Renewable Energy Materials Properties Database: Summary

Aubryn Cooperman, Annika Eberle, Dylan Hettinger,
Melinda Marquis, Brittany Smith, Richard F. Tusing,
and Julien Walzberg

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
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List of Acronyms

DOE	U.S. Department of Energy
kg	kilogram
t	metric ton
GW	gigawatt
IRA	Inflation Reduction Act of 2022
m	meter
MW	megawatt
NREL	National Renewable Energy Laboratory
PERC	passivated emitter and rear contact
PV	photovoltaic
REMPD	Renewable Energy Materials Properties Database
SETO	Solar Energy Technologies Office
UPV	utility photovoltaic
USGS	United States Geological Survey
WETO	Wind Energy Technologies Office

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1 Background

Renewable energy is providing a growing share of electricity generation in the United States, with utility-scale wind and solar increasing by 12% and 29%, respectively, in 2021. Approximately 9% of U.S. electricity generation in 2021 was from wind and 4% from solar (Energy Information Administration 2021). Installing new renewable energy facilities requires material inputs that range from common construction materials to specialized, high-performance materials that may have limited availability. This report summarizes a new database of materials used in domestic wind and solar installations that was developed by the U.S. Department of Energy (DOE) Wind Energy Technologies Office and DOE Solar Energy Technologies Office.

The Energy Act of 2020 directs the Wind Energy Technologies Office and Solar Energy Technologies Office to deliver a "comprehensive physical property database of materials for use in [wind and solar] energy technologies, which shall identify the type, quantity, country of origin, source, significant uses, projected availability, and physical properties of materials used in [wind and solar] energy technologies" by no later than September 1, 2022. This report provides a summary of the Renewable Energy Materials Properties Database (REMPD). The related full text of the Energy Act of 2020 is provided in Appendix A. In August 2022, Congress passed the Inflation Reduction Act (IRA), which has several provisions that incentivize wind and solar energy deployment. Estimates of future material quantities for wind energy in Table 7 are based on annual capacity additions that incorporate anticipated effects of IRA incentives; however, full details on how the IRA will be implemented were not available when this report was completed and, thus, the wind-related material quantity projections cannot fully anticipate all of the market reactions to the IRA.

The focus of the REMPD and this accompanying report is on quantifying the raw and processed materials used in renewable energy technologies. The database contains information on the amount of each material that goes into wind and solar power plants, descriptions of the relevant material properties, and the primary countries of origin for each material. Some materials go through several stages of processing and/or are incorporated into subcomponents that make up the completed electricity-generation facilities. This report does not analyze supply chains for producing renewable energy plant components. However, DOE conducted related analysis in response to Executive Order 14017, which directed production of "America's Supply Chains" reports for wind and solar. The supply chain reports can be found at https://www.energy.gov/policy/securing-americas-clean-energy-supply-chain; links to individual reports are provided below:

- Wind
- Solar.

Additional reports in this series that are relevant to wind, solar, and hybrid plants include:

- Grid energy storage
- Rare earth permanent magnets.

1.1 General Description of the REMPD

The REMPD is a consolidated repository for data on the materials used in wind and solar plants. It lists the materials used and the amount of material required per megawatt (MW) of generation capacity. The database also provides information about each material and its sources. The REMPD information was collected by combining proprietary and nonproprietary information from wind and solar manufacturers and suppliers, along with peer-reviewed publications. The publicly accessible database information protects the proprietary inputs by aggregating data into material types and providing ranges that are indicative of the most common wind and solar installations.

1.2 Technical Description of the REMPD

The REMPD is a relational database developed using the open-source database server PostgreSQL (PostgreSQL Global Development Group 2022). Relational databases define relations (tables) comprising unique rows of data. In the future, the REMPD could be expanded to include additional information such as externalities (e.g., emissions from transportation, material requirements for transmission, impacts on local communities) or additional energy categories, such as other generation and energy system types; for example, geothermal plants, marine and hydrokinetic plants, hydrogen electrolyzers, or battery energy storage systems.

1.2.1 Data Taxonomy

The REMPD uses a six-tiered approach to collect and organize data, which is shown in Figure 1. This taxonomy was developed for use across a wide range of energy technologies. Examples are provided in Figure 1 for wind and solar energy.

The top tier comprises all components and materials required to construct facilities in the selected category (e.g., all solar photovoltaics [PV] plants in the United States). The next level captures individual system components, such as the wind turbine, PV module, substation, and electrical cables. Each component is associated with subassemblies and subcomponents; materials data are provided whenever they are available to populate these levels (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, 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 breakdown the material requirements by component.

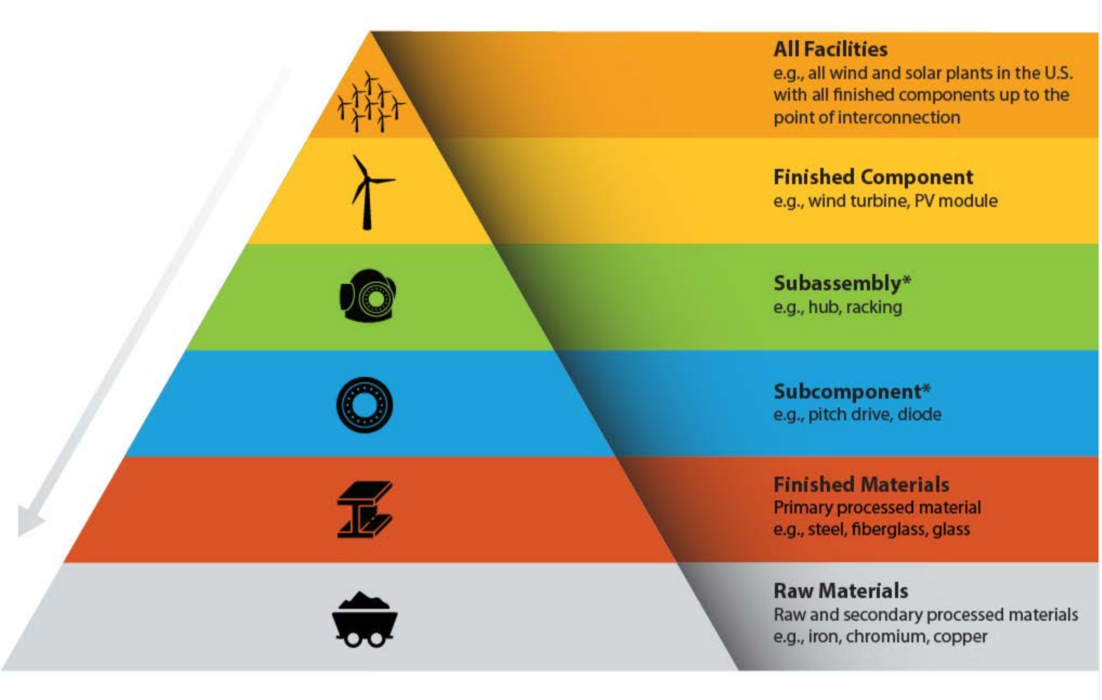

Figure 1. Taxonomy used to organize data in the REMPD. ***Illustration by Nicole Leon, National Renewable Energy Laboratory (NREL)***

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.

In some cases, because of data constraints and the desire for the database to focus primarily on material quantities, the REMPD does not necessarily have all data at the subassembly or subcomponent levels. In addition, to protect proprietary information, data in the publicly released version of the database are aggregated at the subassembly level. For example, substation data are broken down only by material type and are not subdivided at the subassembly or subcomponent levels, and wind turbine and PV module data are reported at the subassembly level. In all cases, the REMPD includes data for the raw and finished materials associated with each component.

1.2.2 Definitions

As requested in the Energy Act of 2020, the REMPD provides the following information regarding the materials used in wind and solar plants (see Table 1):

- Country of origin
- Source
- Significant uses
- Projected availability
- Physical properties
- Type
- Quantity.

Table 1. Definition of Terms Used in the REMPD

Term	Definition
Country of origin	The country where the material is produced, focusing on the earliest production stage for the material (i.e., mining when applicable).
Critical mineral	Any mineral on the list of critical minerals published by the U.S. Department of the Interior United States Geological Survey (USGS) (refer to Table 4 for the 2022 USGS list of critical minerals).
Current production	The quantity of material that is currently available, as measured using global production in 2020.
Source	The geographic country of origin of the material.
Significant uses	End uses (other than for renewable energy technologies) of the material that comprise more than 10% of the market share for that material.
Projected availability	The quantity of material that could be available globally in the future, as measured using total known reserves.
Physical properties	The key physical properties of the material that are relevant to its function in wind and solar energy technologies.
Type	The category within which the material belongs.
Quantity	The amount of material needed to manufacture, operate, and decommission a selected set of renewable energy technologies at a given time and under a given scenario of deployment and technology innovation.
Solar energy material	Any nonfuel mineral, element, substance, or material used in the production, use, or disposal of solar energy technologies.
Wind energy material	Any nonfuel mineral, element, substance, or material used in the production, use, or disposal of wind energy technologies.
Vulnerable material	Any nonfuel mineral, element, substance, or material that the DOE Office of Energy Efficiency and Renewable Energy determines has a high risk of a supply chain disruption and serves an essential function in one or more energy technologies, including technologies that produce, transmit, store, and conserve energy or a critical mineral.

1.3 Metrics

In addition to the attributes listed in Table 1, the REMPD can calculate a variety of metrics for analysis. Table 2 provides a selected list of such metrics, including material intensity, annual material quantity, and percentage of projected availability.

Table 2. Selected List of Metrics That Can be Computed by the REMPD

Metric	Units	Description	Levels of Aggregation
Material intensity	kilogram (kg)/ megawatt (MW)	Estimated mass of material required per rated capacity	By material type, material class, or material category at the facility, component, or subassembly* levels
Annual material quantity	kg/year (yr)	Estimated mass of material needed to meet specified annual deployment level	By material type, material class, or material category at the facility, component, or subassembly* levels
Percentage of current production	%	Relative amount of material needed for a selected set of U.S. renewable energy technologies compared to current global production (as measured using 2020 global production)	By material type
Percentage of projected availability	%	Relative amount of material needed for a selected set of U.S. renewable energy technologies compared to projected global availability (as measured using global reserves)	By material type

* Not all components in the database have data at the subassembly level. This tier is populated based on available data (i.e., whether the materials needed for each component can be disaggregated to the subassembly level, or if they are instead reported at a higher level, such as the component level). Ability to aggregate or disaggregate at the subassembly level data depends on data availability.

1.4 REMPD Access

Access to an open-source version of the REMPD, along with supporting data visualizations, are available through OpenEI at https://apps.openei.org/REMPD. On this website, several complete tables are available to download as CSV files, including data on physical properties, significant uses, sources, and material quantities. The full database schema and anonymized data are also available for advanced users who wish to use the underlying relational database structure for additional analysis on their own servers; instructions for accessing wind and solar materials properties database content are available in Appendix B.

2 Wind Materials Summary

2.1 Wind Plant Description

The REMPD includes all components and associated materials required for utility-scale wind energy technologies up to the points of interconnection. For wind energy, this includes foundations or substructures, towers, nacelles, rotors, and balance-of-system components. It does not include transportation and capital equipment required to install, maintain, operate, or decommission wind power plants. Figure 2 illustrates the system components for wind energy in the REMPD, including wind turbines, onshore and offshore substations, and transmission cables.

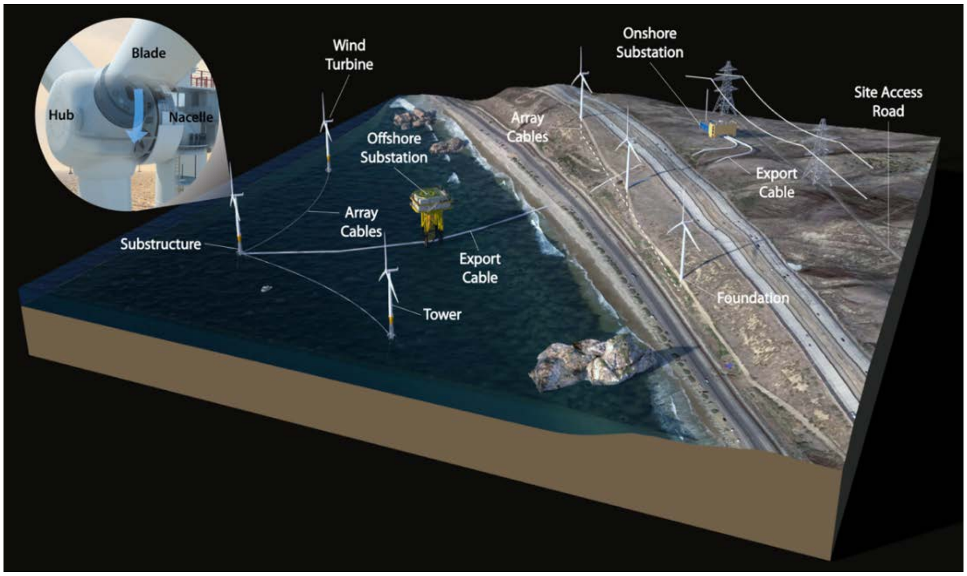

Figure 2. System components included in the analysis of wind energy material requirements. Illustration by Joshua Bauer, NREL

Utility-scale wind turbines included in the REMPD have a rated capacity of at least 1 MW and are installed within large wind plants that require additional infrastructure such as electrical cables and one or more substations. Land-based wind plants also require access roads. Roads are included because they are required throughout the operation of the wind plant; however, delivery and installation equipment, such as trucks, cranes, wrenches, and harnesses do not remain on-site at the wind plant and, therefore, are not included in the database. The REMPD assumes a typical plant size of 200 MW (Wiser et al. 2021)[1] to estimate the amount of material required for land-based wind energy production. Offshore wind plant sizes are typically larger than land-based wind plants; the REMPD assumes a typical offshore wind plant capacity of 1,000 MW, based on a wide range of publicly disclosed planned future offshore plant installations.[2] Offshore wind plants require different substructures than land-based wind turbine foundations; for example, steel monopiles have been used in many existing installations but other configurations are

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[1] Figure 4 of the U.S. Department of Energy's (DOE) *Land-Based Wind Market Report: 2021 Edition* (Wiser et al. 2021) indicates a wide range of land-based wind plant sizes, but a 200-MW wind plant size was selected as typical for recently installed wind plants.

[2] Table 3 of the *Offshore Wind Market Report: 2022 Edition* (Musial et al. 2022) indicates a wide range of offshore wind plant sizes, but a 1,000-MW offshore wind plant size was selected as typical of new offshore wind plants.

possible, including floating offshore wind in deep water. Table 3 lists the specific wind energy components and subassemblies that are included in the REMPD.

Table 3. REMPD Wind Energy Component and Subassembly Organizational Structure

Facility Type	Component	Subassembly (Technology Type[a])	Reference(s) for Material Quantities
Land-based wind	Array and export cables	Total[b]	Proprietary data from original equipment manufacturers (OEMs)
	Foundation	Total[b]	Proprietary data from OEMs; selected Vestas life cycle assessments[c]; Crawford (2009); Eberle et al. (2019); Schreiber, Marx, and Zapp (2019)
	Roads	Total[b]	Eberle et al. (2019)
	Substation	Total[b]	Proprietary data from OEMs; Alsaleh and Sattler (2019)
	Turbine	Blade (conventional; segmented)	Proprietary data from OEMs; Eberle et al. (2023)
		Hub	Proprietary data from OEMs; Crawford (2009)
		Nacelle (direct drive; gearbox)	Proprietary data from OEMs; Alsaleh and Sattler (2019); Martínez et al. (2009); Ozoemena, Cheung, and Hasan (2018); Rajaei and Tinjum (2013)
		Tower (conventional; spiral welded; hybrid)	Proprietary data from OEMs; Crawford (2009); Guezuraga, Zauner, and Pölz (2012)
Offshore wind	Array and export cables	Array cable	Proprietary data from OEMs; ABB (2010); Arvesen et al. (2014); Ikhennicheu et al. (2020)
		Export cable	
		Onshore cable	
	Substation	Substation equipment	Proprietary data from OEMs; Arvesen et al. (2014)
		Substation structure	
	Substructure	Gravity base (fixed gravity base)	4C Offshore (2022); Negro et al. (2017)
		Jacket (fixed jacket)	
		Monopile (fixed monopile)	
		Piles (fixed jacket)	
		Spar (floating)	
		Suction buckets (fixed jacket)	
		Transition piece (fixed monopile)	
	Turbine	Blade (conventional; segmented)	Proprietary data from OEMs; Eberle et al. (2023)
		Hub	Proprietary data from OEMs; Crawford (2009)
		Nacelle (direct drive)	Proprietary data from OEMs
		Tower (conventional; spiral welded)	Proprietary data from OEMs; Crawford (2009); Guezuraga, Zauner, and Pölz (2012)

a. The technology type used in the REMPD depends on the analysis scenario defined by the user (e.g., a user can select conventional or spiral welded, or hybrid for land-based wind towers).

b. 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.

c. Selected Vestas LCAs include Vestas (2012, 2017a, 2017b, 2017c, 2017d, 2017e, 2018a, 2018b, 2019, 2022a, 2022b).

The material composition of wind energy technologies can vary significantly depending on the facility type (e.g., land-based or offshore), generation capacity, rotor diameter, tower height, drivetrain technology, and manufacturer. Excluding foundations, roads, and grid connection equipment, wind turbines are typically made of a combination of steel and iron alloys, fiber-reinforced polymers and composites, and other metals and alloys such as copper, bronze, and aluminum (Figure 3). When considering an entire land-based wind power plant, road aggregate, concrete, and steel are the three primary materials by weight, measured in terms of kilograms (kg) per megawatt of capacity. Concrete is the primary material in land-based wind turbine foundations and steel is mainly used in the tower and nacelle. For an entire offshore wind plant, steel is the primary material by weight (kilogram (kg)/MW) and is used mostly in the substructure, tower, and nacelle. In both land-based and offshore wind plants, glass- or carbon-fiber-reinforced polymers and composites are primarily used in the nacelle and rotor blades; copper and aluminum are used primarily in electrical cables; and a variety of alloys—such as bronze, brass, cast iron, and electrical steel—are used within the nacelle, which houses the drivetrain and power conversion systems.

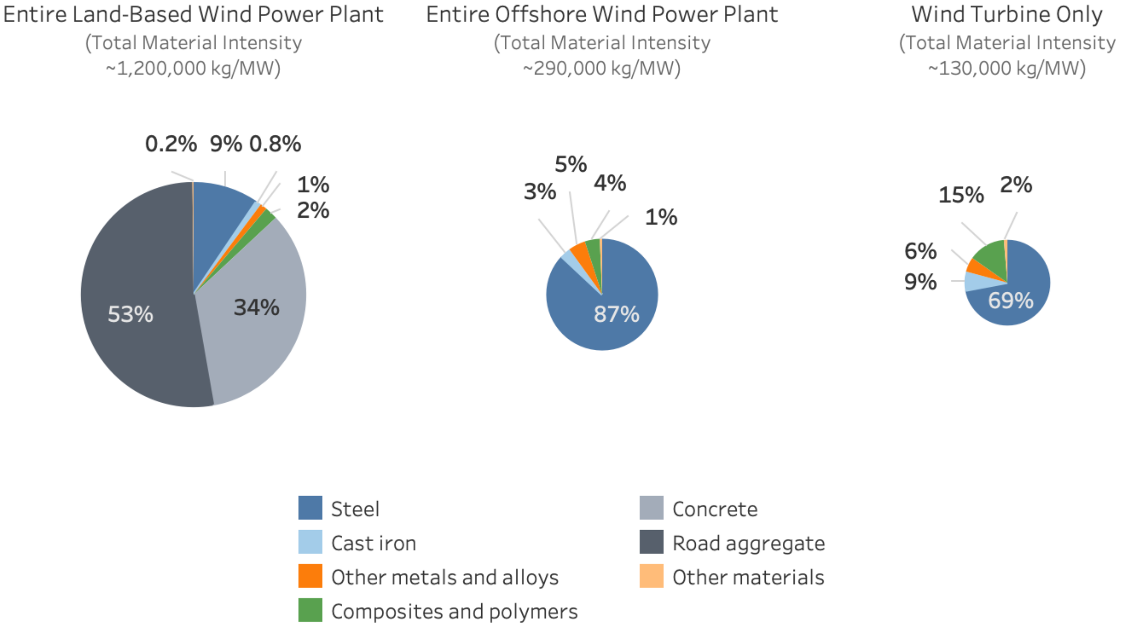

Figure 3. Typical high-level breakdown of wind energy materials by mass as reported in the REMPD

As reported in the REMPD, the main components of a utility-scale wind plant and typical materials used for each component include the following mass amounts[3] for each subsystem:

- **Wind turbine (80,000–170,000 kg/MW).**
    - **Blades (11,000–17,000 kg/MW per three blades)**.
        - The blades primarily comprise composite materials that combine a polymer resin (e.g., epoxy; 2,000–5,000 kg/MW) with glass or carbon fibers (7,000–10,000 kg/MW) and a balsa wood or polymer foam core (1,200–1,300 kg/MW). There are typically three blades per wind turbine.
        - Land-based: 13–18 metric tons (t) per blade
        - Offshore: 65–80 t per blade
    - **Hub (4,300–13,000 kg/MW)**.
        - The hub is made of cast iron (1,200–4,000 kg/MW) and is the structure that connects the blades to the nacelle and tower. Within the hub, the pitch system—which controls the orientation of the blades—predominantly comprises steel and other metals (3,100–9,000 kg/MW).
        - Land-based: 18–44 t per turbine
        - Offshore: 64–179 t per turbine
    - **Nacelle (18,000–36,000 kg/MW)**.
        - The nacelle includes an enclosure that is typically made of fiberglass (300–3,500 kg/MW) over a steel frame (3,500–10,000 kg/MW) and cast-iron bedplate (3,000–5,000 kg/MW). Additional materials (6,800–17,500 kg/MW) used within the nacelle vary depending on the wind turbine configuration and differences between these configurations contribute to the wide range of nacelle masses. A geared turbine requires a gearbox, which contains alloy steel, brass or bronze, and cast iron. Most direct-drive generators use permanent magnets that contain rare-earth elements. The power transformer, which may be located in the nacelle or tower, contains steel, electrical steel, and copper or aluminum.
        - Land-based: 90–240 t per turbine
        - Offshore: 270–550 t per turbine
    - **Tower (44,000–100,000 kg/MW)**.
        - Most towers are constructed from tubular steel sections, although concrete or a combination of concrete and steel sections can also be used. Variation in the tower mass is primarily driven by different hub heights. Additional

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[3] Representative masses are provided for each subassembly based on the range of material intensities for current land-based and offshore wind energy technologies. In this report, current land-based wind energy technology is assumed to have a turbine rated capacity of 3.4 megawatts (MW), a hub height of 110 meters (m), and a rotor diameter of 130 m (Bortolotti et al. 2019). Current offshore wind energy technology is assumed to have a turbine rated capacity of 15 MW, a hub height of 150 m, and a rotor diameter of 240 m (Gaertner et al. 2020).

quantities of steel, copper, or aluminum are used in power cables and for personnel access equipment.

        - Land-based: 310–340 t per turbine
        - Offshore: 660–710 t per turbine

- **Land-based foundation (410,000–460,000 kg/MW)**.
    - Land-based wind turbine foundations primarily comprise concrete (390,000–410,000 kg/MW) with steel reinforcement (20,000–50,000 kg/MW).
    - Land-based: 1,400–1,600 t per turbine
- **Offshore substructure (82,000–360,000 kg/MW)**.
    - Offshore wind turbine substructures—including monopiles, jackets, and floating platforms—are typically made from steel plate.
    - Offshore: 1,400–5,400 t per turbine
- **Array and export cables (5,000–31,000 kg/MW)**.
    - Electrical cables use aluminum or copper conductors and polymer insulating material (e.g., polyethylene). Submarine cables, which are used for offshore wind energy, require additional layers of lead or steel surrounding the conductive core(s). The total mass of cables varies widely depending on the distance from a wind power plant to the electrical grid, the choice of material (aluminum is lighter than copper), the electrical capacity of the cable, and whether the cable is installed overhead, buried, or subsea.
    - Land-based: 5–20 kg per meter of cable
    - Offshore: 15–50 kg per meter of cable
- **Substation (650–9,000 kg/MW)**.
    - Substations require steel (200–1,300 kg/MW) and electrical steel (200–1,600 kg/MW) for power transformers and switchgear and copper (40–700 kg/MW) for wiring. Offshore substations require a steel support structure (7,000 kg/MW), whereas land-based substations use concrete foundations (200–3,600 kg/MW).
    - Land-based: 400–1,800 t per wind power plant
    - Offshore: 7,000–8,000 t per wind power plant
- **Roads (480,000–590,000 kg/MW)**.
    - Site access roads within a wind power plant are typically made from aggregate comprising crushed stones, gravel, or recycled concrete.
    - Land-based: 100,000–120,000 t per wind power plant
- **Miscellaneous**.
    - Additional materials that are not detailed here, but are further specified in the database, include protective coatings and paints that contain zinc (for corrosion resistance) or polymers such as epoxy. Electronic controls, sensors, lighting, and safety equipment contain various materials, notably semiconductors, which contain critical minerals.

2.2 Vulnerable Wind Materials

We use the term "vulnerable material" to describe any nonfuel mineral, element, substance, or material that the DOE Office of Energy Efficiency and Renewable Energy determines has a high risk of a supply chain disruption and serves an essential function in one or more energy technologies, including technologies that produce, transmit, store, and conserve energy; or a critical mineral (as defined by the United States Geological Survey [USGS]).[4] Section 2.3 provides an overview of critical minerals and their relevance to wind energy technology. Vulnerable wind materials include these critical minerals as well as other materials that play an important role in wind energy generation facilities and have a high risk of supply chain disruption (such as electrical steel).

2.3 Critical Minerals and Their Relevance to Wind Energy Technology

In its most recently published list (USGS 2022b), USGS identified 50 critical minerals, which are shown in Table 4 categorized by their relevance to wind energy technologies. The table indicates that fewer than 20 of them have a significant role in wind energy.

Table 4. Critical Minerals (USGS 2022b) and Their Relevance to Wind Energy

Type of Material	Role in Wind Energy Generation Facilities
Aluminum	Power cables, nacelle/tower internal equipment
Chromium, cobalt, manganese, nickel, niobium, titanium, vanadium	Steel alloying elements
Graphite, lithium, nickel	Batteries
Dysprosium, neodymium, praseodymium, terbium	Rare-earth permanent magnets
Gallium	Wide-bandgap semiconductors for power electronics
Tin	Bronze
Zinc	Anticorrosion coatings (galvanization)
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	Minor or no role

The minerals used in wind turbines with the highest supply risk are neodymium, dysprosium, and praseodymium (Nassar et al. 2020). These metals are mainly contained in the permanent magnets used in the generator for direct-drive wind turbines. Certain minerals used in steel alloying (i.e., nickel and cobalt) may also present supply challenges under high levels of wind deployment (Eberle et al. 2023).

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[4] The United States Geological Survey assesses material criticality using a three-part score that evaluates the supply risk of each material based on disruption potential, trade exposure, and economic vulnerability (Nassar et al. 2020).

2.4 Wind Technology Materials Summary

Annual installations of land-based wind power generating capacity in the United States between 2015 and 2021 are presented in Figure 4. The average annual capacity addition during this time frame was 10 gigawatts (GW) per year (Wiser et al. 2021; American Clean Power [ACP] 2022). Only 42 MW of offshore wind capacity were installed between 2016 and 2021, representing all of the offshore wind energy capacity in the United States as of 2022.

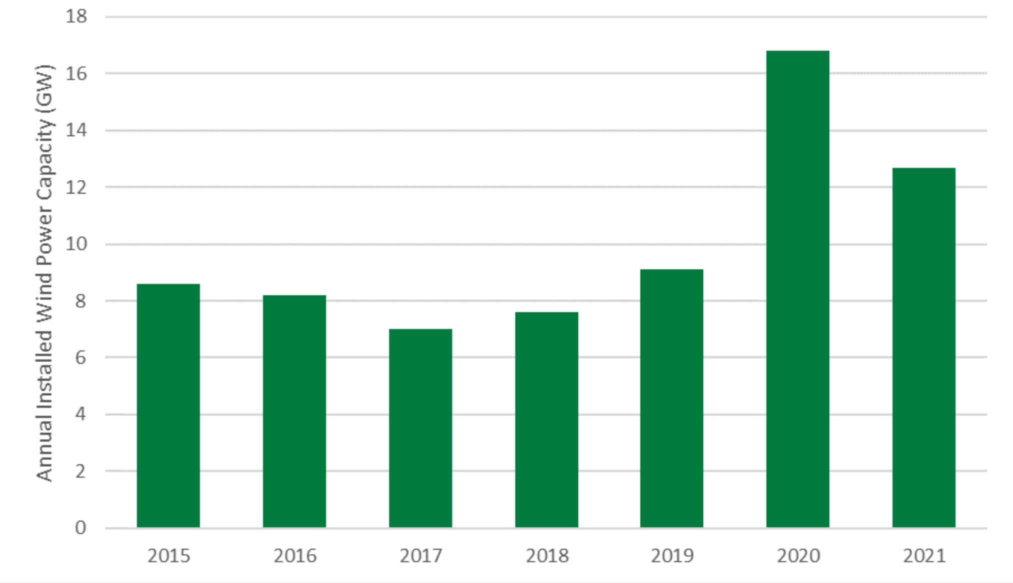

Figure 4. U.S. land-based wind power capacity additions. ***Sources: Wiser et al. (2021) and American Clean Power (2022)***

There are more than 200 unique finished materials and more than 1,700 unique raw materials in the REMPD. To protect proprietary data in the publicly accessible database, these materials are aggregated into 45 material types. To improve the interpretability of the wind energy technology data, we grouped these materials into seven major categories:

1. Concrete
2. Road aggregate
3. Steel
4. Composites and polymers
5. Cast iron
6. Other metals and alloys
7. Other materials.

These seven categories are used in Figure 3 and Table 5 to summarize the material quantities required in U.S. wind power plants.

Tables 5, 6, and 7 provide examples of the type, source, significant uses, country of origin, projected availability, and quantity data that are available in the REMPD for current wind energy technologies. Table 5 provides a high-level overview of material intensities for current wind energy technologies; the range of material intensities reported reflect variations in material use between specific models and maintain the confidentiality of proprietary data. Vulnerable wind materials are included within the relevant categories in Table 5 and are defined further in Table 6, which provides material intensities specific to each type of vulnerable material. Although Table 5 shows a categorization of all materials used in wind plants, Table 6 and Table 7 show a subset of these materials, the subset being vulnerable materials (defined in Section 2.2). The amount of material needed for current annual wind energy deployment can be estimated by multiplying the current material intensity in Tables 5 and 6 by an annual capacity addition of wind energy. Table 7 summarizes the quantity of vulnerable materials needed for current[5] and potential future annual wind deployment levels and summarizes the current production and projected availability of these materials in millions of kilograms. More detailed analysis of the quantities and availability of wind energy materials under two future scenarios can be found in Eberle et al. (2023). In addition, Table C-1 provides a sample of the physical properties data that are available in the REMPD.

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[5] To estimate the quantity of material needed for current annual wind deployment, Table 7 assumes the following: 1) an annual capacity addition of 10 gigawatts (GW) of wind energy per year, which is equal to the annual average U.S. wind deployment from 2015 to 2021 (Wiser et al. 2021; American Clean Power 2022); 2) all 10 GW of wind deployment per year come from land-based wind technology (offshore wind capacity between 2015 and 2021 totaled 42 MW); and 3) material intensities equal to those reported in Table 6.

Table 5. Current Wind Plant Materials

Material Category	Primary Role in Wind Energy Generation Facilities	Other Significant Uses[a]	Land-Based Wind Material Intensity (kg/MW)	Offshore Wind Material Intensity (kg/MW)	Source (Percentage of Global Production by Country of Origin)[a]
Concrete	Foundation, substation, tower[b]	Construction	394,000–414,000	Minimal	Widely available globally
Road aggregate	Roads	Construction (primarily road construction)	552,000–674,000	Not used	Widely available globally
Steel	All (tower, hub, nacelle, blade, land-based foundation, substructure, cables, substation)	Construction, transportation (automotive), metal products, machinery and appliances	107,000–179,000	130,000–419,000	China (54%) India (6%) Japan (5%) United States (5%) Others (30%)
Composites and polymers	Blade, nacelle, cables, land-based foundation, substation, hub, tower	Consumer goods, packaging, transportation (automotive, marine, aerospace)	18,000–39,000	10,000–28,000	China (8%) Canada (8%) Germany (6%) Russia (5%) Saudi Arabia (9%) South Korea (8%) Thailand (7%) United States (5%) Others (44%)
Cast iron	Nacelle, hub, substation	Construction, machinery and appliances	9,000–15,000	7,000–14,000	China (63%) India (6%) Japan (6%) Others (25%)
Other metals and alloys	All	Various	10,000–28,000	7,000–37,000	Various
Other materials	All	Various	1,000–5,000	1,000–5,000	Various

a. 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 (2020a, 2020b).

b. Denotes component/material combinations that are not used in all wind power plants. For example, geared induction generators do not use rare-earth permanent magnets.

Table 6. Vulnerable Materials in Current Wind Power Plants

Type of Material	Primary Role in Wind Energy Generation Facilities	Other Significant Uses[a]	Land-Based Wind Material Intensity (kg/MW)	Offshore Wind Material Intensity (kg/MW)	Source (Percentage of Global Production by Country of Origin)[a]
Carbon fiber	Blades	Transportation (aerospace, automotive, marine), consumer goods (pressure vessels, sports equipment)	590–2,300	580–1,180	United States (28%) Japan (13%) China (13%) Turkey (12%) Hungary (5%) Taiwan (5%) Others (24%)
Electrical steel	Nacelle, substation	Machinery and appliances (transformers, motors, inductors)	1,500–5,300	2,700–3,600	South Korea (14%) China (14%) Japan (12%) Germany (11%) Russia (10%) Others (39%)
Critical Minerals					
Aluminum	Nacelle, tower, cables[b]	Transportation (aviation and automotive), consumer goods, packaging, construction, electrical, machinery, appliances	2,900–4,200	600–2,600	China (57%) Russia (6%) India (5%) Canada (5%) Others (27%)
Chromium	Nacelle, tower, land-based foundation, offshore substructure, hub	Steel (stainless and heat-resisting steel), other steel alloys	1,200–4,000	180–510	South Africa (36%) Turkey (22%) Kazakhstan (19%) India (7%) Finland (6%) Others (10%)
Cobalt	Nacelle, land-based foundation, offshore substructure, tower	Alloys (superalloys, other alloys), chemicals, steel	3–6	3–7	Congo (73%) Russia (5%) Others (22%)

Type of Material	Primary Role in Wind Energy Generation Facilities	Other Significant Uses[a]	Land-Based Wind Material Intensity (kg/MW)	Offshore Wind Material Intensity (kg/MW)	Source (Percentage of Global Production by Country of Origin)[a]
Dysprosium[c]	Generator[b]	Magnets, ceramics and glass, battery alloys, catalysts	2–8	6–8	China (58%) United States (16%) Burma (12%) Australia (7%) Others (7%)
Gallium	Nacelle, land-based foundation, offshore substructure, tower	Electronics (integrated circuits, optoelectronic devices)	0.05–0.1	0.03–0.1	China (97%) Others (3%)
Graphite (natural)	Tower	Metal products (bearings, brake lining, lubricants), rubber	3–17	5–9	China (79%) Brazil (7%) Others (14%)
Lithium	Tower	Batteries, ceramics and glass, lubricating greases	0.7–3	0.9–2	Australia (48%) Chile (26%) China (16%) Argentina (7%) Others (3%)
Manganese	Nacelle, land-based foundation, offshore substructure, tower	Steel	1,900–3,000	2,400–7,800	South Africa (34%) Australia (18%) Gabon (18%) China (7%) Others (23%)
Neodymium[c]	Generator[b]	Magnets, ceramics and glass, battery alloys, catalysts	40–160	90–150	China (58%) United States (16%) Burma (12%) Australia (7%) Others (7%)

Type of Material	Primary Role in Wind Energy Generation Facilities	Other Significant Uses[a]	Land-Based Wind Material Intensity (kg/MW)	Offshore Wind Material Intensity (kg/MW)	Source (Percentage of Global Production by Country of Origin)[a]
Nickel	Nacelle, land-based foundation, offshore substructure, tower	Steel (stainless and heat-resisting steel), superalloys, batteries	2,200–4,800	1,900–6,100	Indonesia (31%) Philippines (13%) Russia (11%) New Caledonia (8%) Australia (7%) Canada (7%) China (5%) Others (18%)
Niobium	Nacelle, land-based foundation, offshore substructure, tower	Steel, superalloys	0.3–0.5	0.4–1.2	Brazil (90%) Canada (10%)
Praseodymium[c]	Generator[b], land-based foundation, tower	Magnets, ceramics and glass, battery alloys, catalysts	0.5–0.8	44–88	China (58%) United States (16%) Burma (12%) Australia (7%) Others (7%)
Terbium[c]	Generator[b], land-based foundation, substation, tower	Magnets, ceramics and glass, battery alloys, catalysts	<0.0001	0.4–0.8	China (58%) United States (16%) Burma (12%) Australia (8%) Others (6%)
Tin	Nacelle, tower, land-based foundation, offshore substructure	Alloys, coatings (tinplate), chemicals, metal products (solder)	0.2–0.3	0.4–1.0	China (32%) Indonesia (20%) Burma (11%) Peru (8%) Congo (7%) Bolivia (6%) Brazil (6%) Others (10%)

Type of Material	Primary Role in Wind Energy Generation Facilities	Other Significant Uses[a]	Land-Based Wind Material Intensity (kg/MW)	Offshore Wind Material Intensity (kg/MW)	Source (Percentage of Global Production by Country of Origin)[a]
Titanium	Nacelle, tower, land-based foundation, offshore substructure	Steel, superalloys	49–77	61–200	China (53%) Japan (21%) Russia (13%) Kazakhstan (7%) Others (6%)
Vanadium	Nacelle, cables, land-based foundation, offshore substructure, tower	Steel, other alloys, catalysts	0.0002–0.0005	0.0001–0.0006	China (67%) Russia (19%) South Africa (8%) Brazil (6%)
Zinc	Tower, nacelle, land-based foundation, offshore substructure, cables	Coatings (galvanization), rubber, chemicals, paint, agriculture	30–110	20–130	China (34%) Australia (11%) Mexico (5%) Peru (11%) United States (6%) India (6%) Others (27%)

a. 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 (2020a), and Alves Dias et al. (2020).

b. Denotes component/material combinations that are not used in all wind power plants. For example, geared induction generators do not use rare-earth permanent magnets.

c. 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.

Table 7. Quantity and Availability of Vulnerable Wind Materials Needed To Satisfy Annual U.S. Wind Deployment

Type of Material	U.S. Import Sources (2016–2019)	Current Production[a] (millions of kg/year)	Projected Availability[b] (millions of kg)	Quantity Needed for Annual U.S. Wind Deployment (millions of kg/year)		Percentage of Current Production Required for U.S. Wind Deployment[e]	
				Current Levels (10 GW/yr)[c]	*Potential Future Levels (90 GW/yr)[d]*	*Current Levels (10 GW/yr)[c]*	*Potential Future Levels (90 GW/yr)[d]*
Carbon fiber	Data not available	192	N/A	6–23	53–200	3%–12%	28%–104%
Electrical steel	Japan (21%) Korea (21%) France (13%) Austria (11%) China (6%) Others (28%)	20,000	N/A	15–53	150–460	0.08%–0.3%	0.8%–2%
Critical Minerals							
Aluminum	Canada (50%) United Arab Emirates (10%) Russia (9%) China (5%) Others (26%)	65,200	32,000,000	29–42	240–360	< 0.1%	0.4%–0.5%
Chromium	South Africa (39%) Kazakhstan (8%) Mexico (6%) Russia (6%) Others (41%)	37,000	570,000	12–39	97–320	0.03%–0.1%	0.3%–0.9%
Cobalt	Norway (20%) Canada (14%) Japan (13%) Finland (10%) Others (43%)	165	7,600	0.03–0.06	0.2–0.5	< 0.1%	0.1–0.3%

Type of Material	U.S. Import Sources (2016–2019)	Current Production[a] (millions of kg/year)	Projected Availability[b] (millions of kg)	Quantity Needed for Annual U.S. Wind Deployment (millions of kg/year)		Percentage of Current Production Required for U.S. Wind Deployment[e]	
				Current Levels (10 GW/yr)[c]	*Potential Future Levels (90 GW/yr)[d]*	*Current Levels (10 GW/yr)[c]*	*Potential Future Levels (90 GW/yr)[d]*
Dysprosium[f]	China (80%) Estonia (5%) Japan (4%) Malaysia (4%) Others (7%)	2.4	44	0.02–0.08	0.2–0.7	0.8%–3%	9%–28%
Gallium	China (55%) United Kingdom (11%) Germany (10%) Others (24%)	0.33	100	0.0005–0.001	0.004–0.01	0.2%–0.4%	1%–3%
Graphite (natural)	China (33%) Mexico (23%) Canada (17%) India (9%) Others (18%)	970	320,000	0.03–0.17	0.3–1.5	< 0.1%	0.03%–0.2%
Lithium	Argentina (55%) Chile (36%) China (5%) Others (4%)	83	22,000	0.007–0.03	0.06–0.3	< 0.1%	0.1%–0.4%
Manganese	Gabon (20%) South Africa (19%) Australia (15%) Georgia (10%) Others (36%)	19,000	1,500,000	19–30	180–320	0.1%–0.16%	0.9%–1.7%
Neodymium[f]	China (80%) Estonia (5%) Japan (4%) Malaysia (4%) Others (7%)	40.8	1,200	0.4–1.6	4–14	1%–4%	10%–35%

Type of Material	U.S. Import Sources (2016–2019)	Current Production[a] (millions of kg/year)	Projected Availability[b] (millions of kg)	Quantity Needed for Annual U.S. Wind Deployment (millions of kg/year)		Percentage of Current Production Required for U.S. Wind Deployment[e]	
				Current Levels (10 GW/yr)[c]	*Potential Future Levels (90 GW/yr)*[d]	*Current Levels (10 GW/yr)*[c]	*Potential Future Levels (90 GW/yr)*[d]
Nickel	Canada (42%) Norway (10%) Finland (9%) Russia (8%) Other (31%)	2,500	95,000	22–48	190–440	0.9%–1.9%	7%–18%
Niobium	Brazil (66%) Canada (22%) Others (12%)	65	18,000	0.003–0.005	0.03–0.05	< 0.1%	< 0.1%
Praseodymium[f]	China (80%) Estonia (5%) Japan (4%) Malaysia (4%) Others (7%)	14.4	370	0.005–0.008	0.5–0.9	< 0.1%	3%–7%
Terbium[f]	China (80%) Estonia (5%) Japan (4%) Malaysia (4%) Others (7%)	0.5	10	<0.0001	0.004–0.008	< 0.1%	1%–2%
Tin	Indonesia (24%) Malaysia (21%) Peru (20%) Bolivia (17%) Other (18%) Scrap: Canada (99%)	260	4,900	0.002–0.003	0.02–0.04	< 0.1%	< 0.1%
Titanium	Japan (90%) Kazakhstan (7%) Others (3%)	230	750,000	0.5–0.8	5–8	0.2%–0.3%	2%–4%

Type of Material	**U.S. Import Sources (2016–2019)**	**Current Production[a] (millions of kg/year)**	**Projected Availability[b] (millions of kg)**	**Quantity Needed for Annual U.S. Wind Deployment (millions of kg/year)**		**Percentage of Current Production Required for U.S. Wind Deployment[e]**	
				Current Levels (10 GW/yr)[c]	*Potential Future Levels (90 GW/yr)[d]*	*Current Levels (10 GW/yr)[c]*	*Potential Future Levels (90 GW/yr)[d]*
Vanadium	Canada (26%) China (14%) Brazil (10%) South Africa (9%) Others (41%)	105	24,000	< 0.0001	< 0.0001	< 0.1%	< 0.1%
Zinc	Peru (98%) Others (2%)	12,000	250,000	0.3–1.1	3–10	< 0.1%	< 0.1%

a. The quantity of material that is currently produced globally as of the latest available data (2018−2020). 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 S&P Global (2021), BloombergNEF (2020a), and Alves Dias et al. (2020).

b. The quantity of material that could be available globally in the future, as measured using total known reserves. Data are primarily drawn from the USGS (2022a) and are supplemented with data from Alves Dias et al. (2020).

c. The quantity needed for current levels of annual wind energy deployment for each material is estimated by multiplying the material intensity in Table 6 by the average annual capacity addition of wind energy from 2015 to 2021: 10 GW per year (Wiser et al. [2021]; ACP [2022]). Because less than 100 MW of offshore wind capacity was installed between 2015 and 2021, the values reported here assume that all 10 GW per year come from land-based wind technology.

d. The potential quantity needed for future annual wind energy deployment for each material is estimated by multiplying the material intensity in Table 6 by a total of 90 GW/yr (comprised of 80 GW of land-based wind and 10 GW of offshore wind). This level of deployment is based on the average level of deployment between 2030 and 2050 required in the 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 by 2050. In August 2022, Congress passed the Inflation Reduction Act (IRA), which has several provisions that incentivize wind and solar energy deployment. The estimates of future annual capacity additions used here incorporate anticipated effects of these incentives; however, full details on how the IRA will be implemented were not available when this report was completed. Specific assumptions used in deployment scenarios are described in Denholm et al. (2022).

e. The relative amount of material needed for U.S. energy technologies compared to current global production, calculated by dividing the “Quantity Needed for Current Annual Wind Deployment” by “Current Production” and multiplying by 100%.

f. The U.S. import sources 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.

2.5 Ability To Explore Future Wind Technology and Demand

In addition to identifying current material needs, the REMPD can be used to assess the types and quantities of materials required to develop the wind turbines associated with future deployment scenarios. In the REMPD, an analysis scenario is defined by combining three factors:

1. **Capacity projection**, which defines the annual amount of renewable-energy-generating capacity that is anticipated each year over the period of interest.
2. **Facility 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, 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).

From the capacity projection, facility configuration, and technology configuration factors defined in the scenario, the REMPD determines the required materials. The REMPD's scenario analysis capabilities can be used to understand the constraints and vulnerabilities linked to physical materials production and manufacturing supply chains and help identify new technologies that could mitigate resource constraints. An example of REMPD's scenario analysis capabilities, including a more detailed analysis of the quantities and availability of wind energy materials under two future scenarios, can be found in Eberle et al. (2023).

3 Solar Photovoltaic Materials Summary

3.1 Solar PV System Descriptions

The REMPD documents material requirements for four types of solar PV systems: residential, commercial, utility PV (UPV) systems with crystalline silicon (c-Si) modules, or UPV systems with cadmium telluride (CdTe) modules. Silicon modules are assumed to contain monocrystalline passivated emitter and rear contact (PERC) cells, as this technology currently maintains the largest market share in the industry (Zuboy et al. 2022). We selected these system types and characteristics to represent a typical system in the given market sector that is consistent with those used in the annual NREL PV system cost benchmark (Ramasamy et al. 2021).

Further system characteristics are defined in Table 8, including the inverter loading ratio, which is used to convert direct current watts (W_{DC}) to alternating current watts (W_{AC}).

Table 8. REMPD Solar PV System Types and Characteristics

PV System Type	Size	Module Type	Module Power	Module Size	Racking	Inverter Type	Inverter Loading Ratio
c-Si UPV	100 MW_{DC}	c-Si PERC	450 W	2.2 m^2	One-axis tracker	Central, 0.5 MW_{AC}	1.28
CdTe UPV	100 MW_{DC}	CdTe	430 W	2.47 m^2	One-axis tracker	Central, 0.5 MW_{AC}	1.28
Commercial rooftop	200 kW_{DC}	c-Si PERC	330 W	1.7 m^2	Ballast	String, 20 kW_{AC}	1.15
Residential rooftop	5.75 kW_{DC}	c-Si PERC	330 W	1.7 m^2	Roof mount	String, 5 kW_{AC}	1.15

In the REMPD, solar PV system materials are inventoried for the following components: PV modules, inverters, cabling, transformers, racking, and structural balance-of-system components. A typical utility PV system is illustrated in Figure 5. The organizational structure of system type, components, and subassemblies are provided in Table 9. The REMPD does not consider transportation and capital equipment required to install, maintain, operate, or decommission solar PV systems. All solar PV system material use is reported in units of kilograms per kilowatt of module rated capacity for ease of use across component and system types.

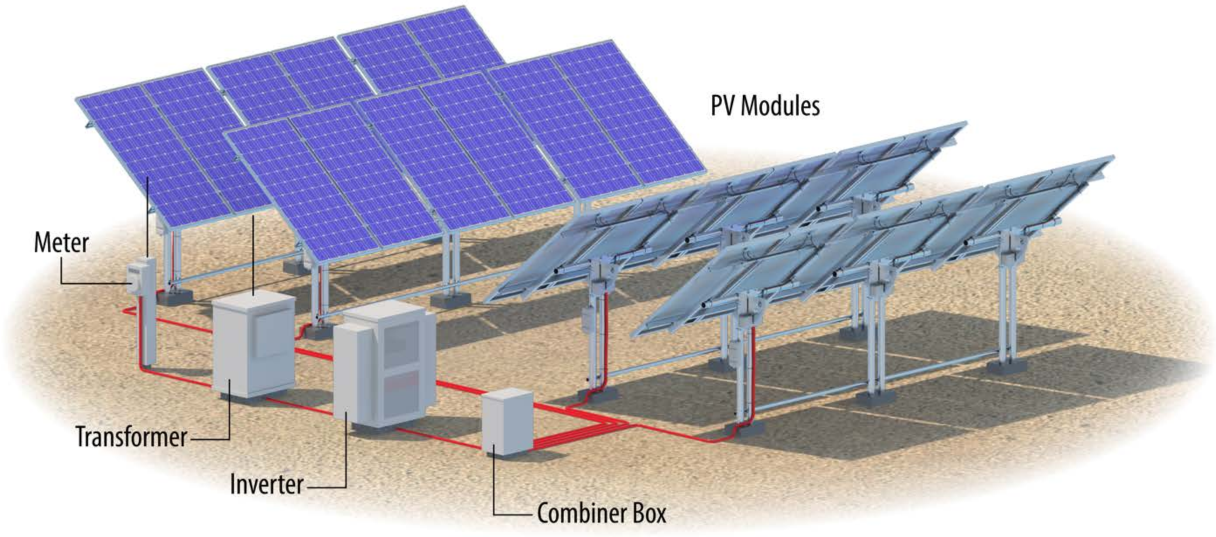

Figure 5. Illustration of a typical c-Si utility PV system on a single-axis tracker.
Illustration courtesy of NREL

Table 9. REMPD Solar PV Component and Subassembly Organizational Structure

System Type	Component	Subassembly	Reference(s) for Material Quantities
UPV types: **Solar PV – c-Si UPV** **Solar PV – CdTe UPV**	PV module	Cell or absorber	Frischknecht et al. (2020)
		Interconnect	
		Packaging	
		Frame	
		Diode	
	Inverter	General inverter	Jungbluth et al. (2012)
		Printed board assembly	
	Transformer	Transformer	Antonanzas et al. (2019)
	Cabling	Cabling	Frischknecht et al. (2020)
	Racking	Tracker support	Antonanzas et al. (2019)
		Tracker motor	
		Tracker battery	
		Tracker minimodule	
	Remaining structural balance of system	Fence	Antonanzas et al. (2019) and Sinha and de Wild-Scholten (2012)
		Conduit	
		Inverter foundation	
Rooftop types: **Solar PV – Commercial rooftop** **Solar PV – Residential rooftop**	PV module	Cell	Frischknecht et al. (2020)
		Interconnect	
		Packaging	
		Frame	
		Diode	
	Inverter	General inverter	Tschümperlin et al. (2016)
		Printed board assembly	
	Cabling	Cabling	Frischknecht et al. (2020)
	Racking	Rooftop racking (Commercial: ballast); (Residential: roof mount)	Frischknecht et al. (2020)

An abridged overview of the main materials by component are:

- **PV modules**. The primary cell or absorber materials are silicon or cadmium telluride, whereas the interconnect materials are copper, tin, and lead. The packaging includes ethylene vinyl acetate, glass (solar-grade rolled glass or float), a laminate of polyethylene and polyvinylfluoride, and finally silicone sealant and glass-reinforced plastic for diode housing. The module frame is made from an aluminum alloy primarily with magnesium. The diode primarily contains molybdenum, copper, and glass along with silicon, tin, lead, and epoxy resin.
- **Inverters**. The largest masses of material in the housing are steel, copper, aluminum, and plastics. Other major materials are the compounds and chemicals embedded in the printed boards and their components, which are numerous.
- **Transformers**. Primarily rely on concrete, ferrite, transformer oil, copper, steel, plastic, and epoxy resin.
- **Cabling**. Copper conductors and polymer insulating material (e.g., polypropylene).
- **Racking.** Trackers are largely comprised of steel, zinc, and aluminum as well as chromium steel, with some reliance on copper and specialty compounds for the battery including lithium as well as PV module materials used for dedicated tracker power. Rooftop racking types primarily rely on aluminum and polyethylene structures, along with a small amount of steel components.
- **Remaining structural balance of system**. Includes polyvinylchloride conduit, steel, concrete, and zinc coatings for fencing, and concrete foundations for inverters.

A breakdown of typical material quantities in a c-Si UPV system is shown in Figure 6.

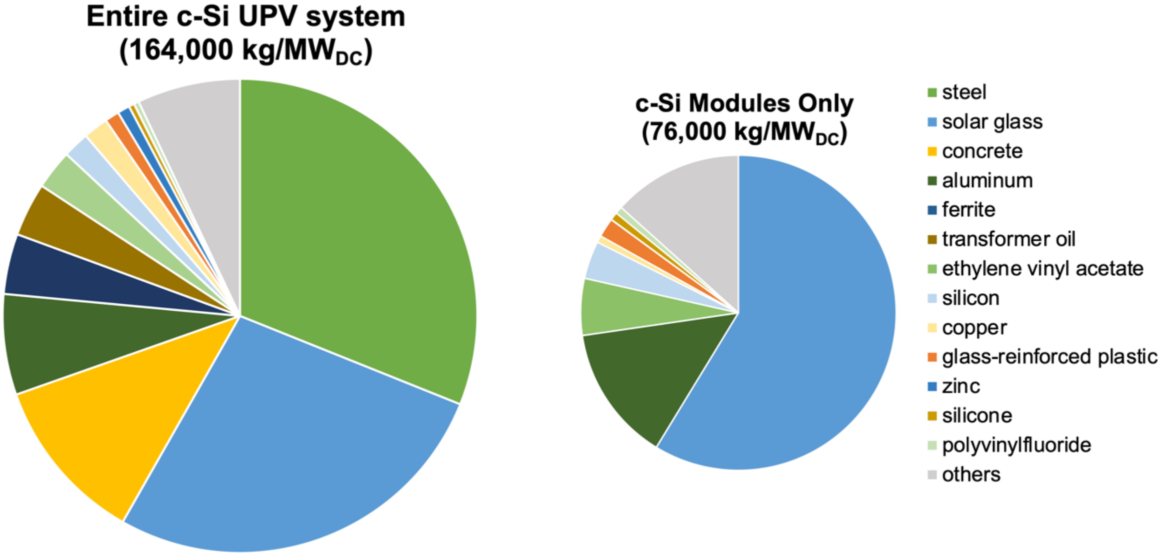

Figure 6. Typical high-level breakdown of c-Si utility PV system materials in kilograms (kg) per MW$_{DC}$

3.2 Critical Minerals and Their Relevance to Solar PV Technology

Critical minerals, as identified in USGS (2022b) and relevant to solar PV systems, are categorized in Table 10 by their relevance to solar PV subassemblies or subcomponents as defined in the REMPD.

Table 10. Critical Minerals (USGS 2022b) and Their Relevance to Solar PV

Component	Critical Minerals
c-Si modules	Aluminum, chromium, fluorspar, magnesium, manganese, tin, zinc
CdTe modules	Aluminum, chromium, magnesium, manganese, tellurium, tin, zinc
Racking (tracker)	Support: aluminum, chromium, zinc Battery: fluorspar, graphite, lithium, manganese Minimodule: aluminum, chromium, fluorspar, magnesium, manganese, tin, zinc
Racking (rooftop)	Aluminum
Inverters	Aluminum, arsenic, barite, fluorspar, manganese, nickel, tin, titanium, zinc, zirconium
Fencing	Zinc
Transformers	Manganese, nickel, zinc

3.3 Future Solar PV Technology and Demand

The solar PV data in the REMPD are intended to represent technologies in 2022. Because PV systems for different sectors (utility, commercial, and residential) are different sizes, this database captures an approximate relationship between material intensity and system size. However, it should be noted that systems within a given sector are effectively assumed to have material use scale linearly with system size. For analysis comparable to the technology and demand scenarios established for the wind materials, as in Table 7, see DOE's "Solar Futures Study," which considers technology advances and demand projections in extensive detail (Ardani et al. 2021).

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Appendix A. Energy Act of 2020

SEC. 3003. WIND ENERGY RESEARCH AND DEVELOPMENT.

(5) WIND ENERGY TECHNOLOGY MATERIALS PHYSICAL PROPERTY DATABASE.—

(A) IN GENERAL. —Not later than September 1, 2022, the Secretary shall establish a comprehensive physical property database of materials for use in wind energy technologies, which shall identify the type, quantity, country of origin, source, significant uses, projected availability, and physical properties of materials used in wind energy technologies.

(B) COORDINATION. —In establishing the database described in subparagraph (A), the Secretary shall coordinate and, to the extent practicable, avoid duplication with—

(i) other Department activities, including those carried out by the Office of Science;

(ii) the Director of the National Institute of Standards and Technology;

(iii) the Administrator of the Environmental Protection Agency;

(iv) the Secretary of the Interior; and

(v) relevant industry stakeholders, as determined by the Secretary.

SEC. 3004. SOLAR ENERGY RESEARCH AND DEVELOPMENT.

(5) SOLAR ENERGY TECHNOLOGY MATERIALS PHYSICAL PROPERTY DATABASE.—

(A) IN GENERAL. —Not later than September 1, 2022, the Secretary shall establish 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.

(B) COORDINATION. —In establishing the database described in subparagraph (A), the Secretary shall coordinate with—

(i) other Department activities, including those carried out by the Office of Science;

(ii) the Director of the National Institute of Standards and Technology;

(iii) the Administrator of the Environmental Protection Agency;

(iv) the Secretary of the Interior; and

(v) relevant industry stakeholders, as determined by the Secretary.

Appendix B. Instructions for Accessing the Renewable Energy Materials Properties Database

Installation Guide

Access to an open-source version of the Renewable Energy Materials Properties (REMPD) database is available at https://apps.openei.org/REMPD. Several summary files are available as well as a complete, plain-text PostgreSQL dump created using the `pg_dump` utility. Users may import the complete database into a server of their choice using the `pg_restore` utility. More information is available at https://www.postgresql.org/docs/current/app-pgrestore.html.

`PgAdmin` is the PostgreSQL integrated development environment recommended by the National Renewable Energy Laboratory for constructing custom queries. More information is available at https://www.pgadmin.org/.

Contents

Key data tables are described in Table B-1. Several ancillary domain tables exist to facilitate referential integrity but are not described explicitly. These data tables are joined through several database views, which dynamically combine information from multiple tables to create various summaries and complete records. See Table B-2 for a complete listing and description.

Table B-1. Key REMPD Tables

Name of Table	Description
avg_subassembly_total_quantity	Uses data source characteristics (e.g., wind turbine rating) and the foreground material inputs (e.g., mass per megawatt [MW] turbine rating in foreground_material_requirements) to calculate an anonymized average mass of each subassembly.
capacity_projection	Defines the annual amount of capacity (in MW) that is anticipated each year over the period of interest.
data_source	Lists the data sources used in the database, along with a qualitative measure of data quality and an identifier for proprietary data.
data_source_property	Lists the facility properties associated with each data source (e.g., hub height, plant size).
facility_configuration_property	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.
foreground_material_requirements*	Identifies the amount of material required for each component, subassembly, and subcomponent (if available) for each facility_id and subassembly_technology_id by material_id. Units of material requirements can vary and are specified using the unit_numerator and unit_denominator columns. Material requirements vary by data_source_id.

Name of Table	Description
lca_material	Lists the types of materials and associated proxy materials used for connecting life cycle inventory data.
lci_data*	Identifies the life cycle inventory data for each life cycle inventory proxy material. Identifies background material flows for each foreground material.
material_production	Identifies the country of origin and projected availability for each type of material via various metrics (e.g., annual production, production capacity, import, exports, reserves).
material_property	Provides a qualitative summary of physical properties associated with each type of material.
material_use	Identifies other uses (than for wind or solar energy technologies) for each type of material and the relative market fraction that corresponds to each type of use.
scenario	Defines which facility configuration, technology configuration, and capacity projection should be used for a given analysis scenario.
subassembly_material_fraction	Computes the anonymized minimum, maximum, and average fractional contributions of each material type to the total mass of each subassembly by averaging over all data sources in the foreground_material_requirements table.
technology_configuration	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., gearbox vs. direct-drive permanent-magnet generator vs. direct-drive superconducting generator).

** Not released in the publicly accessible version of the REMPD because it contains proprietary data.*

Table B-2. REMPD Summary and Data Views

Name of View	Description	Supporting Views	Supporting Tables
annual_material_quantity_by_subassembly_and_type	Quantity of material needed to construct all U.S. wind and solar plants associated with each scenario_id over time (year 2020 through 2050) at the subassembly level (i.e., for each component and subassembly) by facility_id and type of material.	subassembly_scaling subassembly_material_fraction	technology_configuration
background_flow_by_year*	Joins foreground material quantities with background materials.	annual_material_quantity_by_subassembly_and_type	lci_data, lca_material
background_vulnerable_material_quantity_by_year	Sums background material quantities for critical material quantities, grouping by scenario_id, facility_id, and year.	annual_quantity_background_material_by_subassembly	
current_availability_summary	Projected U.S. wind energy demand for vulnerable wind materials (from 2020 through 2050) as a percentage of annual global production of the material in 2020.	annual_material_quantity_by_subassembly_and_type	material_production
current_material_quantity_per_plant	Quantity of material required to construct a single wind or solar plant.	annual_material_quantity_by_subassembly_and_type	facility_configuration_property
current_material_quantity_per_turbine	Quantity of material required to construct a single wind turbine.	annual_material_quantity_by_subassembly_and_type	facility_configuration_property
current_material_intensity_summary	Overview of energy material intensities (kilograms/MW) for current energy technologies summarized at the material category level.	material_intensity_by_year	

Name of View	Description	Supporting Views	Supporting Tables
physical_property_summary	Qualitative summary of the associated physical properties for each type of material.	annual_material_quantity_by_subassembly_and_type	material_property
projected_availability_summary	Projected U.S. wind energy demand for each material (from 2020 through 2050) as a percentage of total global reserves for that mineral (as estimated in 2020).	annual_material_quantity_by_subassembly_and_type	material_production
scenario_capacity_projection	Joins each scenario with the associated capacity projection.		scenario, capacity_projection
scenario_capacity_projection_facility_configuration	Joins each scenario and capacity projection with the associated facility configuration.	scenario_capacity_projection	facility_configuration_property
significant_use_summary	Summary of significant uses for each type of material.	annual_material_quantity_by_subassembly_and_type	material_property
source_summary	Amount of material available from each country of origin.	annual_material_quantity_by_subassembly_and_type	material_production
subassembly_by_foreground_material_pct_total_quantity*	Computes the fractional contribution of each material_id to the total mass of each subassembly by subassembly_technology_id and data_source_id.	subassembly_total_quantity	data_source_property, foreground_material_requirements

Name of View	Description	Supporting Views	Supporting Tables
subassembly_by_material_class_and_type_pct_total_quantity*	Computes the fractional contribution of each material type to the total mass of each subassembly by subassembly_technology_id and data_source_id (converts from material_id to material type so that data can be averaged over multiple data sources with different underlying material_ids but similar material types).	subassembly_by_foreground_material_pct_total_mass	foreground_material_requirements, foreground_material_type
subassembly_scaling	Implements mass scaling relationships based on facility configurations for each year (e.g., mass of wind turbine foundations scale nonlinearly with hub height and turbine rating). Scales quantity of each material to represent the facility configuration outlined in the scenario definition.	scenario_capacity_projection_facility_configuration, subassembly_total_quantity	foreground_material_join
subassembly_total_quantity*	Uses data source characteristics (e.g., turbine rating) and the foreground material inputs (e.g., mass per MW turbine rating) to calculate the total mass of each subassembly by subassembly_technology_id for each data_source_id.		data_source_property, foreground_material_requirements

** Not released in publicly accessible version of the REMPD because it contains proprietary data.*

Query Example

In the database, some information can be derived from single tables. For example, to calculate the mass of dysprosium used in 1 gigawatt of land-based wind facilities, summarize over the current_vulnerable_material_intensity_summary table:

```
SELECT “facility_id”, “material_type_id”,
SUM(“avg_material_intensity_kg_per_mw”) * 1e12 AS
      “total_mass_kg”

FROM “current_vulnerable_material_intensity_summary”

WHERE “facility_id” = ‘land-based wind’ AND “material_type_id” =
‘dysprosium’ GROUP BY “facility_id”, “material_type_id”;
```

Appendix C. Sample of Renewable Energy Materials Properties Database Physical Properties Data

The Renewable Energy Materials Properties Database (REMPD) includes qualitative summaries of key physical properties associated with each type of material. Table C-1 provides an example of the REMPD physical properties data for four materials: aluminum, copper, electrical steel, and lithium. Physical properties data for other materials can be found in the publicly released version of the database.

Table C-1. Sample Physical Properties Data for Four Materials in the REMPD

Type of Material	Key Physical Properties	Data Source(s)
Aluminum	Aluminum is available in commercial grades from 99.0% to 99.99% purity. The metal and its alloys are used because of their lightness, corrosion resistance, and strength. Aluminum alloys weigh approximately one-third as much as steel, with a much better corrosion resistance to atmospheric conditions. Depending on the alloys, its strength can be comparable to that of low-alloy steel.	Ross (1992). Aluminum Al. In: Metallic Materials Specification Handbook. Springer, Boston, MA. https://doi.org/10.1007/978-1-4615-3482-2_1
Copper	Copper has high strength and hardness (which can be increased by alloying), high ductility, great electrical conductivity, and is a good conductor of heat (it conducts heat about 30 times better than stainless steel and 1.5 times better than aluminum).	European Copper Institute, Copper Alliance (2018). https://copperalliance.org/sustainable-copper/about-copper/.
Electrical steel	Electrical steel has high permeability (i.e., increased capacity to support magnetic fields), low magnetostriction (low tendency to expand or contract in magnetic fields), high electrical resistivity (reduces core loss), and decreased hysteresis loss (i.e., lower energy losses).	T. Ros-Yanez, Y. Houbaert, O. Fischer, J. Schneider. (2003). "Production of high silicon steel for electrical applications by thermomechanical processing." *Journal of Materials Processing Technology*, vol. 143-144, Dec., pp. 916-921. https://www.infona.pl//resource/bwmeta1.element.elsevier-2358875c-2821-3615-a63a-905b14d85921.
Lithium	Lithium has a low atomic mass, low coefficient of thermal expansion, and high electrochemical reactivity, making it one of the most attractive battery materials of all the elements.	Jaskula, Brian W. (2020). Lithium. In *Minerals Yearbook 2017*. United States Geological Survey.