass scales linearly with export cable length (assumed to be 70 kilometers (km) based on project announcements) • Land-based: mass scales linearly with distance to interconnection (assumed to be 8 km)	Array cable mass is assumed to scale linearly with plant size; export cable length varies based on relevant export distances
Turbine, nacelle	$mass = 108813.2 - 642.5C - 76252.4D_r + 2920.3h$	Linear regression performed for this report
Turbine, hub	$mass = (0.954M_{singleblade} + 5680.3)$	Fingersh, L., M. Hand, A. Laxson. 2006. *Wind Turbine Design Cost and Scaling Model.* Golden, CO: NREL. NREL/TP-500-40566. https://www.nrel.gov/docs/fy07osti/40566.pdf.
Turbine, blade	$m_{Blade} = {L_{Blade}}^{x}$, where x varies based on the facility type and technology configuration (see Section D.7 for details)	Derived based on expert input

Component, Subassembly	Scaling Relationship	Data Source
Turbine, tower	$\ln(mass)$ = 1.206 + 2.432 * ln(h)	Linear regression performed for this report

Abbreviations: N_t= number of turbines (unitless); D_r = rotor diameter (m); C = turbine rated capacity (MW); P_c = plant rated capacity; h = hub height (m); $M_{singleblade}$ = mass of a single blade (kg); R = rotor radius (m).

D.1 Land-Based Roads

The total material volume needed to construct roads for land-based wind plants, V_r (in loose cubic yards), is calculated based on the length of the road, L_r, (in m) and is given by

$$V_r = (L_r * W_r * t_r) * 1.39 \quad \text{(D-1)}$$

$$L_r = (N_t - 1) * D_r * S_t + l_{adder} \quad \text{(D-2)}$$

where N_t is the number of wind turbines, D_r is the rotor diameter in meters, S_t is the spacing of the turbines relative to the rotor diameter (unitless; assumed to be 4), and l_{adder} is the excess roads for access to road strings from existing public roads and/or a highway (in meters (m); assumed to be 5,000 m), W_r is the width of the road (in m; assumed to be 4.9 m), t_r is the thickness of the road (in m; assumed to be 0.2 m), and 1.39 is a factor from RSMeans that converts embankment cubic yards to loose cubic yards (Eberle et al. 2019).

Substituting in the assumed values for road width, thickness, turbine spacing, and road adder, provides:

$$V_r = ((4(N_t - 1) * D_r + 5000) * 4.9 * 0.2) * 1.39 \quad \text{(D-3)}$$

which further simplifies to:

$$V_r = 5.45(N_t - 1) * D_r + 6811 \quad \text{(D-4)}$$

To compute the mass of material (in this case, aggregate) needed to construct roads, we multiply by the density, such that:

$$M_r = d_a(5.45(N_t - 1) * D_r + 6811) \quad \text{(D-5)}$$

where d_a, is the density of road aggregate, which we assume to equal 2,240 kg/m^3 (Iowa Department of Transportation 2021).

D.2 Land-Based Foundation

The mass scaling model for wind turbine foundations assumes a linear relationship between the foundation mass and the product of the rotor swept area and hub height. Empirical data were combined with modeled data from NREL's Land-based Balance of System Systems Engineering (LandBOSSE) model (Eberle et al. 2019) to create a data set of 25 turbines covering 2 megawatts (MW) to 15 MW capacity, 80-m to 315-m rotor diameter, and 72-m to 200-m hub height designs. We regressed the concrete mass against the rotor swept area ($\frac{\pi}{4}D_r^2$) and the hub height, h, obtaining an R^2 of 0.989, such that:

$$mass = 444740 + 0.67042 * h * \tfrac{\pi}{4}D_r^2. \tag{D-6}$$

Based on industry data for spread-foot foundations, the total mass of a spread-foot wind turbine foundation is assumed to be 98.5% concrete and 1.5% steel.

D.3 Offshore Substructure

For offshore wind energy, the mass of the substructure is assumed to scale linearly with wind turbine size.

D.4 Substation

The mass of materials required for substations is assumed to scale linearly with plant size.

D.5 Array and Export Cables

For offshore wind energy, export cables are assumed to scale linearly with distance to shore. For land-based wind energy, export cables are assumed to scale linearly with the distance to interconnection. Because we do not vary the distance to shore or the distance to interconnection in this analysis, the material requirements for export cables remains constant for all scenarios.

Array cables are assumed to vary based on the number of wind turbines and the rotor diameter.

D.6 Wind Turbine: Nacelle

The nacelle mass scaling model was developed in R (V.4.1.2) using the base linear regression function with leave-one-out cross validation. We regressed the nacelle mass against the hub height, h, rated turbine capacity, C, and rotor diameter, D_r, obtaining an R^2 of 0.987 and F-statistic P-value < 0.001, such that:

$$mass = 108813.2 - 642.5 * C - 76252.4 * D_r + 2920.3 * h. \tag{D-7}$$

D.7 Wind Turbine: Hub

The mass scaling relationship for the hub is based on Fingersh et al. (2006), such that:

$$mass = (0.954M_{singleblade} + 5680.3 + 0.954 * M_{singleblade}, \tag{D-8}$$

where $M_{singleblade}$ is the mass of a single blade.

D.8 Wind Turbine: Blade

Wind turbine blades primarily comprise fiber-reinforced composite materials that combine a polymer resin (e.g., epoxy) with glass or carbon fibers, and a balsa wood or polymer foam core. Fiber-reinforced composites are an engineered material in which a polymeric resin is combined with reinforcement fibers and then cured to become a solid composite. The technology configurations used in this analysis rely on different combinations of a reinforcement fiber and resin system, as well as two different composite manufacturing processes. An E-type fiberglass is the predominant reinforcement fiber (by mass) in each of the designs, being used in all parts of the blade, except for the spar cap in some cases. Carbon-fiber reinforcement is only used in the spar cap, wherein the high relative costs and mechanical performance of carbon fiber are best utilized.

The traditional manufacturing process for a wind turbine blade uses a vacuum-assisted resin transfer molding (VARTM) infusion, wherein dry fabric (reinforcement fibers) and the core material are laid up in molds, covered with vacuum bags, and a pressure vacuum is applied to infuse the resin system into the mold and blade materials. The VARTM process is standard across the wind energy industry and results in low-cost, structurally efficient composites. A slight modification to this process occurs when using pultruded composites for the spar cap. A pultrusion manufacturing process is where reinforcement fibers are wetted by the resin (through a resin bath or spray, based on resin system) and then pulled through a heated die, resulting in a fully cured fiber-reinforced composite with a constant cross section. Pultrusion manufacturing is an intermediate step for wind turbine blades and the only composite form being considered for use of carbon fiber in spar caps, due to the high consistency and control of the manufacturing process.

Wind turbine blade mass, m_{Blade}, scales exponentially with blade length, L_{Blade}, as given by:

$$m_{Blade} = {L_{Blade}}^{x} \tag{D-9}$$

where x is a value greater than 2. The precise exponent depends on several design factors, including the wind speed classification, structural reinforcement materials used, power rating for a given blade length, blade segmentation, and the aerodynamic design. Due to the exponential relationship of blade mass with swept area and energy capture, cost relationships favor longer blades to achieve lower levelized cost of energy. Thus, current designs may continue to push toward longer blade lengths to enable continued reductions in the levelized cost of energy.

For the purposes of this analysis, we vary the blade mass scaling exponent as outlined in Table D-2. To simplify the analysis to fewer levels of discretization, the scaling exponents are specified based only on two parameters: (1) spar-cap reinforcement materials (fiberglass or carbon fiber) and (2) siting conditions (land-based or offshore). The mass scaling exponents used in this analysis are a function of spar-cap reinforcement fiber (carbon fiber or fiberglass) and vary slightly for offshore versus land-based machines, mostly a result of higher wind speed sites offshore. The scaling exponent varies further within this discretization for specified design configurations and wind classification, so the values used are averages based on recent design models (Ennis et al. 2019; Johnson et al. 2021; Gaertner et al. 2020) and based on blade mass for relevant commercial wind turbine blades.

Table D-2. Wind Turbine Blade Mass Scaling Exponents

Spar Reinforcement	Land-Based	Offshore
Fiberglass, VARTM infusion	2.39	Not studied
Carbon, pultrusion	2.31	2.34
Fiberglass, pultrusion	Not studied	2.39 (reduced blade mass calculated by database)

When using pultruded spar material, fully cured pultruded planks are added in the blade mold with the dry fabric and core material for the VARTM infusion to adhere the pultruded planks to the rest of the blade materials. As a result of the distinction in the manufacturing processes, the resin system for the VARTM blade infusion and for the pultruded members do not have to be the same. For example, even when using an epoxy resin throughout the blade, there are slight distinctions for the pultrusion resin and the infusion resin. The resin systems included in the analysis are summarized in Table D-3, including the associated manufacturing process.

Table D-3. Study Resin Systems, Composite Manufacturing Processes, and Representative Densities

Resin System	Manufacturing Method	Density [kg/m^3]
Epoxy	VARTM infusion	1,150
Epoxy	Pultrusion	1,225
Vinylester	Pultrusion	1,100
Polyurethane	Pultrusion	1,130
Reversible epoxy	VARTM infusion	1,150
Thermoplastic	VARTM infusion	1,035

To determine the fundamental material requirements for a wind turbine blade, we divide the blade mass into the major components, or regions. These components serve various purposes during the operation of a wind turbine, both structural and to produce the aerodynamic shape of the blade. The component mass is calculated using a mass fraction of the total blade weight based on trends that have been generalized for this analysis. The component mass fractions are distinct based on the spar-cap reinforcement material (carbon fiber or fiberglass) but are not treated independently for land-based versus offshore applications.

The mass fraction values used in this analysis for the major underlying components in a wind turbine blade are shown in Tables D-4 and D-5, representing current material and manufacturing approaches. This component list for materials in a wind turbine blade does not include lightning protection (primarily using aluminum), leading-edge protection, or paint, as these materials represent an insignificant portion of the wind turbine blade or are considered abundant and do not require assessment. It is worth noting that a blade with a fiberglass spar cap is around 25% more massive than one using a carbon-fiber spar cap (Ennis et al. 2019), so keep this in mind when comparing mass percentages directly between Tables D-3 and D-4.

Table D-4. Blade Component Mass Breakdown for Blades With a Fiberglass-Reinforced Spar Cap

Blade Mass Breakdown — Fiberglass Spar (Percentage of Blade Weight)	
Glass-fiber-reinforced polymer spar	30%
Root buildup	15% (80% triaxial, 20% root fasteners)
Trailing-edge reinforcement	10%
Shell panel	33% (80% biaxial, 20% core)
Shear web	8% (67% biaxial, 33% core)
Gelcoat	2%
Adhesive	2%

Table D-5. Blade Component Mass Breakdown for Blades With a Carbon-Fiber-Reinforced Spar Cap

Blade Mass Breakdown — Carbon Spar (Percentage of Blade Weight)	
Carbon-fiber-reinforced polymer spar	12%
Root buildup	15% (80% triaxial, 20% root fasteners)
Trailing-edge reinforcement	8%
Shell panel	51% (80% biaxial, 20% core)
Shear web	10% (67% biaxial, 33% core)
Gelcoat	2%
Adhesive	2%

There are various material and design approaches used for commercial wind turbines beyond the spar cap material type. These variations include resin systems currently used or considered in the infusion and pultrusion composite manufacturing processes, core materials used, and blade segmentation. Tables D-4 and D-5 are used for each technology approach being considered, with minor modifications. For fiber-reinforced polymers, many of the mechanical properties are determined by the volume of the composite (through the reinforcement fiber amount) and not its mass. For composites using various resin systems, we assume that the composites will have a fixed volume fraction for each resin system, but the mass of the composite will vary based on the density of the resin. The mass fractions mentioned earlier are modified by the relative composite weight ratio for the non-epoxy composites studied. This approach assumes there is the same mass of reinforcement fibers and the same volume of the various resin systems, which causes a modified component mass fraction due to minor differences in the resin densities.

Commercial wind turbine blade designs vary based on design decisions related to siting and energy considerations, as well as underlying materials. Designs will continue to develop and use different materials based on future technology approaches, advances, and constraints. As outlined in this report, two technology configurations were developed for land-based and offshore wind turbines, which are used in the analysis study scenarios to represent expected advancements in wind turbine blade design.

The blade component technology configurations used in this report are based on both material and design choices or advances and are subject to fundamental differences between land-based and offshore applications. Land-based wind turbines are mostly constrained by the capital cost of the wind turbine and transportation limits. Offshore wind turbines are primarily constrained by mass of the turbine and the implications it has on system costs, in addition to technologies that assist with long blade lengths. One distinction this constraint causes for the Low Innovation technology configuration is that the land-based wind turbine is designated to have an infused fiberglass spar cap due to the higher relative costs of commercial carbon-fiber systems, whereas the offshore turbine uses carbon-fiber spar caps to control the mass and resist large deflections. Because of the system mass sensitivities, offshore wind turbines are not expected to have infused fiberglass spar caps; yet, would have a slight mass penalty. However, due to the variety of design approaches for blade joints in the industry, the additional mass and material requirements for the joint are not quantified in this analysis. The added mass of a blade joint is small relative to the total blade mass; therefore, given the averaging of blade mass scaling exponents in the analysis this approach is justified.

The Moderate Innovation technology configuration for land-based and offshore wind turbines assumes the same fundamental materials as the Low Innovation configuration, but the land-based blades are segmented with an additively manufactured (three-dimensional-printed) tip portion of the segmented blade. Additional innovations could include printed tips through ongoing research efforts by several national laboratories and industry partners where value has been identified in using printed materials for this reduced stress portion of the blade.

The resulting Low Innovation and Moderate Innovation technology configurations for land-based and offshore wind turbines are summarized in Table D-6. This table also shows the market share distribution for core material and resin systems at the different levels, where applicable.

Table D-6. Wind Turbine Blade Technology Configurations Used for the Study Scenarios

	Current Policies Scenario	**High Deployment Scenario**
	Technology Configuration: Low Innovation	*Technology Configuration: Moderate Innovation*
Land-based wind	• Fiberglass/thermoset shell (glass fibers and epoxy resin using VARTM infusion) • Fiberglass/thermoset spar cap using VARTM infusion • Core: 50% balsa, 50% polyvinyl chloride (PVC)	• Fiberglass/thermoset shell with epoxy resin for VARTM infusion • Segmented blade tip • Carbon-pultruded spar cap (85% epoxy, 15% vinylester) • Core: 50% balsa, 50% PVC
Offshore wind	• Fiberglass/thermoset shell with epoxy resin for VARTM infusion • Carbon-pultruded spar (85% epoxy, 15% vinylester) • Core: 50% balsa, 50% PVC	• Fiberglass/thermoset shell with epoxy resin for VARTM infusion • Carbon-pultruded spar (85% epoxy, 15% vinylester) • Core: 50% balsa, 50% PVC

The REMPD combines the technology configurations (Table D-6) with the mass calculation assumptions listed in Tables D-2 through D-5 to estimate the fundamental material requirements for various wind energy development scenarios.

For each of the reference turbines, we used Eq. D-9 to calculate two reference blade mass values for a fiberglass and carbon-fiber spar cap with the baseline exponents from Table D-2. These baseline mass values are not equal to the resulting blade mass value calculated by the database for each of the technology configurations. The baseline blade mass values are inputs to the database, which then recalculate the resulting blade mass based on the technology configurations and their inherent assumptions listed in Table D-6. The resulting blade mass for the two technology configurations is shown in Table D-7 as a percentage of the baseline blade mass when using fiberglass or carbon-fiber reinforcement in the spar cap.

Table D-7. Relative Blade Mass Values for the Study of Technology Configurations (for Land-Based and Offshore Wind Turbine Designs)

	Land-Based Turbine		**Offshore Turbine**	
Fiber reinforcement	Low Innovation	Moderate Innovation	Low Innovation	Moderate Innovation
Fiberglass spar	**100%**	n/a	n/a	n/a
Carbon-fiber spar	n/a	**100%**	**100%**	**100%**

The study-defined technology configurations, mass percentages, and blade mass scaling exponents help calculate the constituent materials required for the reference wind turbines used in the study scenarios. The underlying blade materials are divided into four fundamental categories of reinforcement fiber, resin systems, core materials, and assembly materials. The set of materials for a given technology configuration is not the same as for other technology configurations, as shown in Table D-6, but the full set in the analysis includes the following materials:

- **Reinforcement fibers**:
  - Fiberglass used in unidirectional, biaxial, or triaxial composites
  - Carbon fiber used in unidirectional pultrusions only
- **Resin systems**:
  - Traditional epoxy; slight variations for pultruded spar caps or VARTM infusion
  - Vinylester
  - Polyurethane
- **Core materials**:
  - Balsa wood
  - Polyvinyl chloride (PVC) foam
  - Polyethylene terephthalate foam
- **Assembly materials**:
  - Steel root fasteners
  - Epoxy adhesive
  - Methyl methacrylate adhesive.

As mentioned previously, the REMPD's calculated blade mass accounts for different component mass fraction values (compared to Tables D-4 and D-5) resulting from minor variations in the underlying composite mass based on the resin system used. Fiber-reinforced polymers combine reinforcement fiber (in various orientations) and resin, and an important property is the relative portion of fibers in a given volume, known as the fiber volume fraction. For wind turbines with VARTM infusion manufacturing, the fiber volume fraction varies between 49% and 57% based on the orientation of adjacent fiber layers (laminae) in a composite (unidirectional, biaxial, triaxial). Modern carbon-fiber pultrusions are moving to a fiber volume fraction of around 68%, which is used in this study to represent pultruded composites using carbon or glass fiber. To calculate the constituent material mass, the fiber mass fraction is used in the database for the various fiber-reinforced polymers that depend on the fiber volume fraction and fiber and resin system. Tables D-8 and D-9 list the fiber mass fractions for the various composites defined for use in the Low Innovation and Moderate Innovation technology configurations. The tables list the mass fractions for glass-fiber-reinforced polymers and for carbon-fiber-reinforced polymers, respectively.

Table D-8. Glass-Fiber-Reinforced Polymer Mass Fractions for Various Volume Fractions and Resin Systems Using Pultrusion on Infusion Manufacturing

	Composite Fiber Volume Fraction and Manufacturing Method			
Resin systems	68% pultrusion	57% unidirectional infusion	54% biaxial infusion	49% triaxial infusion
Traditional epoxy	0.816	0.746	0.722	0.681
Thermoplastic	n/a	0.766	0.743	0.703
Reversible epoxy	n/a	0.746	0.722	0.681

Table D-9. Carbon-Fiber-Reinforced Polymer Mass Fractions for Various Volume Fractions and Resin Systems Using Pultrusion Manufacturing

	Composite Fiber Volume Fraction and Manufacturing Method			
Resin systems	68% pultrusion	57% unidirectional infusion	54% biaxial infusion	49% triaxial infusion
Epoxy	0.752	n/a	n/a	n/a
Vinylester	0.772	n/a	n/a	n/a
Polyurethane	0.767	n/a	n/a	n/a

The preceding approach enables a representative calculation of the mass of constituent materials in future wind turbine blades, with blade lengths between 70 to 128 m, assuming material mechanical properties consistent with commercial materials being used today. There are alternative material approaches being developed for use in fiber-reinforced polymers for a variety of reasons, including reduced cost, recycling and reuse, and reduced carbon emissions.

Additional future technology configurations for wind turbine blades could consider circular economy considerations for the fiber-reinforced polymers to enable materials to be downcycled into other markets or reprocessed to aid in the production of future wind turbine blades. Such a configuration would assume improvements in manufacturing, inspection, and/or design of wind turbine blades (e.g., the blade components might only require 90% of the baseline mass fractions or blade composite materials might use reversible epoxies). However, we do not consider any such configuration in this analysis.

D.9 Wind Turbine: Tower

The tower mass scaling model was developed in R (V.4.1.2) using the base linear regression function with leave-one-out cross validation. We regressed the tower mass against the hub height and the rated turbine capacity. Based on the results, the rated capacity is not considered a significant explanatory variable at the $p < 0.001$ level of significance. Data were then logtransformed, and the regression was re-run, regressing tower mass on hub height, h, obtaining an R^2 of 0.931 and F-statistic P-value < 0.001, such that:

$$\log(mass) = 1.206 + 2.432 * \log(h). \tag{D-10}$$

Appendix E. Material Intensities for Vulnerable Materials

Tables E-1 and E-2 provide the underlying data the authors used to generate Figure 7. These tables summarize material intensities for vulnerable materials in current and future wind energy technologies. Current technology is represented using results from the Current Policies scenario in the year 2020. Potential future technology is represented using results from the High Deployment scenario in the year 2050. Table E-3 documents the data sources that were used to calculate the material intensities in Tables E-1 and E-2.

Table E-1. Average Material Intensity for Vulnerable Materials in Current Wind Energy Technology

	Land-Based Wind Material Intensity (kg/MW)				Offshore Wind Material Intensity (kg/MW)			
	Cables	Foundation	Substation	Turbine	Cables	Substructure	Substation	Turbine
Aluminum	2,400	1.3	4.1	680	242			680
Carbon fiber				590				580
Chromium	2.9	170	7.2	1,000	6.4	72	5.3	150
Cobalt	5.4E-07	0.42	0.08	2.1	0.01	3.2	0.14	1.1
Dysprosium		6.6E-06	5.3E-06	1.9	7.9E-07	6.2E-05	2.2E-06	6.6
Electrical steel			510	1,300			200	2,600
Gallium		8.0E-03	5.9E-04	0.04	2.7E-04	0.04	1.6E-03	0.01
Graphite				3.4				4.7
Lithium		2.8E-03	4.5E-06	0.68	6.3E-07	5.3E-05	1.9E-06	0.93
Manganese	0.64	38	14	1,600	11	3,700	130	830
Neodymium				40				110
Nickel		40	9.1	1,800	12	2,800	100	680
Niobium		0.07	1.5E-03	0.24	1.7E-03	0.57	0.02	0.12
Praseodymium		0.10	2.7E-03	0.42	3.0E-03	1.0	0.04	43
Terbium		3.9E-06	3.2E-06	1.9E-05	4.7E-07	3.7E-05	1.3E-06	0.38
Tin	1.1E-04	0.03	0.01	0.13	9.2E-04	0.25	0.01	0.26
Titanium	0.01	9.7	0.28	40	0.31	94	3.4	21
Vanadium	1.4E-05	1.6E-05	7.8E-07	1.3E-04	5.2E-05	1.4E-04	5.0E-06	3.7E-05
Zinc	0.09	0.35	0.22	27	11	31	1.1	7.7

Table E-2. Average Material Intensity for Vulnerable Materials in Potential Future Wind Energy Technology

	Land-Based Wind Material Intensity (kg/MW)				Offshore Wind Material Intensity (kg/MW)			
	Cables	**Foundation**	**Substation**	**Turbine**	**Cables**	**Substructure**	**Substation**	**Turbine**
Aluminum	2,400	1.4	4.1	680	240			890
Carbon fiber				2,300				1,100
Chromium	2.9	190	7.2	1,000	6.4	80	5.3	200
Cobalt	5.4E-07	4.6E-01	0.08	1.9	0.01	3.5	0.14	1.5
Dysprosium		7.2E-06	5.3E-06	1.9	7.8E-07	6.9E-05	2.3E-06	6.5
Electrical steel			510	1,300			200	2,700
Gallium		8.7E-03	5.9E-04	0.04	2.7E-04	0.04	1.6E-03	0.02
Graphite				1.8				8.8
Lithium		3.0E-03	4.5E-06	0.35	5.9E-07	1.4E-04	1.9E-06	1.8
Manganese	0.64	410	14	1,300	11	4,100	130	1,200
Neodymium				44				110
Nickel		430	9.1	1,600	12	3,100	100	1000
Niobium		0.06	1.5E-03	0.20	1.7E-03	0.63	0.02	0.19
Praseodymium		0.10	2.7E-03	0.36	3.0E-03	1.1	0.04	43
Terbium		4.3E-06	3.2E-06	1.6E-05	4.7E-07	4.1E-05	1.4E-06	0.37
Tin	1.1E-04	0.03	0.01	0.11	9.2E-04	0.28	0.01	0.29
Titanium	0.01	11	0.28	34	0.31	110	3.4	31
Vanadium	1.4E-05	1.7E-05	7.8E-07	1.0E-05	5.2E-05	1.5E-04	5.1E-06	5.4E-05
Zinc	0.09	3.9	0.22	22	11	34	1.1	11

Table E-3. Data Sources Used To Compute Wind Energy Material Quantities in the Renewable Energy Materials Properties Database (REMPD)

Facility Type	Component	Data Source(s) Used to Compute Wind Energy Material Quantities in the REMPD
Land-based wind	Array and export cables	- Proprietary data from original equipment manufacturers (OEMs)
	Foundation	- Proprietary data from OEMs - Selected Vestas life cycle assessments[a] - Crawford (2009) - Eberle et al. (2019) - Schreiber, Marx, and Zapp (2019)
	Roads	- Eberle et al. (2019)
	Substation	- Proprietary data from OEMs - Alsaleh and Sattler (2019)
	Turbine	- Proprietary data from OEMs - Scaling relationships documented in Appendix D - Crawford (2009) - Alsaleh and Sattler (2019) - Martínez et al. (2009) - Ozoemena, Cheung, and Hasan (2018) - Rajaei and Tinjum (2013) - Guezuraga, Zauner, and Pölz (2012)
Offshore wind	Array and export cables	- Proprietary data from OEMs - ABB (2010) - Arvesen et al. (2014) - Ikhennicheu et al. (2020)
	Substructure	- 4C Offshore (2022) - Negro et al. (2017)
	Substation	- Proprietary data from OEMs - Arvesen et al. (2014)
	Turbine	- Proprietary data from OEMs - Scaling relationships documented in Appendix D - Crawford (2009) - Guezuraga, Zauner, and Pölz (2012)

a. Selected Vestas LCAs include Vestas 2013, 2017a, 2017b, 2017c, 2017d, 2017e, 2018a, 2018b, 2019, 2022a, and 2022b.

Appendix F. Opportunities To Recycle Rare-Earth Elements

The rare-earth elements that are most used in the wind energy industry are neodymium and dysprosium, plus small quantities of praseodymium and terbium. Alloys of these four elements are key constituents of the powerful neodymium iron boron permanent magnets used in synchronous generators employed in some wind turbines. Compared to other applications, like vehicles, the generators of modern wind turbines are relatively large (1,000–2,000 kilograms). Supply and demand challenges for rare-earth elements are reviewed in Alves Dias et al. (2020a).

The primary processing steps in the rare-earth permanent-magnet supply chain are:

1. **Mineral Production.** Rare-earth ores (monazite, bastnaesite, and xenotime) are discovered and mined.

2. **Mineral Processing.** Rare-earth ores are crushed and milled. A flotation process is typically used to separate the tailings from the rare-earth elements.

3. **Chemical Extraction.** The most common extraction process is leaching, which involves dissolution of the valuable metals into an aqueous solution. Monazite, which contains neodymium, is often processed with sulfuric acid (Parker and Baroch 1971).

4. **Separation.** This step may be the most challenging due to the nearly identical chemical properties of the rare-earth elements. Common separation techniques include leaching, solvent extraction, and ion exchange followed by precipitation.

5. **Reduction.** Reduction is an energy-intensive process that can be carried out using metallothermic (Sharma 1987) or electrochemical (Dysinger 1994) methods.

6. **Magnet Production.** Refined rare-earth metal(s) are alloyed with other metals that will produce the desired microstructure and magnetic properties in the final product. The alloy is heated in a vacuum furnace and a stream of molten metal is forced under pressure onto a cooled drum where it is rapidly cooled to produce very small grains of metal. Next, a jet mill (a high-speed stream of cyclonic inert gas) grinds the alloy into powder. The cyclone automatically classifies the particles by size as they go through the system, so a narrow—and very favorable—particle size distribution is maintained. The powder enters a mold and is pressed between plates while under a strong magnetic field, forming a block of material. The magnetic field orients the grains so that the magnetic domains remain aligned in the designed direction. It is then machined and ground. The final step is applying a coating to avoid corrosion.

Currently, there is no effective method of recycling rare-earth magnets. Only 3% to 7% of rare-earth magnets are recycled from end products because current processes are uneconomical and/or generate huge amounts of toxic waste. While current processing methods are still at various research and development stages, it is estimated that in the coming 10 to 15 years, the recycled rare-earth elements from end-of-life permanent magnets will play a significant role in the total supply of rare-earth elements for the magnet sector (Yang 2017). As a result, there is a need to develop and implement efficient recycling technologies.

A significant amount of waste is produced during machining and grinding, generating what is known as "swarf" (Yang 2017). Many tonnes of rare-earth-element-rich grinding slurry are accumulated each year, representing nearly one-third of the rare-earth-elements' input to the manufacturing process (Binnemans et al. 2013; Jowitt et al. 2018). This slurry is a valuable resource, yet an appropriate, cost-effective, and clean recycling process is still a challenge. The swarf can potentially be inserted in the following steps in the manufacturing supply chain (see Figure F-1).

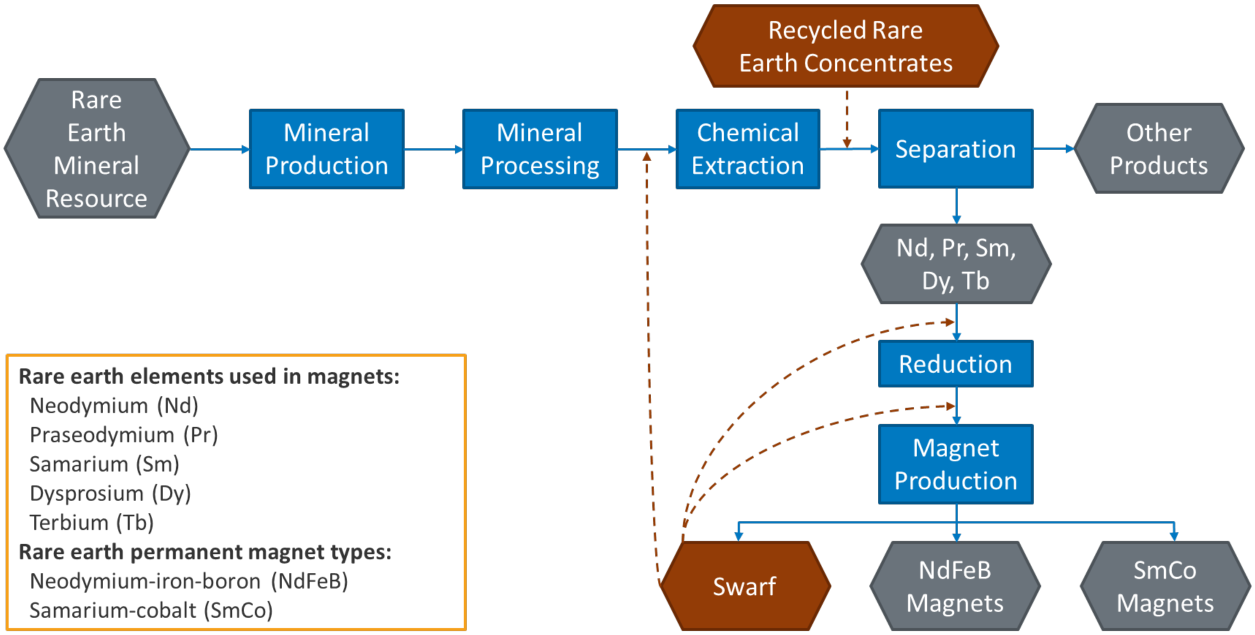

Figure F-1. Opportunities to insert recycled materials (swarf and recycled rare-earth concentrates) into the manufacturing supply chain of rare-earth permanent magnets

Waste from electrical and electronic equipment (notably from computer hard-disk drives and mobile phones) can be used as a more valuable source of rare-earth elements from end-of-life magnets. Dismantling and separation are mostly performed by manual and mechanical processes, and their methods are applied depending on the type of waste products generated. The preprocessing waste from electrical and electronic equipment involves the automatic sorting of neodymium magnets, potentially resulting in crushed magnetic components being attracted to ferrous metal scrap. Although this method can effectively separate the rare-earth element into a single output stream, the resulting mass concentrations are typically low. Further, in most cases, this approach can contaminate this stream (Ueberschaar et al. 2017), potentially meaning that the recovery of rare-earth elements from this recycling stream is not possible. Hitachi developed the process using a rotating drum for disassembling hard-disk drives, and the National Institute for Materials Science developed a small-scale electronic crushing device and three-dimensional ball mill, resulting in a shortened work time (United States Environmental Protection Agency 2012; Hitachi 2010).

Some opportunities for recycling the rare-earth elements found in rare-earth magnets include:

- Traditional hydrometallurgical recovery techniques where magnets are dissolved in acids (or potentially in the future using ionic liquids) before the rare-earth elements are precipitated out of the solution [e.g., Lyman 1993, Wellens et al. 2012, Jakobsson 2016].
- A hydrometallurgical approach (Bogart 2016) that enables fast, efficient separations through a simple leaching process.
- Pyrometallurgical recovery techniques where rare-earth-element alloys are re-melted, separated from alloyed transition melts in a liquid metallic state, refined in an electroslag process, or dissolved out of alloys by reaction with a molten flux, with the rare-earth element then supercooling with the flux to form a glass. The approach used depends on the nature of the rare-earth-element alloys within the magnets (e.g., Saito 2003). Molten salts have also been explored (Shirayama 2018).
- Gas phase extraction methods wherein the rare-earth elements are transferred to a volatile chloride phase and separated based on differences in volatility (Itoh 2009; Uda 2002).
- Hydrogen decrepitation has been tried, wherein hydrogen is intentionally induced into the alloy to promote embrittlement to produce powers (Zakotnik 2008).
- An innovative method, big area additive manufacturing, has been developed to fabricate isotropic and anisotropic near-net-shape neodymium-bonded magnets (Li et al. 2016; Kinjal et al. 2020; Paranthaman 2016). Potentially, this method could allow the swarf to be reused at the last stage for magnet production (Figure 1), thereby eliminating the need for solvents and other materials used in earlier stages (Kinjal et al. 2019).

F.1 Industrial Efforts

Several North-American-based industrial efforts are on their way to utilizing secondary rare-earth-element feedstock. However, assessing their technoeconomic viability is beyond the scope of this study. The following provides a brief description of these efforts, based on what is openly available.

Rare Earth Salts is based in Beatrice, Nebraska. The company claims to have developed a methodology for separating and refining all rare-earth elements to high purity from ore-based and recycled feedstock. They have a proprietary, patented modular technology that efficiently separates the rare-earth element in a cost-effective and environmentally friendly process. A critical component of the separations process is based on chemical electro-winning. Furthermore, the process can be performed at a range of temperatures, (including ambient), operated with low-cost consumables, and allows for continuous operations.

Geomega is based in Quebec, Canada, and claims to be able to process 1.5 tonnes of magnet waste per 8-hour day. Their technology, developed by their subsidiary Innord, seems to be based on a reusable reagent. The separation was originally based on electrophoresis; the current method (Innord's Separation of Rare Earths) is not revealed but achieves separate elements and uses zero organic solvents.

Noveon Magnetics (formerly Urban Mining Company) is based in San Marcos, Texas, and claims that its M2M technology uses waste or recycled magnetic material to support its neodymium-magnet manufacturing process. Their approach is to recover rare-earth particulate material by exposing a rare-earth magnet to hydrogen gas to effect hydrogen decrepitation of the rare-earth magnet and produce a rare-earth particulate material that can be separated from the rest of the assembly (Harris et al. 2011). The company has demonstrated their method using recycled feedstock (e.g., Benke et al. 2020 and Prosperi 2019).