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Recycling Wind Energy Systems in the United States

Part 1: Providing a Baseline for America's Wind Energy Recycling Infrastructure for Wind Turbines and Systems

Research, Development, and Demonstration Needs, Gaps, and Opportunities

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Disclaimer

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The authors of this work provided research, development, and demonstration investment priorities solely to the U.S. Department of Energy Wind Energy Technologies Office and its affiliated offices (i.e., Advanced Materials and Manufacturing Technologies Office and Industrial Efficiency and Decarbonization Office) that could achieve the requirements of the wind recycling, development, and demonstration program described in the Energy Act of 2020. These investment priorities do not imply implicitly or explicitly any endorsement of specific products or processes for inland U.S. or international wind energy industry stakeholders.

[1] *See* 42 U.S.C. 16237(b)(4).

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Nomenclature or List of Acronyms

AC	alternating current
ASTM	American Society for Testing and Materials
BF	blast furnace
CMI	Critical Materials Institute
DC	direct current
DOE	U.S. Department of Energy
EAF	electric arc furnace
EPA	Environmental Protection Agency
GHG	greenhouse gas
GW	gigawatt
HDPE	high-density polyethylene
HDRI	hydrogen direct reduced iron
ISO	International Organization for Standardization
LCA	life cycle assessment
LCI	life cycle inventory
LCOE	levelized cost of energy
MW	megawatt
NdFeB	neodymium iron boron
NREL	National Renewable Energy Laboratory
PET	polyethylene
ORNL	Oak Ridge National Laboratory
PMSG	permanent-magnet synchronous generator
PVC	polyvinyl chloride
RD&D	research, development, and demonstration
RCA	recycled concrete aggregate

REMPD	Renewable Energy Materials Properties Database
TEA	techno-economic assessment
TRL	technology readiness level
USGS	United States Geological Survey

Executive Summary

Deployment of wind energy systems is growing rapidly, and the United States may need to deploy up to 1 terawatt (1,000 gigawatts) to achieve its goals of 100% carbon free electricity by 2035; double this capacity may be needed by 2050 to achieve a net-zero greenhouse gas emissions economy (United States Department of State and United States Executive Office of the President 2021; Denholm et al. 2022). The U.S. investments in building this new wind energy capacity will not only mobilize millions of tons of raw and processed materials in existing supply chains, some of which are critical materials, but will also create new types and large volumes of end-of-life decommissioned[2] materials. Establishing efficient, cost-effective, and environmentally responsible end-of-life management of wind energy system components is pivotal for diverting upcoming volumes of decommissioned materials, recovering and reusing critical materials, and reducing life cycle emissions resulting from the production of primary commodity materials used in building wind energy systems.

The Energy Act of 2020, Pub. L. 116-260, funded by the Infrastructure Investment and Jobs Act (which is also known as the Bipartisan Infrastructure Law), Pub. L. 117-58, directs the U.S. Department of Energy's (DOE's) Wind Energy Technologies Office to develop a Wind Energy Technology Recycling Research, Development, and Demonstration program to "create innovative and practical approaches to increase the reuse and recycling of wind energy technologies" (DOE Office of Energy Efficiency and Renewable Energy 2021).[3] In support of the Energy Act provision, a team led by the National Renewable Energy Laboratory and including Sandia National Laboratories and Oak Ridge National Laboratory conducted an assessment to help inform the Wind Energy Technology Recycling Research, Development, and Demonstration program. This assessment also identified broader research, development, and demonstration (RD&D) needs and gaps in existing wind-energy-related material supply chains, with the goal of transitioning to a more sustainable and circular industry for U.S. wind energy systems.

The primary goal of this report—which is part one of two—is to communicate findings from this assessment on how alternate materials, designs, and manufacturing processes could enable more efficient, cost-effective, and environmentally responsible disassembly and resource recovery from wind energy technologies. Part 1 (this report) establishes a baseline by assessing existing U.S. recycling infrastructure and determining whether the U.S. economy has the necessary technologies to disassemble and recycle major wind energy system components under a plausible high-deployment wind technology scenario. Part 2 (forthcoming) provides a deep-dive assessment of recovering materials from difficult-to-recycle system components, such as blades and rare earth permanent magnets in generators and reusing these recovered materials in potential future component designs or other secondary markets. The findings from this work may help prioritize RD&D investment spending to meet the goals in section 3003(b)(4) of the Energy Act of 2020.

The authors use the results of the Part 1 assessment to develop RD&D investment priorities for three main phases: short term (2024–2026), medium term (2026–2035), and long term (beyond 2035), as illustrated in Figure ES-1. The primary stakeholder for our assessment is DOE's Wind Energy Technologies Office; therefore, the authors formulated the phases to align with DOE's relevant wind energy RD&D goals and priorities. The timelines and RD&D priorities do not necessarily imply prioritization of materials, technologies, or any other proposed activity for the wind energy industry or other stakeholders of this work.

[2] Decommissioning refers to activities carried out at the end of wind plant service life to disassemble and remove components and equipment typically followed by site repowering or site restoration for further use.
[3] The full text of section 3003(b)(4) of the Energy Act of 2020 on establishing a wind energy recycling program is provided in Appendix A.

As shown in Figure ES-1, the three main phases of the wind recycling assessment report include the following:

- Short term (2024–2026). This phase reflects the recycling technologies needed in the next 2-3 years to reduce disposal of fiber-reinforced composites and rare earth permanent magnets as waste. Research reveals that operators of existing U.S. recycling facilities find it difficult to process the materials in wind turbine blades and generators. Short-term priorities also encompass broader systems-level suggestions to improve access to wind decommissioned materials streams and end-use markets. Other priorities include addressing challenges in the decommissioning process to preserve recovered material quality, reduce the life cycle of environmental impacts, and support effective stewardship of resources such as critical materials.
- Medium term (2026–2035). RD&D priorities in this phase reflect broader goals, such as increasing supply security for critical materials in the U.S. wind energy sector and boosting the role of recycling and reuse to ensure secure, cost-effective, and sustainable wind energy deployment to meet national clean energy and decarbonization goals. Priorities include funding research programs for expanding additive manufacturing methods for bonded magnets, increasing the use of greener solvents for refining rare earth metals, and reducing the weight while increasing the modularity of wind turbine tower designs. Also prioritized are demonstrations of low-cost decommissioning technologies for offshore substructures, as well as funding the use of low embodied carbon steel[4] and concrete in wind turbines.
- Long term (beyond 2035). In this phase, RD&D priorities are tied to broader wind energy and cross-sector integration and optimization of wind-related recycling technologies including encouraging design for circularity[5] and disassembly and decarbonizing material supply chains. Priorities include establishing certification standards for recycled fibers and shredded composites used in blades, developing natural or bio-based fibers and resins that can replace petroleum-based composites to reduce reliance on oil-and-gas supply chains, and demonstrating recycling of electrical steel scrap in production facilities. Developing and demonstrating modular designs for wind turbine blades and for land-based-wind turbines foundations are also prioritized.

Prior work conducted using DOE's Renewable Energy Materials Properties Database reported on projected material requirements and availability associated with U.S. utility-scale, land-based, and offshore wind energy systems under plausible high-deployment scenarios needed to achieve national decarbonization goals (Eberle et al. 2023; United States Department of State and the United States Executive Office of the President 2021). In this report, we estimated the amount of decommissioned primary materials in major wind power plant components from 2020 to 2050 under the high-deployment scenario reported by Denholm et al. (2022) and used by Eberle et al. (2023) to project an upper bound for U.S. wind energy material needs.[6] Under this scenario, U.S. wind energy deployment is projected to reach 1 terawatt (1,000 gigawatts) by 2035 and 2.2 terawatts by 2050. In 2023, total installed capacity of wind energy in the United States reached 148 gigawatts (Wiser 2023). In a scenario where demand for renewable energy continues to increase, today's rate of

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[4] Steel or concrete label of "low carbon" refers to the materials produced from manufacturing pathways that have lower greenhouse gas emissions compared to the most commonly used pathways today. DOE's industrial decarbonization roadmap report provides detailed explanations and recommendations of decarbonization production pathways for both steel and concrete: https://www.energy.gov/industrial-technologies/doe-industrial-decarbonization-roadmap.

[5] Circularity refers to material management activities in the circular economy. The U.S. government defined the circular economy in SAVE OUR SEAS 2.0 ACT, Pub. L. 116-224 as an "economy that uses a systems-focused approach and involves industrial processes and economic activities that (A) are restorative or regenerative by design; (B) enable resources used in such processes and activities to maintain their highest values for as long as possible; and (C) aim for the elimination of waste through the superior design of materials, products, and systems (including business models)." PUBL224.PS (congress.gov)

[6] Eberle et al. (2023) evaluated material needs for wind energy under two U.S. wind deployment scenarios: current policies and high deployment. The current policies scenario reflects a business-as-usual level of wind energy deployment, whereas the high-deployment scenario reflects high levels of wind energy deployment to achieve the goal of 100% clean electricity by 2035 and a net-zero emissions economy by 2050. Denholm et al. (2022) reported on an all-options scenario, a 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. In the all-options scenario, the average future annual wind energy deployment is expected to reach 90 gigawatts (GW)/year (80 GW land-based and 10 GW offshore) between 2030 and 2050. The average annual wind energy deployment between 2015 and 2021 is estimated to be 10 GW/year.

deployment (10-14 GW/yr) would have to increase by a factor of about 7 (to 88 GW/yr) between 2026 and 2035 to meet decarbonization goals. The authors would like to note that this scenario represents a higher degree of deployment than some other recent studies, and it is chosen to be illustrative of the volumes of material the U.S. economy might need to handle should deployment continue to ramp up rapidly. We used historical U.S. wind energy deployment data and the aforementioned high-deployment scenario capacity projections to estimate the resulting volumes of decommissioned materials and the ability of the existing U.S. recycling infrastructure to process these materials.

We conducted process modeling, life cycle assessment, and technoeconomic analyses to quantify metrics related to technical, environmental, and economic potential and trade-offs of alternative recycling processes[7] for major wind energy components. Our focus included wind turbine component designs that may start entering the waste stream in the next few years. We then used the results from this analysis, aggregated those that relate to each other, and developed priorities for RD&D needs and opportunities for each major wind power plant component to meet the goals of the Energy Act of 2020.

Key Findings

The key findings of this work include the following:

- Under the high-deployment scenario for wind energy in 2020 through 2050, the existing U.S. recycling infrastructure can process the anticipated volume of decommissioned material for concrete aggregates[8] in foundations and access roads as well as steel components in the tower, nacelle, and drivetrain. Anticipated volumes of decommissioned iron and steel component scraps do not exceed 10% of 2020 U.S. recycling capacity. Calculated volumes of decommissioned materials do not consider potential future wind plant or component repowering[9] operations. Although recycling capacity for steel and concrete appears sufficient, RD&D investments are needed to decarbonize their production to further reduce the life cycle impacts of wind energy systems, reduce loss of critical alloying elements during end-of-life management, and develop enhanced disassembly operations that could facilitate component reuse and/or recovery of high-value recycled materials.
- As of 2023, the U.S. infrastructure cannot recycle the existing and anticipated volumes of end-of-life fiber-reinforced composites in wind turbine blades and nacelle covers as well as several critical materials: rare earth elements in permanent magnets; electrical steel[10] in generators; and cobalt, nickel, and chromium used as alloying elements in steel types.
- Researchers estimate that up to 30% of the total U.S. recycling capacity for copper and aluminum in 2021 could be occupied by wind energy systems by 2040; therefore, the nation could benefit from expanding its production and subsequent recycling infrastructure for these materials.
- RD&D investments in large-scale recycling of fiber-reinforced composites and rare earth permanent magnets could have the greatest short-term impact on preventing disposal, easing U.S. reliance on critical materials, and reducing associated life cycle emissions from production of these materials. In the short- and medium-term phases, RD&D investments would help to develop and deploy specialized recycling technologies for electrical steel in generators and to build and expand additive manufacturing solutions for permanent magnets. These priorities would boost U.S. rare earth resource efficiency,

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[7] Recycling processes differ in methods of separation and purification of materials; some processes use physical methods and others use chemical methods (e.g., solvent extraction and hydrogen decrepitation). Section 3 of this report discusses these processes.
[8] Aggregates are geological materials, such as gravel, crushed rock, and sand.
[9] Repowering refers to retrofitting and modernizing power plants, usually with newer, more efficient wind turbines. No publicly available data were available at the time of this study to project the magnitude of wind plant repowering operations in the United States.
[10] See Section 3.5.1.2 for a discussion of electrical steel, also called silicon steel.

particularly for generators used in offshore systems that use more rare earth content than land-based generators (DOE 2023a).

- In the medium- and long-term phases, investments would help to develop recycling technologies for silicon-carbide and gallium-nitride materials used in substations (e.g., wind turbine power converters), both of which are classified by DOE as critical engineered materials. Investments in wind turbine design for recyclability and durability are also prioritized in the medium- and long-term phases to reduce the volume of composite waste as well as life cycle energy and greenhouse gas (GHG) emissions.

Fiber-Reinforced Composites

As mentioned earlier, we found that as of 2023, the U.S. infrastructure cannot recycle at-scale fiber-reinforced composites. Therefore, to enable the recyclability of composites in wind turbine blades and nacelle covers in the short term, cement coprocessing and mechanical recycling could offer the best near-term solutions to avoid disposal of these materials. However, we found that pyrolysis (decomposition by high temperatures) and solvolysis (decomposition by use of solvents) could have larger net GHG emissions than landfill disposal operations for near-term blade waste volumes and designs made of thermoset-based resin systems. Results may vary according to specific blade designs, scale of recycling operation, and modeling techniques used for life cycle emission offsets.

As blade designs evolve to use recyclable resin systems (e.g., thermoplastic-based) and a larger share of carbon fibers, dedicated recycling approaches such as chemical dissolution or pyrolysis might yield substantially lower net GHG emissions compared to cement co-processing and disposal in landfills. This result may vary due to many assumptions but most significantly the maturity of secondary markets that could accept recovered materials in subsequent applications.

For all the blade recycling technologies examined in this report, we found that the sustained profitability of stand-alone recycling facilities is one of the major challenges today. As a result, the following action items are important to enable profitable stand-alone blade recycling operations:

- Requalifying and reusing high-quality recovered fibers in value-added products in secondary markets outside the wind energy industry
- Optimizing recycling process designs to obtain optimized quality profiles for recovered materials that are attractive to buyers in secondary markets
- Developing standardized testing for wind turbine blades made with recycled fibers and/or resins
- Reducing transportation distances from decommissioning sites to recycling operations and tipping fees for composites
- Creating recyclable blade designs to increase recovery of resin systems.

Rare-Earth Permanent Magnets

We found that as of 2023, the U.S. infrastructure cannot recycle at-scale rare earth elements in permanent magnets. In the short term, RD&D investments in large-scale demonstrations for magnet-to-magnet recycling, hydrogen decrepitation (recovery of rare elements by hydrogen gas), and hydrometallurgical-based (use of aqueous solutions for the recovery of metals) recycling process pathways could offer the best approach to overcoming barriers for recycling magnets from wind turbine generators. Innovations in rare-earth-refining technologies and processes are needed to lower operating costs and reduce solvent use and subsequent disposal of solvents, all of which could improve U.S. magnet manufacturing competitiveness and reduce life cycle energy and GHG emissions associated with existing solvent-intensive rare earth element refining operations.

We found that all studied magnet recycling processes yield raw materials that have up to 70% lower life cycle GHG emissions than their conventional counterparts produced from rare earth mining. This emission offset represents the avoided primary production and refining of a metric tonne of a rare earth element (e.g., neodymium) or a rare earth oxide. Techno-economic assessment reveals that direct operational costs are the highest cost of recycling operations. We found magnet-to-magnet recycling including hydrogen decrepitation to have the lowest recycling cost followed by the hydrometallurgical route. Investments in innovations to reduce operational costs of magnet recycling, such as reducing solvents use in the recycling process, could help increase profit margins in U.S. magnet recycling and manufacturing.

In addition to magnet recycling, investments in developing recertification standards for end-of-life magnets and demonstrations for their reuse in similar turbine classifications could alleviate the demand for rare earth elements, especially in the near term. In the medium term, investments in research programs that target the scaling of additive manufacturing methods for bonded magnets could help secure U.S. demand for rare earth elements for wind energy.

Future long-term investments in modular generator designs and resin-bonded magnets have the potential to increase recyclability and durability of wind turbine generators and further reduce U.S. demand for foreign-sourced rare earth elements.

Broader Outlook

The United States may need to increase its production of equipment for disassembling and decommissioning wind power plants in the near future. Using less-intrusive methods, like crane-assisted disassembly instead of toppling or controlled explosions, will help preserve the value of the recovered materials. Additionally, if plant operators maintain digital records of the materials used in wind turbines, it would make the decommissioning process more efficient and improve material sorting for recycling. Creating environmental product declarations[11] for the waste management industry is crucial for tracking and managing the life cycle impacts of recycling wind energy systems. These declarations provide clear information about the environmental impacts of disposing of and recovering materials from decommissioned wind energy systems.

By addressing technical challenges, implementing appropriate RD&D investments, and expanding the domestic recycling infrastructure, the U.S. wind energy industry could reap several benefits including:

- Increased supply chain security for several critical materials
- Reduced life cycle energy, GHG, and other hazardous emissions from primary material sourcing and production processes
- Greater social acceptance of wind energy
- More sustainable, profitable, and stable deployment of wind energy systems.

In addition to providing benefits to the U.S. wind energy industry, building and expanding the U.S. recycling infrastructure for wind-energy-related materials may also result in the following benefits for the country as a whole:

- Conserving U.S. resources

[11] Environmental product declarations are documents that communicate the environmental performance or impact of a product or material over its life cycle. International Standards Organization (ISO) 14025:2006 discloses the guidelines and procedures for developing environmental product labels or declarations. Environmental product declarations are prepared by conducting a life cycle assessment in accordance with ISO 14040 and ISO 14044 standards.

- Reducing pollutants and emissions to land, water, and air
- Helping ease potential energy-related U.S. material supply chain constraints in the clean energy transition.

Key RD&D Investment Priorities
for the Circular Economy of Wind Energy Systems

RD&D Priorities for Recyclability of Primary Materials/Wind Energy System Components	**Short Term (Now through 2026)** **Goal:** Reducing wasteful disposal of hard-to-recycle wind energy system components (i.e., blades, permanent magnets)	**Medium Term (2026–2035)** **Goal:** Optimizing the role of recycling in secure, cost-effective, and environmentally sustainable wind energy deployment to meet U.S. decarbonization goals	**Long Term** **(Beyond 2035)** **Goal:** More robust integration and optimization of cross-sector circularity and decarbonization for wind energy systems
Composites and Polymers/Blades and Nacelles	• Develop research programs for intelligent blade cutting and segmenting (e.g., water and laser jetting methods). • Develop targeted blade decommissioning protocols to segment blade regions based on respective potential value. • Prioritize investing in Re-X before recycling approaches for waste blades (i.e., reuse, repair, remanufacture) to meet relevant regional and community needs. • Develop research programs for regenerating recycled fiber performance from pyrolysis, mechanical, and solvent-based recycling methods for targeted end-use composite applications. • Support replacing baseline thermoset	• Develop research programs for scaling manufacturing methods for blades to enable modular wind turbine blade designs. • Prioritize developing and scaling low-temperature, solvent-based recycling pathways for blades to recover pristine separable resin materials. • Support establishment of regional end-of-life blade service centers for on-site blade repair for reuse and waste collection. • Develop research programs to foster innovations in material design for blade reliability. • Develop research programs that optimize material properties, manufacturability, and reliability of adhesive joints for different resin systems in blades.	• Develop certification standards for using recycled fiber and/or shredded composites in targeted blade performance areas (e.g., core, shear webs). • Develop research programs that demonstrate blade prototyping and performance testing. • Develop and demonstrate use of natural or bio-based fiber and resin materials to replace petroleum-based composites. • Optimize cross-industry composite recycling process designs to reduce cost of transportation, cost of recycling, and life cycle emissions of mixed composite waste streams.

	composites with thermoplastic and/or polyamine-based epoxy resin materials in blade manufacturing.		• Develop testing and certification standards for reuse of end-of-life blades in second-life applications.
Rare Earth Permanent Magnets/Turbine Generators 	• Develop large-scale demonstrations of hydrogen-decrepitation and magnet-to-magnet recycling of waste magnets. • Develop recertification standards for retired magnet testing procedures to qualify for reuse. • Develop demonstrations for magnet reuse in second-life applications (i.e., distributed wind systems). • Develop research and demonstrate solutions for rare earth element-free superconducting generators as well as generator designs that eliminate use of terbium and/or reduce use of dysprosium in sintered and bonded magnets.	• Develop research programs for scaling additive manufacturing methods for bonded magnets. • Develop research programs to support technology innovations that radically reduce operating costs and increase use of greener solvents for rare earth metal refining technologies.	• Develop and deploy hybrid (sintered and bonded) permanent magnet recycling technologies. • Develop and demonstrate the use of modular generator designs.
Steel and Its Alloying Elements/Towers, Nacelles, Drivetrains 	• Establish standardized decommissioning protocols with improved sorting of different steel alloys. • Demonstrate whole tower reuse in new plant buildup.	• Develop and demonstrate feasibility of targeted alloying element recovery from steel scrap. • Develop research programs that demonstrate light weighting and	• Develop and demonstrate feasibility of recycling electrical steel scrap in production facilities.

		modularity of tower designs. • Develop on-site treatment for elimination of alloy elements from steel scrap (e.g., zinc). • Support the use of low embodied carbon steel in wind turbine systems as defined in the Inflation Reduction Act.	
Foundations and Substructures 	• Implement decommissioning strategies that trim the top off the base followed by capping. • Prioritize partial demolition instead of full recovery.	• Develop demonstrations for low-cost, easy-access decommissioning technologies for offshore substructures with emphasis on fixed-bottom technologies for full foundation recovery. • Support the procurement and use of low embodied carbon concrete, asphalt and steel in wind turbine construction and wind-related manufacturing processes that qualify for IRA funding. (as described in Section 3.1.2.3.3).	• Develop and demonstrate modular designs for land-based foundations.
Other Systems-Level Priorities 	• Develop a national standard for reporting environmental product declarations with standardized tools and harmonized data sources. Support reporting of emission hotspots and waste handling strategies. • Develop material passports for wind	• Expand access and U.S. manufacturing capacity of minimally intrusive disassembly equipment for blades and towers. • Develop research programs that demonstrate technological solutions for high-yield, intelligent separation of silicon carbide and gallium	• Develop mobile on-site recycling solutions to reduce costs and emissions of component disassembly and transportation.

	power plants including material intensity, grade, and properties with intellectual property protection measures. • Strategically site new recycling technology capacity based on optimized regional variations (e.g., tipping fees, workforce, location of material suppliers' component manufacturing facility).	nitride in power electronic systems.	

Figure ES-1. Summary of research, development, and demonstration investment priorities for U.S. wind energy systems to transition to a circular economy. *Figure created by Sherif Khalifa and Christopher Schwing, NREL.*

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1 Introduction

Wind energy deployment is growing rapidly in the United States. By the end of 2022, wind energy systems supplied about 11% of total U.S. electricity generation, up from less than 3% in 2011. Installations of those wind systems made up 44% and 22% of new utility-scale capacity additions in the country in 2021 and 2022, respectively, becoming one of the largest sources of U.S. electric power capacity additions; surpassing new fossil-fuel-based generation sources (e.g., coal, gas-fired power plants) and on par with or sometimes exceeding capacities of other renewable energy technologies (i.e., solar photovoltaics and hydropower). Installed capacity of wind systems more than doubled in the period from 2012 to 2022 (Wiser et al. 2023). This rapid growth is expected to increase significantly to achieve the nation's commitment of 100% carbon free electricity by 2035 and net-zero economy wide greenhouse gas emissions by 2050.

To achieve these goals, researchers from the National Renewable Energy Laboratory (NREL) estimate that cumulative installed capacity of wind energy may need to grow to 1,000 gigawatts (GW) by 2035 and near double this volume by 2050, up from 148 GW installed capacity as of 2022 (Denholm et al. 2022). It should be noted that this deployment scenario exceeds those that may be found in some other literature and should not be taken as an actual projection of deployment based on current policies but rather an illustration of a high-end case. Meeting these goals could increase annual wind energy deployment to up to 88 GW/year (yr) between 2026 and 2035, compared to today's 10–14 GW/yr. At this rate of deployment, wind energy could provide up to 45% of total electricity generation in the United States by 2050.

The rapid deployment of wind energy will not only mobilize millions of tons of raw materials in existing supply chains, some of which are critical materials,[12] but also create a corresponding end-of-life waste stream that must be handled in an environmentally responsible and economically viable way. Wind turbine systems typically have an expected lifetime of 25–30 years, but like any other technology, they age and ultimately require decommissioning,[13] recycling, and disposal. As more of the wind turbines deployed in the 1990s and early 2000s reach the end of their useful life, the nation's recycling infrastructure must be ready to efficiently and sustainably process decommissioned materials from the wind industry.

Repowering is one option to extend the life of a wind project and increase productivity. As part of a repowering operation, developers may replace individual turbine components, an entire wind turbine, or an entire power plant after only 10 years with larger, more-efficient components or turbines. Early retiring of wind turbines and systems could also be a result of faster degradation of components (e.g., generators, blades, and hydraulics) in harsh environments or catastrophic events (e.g., fires, tornados). Whether a wind turbine system is replaced at 10 or 30 years, the resulting decommissioned materials must be addressed.

More than 85%–90% of the mass of a typical wind power plant, mainly wind turbine foundations and towers, is made of common construction materials such as steel and concrete, which have an existing recycling infrastructure and well-established supply chain (both domestically and globally). However, the environmental, economic, and social impacts associated with the production and end-of-life handling of these

[12] "Critical materials" refer to any raw or engineered material listed under DOE's 2023 Notice of Final Determination on 2023 DOE Critical Materials List, 88 FR 51792, 51792 (Aug. 4, 2023). See Section 1.2.2 of this report for more information on the types and roles of these materials in wind energy systems. We obtained estimations and information on critical materials for wind energy systems from the Renewable Energy Materials Properties Database.
[13] Decommissioning refers to activities carried out at the end of wind plant service life to disassemble and remove components and equipment typically followed by site repowering or site restoration for further use.

basic materials have not been examined at the scale projected for the wind energy industry in a decarbonized U.S. grid system.

Wind turbine blades and the nacelle are made of fiber-reinforced composites that are lightweight yet offer the strength and durability to withstand mechanical and environmental stresses in the field. However, it is difficult to separate composites to recover constituent raw materials, creating a challenge for operators and recyclers when composites reach the end of their useful life. This challenge is not limited to the wind industry; the automobile, aerospace, marine, and consumer electronics industries also use composites in their product designs. As wind turbines become larger to decrease the levelized cost of energy, the wind industry is also using increasing amounts of carbon-fiber-reinforced composites that offer superior mechanical performance and are lighter than glass-fiber-reinforced composites. Carbon fiber is up to four times more expensive than glass fiber, carries significantly higher environmental impacts, and currently has low production capacity worldwide (Das et al. 2016; Ennis et al. 2019).

The wind energy industry also relies on several critical materials within metallic components, such as the generator, lightning protection systems in wind turbine blades, and connections of blades to the rotor hub. Rare earth metals (e.g., neodymium, dysprosium, and terbium) are used to make permanent magnets that are part of select generator designs. Other critical materials such as nickel, cobalt, and zinc are used as alloying elements.

Previous assessments have not evaluated the feasibility of recycling U.S. utility-scale, land-based, and offshore wind energy technologies under plausible high-deployment scenarios, such as those needed to meet the U.S. goals of carbon free electricity by 2035 and net-zero greenhouse gas emissions economy wide by 2050. This report addresses those scenarios. At the end of the life cycle, many critical wind energy materials are either disposed of or sold in foreign markets because of insufficient decommissioning procedures or lack of recycling infrastructure. This presents a potential environmental justice challenge, as disposal domestically and abroad could end up burdening less developed regions. Ensuring recyclability of all wind turbine components is vital to U.S. energy security and the wind industry's economic competitiveness and environmental sustainability. Therefore, it is essential to understand existing recycling capabilities of wind energy materials under high-deployment scenarios; identify economically viable and environmentally sustainable materials, processes, and technologies that increase recycling rates; and identify other accompanying strategies (e.g., lifetime extension, design for disassembly, and separation).

1.1 Motivation and Goals

The Section 3003(b)(4) of the Energy Act of 2020, Pub. L 116-260, part of the Consolidated Appropriations Act, 2021, instructs the U.S. Department of Energy's (DOE's) Wind Energy Technologies Office (WETO) to develop a Wind Energy Technology Recycling Research, Development, and Demonstration program "to create innovative and practical approaches to increase the reuse and recycling of wind energy technologies" (DOE Office of Energy Efficiency and Renewable Energy 2021).[14] As defined in the Energy Act, this program aims to award financial assistance to eligible entities for various activities, including:

- Increase the efficiency and cost-effectiveness of recovering raw materials from wind energy components and systems, including enabling technologies such as inverters
- Minimize the potential environmental impacts from recovery and disposal processes

[14] 42 U.S.C. 16237(b)(4)(A).

- Advance technologies and processes for the disassembly and recycling of wind energy components
- Develop alternative materials, designs, and manufacturing processes that enable efficient, cost-effective, and environmentally responsible disassembly of and resource recovery from wind energy technologies
- Enable strategies to increase consumer acceptance of, and participation in, the recycling of wind energy technologies.[15]

This report provides comprehensive research, development, and demonstration (RD&D) investment priorities for each major wind energy component to inform Wind Energy Technology Recycling RD&D program development as instructed by Section 3003(b)(4) of Energy Act of 2020. RD&D investment priorities were developed based on evaluation of established metrics used to compare recycling technologies and assess existing industry practices along identification and assessment of existing research, development and demonstration landscape including cross-sector opportunities and feasibility of emerging technologies. Part I of this recycling assessment (this report) focuses on evaluating domestic disassembly, recycling, and recovery process capabilities of each major wind energy component and its primary materials at the scales required to realize U.S. commitments to 100% clean electricity by 2035 and net-zero carbon emissions by 2050.

This assessment includes the following four main objectives:

- Evaluate current domestic wind and recycling industry practices for handling end-of-life components and compare existing capabilities to the projected volume of decommissioned material coming offline by approximately 2029
- Perform a life cycle assessment (LCA) that evaluates the environmental impacts of current and emerging disassembly and recovery processes of primary materials and the feasibility of closing material loops within the wind energy industry or adjacent secondary markets
- Analyze the technical, techno-economic, and environmental challenges of recycling and reusing wind energy components of current and potential future wind energy system designs, and list possible solutions to overcome those challenges
- Evaluate alternative materials, manufacturing processes, and other appropriate practices that could increase the recycling rates of critical materials in wind energy systems.

In this report, we estimate the volume of decommissioned materials from various wind energy components; evaluate existing industry practices for decommissioned parts and components and recycling capabilities; assess the RD&D landscape; and identify opportunities for emerging technologies that enable higher recycling rates of primary and critical materials in wind energy system components. The assessment follows a list of technical, environmental, and economic metrics that help compare the competitiveness of materials and technologies and inform priorities for future research needs per the priorities outlined in the Energy Act of 2020. This assessment and priorities may also inform the implementation of the Wind Energy Technology Recycling Research, Development, and Demonstration Program, which provides $40 million from the Bipartisan Infrastructure Law (IIJA 2021)[16] to award financial assistance to eligible entities for research, development, and demonstration, and commercialization projects to create innovative and practical approaches to increase the reuse and recycling of wind energy technologies.

[15] 42 U.S.C. 16237(b)(4)(A)(i)-(v).

[16] Infrastructure Investment and Jobs Act, Pub. Law No. 117-58, Nov. 15, 2021.

1.2 Scope and Assessment Process

This report focuses on utility-scale, land-based, and—to a lesser extent—offshore wind energy systems in the United States. We conducted stakeholder engagement that involved valuable exchanges with international experts and business leaders and confirmed that recycling wind energy components is a major challenge in virtually all parts of the world. Some countries have more well-established decommissioning practices and enhanced capabilities for cost-effective recycling of some components. However, the global wind industry is challenged by recycling fiber-reinforced composites in a cost-effective and environmentally sustainable manner. It is also difficult to recover critical materials from key components such as rare earth elements in magnets, electrical steel in generators, and alloying elements in steel.

These common challenges have helped streamline the technical solutions being investigated across the globe. The priority for most wind turbine manufacturers is to end wasteful disposal of thermoset-based composites present in wind turbine blade designs and nacelle and hub covers in the most cost-effective way. Reducing reliance on and import of critical materials (e.g., rare earth elements) are additional near-term priorities for manufacturers to reduce price volatility and avoid running out of inventory. Longer-term goals for wind manufacturers include decreasing material manufacturing waste, reducing life cycle emissions associated with material sourcing, and creating broader recycling and reuse cross-sector solutions for fiber-reinforced composites.

To address the needs of different stakeholders, we focused on two main timelines: 1) a baseline case examining existing wind turbine designs and capabilities of the U.S. wind energy industry, and 2) a potential future case where alternative emerging materials and practices are identified and analyzed. Key RD&D priorities are grouped into short-, medium-, and long-term timelines.

In this report, we define the short term (2024–2026), medium term (2026-2035), and long term (beyond 2035) phases to reflect the different needs and goals of WETO. The short term reflects immediate recycling technology needs to end wasteful disposal of wind-energy-related materials and deployment of more sustainable materials, where available, that could facilitate component recyclability. Medium-term priorities reflect broader goals including increasing supply security for critical materials and reducing life cycle emissions caused by decommissioning, disassembly, and recycling technologies. Long-term priorities are tied to a grander circular economy vision for the U.S. wind energy sector including design for disassembly, circularity (i.e., recyclable materials, separable subcomponents), and reliability as well as cross-sector integration and optimization of recycling technologies.

1.2.1 Component-Level Assessment

We conducted the analysis presented in this report at the component level of land-based and offshore wind energy power plants. Figure 1 illustrates the wind energy components investigated in this study.

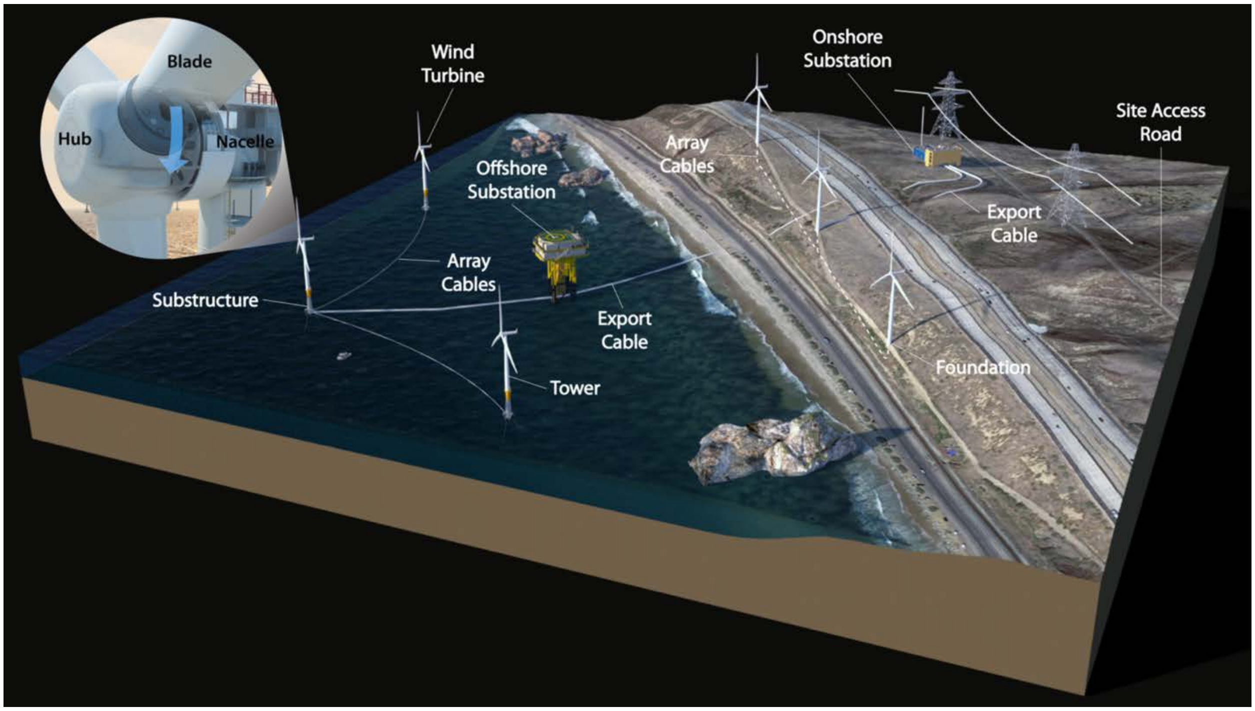

Figure 1. System components included in the utility-scale wind recycling assessment study.
Illustration by Joshua Bauer, NREL

The assessment comprises six major components:

1. Foundation (land-based wind energy systems) or substructure (offshore wind energy systems); including site access roads for land-based systems
2. Wind turbine tower
3. Nacelle, hub, and drivetrain; excluding generator[17]
4. Generator and permanent magnets (examined separately from the drivetrain due to their complexity and detailed requirements)
5. Wind turbine blades
6. Power electronics, including array and export cables.

We investigated the recyclability of all materials in a wind turbine (e.g., composites in blades, steel in the tower, lubricating oil/grease, and other steel grades, such as those found in the generator, nacelle, and drivetrain). We also evaluated the balance-of-system materials (e.g., concrete aggregates in foundations, substructures, and roads; copper and polymers in electrical cables) located in the area from the wind turbine to the point of grid interconnection. We excluded the recyclability of materials in equipment associated with transporting, installing, or decommissioning components (e.g., cranes, cutting saws, shredders).

[17] Generators are part of the drivetrain and are present in the nacelle. However, we considered generators separately due to the level of detail required by project stakeholders and complexity of generator designs as well as to encourage deeper discussion on rare earth elements deemed as critical materials by DOE.

1.2.2 Critical Materials: Definitions and Quantities

In this report, we use the term "critical materials" to refer to select materials that are predefined by DOE. Section 7002(a)(2) of the Energy Act of 2020 defines critical materials as: *"(A) Any non-fuel mineral, element, substance, or material that the Secretary of Energy determines (i) has high risk for supply chain disruption; and (ii) serves an essential function in one or more energy technologies, including technologies that produce, transmit, store, and conserve energy [referred to here as a critical material for energy]; or (B) a critical mineral [as designated by the Secretary of the Interior]."*[18]

Specifically, the final critical materials list published in 2023 includes those used for energy, as determined by the Secretary of Energy, acting through the Undersecretary for Science and Innovation (DOE 2023a).

In the 2023 DOE Critical Minerals list[19], the following materials are used in the life cycle of wind energy systems per DOE's Renewable Energy Materials Properties Database (REMPD):

- Electrical steel
- Nickel
- Cobalt
- Rare earth elements, such as neodymium, dysprosium, praseodymium, and terbium
- Silicon and silicon carbide
- Aluminum
- Copper
- Gallium
- Natural graphite.

The quantities and role of many of these critical materials are discussed in Section 1.2.2.1 of this report.

1.2.2.1 Material intensity estimations for wind-related critical materials and other noncritical materials of interest

REMPD is a DOE-owned database that includes life cycle data on the material types and requirements for wind and solar photovoltaic power plants. It lists the type and quantity of different materials, including the mass of critical materials required per installed capacity (e.g., gigawatts), and provides information about material properties and sources. The *Materials Used in U.S. Wind Energy Technologies: Quantities and Availability for Two Future Scenarios* report projects U.S. wind energy demand for different primary materials using REMPD and compares it to U.S. and global material production capacities under two scenarios: current (as of 2020) and high deployment (Eberle et al. 2023). The high-deployment scenario was modeled to meet U.S. clean energy targets to reduce net greenhouse gas emissions by 50-52% by 2035 and to achieve a net-zero emissions economy by 2050, including potential increases in the number of installed wind turbines after the passage of the Inflation Reduction Act of 2021. The study concludes that nine materials, six of which are considered critical, are highly vulnerable to supply disruption in the United States and that recycling and reuse of those materials is a significant strategy toward securing U.S. national interests and wind energy deployment goals. Table 1 summarizes the nine wind energy materials identified by the Eberle et al. (2023) study, their

[18] *See* 30 U.S.C. 1606(a)(2).

[19] See DOE's 2023 Noice of Final Determination on 2023 DOE Critical Minerals List. 88 FR 51792, 51792 (Aug. 4, 2023)

range of projected material needs under the high-deployment scenario, and their percentage of 2020 U.S. and global production levels.

In addition to the critical materials identified by DOE, other noncritical wind-energy-related materials (e.g., carbon fiber, glass fiber, and balsa wood)[20] were identified as being vulnerable to supply disruption in the short and medium terms under the high-deployment scenario. This vulnerability is because the volumes needed could reach or exceed current levels of global production (Eberle et al. 2023).

[20] The study in the *Materials Used in U.S. Wind Energy Technologies: Quantities and Availability for Two Future Scenarios* report estimates that projected average annual U.S. wind energy demand for carbon fiber, glass fiber, and balsa wood will be between 2030 and 2036 to occupy 120%, 27%, and 520% of 2020 global production levels of these materials under the high-deployment scenario needed to achieve U.S. decarbonization goals. While these materials are not part of the 2023 critical materials list, they are important to consider in this report due to their supply chain constraints, large use in wind turbine blade designs, and impacts on the levelized cost of energy. For more information about these estimations and assumptions, see Eberle et al. (2023).

Table 1. Summary of Quantities and Availability of Key Wind Energy Materials Prioritized in This Recycling Assessment Study

Note: The role and quantity of materials are defined according to the technology configuration and high-deployment scenario provided in REMPD.[21] How this projected demand for materials compares to maximum annual U.S. and global production levels (in 2020) is provided as a percentage.

Type of Material(s)	Material Designation	Role in Wind Energy	Projected Annual Material Needs for U.S. Wind Energy Technologies (millions of kilograms (kg/year)	Range Percentage of 2020 Global Production	Range Percentage of 2020 U.S. Production
Neodymium	Critical	Rare earth permanent magnets in generators	6.0–18	11%–35%	24%–73%
Dysprosium	Critical	Rare earth permanent magnets in generators	0.3–0.8	9%–28%	23%–60%
Praseodymium	Critical	Rare earth permanent magnets in generators	0.5–0.9	3%–7%	No reliable data available
Electrical steel	Critical	Power generator and transformers	190–570	5%–15%	132%–397%
Nickel	Critical	Steel alloying elements	240–550	9%–21%	561%–1,285%
Cobalt	Critical	Steel alloying elements	0.3–0.6	8%–16%	18%–35%
Carbon fiber	Noncritical	Structural elements in blades	240–260	101%–110%	111%–120%

[21] Estimations of critical and noncritical materials of interest are obtained from the Renewable Energy Materials Properties Database (REMPD) under the high-deployment scenario and assuming 2020 global material production levels. For more information, see https://apps.openei.org/REMPD/.

Type of Material(s)	Material Designation	Role in Wind Energy	Projected Annual Material Needs for U.S. Wind Energy Technologies (millions of kilograms (kg/year)	Range Percentage of 2020 Global Production	Range Percentage of 2020 U.S. Production
Glass fiber	Noncritical	Structural elements in blades	2,600–25,000	30%–300%	3%–27%
Balsa	Noncritical	Structural elements in blades	240–3,450	48%–72%	36%–520%

In this study, we considered current U.S. and global recycling capabilities and potential future recycling technologies for recovering these eight materials from their respective components and associated challenges.

1.2.3 Methods and Approach

Figure 2 shows the assessment approach we followed to evaluate the recyclability of each wind energy component.

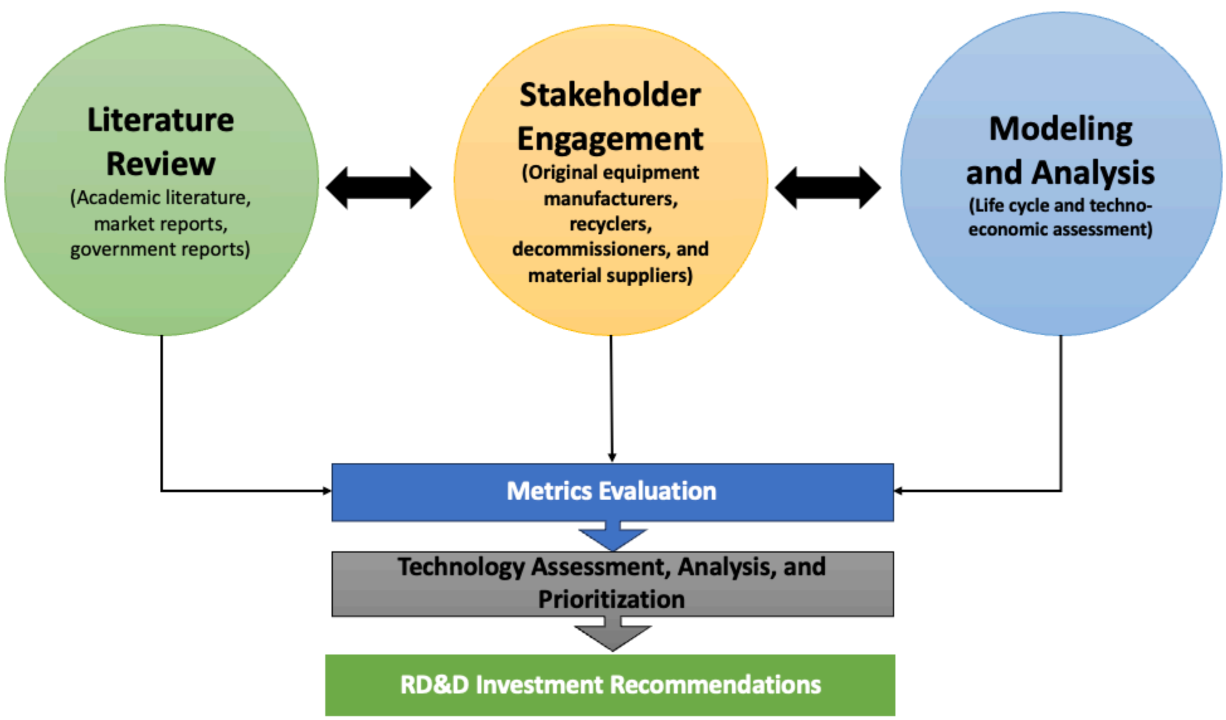

Figure 2. Methods used to evaluate RD&D needs for recycling wind energy components. *Diagram created by Sherif Khalifa, NREL.*

For each major component listed in Section 1.2.1, we applied the research approach described in Figure 2. We then developed a list of technical, environmental, and economic metrics as discussed in Section 1.3. to evaluate and rank component recycling technologies. Next, we conducted data collection and independent analysis to quantify the metrics list. From the compiled metrics list, we performed a cross-technology and cross-component assessment to understand the strengths and weaknesses of each promising technology. We then developed appropriate prioritization for RD&D investments using the following data collection approaches:

- **Literature review**. The main goal of this task was to better understand existing recycling approaches for each wind energy component at all scales and technology readiness levels (TRLs). We reviewed available technical approaches, life cycle impact assessments, cost estimations, and ability to scale up to the needed volumes. We sought specific information including process description, separation efficiency of primary materials from components, quality of recovered and associated materials, and energy consumption in the recycling process. We presented the range of these technical solutions and their associated data to wind energy stakeholders to obtain their views on the viability and challenges of each recycling technology, where available.
- **Stakeholder engagement.** This task was pivotal to understanding existing industry practices in managing wind turbine component waste streams. To achieve this goal, we obtained state-of-the-art solutions, industry capabilities, and the volume or mass being handled from a broad range of stakeholders including wind turbine component manufacturers, commodity materials recyclers, waste management entities, academic researchers, and policy analysts. We then presented the results from the modeling and analysis tasks to the stakeholders to elicit their feedback.
- **Modeling and analysis.** In this task, we conducted an assessment to quantify the technical, environmental, and economic metrics that are used to rank and inform the RD&D priorities. Life cycle assessment and techno-economic modeling were the metrics most commonly used to help quantify environmental impacts, cost-effectiveness, and viability of existing and emerging component recycling processes.

1.3 Metrics

Metrics are critical to tracking the technical, environmental, and economic viability of a recycling process. Table 2 provides the metrics we assessed and their definitions.

Table 2. Assessed Metrics and Their Definitions, Units, and Methods Used

Metric	Impact Area	Definition	Unit	Methods/Tools
Disposal percentage	**Environmental**	**Percentage of component put into landfill today**	**%**	**Stakeholder engagement**
GHG emissions	Environmental	Supply chain GHG emissions produced	(kilogram of carbon dioxide equivalent (kg CO_2 eq.)	TRACI 2.1[a]
Embodied energy	Environmental	Supply chain direct and indirect energy usage	megajoule (MJ)	Cumulative Energy Demand 1.01
Water use	Environmental	Water withdrawal rates from natural resources	meter^3 (m^3)	ReCiPe[b]
Human toxicity	Environmental	Carcinogenic and noncarcinogenic toxicological effects on humans	Comparative toxic unit for human (CTUh)	ReCiPe
Cost of recycling	Economic	Estimated capital and operating costs of recycling process	U.S. dollars (USD)	Stakeholder engagement/process modeling
Market selling price	Economic	Estimated selling price of recyclate[d]	USD	Stakeholder engagement
Material yield	Technical	Percentage of primary material recovered from recycling process	%	Experimentation literature/industry
Material quality ratio	Technical	Technical quality of output scrap from recycling process in comparison to virgin material	Material-specific ratio	Experimentation literature/industry

[a] The Environmental Protection Agency's Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts

[b] A harmonized life cycle impact assessment method at midpoint and endpoint levels

[d] Recyclate refers to recycled material

We selected the metrics based on the following factors:

- The Energy Act of 2020 (metrics were selected that were related to minimizing environmental impacts of recovery processes and increasing recovery and cost-effectiveness of recycling processes)
- Industry and stakeholder interests
- Versatility and applicability to assess different materials and components (i.e., cross-technology and cross-component assessment)
- Well-established and well-known metrics that have reasonable acceptance in the wind energy and environmental sustainability fields.

The metrics encompass three main areas:

- **Technical**. Material yield and material quality ratio are technical metrics that we gathered from existing literature. Material quality ratio encompasses a range of metrics that are material-specific (e.g., knockdown factor for fibers, purity for rare earth elements, energy density for resins). These technical metrics are defined on a material-by-material basis in their respective component(s).
- **Economic**. Cost of recycling and market prices are economic metrics that help assess the cost-effectiveness of the materials and technologies used. Material and energy balances from process models are developed to estimate the needed capital investments and operating expenses. Prices are extracted from market reports (e.g., IHS Markit, Wood Mackenzie, and Bloomberg) and industry stakeholders. For some materials like recovered fibers or rare earth elements, material prices are volatile because of the absence of solid markets downstream or supply and demand dynamics. A range of recent prices or breakeven costs are indicated in these instances.
- **Environmental.** GHG emissions, embodied energy, water use, human toxicity, and disposal percentages are environmental metrics that assess how candidate recycling process technologies may damage the environment and human health. We chose these metrics based on emerging recycling methods that rely on energy-intensive processes (e.g., pyrolysis, melting) and toxic solvents as well as stakeholder interest.

1.3.1 Approach to Data Collection for Modeling and Analysis

We conducted independent modeling and analysis to quantify the technical, environmental, and economic metrics provided in Table 2 for baseline designs of wind turbine components. We developed process models for alternate recycling technologies by quantifying inputs (e.g., materials used, energy consumption of unit operations) and outputs (e.g., air pollution emissions, discharges to water, scrap losses, and by- and fate of co-products of processes). The modeling and analysis approach is consistent across all recycling technologies under consideration in the "gate-to-gate" boundary.[22] We then used the developed process models as the basis to conduct LCA and techno-economic analysis (TEA) to quantify environmental impact categories and cost-related metrics, where feasible. Because metric values change if the volume of recycled materials increases significantly, we assumed a fixed recycling capacity of one metric tonne of each respective component.

Due to varying data availability and certainty for recycling technologies of different components, we sometimes relied on environmental and/or economic data from available literature (e.g., journal articles, market reports) and/or stakeholders (e.g., manufacturers, suppliers, recyclers) to quantify metrics for components and/or primary materials within components. If we obtained proprietary data from a stakeholder, we concealed their identity. When developing the detailed process models, we prioritized candidate recycling technologies of materials and components that lacked established U.S. recycling infrastructure, primarily fiber-reinforced composites in wind turbine blades and nacelle structures, and critical materials in rare earth

[22] The "gate-to-gate" boundary begins when a component reaches its end of life in a wind power plant and ends when the component has been decommissioned, disassembled, processed in a recycling facility, transformed into its constituent primary or new materials, and ready to enter the manufacturing phase again, within or outside the life cycle of the wind energy system.

permanent magnets inside generators. When data for a specific metric were unavailable, had significant uncertainty, or did not apply to the United States, we excluded them and noted it.

For additional details on data sources, assumptions, and modeling choices, see Appendix B.

1.3.1.1 Details on scope and data used for techno-economic analysis

We used TEA to quantify the cost of recycling operations for selected recycling processes including capital expenditures, operational expenditures, and utility and labor costs for each process step modeled. We excluded supply chain costing factors such as warehousing, management, and other utilities not pertinent to the process. We collected available pricing data from various tools such as TECHTEST, Bloomberg commodities, and S&P Global.[23]

[23] TECHTEST is an Microsoft-Excel-based tool for evaluating technoeconomic, energy, and carbon impacts of early-stage technologies. For more information, see: https://www.energy.gov/sites/default/files/2023-07/2023-04-14%20-%20TECHTEST%20PDF.pdf.
Bloomberg: https://www.bloomberg.com/markets/commodities.
S&P Global: https://www.spglobal.com/en/.

2 Wind Energy Material Composition, Life Cycle Impacts, and Waste Projections and Classification

Projecting the quantity and type of decommissioned materials from wind energy power plants is important to understanding the nation's ability to recycle wind turbine primary materials[24]. In this report, we used a bottom-up approach to estimate the quantity of primary materials expected to be decommissioned through 2050. In addition, we provide an overview of material composition by type, economic value, and life cycle GHG emissions along with material waste classification (e.g., metals and alloys, cast iron, steel, composites and polymers, concrete, road aggregate, and other materials).

2.1 Material Composition by Weight, Economic Value, and Life Cycle Emissions

2.1.1 Mass Breakdown

Figure 3 shows the material breakdown, by weight, for current and future land-based and offshore wind energy systems. We used REMPD to define those wind turbine designs (Cooperman et al. 2023). Existing installations in the United States are land-based systems except for two offshore projects off the East Coast. Under the high-deployment scenario, offshore systems are expected to grow and could contribute up to 9% of the domestic wind energy capacity in the future (Denholm et al. 2022). Offshore wind power plants do not require site access roads, thereby they have only a few aggregate requirements. However, one of the major economic challenges the industry faces is the cost of transporting larger components. In addition, future land-based wind power plants are projected to have a high nameplate capacity,[25] which could make these systems taller and larger. As a result, these future systems could have bigger foundations that use more concrete than current designs.

[24] Primary materials refers to basic or commodity materials used in to fabricate wind energy components or equipment such as steel, concrete, fiberglass, rare earth elements and others. In this context, primary materials could include critical materials identified earlier in the report such as rare earth elements, aluminum, copper and electrical steel. See Table 1 for full list of critical materials used for wind energy.

[25] The maximum rated output of a generator under specific conditions, typically the maximum usable wind speed, designated by the manufacturer.

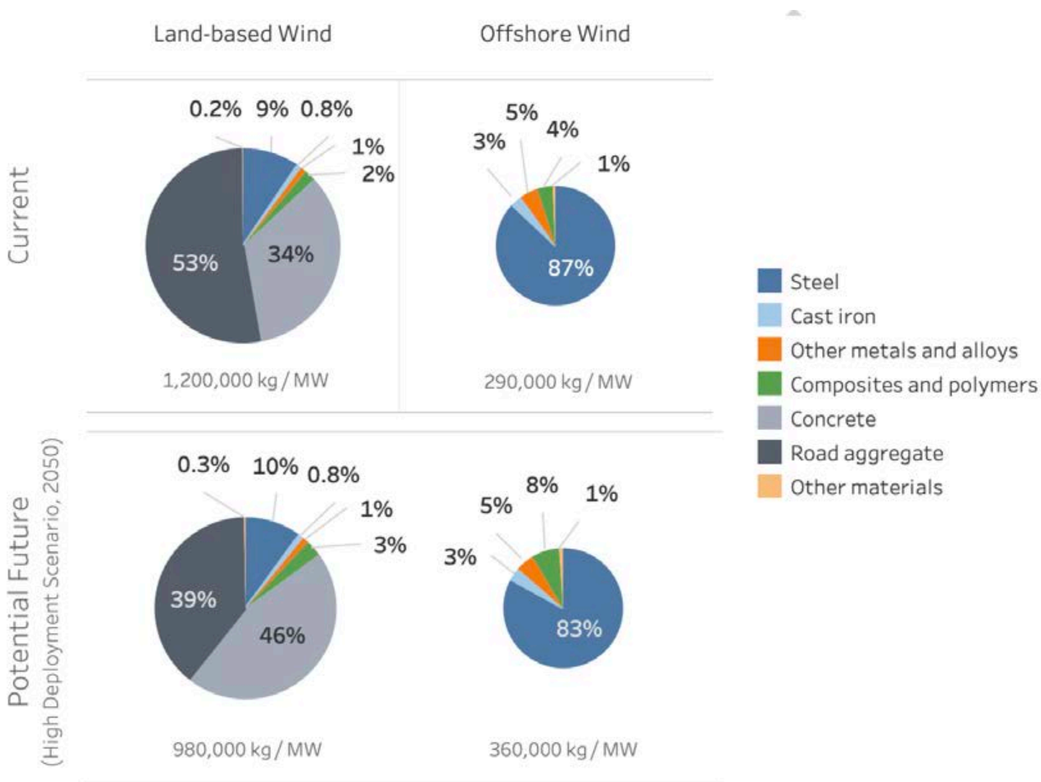

Figure 3. Material breakdown by weight of current and (potential) future designs of land-based and offshore wind energy technologies (as defined in REMPD). *Adapted from Materials Used in U.S. Wind Energy Technologies: Quantities and Availability for Two Future Scenarios (Eberle et al. 2023).*

Note: kg = kilogram, MW = megawatt

2.1.2 Levelized Cost of Energy and Projected Impacts of Decommissioning and Recycling

Figure 4 illustrates the component-level levelized cost of energy (LCOE) breakdown for land-based and fixed-bottom offshore wind power plants for 2.8-megawatt (MW) and 8.0-MW wind turbine ratings, respectively. We obtained capital and operational expenditures from NREL's *2021 Cost of Wind Energy Review* that represent data and results for commissioned wind power plants in the United States (Stehly and Duffy 2022). Capital costs (wind turbines and balance-of-system components) have the largest contribution to LCOE and total cost of ownership for both land-based and offshore power plants. Offshore wind systems require more than double the capital and operating costs needed for land-based systems. Wind-turbine-related costs (i.e., rotor, nacelle, and tower) dominate capital investments for land-based systems by 70%, whereas balance-of-system component costs (e.g., substructure, foundation, and electric infrastructure) dominate capital investments of offshore wind power plants by about 50%. Turbine-related costs of offshore wind systems contribute about 35% of total capital expenditures. In the wind turbine, nacelles are usually the most expensive component, followed by the rotor and tower.

Heavy metal steel and copper materials used predominantly in towers and nacelles, respectively, comprise more than 80% of the salvage value of materials in today's end-of-life management of wind energy systems in the United States. Materials in nacelles and towers can be more easily accessed during the decommissioning phase and have a relatively high resale value in scrap markets.[26] Fiberglass composites found in blades and hub spinners, typically disposed of in landfills or incinerated with energy recovery[27] today (see Section 3.6), have a net economic burden to the decommissioning project estimated at an average of $870 per metric tonne of material.[28]

A decommissioning cost estimate of 48 Gamesa 126-2.625-MW land-based wind turbines in New York indicates an estimated net decommissioning cost of ~$4,000 per turbine (2017 USD).[29,30] Total decommissioning costs—including removing the turbines, foundation, access road, substation, and interconnection station; excavating the site; and performing topsoil restoration—are reported to be almost $8 million. Over 60% of the power plant decommissioning cost is attributed to turbine removal alone; followed by foundation removal (17%), access road removal (15%), and topsoil restoration (8%). The total salvage value of materials is estimated at $7.82 million; thus, the net decommissioning cost is estimated to be $194,500 for all 48 turbines or $4,050 per turbine. About 97% of the total salvage value is steel and copper[31] in wind turbines; the balance is the aggregate salvage value from foundations and access roads. Recovered aggregate can be reprocessed into a base coarse gravel or general fill (see Section 3.1). However, whole foundations and roads cannot be reused and must be decommissioned at the end of project life based on feedback from several project owners. Recovering and reselling rare earth elements/magnets from generators as well as fibers and polymers from blades could reduce these costs.

More recent stakeholder interviews revealed that decommissioning and removal costs tend to vary significantly due to factors such as site accessibility, remoteness, soil types, topology, and wind turbine class and size. Depending on those factors, turbine removal costs, excluding the foundation and earthwork, could range from $35,000 to $100,000 (2023 USD) per turbine. Removal of foundations, access roads, and the substation could add up to $25,000 per turbine for full site restoration. Variations in turbine decommissioning practices, such as using different equipment and labor plans, lead to significant variations in decommissioning costs, quality of decommissioned material parts and scrap, and the overall profitability of subsequent recycling operations. To help overcome this challenge, in 2023 the International Electrotechnical Commission released standard 88/952/RQ, which outlines required processes for full site restoration, wind turbine removal, and subsequent preparation for wind turbine recycling.

Recycling and reusing components could reduce the amount of raw materials used in part and component fabrication. As a result, this reduction could lead to a lower cost share of materials in the LCOE.

Examining the cost dynamics between raw and recycled materials is outside the scope of this assessment. Section 3 focuses on the relative comparison of the cost of various material recycling technologies for different wind power plant components, where data are available.

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[26] Heavy melt steel has an average price of $241/USD ton and copper (88%–99% purity) has an average price of $2.25/pound or $4,500/U.S. ton. Retrieved on December 2023 at http://www.scrapregister.com/scrap-prices/united-states/260.
[27] "Energy recovery" in this context refers to the harness of energy created through the combustion process for reuse in power generation.
[28] Total cost of disposal including waste management operation. The average value was obtained from an actual bid for decommissioning 50 turbines with a 1.6-MW nameplate capacity as of June 2023. Retrieval of fiberglass composites costs around $3,595 per blade. The transport and disposal of fiberglass composites cost about $5,550 per blade or $17,250 per wind turbine (polymer composites from blades and hub spinners).
[29] Cassadaga Wind Farm: Decommissioning Cost Estimate (Towns of Charlotte, Cherry Creek, and Arkwright Chautauqua County, New York), 2017
[30] https://docs.wind-watch.org/decommission-ghd-cassadaga.pdf
[31] International Electrotechnical Commission standard 88/952/RQ can be found at: https://www.iec.ch/dyn/www/f?p=103:30:::::FSP_ORG_ID:1282.

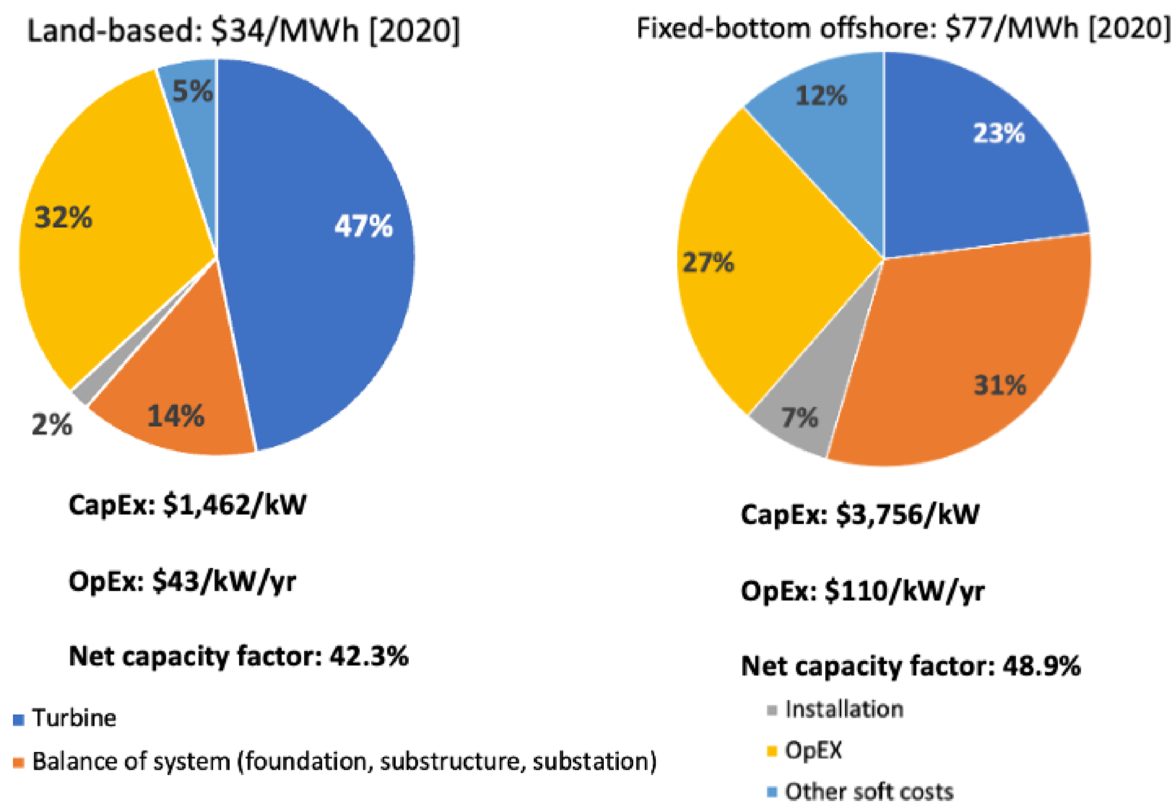

Figure 4. Component-level levelized cost of energy breakdown for U.S. land-based and offshore wind power plants. *Reproduced from NREL's 2021 Cost of Wind Energy Review (Stehly and Duffy 2022).*

Note: MWh = megawatt-hour; CapEx = capital expenditures; OpEx = operational expenditures; kW = kilowatt; yr = year

2.1.3 Life Cycle Greenhouse Gas Emissions

Figure 5 illustrates the different stages of life cycle GHG emissions for land-based and offshore wind energy systems. We compiled data for most of the deployed wind turbine nameplate capacities of 2 to 3 MW for land-based wind plants and 6 to 8 MW for offshore plants. We then compared life cycle assessment studies (Liew 2021; Bonou, Laurent, and Olsen 2016; Razdan and Garrett 2022; Dolan and Heath 2012) to estimate the potential emissions.

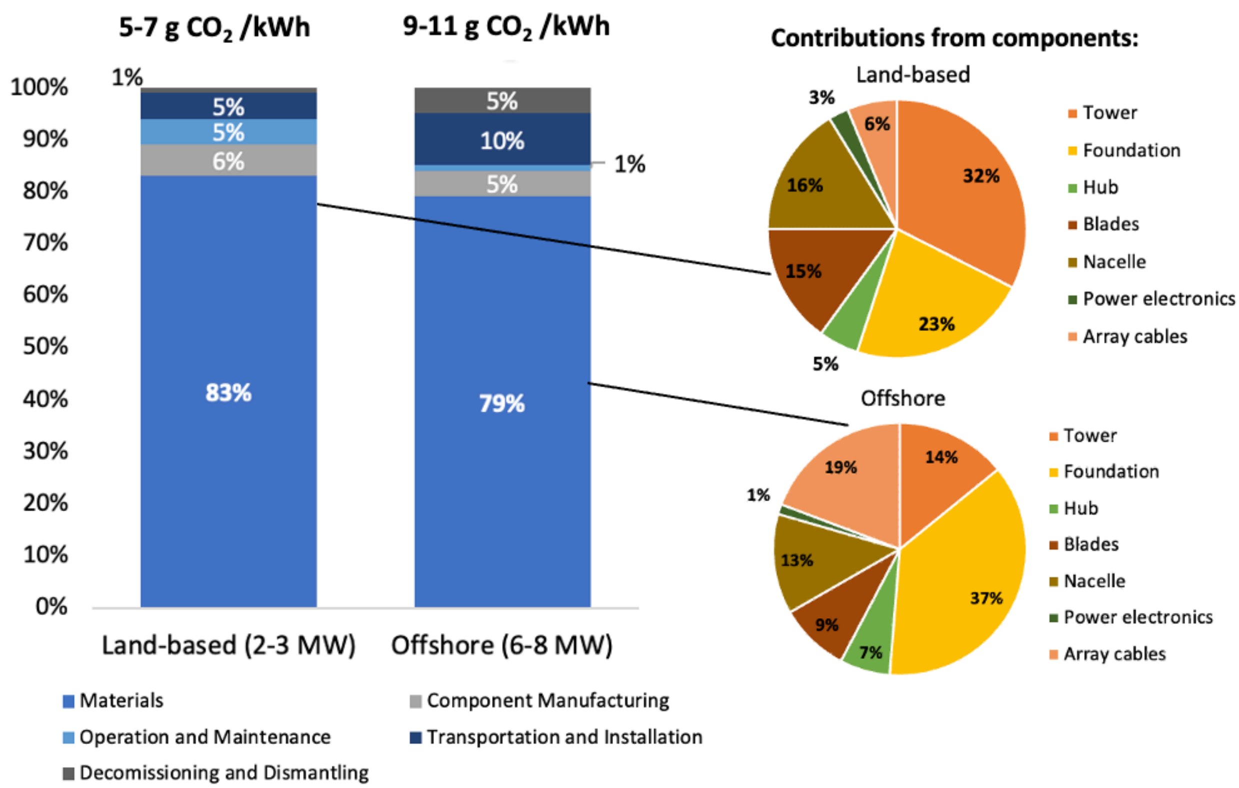

Figure 5. Breakdown of greenhouse gas emissions for life cycle stages and materials for land-based and offshore wind power plants. *Figure by Sherif Khalifa, NREL.*

Note: g = grams, CO_2 = carbon dioxide, kWh = kilowatt-hour

Wind energy systems have great potential because of their low life cycle GHG impacts when compared to fossil-based and even other renewable energy systems, such as solar photovoltaics or hydropower (NREL 2013). As shown in Figure 5, life cycle GHG emissions for wind plants range from 5-11 grams of carbon dioxide per kilowatt-hour (g CO_2/kWh). Moving larger offshore wind turbine components results in higher transportation and maintenance-phase emissions, as well as higher total life cycle emissions compared to land-based systems. This quantity (5-11 g CO_2/kWh) contrasts with significantly higher life cycle GHG emissions of 900-1,200 g CO_2/kWh for coal-fired and 480–650 g carbon dioxide equivalent (CO_2 eq.)/kWh for natural-gas-fired power plants (e.g., combined heat and power). Considerably higher emissions for coal-fired plants occur at the operational phase (e.g., >95% of total life cycle emissions (Fthenakis and Leccisi 2021; Dolan and Heath 2012).

2.1.3.1 Greenhouse Gas Emissions by Life Cycle Stage and Component

Figure 5 shows that material sourcing and manufacturing dominate 79%–83% of life cycle GHG emissions for wind energy followed by transportation and installation of wind turbine components. At the component level, towers and foundations contribute 51%–55% to life cycle GHG emissions from materials extraction and manufacturing. Blades contribute 9%-15% of total life cycle GHG emissions for the same scope. Total steel and concrete material intensity[32] contribute to more than 90% of raw material GHG emissions. The total GHG emissions from producing materials for wind energy components range from 1,300–1,700 tons CO_2 (land-

[32] Material intensity refers to the quantity of materials used per manufacturing value added.

based) and 4,700-5,300 tons CO_2 (offshore) equivalent units, respectively. Despite offshore systems having an overall higher material intensity than land-based systems, the larger contribution of steel components as well as transportation, seabed drilling, and installation generate about 3 to 4 times more GHG emissions for offshore than land-based turbines on a net basis. On a per-generation unit basis, capacity factors for offshore systems are typically higher, mainly due to bigger wind turbine sizes and favorable wind speeds. Therefore, life cycle GHG emissions per kilowatt-hour from offshore systems are about twice that of land-based systems.

2.1.3.2 Effects of Larger Wind Turbines

Results in Figure 5 are sensitive to many assumptions, such as material source, energy mix, wind turbine size, and capacity factor, assumed for different turbine systems. The path toward lower LCOE ($/kWh) is achieved through higher nameplate capacity turbines. More recently, wind turbines up to 16 MW have been demonstrated, and installing offshore turbines exceeding 8–10 MW is not uncommon. These turbines have larger rotors, taller towers, and longer blades with higher capacity factors than their smaller counterparts. Although offshore turbine sizes are likely to grow, the increase in their material intensity is not linear. Original equipment manufacturers attempt to reduce overall turbine weight while increasing structure size. REMPD estimates potential future offshore wind turbines that may be installed closer to 2050 (>10 MW) to weigh only about 25% more than their 6- to 8-MW counterparts. Some experts in our stakeholder engagement speculate that the gain in capacity factors may be in the range of 10%–20% compared to smaller turbine counterparts. Overall, larger turbines could have similar or slightly larger life cycle GHG emissions, conservatively assuming that existing material types and sources will be used.

2.1.3.3 Decommissioning Stage

The decommissioning stage contributes 5%-6% of life cycle GHG emissions for both offshore and land-based wind power plants. Although there is typically less weight to remove when decommissioning offshore wind projects because these systems do not have roads or large foundations, the remoteness of offshore systems and difficulty of removing subsea cables and substructures consume more energy than removing the foundations of land-based wind systems. However, land-based wind systems have significantly more material weight, which makes the overall life cycle GHG emissions for both systems similar.

2.1.3.4 Steel and Concrete

Decarbonizing steel and cement production industries is expected to significantly reduce life cycle GHG emissions of wind energy systems. However, decarbonized production pathways typically cost 2–3 times conventional manufacturing pathways (Liewx 2021). Using these lower-emission materials today in the wind industry might increase LCOE. Therefore, future RD&D efforts should strive to ensure the cost of green steel and concrete is on par with conventional technologies.

Recycling steel provides environmental and economic benefits to the wind energy industry. For example, detailed LCA studies show that recovered steel (mainly from the tower and nacelle) offers an emission offset of about 20%–25% of the life cycle GHG emissions produced from materials and components (Razdan and Garrett 2022; D'Souza et al. 2011). Using secondary steel scrap is also known to reduce energy consumption in steel foundries and reduce the need for emission-intensive primary ore refining.

Concrete is not commonly recycled but rather disposed of in landfills or repurposed into general fill or aggregate base course gravel, depending on the distance to the nearest available waste disposal option. If repurposed, concrete could offer emission and cost savings mainly from displacement of cement or aggregate production. Increased recovery of other blade materials such as fibers in composites and critical materials (e.g., nickel from steel alloys, rare earth elements from permanent magnets) could offer additional environmental and economic benefits as well as supply chain security. A more detailed analysis and discussion of the impact of removing the foundation and tower as well as using different grades of steel alloys in wind plants is provided in subsequent sections of this report.

2.2 Material Waste Estimates

Wind turbine components reach their end-of-service life at different rates because of varying technical and economic factors (Tazi et al. 2019; Dao, Kazemtabrizi, and Crabtree 2019; Wiser and Bolinger 2019; Cao et al. 2019). It is outside the scope of this project to obtain a detailed component-level waste projection. However, we attempted to make a first-order estimation of the magnitude of the primary materials' waste within components. We developed an approach based on the probability density function for blades and average economic project lifetime/warranty period for the rest of the components. This is a simplified, conservative approach to estimate projected volumes of decommissioned components that would facilitate a first-order comparison with existing domestic recycling capabilities while still capturing the evolution in wind turbine design and size over time and the various underlying factors of their decommissioning.

In a component reliability review study encompassing more than 18,000 land-based and offshore wind turbines, the highest failure rates were observed for blades and hub components followed by electrical, control, and pitch systems (i.e., power electronics in this study) (Dao, Kazemtabrizi, and Crabtree 2019). Generators, which are a major source for component replacements, now show improved field performance and durability compared to older designs. To date, there is little public data that indicate a statistical failure distribution at the subcomponent level (i.e., pitch, generator modules).

Failures can occur in any wind turbine component. To simplify our modeling, we modeled the failure behavior for only the blade component as it has been thoroughly investigated in previous literature. Prior work by Cooperman et al. estimated blade waste to be about 2.2 million tons through 2050 (Cooperman, Eberle, and Lantz 2021). This estimation is based on historic and future estimates of installed capacity provided by the U.S. Wind Turbine Database and NREL's mid-case Annual Standards Scenario published in 2018 (Cole 2018). The study compared waste projections using a constant blade lifetime (e.g., 20 years) and a Weibull probability distribution that models the failure behavior as a function of blade age in premature, regular, and late life failures. The Weibull distribution used includes shape and scale parameters fitted to reliability data from offshore wind turbine blades located in Denmark (Faulstich et al. 2016). For this study, we applied the same probability distribution in the high-deployment scenario to obtain blade composite and polymer waste estimates. Waste estimations do not include projections for potential plant repowering operations for which data are unavailable.

We modeled the rest of the wind turbine components, including foundations and substructures, to follow a dynamic growth in expected useful life of U.S. land-based wind power plants surveyed by the Lawrence Berkeley National Laboratory (Wiser and Bolinger 2019). The survey shows—as reported by project developers—a steady increase in project life, with a typical term of 15 years in the late 1990s, 20 years in the early 2000s, 25 years by mid-2010, and 30 years more recently in 2020. Some projects are now contracted for 35 years of operation.

Figure 6 shows the average annual and cumulative waste projections of primary materials included in wind energy components under the high-deployment scenario using the dynamic baseline approach.

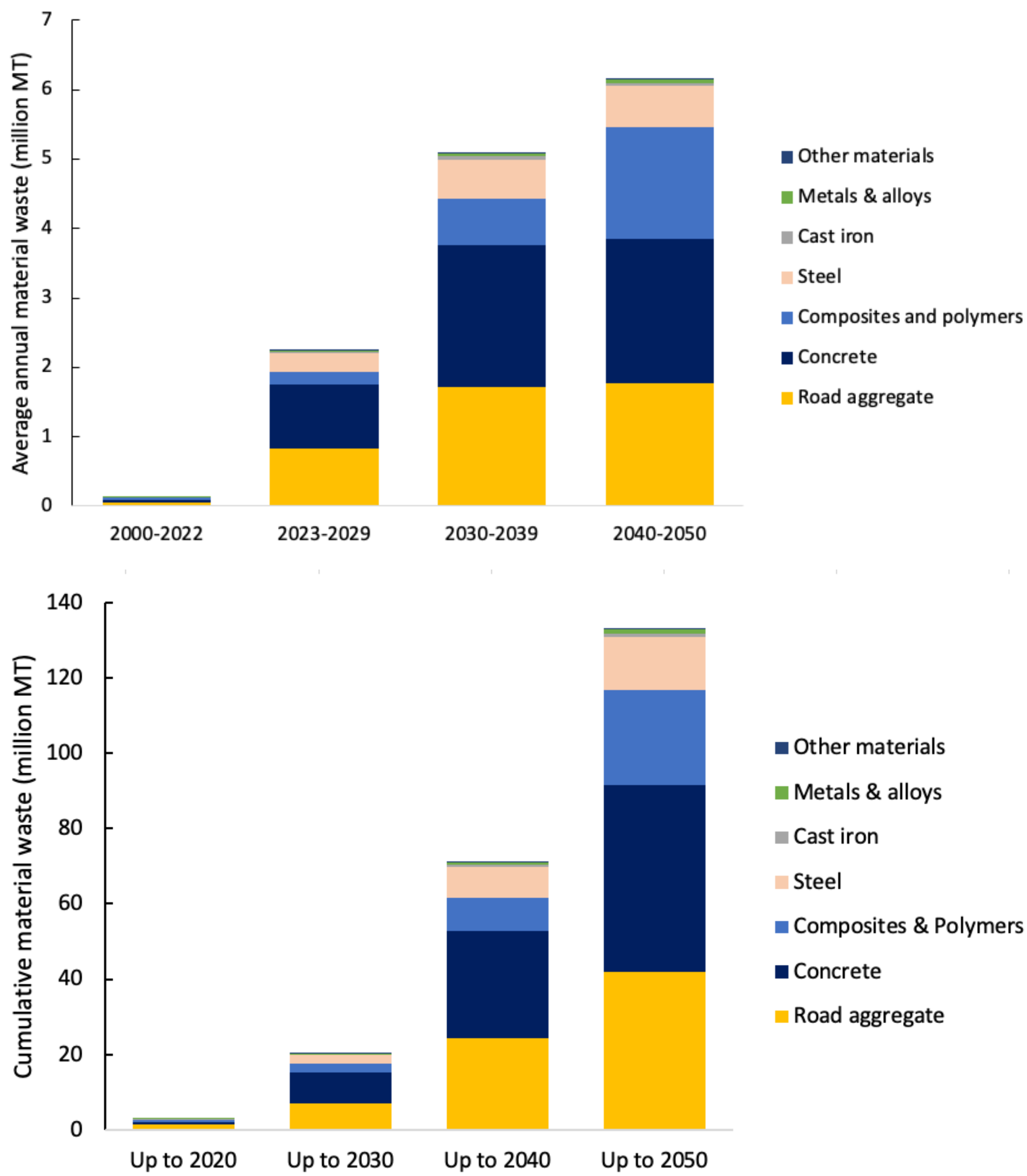

Figure 6. Annual (top) and cumulative (bottom) waste projections for wind energy materials under the high-deployment scenario by 2050. *Figure by Sherif Khalifa, NREL.*

Note: MT = million metric tonnes

Results show that the cumulative decommissioned material from U.S. wind energy systems could reach up to 133 million metric tonnes by 2050, with the waste stream beginning to increase sharply in 2030. Together, steel and concrete contribute up to 90% of decommissioned material mass. However, steel and concrete component retirements do not happen every year because most of the projects will likely still be in operation. As a result, we only modeled full plant decommissioning and did not consider potential repowering operations. Composite materials, especially from blades, have steadily increasing volumes of waste by 2050 and are expected to be decommissioned every year. The percentage of composite waste, relative to total decommissioned materials, is also likely to increase, especially from decommissioned materials coming from installations in 2028-2032. Cumulative composite waste is projected to reach 25 million metric tonnes by

2050. Beginning in 2032, composite waste starts to rapidly increase and doubles approximately every 4–6 years. This result reflects the high-deployment scenario modeled in Denholm et al. (2022) and used by Eberle et al. (2023) in estimating material requirements for wind energy in the same scenario projected to achieve a clean, carbon-free electricity grid by 2030 and U.S. decarbonized economy by 2050.

2.3 Existing Wind Material Recycling Capacity in the United States

In the previous section, we estimated the volume of decommissioned materials at the expected end of life of wind power plants. Now, we present our findings on the existing recycling capacity of major primary materials within the United States. We collected data for the processing capacity of scrap primary materials in the United States from the United States Geological Survey Mineral Commodity Summary reports, the Environmental Protection Agency's (EPA) Recycling Economic Information and datasets published in Advanced Sustainable Management reports, and interviews with scrap metal recyclers in the United States. We compared the highest annual material waste from 2020 through 2050 to the latest domestic material recycling capacity to understand the extent to which the existing recycling capacity could be occupied by the projected wind material waste stream. We used REMPD to identify critical and noncritical materials projected to exceed 20% of U.S. production capacity. Table 3 summarizes the existing U.S. recycling capacity for wind energy primary materials and the maximum annual occupancy expected by decommissioned wind material.

Table 3. Average Annual U.S. Recycling Capacity for Select Wind Energy Materials and Their Maximum Annual Occupancy of Recycling Capacity Under the High-Deployment Scenario

Primary Material	Average Annual Recycling Capacity in the United States (metric tonnes)	Fraction of Current U.S. Recycling Capacity of Estimated Decommissioned Wind Energy Materials Waste in 2050 (%)	Year Data Last Available	Source
Iron and steel, including cast iron	52,400,000	<5%	2018	United States Geological Survey (USGS)
Rare earth elements	<5,000	>100%	2022	Interviews
Concrete and aggregate	>100,000,000	<10%	2020	USGS
Electrical steel	Negligible/not reported	Not applicable (N/A)	2022	Interviews
Cobalt	500-1,000	>100%	2020	USGS
Nickel	Negligible/N/A	N/A	2018	USGS
Chromium	Negligible/N/A	N/A	2018	USGS
Aluminum	2,300,000	<23%	2021	U.S. Environmental Protection Agency (EPA)
Copper	950,000	>30%	2021	EPA
Zinc	1,200,000	<1%	2021	EPA
Fiber-reinforced composites	10,000–13,000	>100%	2022	Market reports, survey
Fiber-reinforced composites	10,000–13,000	>100%	2022	Market reports, survey

Analysis shows that the existing U.S. recycling infrastructure could handle processing carbon steel, concrete, and zinc scrap materials from the wind energy industry under the high-deployment scenario. The infrastructure could also process aluminum and copper, but it would likely be strained depending on the volumes of material scrap waste from other sectors. Thus, the United States could benefit from expanding the recycling capacity for aluminum and copper scrap materials. It is important to note that this comparison is only focused on the volume capacity of the existing infrastructure to process decommissioned materials, but it does not identify the cost efficiency and environmental sustainability of the related practices for those materials.

The United States does not currently have sufficient capacity to process the projected volume of fiber-reinforced composites, rare earth elements (neodymium and dysprosium), electrical steel, nickel, chromium, and cobalt. The recycling infrastructure for these materials is either not present or has little capacity for decommissioned wind materials. Because some materials are also critical to the supply chain (e.g., nickel, cobalt, and chromium), the United States may need to ramp up its recycling infrastructure for targeted recovery of these alloying elements from steel or to foster technological innovations and material handling strategies that minimize or eliminate loss of these critical materials during steel recycling at the end of life. Furthermore, domestic rare earth metal recyclers state that collection and disassembly of enough volumes of rare earth element-containing devices is a barrier to offset existing recycling costs. Therefore, there is little incentive to expand recycling capacity, which could be another area that needs more immediate attention.

3 Component-Level Results

In this section, we assess the components listed in Section 1.2.1: foundation and substructures; towers; nacelles; drivetrains; generators and rare earth permanent magnets; blades; and power electronics, substations, and cables. We provide an overview of each component that includes a discussion of end-of-life management practices (i.e., decommissioning, excavation, and equipment removal); recycling technology solutions; results of stakeholder engagement and metrics analysis; and a list of RD&D needs, gaps, and opportunities.

3.1 Foundation and Substructures

Foundations represent the largest mass component of the wind turbine and the second largest of the entire wind power plant after mass of access roads. In this subsection, we present different types of foundations along with existing waste management practices for those foundations during wind power plant decommissioning. We then propose several R&D priorities to help achieve more sustainable and economically efficient foundation removal and recycling practices.

3.1.1 Material Breakdown for Foundations and Substructures

Land-based wind turbine foundations are mainly built using steel-reinforced concrete, which comprises steel (used as reinforcement bars) and concrete. Both materials have existing domestic large-scale recycling industries that have enough capacity (see Section 2.2.) and technological maturity to process upcoming material waste from wind power plants. However, limited second use of recovered materials, high cost, and environmental impacts of some decommissioning practices and suboptimal land restoration activities are key areas that need improvement. Removing the foundation materials is part of the decommissioning process. While current U.S. regulations do not require recycling recovered materials, virtually all existing contracts involve removing all or some (when permitted) of the foundation. Contracts in the United States require wind power plant owners to account for costs of foundation removal and excavation. Foundations are embedded in the ground (up to 15 feet (ft) deep for gravity-base foundations and 100 ft for pile-driven foundations) or in the seabed (up to 60 meters deep).

3.1.2 End-of-Life Management Practices for Foundations and Substructures

When a wind power plant reaches the end of its life and cannot be repowered, developers and project owners begin the decommissioning process, which is typically dictated by the foundation type (i.e., land-based, monopile, jacket, floating) as well as the location/remoteness of the plant. To date, it is unclear what fraction of decommissioned foundations can be recycled. As discussed in more detail in the following sections, factors such as transportation costs, proximity of recycling centers, and end-user applications, which are local in nature and project-specific, play a role in whether a foundation is recycled.

3.1.2.1 Land-Based Foundations

Land-based foundations typically comprise backfill (generally soil and some gravel) below the surface and a concrete base above the surface. Backfill above and around the base is accessible and thus easy to dismantle with earth-moving equipment (e.g., backhoes, excavators, and dump trucks). To reduce the cost of transportation to recycling centers, project owners typically use recovered backfill on-site to fill voids. Recovered backfill can also be used for other local community projects.

Concrete bases are more difficult and costly to remove than other turbine components primarily because of their depth. Interviews with decommissioners indicate that they only remove the top 3-5 ft of the foundation while leaving the rest of the base in place. This approach helps reduce decommissioning costs (e.g., number of days on-site, number of crew members, required equipment). Decommissioners typically add backfill or new organic topsoil to restore land to the quality specified by landowners for future applications. Future land applications must then be designed to accommodate the abandoned wind turbine foundation segment remaining underground.

Larger, more energy-consuming equipment (i.e., bulldozers, hydraulic hammers) is often used to remove the below-ground foundation base. Some decommissioners will blast a foundation base using explosives to reduce labor and cycle times that already dominate the cost of decommissioning. Therefore, a trade-off exists between decommissioning cost and full land restoration for future uses.

After demolition, the resultant large-scale reinforced concrete rubble from the foundation—which includes concrete and steel rebars—is then loaded into trucks and transported in two steps: 1) from the decommissioning site to the nearest concrete recycling plant, and 2) from the concrete recycling plant to the end-use facilities to process base, filler, aggregate (for concrete), and steel rebar scrap.

3.1.2.2 Offshore Substructures

As of 2024, there are only two operating offshore wind energy projects in the United States. They were commissioned in 2016 and 2020; therefore, decommissioning and recycling are not expected soon. Nonetheless, planning for decommissioning offshore systems becomes more relevant as deployment ramps up to meet the U.S. decarbonization goal of 30 GW by 2030 (The White House 2021).

Monopiles are the most deployed substructure for offshore wind power plants globally especially in shallow water applications. Alternate structures—such as jackets, tripods, and floating foundations—are more suitable for deep water (> 60-meter depth; Lopez et al. 2022). However, these alternate substructures are not used as often because they are generally more expensive. Larger wind turbine systems in the future are expected to have a nonmonopile substructure to reduce overall system weight, individual component weight, and transportation costs. Because these alternative structures are not commonly used, the decommissioning and recyclability challenges are unknown and must be explored further.

The dismantling and decommissioning process for offshore wind substructures is more challenging than for land-based foundations because most of the substructure is below sea level for fixed-bottom foundations and made of larger fractions of steel. Furthermore, offshore wind substructures are significantly larger than land-based foundations and require work at sea. The type of substructure, its depth, and the distance from shore dictate the choice and complexity of the decommissioning approach. In general, decommissioning offshore wind substructures requires more powerful equipment along with approaches such as torching or grinding,[33] which require larger amounts of excavation and support systems to control the tools. Alternatives to torching (a labor-intensive process using torches to cut foundation into pieces) include hydraulic extraction, which is a minimally intrusive process that applies even force to lift the foundation out of the ground. However, this approach comes with its own challenges; most notably to secure an airtight seal to pressurize the interior of the monopile. Pressurizing the interior of a foundation helps prevent groundwater infiltration, which could lead to corrosion and structural degradation. Offshore wind turbine foundations can be classified into three areas of increasing complexity and cost for removal:

1. Above-sea-level parts, such as the transition piece (least complex and least expensive to remove)

[33] Torching is the use of a flame to cut and/or incinerate materials, including wind turbine foundations. Grinding is the scraping and reduction via friction of materials, including turbine foundations.

2. Subsea structures (such as the main body of a monopile foundation), which are more difficult and time-consuming to install and remove than above-sea-level parts due to underwater working conditions (more complex and more expensive to remove)
3. The remaining portion of the foundation that is under the seabed, which is the most difficult to install as well as remove because it requires extensive excavation for partial removal (torching) or extensive preparation for pressurizing or vibrating during full removal (most complex and most expensive to remove).

Components above the water line, while still massive, require less specialty equipment for removal than components below sea level (i.e., even if torching is needed, air torching is drastically simpler than underwater torching, though heavy cranes and large construction vessels are still required). Environmental conditions such as high winds and waves could complicate, compromise, or delay the decommissioning of offshore wind power plants. Potential scarcity of vessels and powerful decommissioning equipment could also make decommissioning future U.S. offshore wind power plants difficult. The Merchant Marine Act of 1920, commonly known as the Jones Act,[34] is expected to impose further challenges because existing coastwise-qualified ships are not large enough or specialized enough to remove and transport offshore wind turbine components (DOE 2023c).

As mentioned earlier, the most common offshore foundation type is the monopile, which will be the most decommissioned in the coming years. Though few have been decommissioned, interviewed decommissioners indicated that the full removal of the foundation (cut at the seabed level, leaving the buried portion) is the leading cost driver when evaluating the decommissioning process. As part of our stakeholder engagement efforts, we interviewed experts in Holland who reported estimates of the substructure removal cost being 45% of the total decommissioning cost, whereas experts in the United Kingdom suggested that the full removal of the foundation leads to a net present value of $-1.04 million per 6-MW wind turbine. Interviewed stakeholders did not report details on the removal of biofouling[35] and its costs. However, we expect that this may be an additional step needed before recycling can start, especially if the seabed area is large enough to interfere with or affect the recycling process.

Steel offshore wind turbine foundations are made of the same types of structural steel used in most other wind turbine components. Because of this, see Section 3.2 for a discussion on the current practices and challenges of recycling large-scale structural steel components.

3.1.2.3 Foundation and Substructure Material Recycling Pathways: Challenges and Benefits

Regardless of the foundation type, dismantled components need to be transported to the appropriate recycling facility. The typical foundation material share of total wind plant mass is about 280,000–340,000 kilograms (kg)/MW, or 25%–31%, for land-based foundations (mostly concrete) and about 175,000–215,000 kg/MW, or 58%-72%, for offshore foundations (mostly steel).

After the concrete is transported to the nearest recycling facility, an excavator with an impact attachment reduces the large pieces. Those reduced pieces are then moved to an impactor that further pulverizes the material to the proper size for the final application (i.e., base material or recycled concrete aggregate [RCA]). During this process, pieces of steel rebar and other metallic impurities are removed from the RCA material. Further processes can use air and/or water to remove wood or other lightweight impurities within the material.

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[34] See Pub. L. 66-261.. Only U.S. built, owned, and crewed vessels may transport merchandise between U.S. points. The Outer Continental Shelf Lands Act extends the laws of the United States to structures affixed to the seafloor.
[35] Biofouling is the accumulation of microorganisms, plants, algae, or small animals on underwater surfaces that degrades their function.

The scrap steel that is reclaimed during the processing of the RCA is compacted into a block of scrap steel, transported from the RCA plant to a steel recycling facility, and then recycled.

3.1.2.3.1 Concrete and Aggregate Recycling Challenges

Currently in the United States, 382 million tonnes of RCA are generated every year across all industries. This amount includes 315 million tonnes of beneficially reused materials (i.e., subbases/bases and backfill, which are crushed rocks and stones of various sizes). Thus, the U.S. capacity to recycle concrete far exceeds the amount of concrete—108 million tonnes—that is expected to be decommissioned from the wind industry through 2050. Even if 100% of the foundations are removed in the future, the U.S. capacity to recycle should be adequate. While the recycling technology is well-developed, the main challenge is that existing RCA in the United States is almost solely used as a downcycled product (i.e., in lower-value, lower-quality applications) rather than producing new concrete to close the material loop. Of the 382 million tonnes of RCA produced in the country, less than 22% is currently upcycled into new concrete. (Cavalline and Fonte 2021). Stakeholder engagement interviews with the American Concrete Institute Committee on Concrete with Recycled Materials revealed that the low quality of and presence of metallic impurities in RCA are major contributors to low closed-loop (recycled materials used in the same original application) recycling rates (ACI 2024). Equally important, there is no standardized testing or characterization tests to qualify RCA as a recycled content in the American Society for Testing and Materials (ASTM) International concrete standards. ASTM International develops global voluntary consensus standards. Our analysis reveals that reusing RCA in concrete could offer strong economic incentives and low-to-modest life cycle GHG benefits.

3.1.2.3.2 Economic Benefits of Concrete and Aggregate Recycling

Interviews with representatives from DH Griffin Companies revealed that using RCA can reduce the overall project cost of materials when compared to virgin aggregate. This reduction is based on the cost of #57 stone, which is most commonly used in land-based foundations, made of RCA being $17–$18 per metric tonne while virgin aggregate is between $40 and $65 per metric tonne. Furthermore, the backfill material is $9.50 per metric tonne while virgin-processed fill is $18.50 per metric tonne. For DH Griffin in North Carolina, it costs roughly $8 per metric tonne for centralized recycling and $13 per metric tonne for on-site recycling to process the concrete, which includes all transportation and breakdown of the material. Therefore, the cost of recycling concrete is lower than disposing of the material. DH Griffin charges roughly $2.00 per metric tonne to take demolished concrete pieces while waste management facilities in that area charge $35-$40 per metric tonne to take the construction waste. However, the cost-effectiveness of recycling concrete depends on the geographic location and distance between the wind power plant site and the nearest recycling center. In addition, some areas have more readily accepted the use of RCA for various applications, which could drive higher levels of recycling or prevent its use.

3.1.2.3.3 Environmental Benefits of Concrete and Aggregate Recycling

Concrete has an average density of 2,416 kg/cubic meter (m^3). The typical composition of 1 m^3 of concrete includes 300−354 kg of cement, 800–850 kg of fine aggregate, 1,000−1,050 kg of coarse aggregate, and 170–190 kg of water. Figure 7 shows comparative life cycle GHG emissions for the virgin production of concrete, two scenarios for fly ash substitution for Portland cement used in concrete production, and concrete made with 100% RCA as recycled content. Portland cement is the most used today in U.S. land-based wind turbine systems.

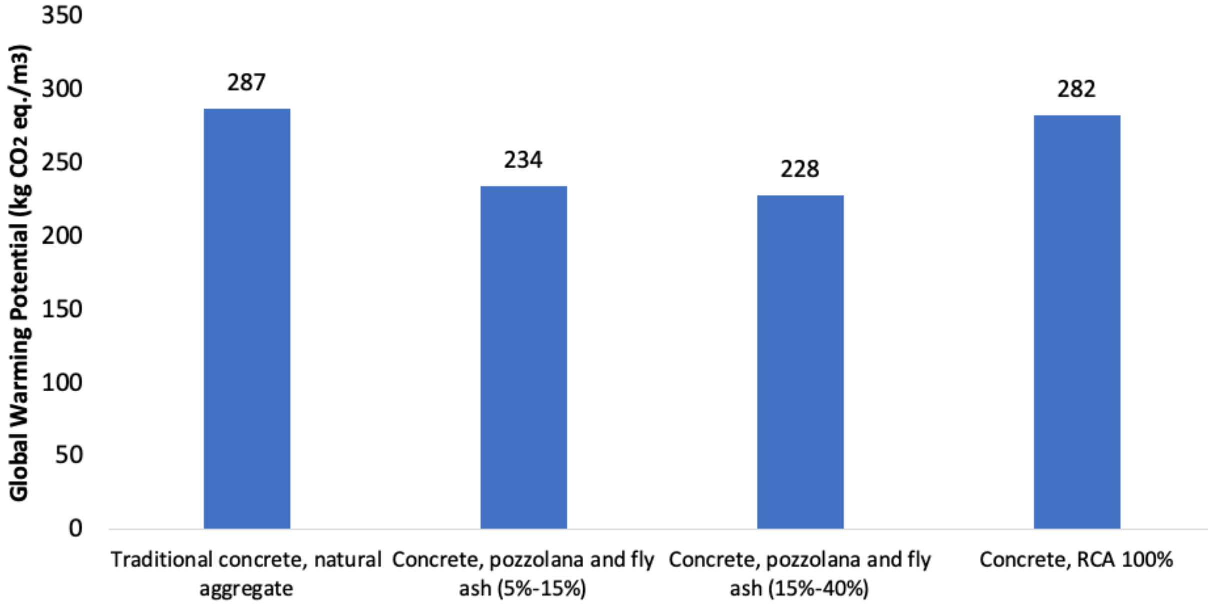

Figure 7. Life cycle GHG comparison of traditional concrete production, two pozzolana and fly ash substitution scenarios of Portland cement, and 100% RCA used in concrete production. *Figure by Sherif Khalifa, NREL.*

Our analysis reveals that life cycle GHG emissions, embodied energy, and life cycle water consumption per 1 m^3 of virgin concrete production in the United States is estimated to be 287 kg CO_2 eq., 1,540 megajoules (MJ), and 322 m^3 of water. Cement production and use contributes >79% to life cycle GHG emissions alone, whereas energy consumption contributes about 10% of total life cycle GHG emissions.

Figure 7 shows that substituting Portland cement with fly ash can reduce between 18% and 20% of life cycle GHG emissions compared to traditional concrete production made solely with Portland cement. Pozzolana is a type of volcanic ash used for mortar or cement that sets under water. Substituting natural aggregate with RCA reduces 1.8% of life cycle GHG emissions. This result is attributed to the high energy consumption used in obtaining RCA versus natural aggregate at the end of life of wind turbine foundations. Therefore, RCA use in concrete production could offer stronger economic and circularity benefits but extremely low life cycle GHG benefits.

Using concrete manufactured with lower GHG emissions, along with development of modular foundation designs and minimally intrusive decommissioning operations, could minimize the environmental impacts associated with foundation removal and overall wind sector sustainability. The Inflation Reduction Act (IRA) funded the U.S. General Services Administration (GSA) to conduct acquisition and installation of construction materials (e.g., steel, concrete, asphalt) and products with substantially lower levels of embodied carbon emissions (LEC).[36] At least 80% of the assembly's cost or total weight needs to be comprised of a qualifying

[36] The Inflation Reduction Act of 2022, Pub. L. 117-169, section 60503 provides the U.S. General Services Administration (GSA) with $2.15 billion for acquisition and installation of construction materials and products with substantially lower levels of embodied carbon (LEC) emissions as compared to estimated industry averages, as determined by the Administrator of the U.S. Environmental Protection Agency. Full guidance, definitions and GHG limits of materials can be found here: https://www.gsa.gov/real-estate/gsa-properties/inflation-reduction-act/lec-program-details/material-requirements.

construction material to qualify for IRA funds. Wind turbines meet this total weight criteria and thus it is encouraged for plant owners to purchase IRA LEC materials in new wind plant construction projects.

3.1.3 Decommissioning and Recycling Metrics for Foundations and Substructures

Table 4 summarizes the compiled metrics for existing decommissioning and recycling of concrete-based foundations. Future decommissioning and recycling technologies for foundations and concrete should ideally perform better than the metric values indicated here, where applicable, allowing for more sustainable end-of-life practices for foundations and substructures.

Table 4. Metrics for Existing Concrete Decommissioning and Recycling Technologies

Metric	Value	Unit
Waste disposal percentage	<10%	%
GHG emissions	250–310	kilogram of carbon dioxide (kg CO_2 eq.)/metric tonne
Embodied energy	1,500–1,600	megajoule (MJ)/metric tonne
Water use	300–340	cubic meter (m^3)/metric tonne
Human toxicity	Not enough data available	CTUh[37]/metric tonne
Cost of recycling	08–15	$/metric tonne
Market selling price	10–20	$/metric tonne
Material yield	>99%	%
Material quality ratio	22%	Material-specific ratio
Technology readiness level	9	1–9
Critical material use	N/A	kg

3.1.4 RD&D Needs, Gaps, and Opportunities for End-of-Life Management Practices for Foundations and Substructures

Section 3.2 includes a detailed discussion of steel recycling and its RD&D gaps; thus, this section only focuses on concrete foundations for land-based and offshore applications. There are many opportunities for fundamental and applied research to improve recycling rates, cost-effectiveness, and environmental sustainability of concrete recovery and recycling pathways from wind turbine foundations. Table 5 provides the RD&D priorities for improving end-of-life practices for foundation/substructure components and the potential impacts of implementing these innovations.

[37] CTUh refers to comparative toxic units for humans; estimating the increase in morbidity in the total human population in the life cycle of the functional unit. This unit is an end point impact assessment metric as described in Section 1.3.

Table 5. RD&D Priorities for End-of-Life Practices for Foundations/Substructures and Potential Impacts of Investments

RD&D Technological Innovation	Potential Impact
Develop modular foundation designs that enable disassembly and reuse; for example: • Expandable and/or interconnected foundations supported on micropiles rather than large deep piles (inland) • Precast segmental concrete pedestals and transition pieces (inland and offshore)	• Maximize the long service life of foundation materials by reusing them with multiple turbine life cycles • Reduce transportation costs of potential future large components • Reduce site excavation activities • Avoid disturbing deep soils • Significantly reduce life cycle GHG emissions per gigawatt
Develop additive manufacturing techniques for foundation parts (inland and offshore)	• Reduce needed capital costs to create manufacturing facilities for large components • Enable easier expansion/retowering
Characterize, certify, and standardize reclaimed RCA in experimental concrete applications for ASTM standards	• Improve cost-effectiveness of RCA reclamation • Incentivize the use of RCA in high-value concrete applications (i.e., buildings) • Increase industry and consumer confidence in replacing natural aggregate with RCA materials • Improve life cycle GHG emissions
Develop innovative, lower-GHG cementitious materials using RCA powders via high-technology readiness level (TRL) and cost-effective methods	Reduce contribution of foundation to life cycle GHG emissions per gigawatt-hour of wind power plants
Develop environmentally friendly offshore foundation materials to create artificial coral reefs	Create a beneficial second life for substations and avoid decommissioning impacts
Develop offshore fixed foundation designs that reduce or eliminate the use of large diameter steel monopiles; for example: • Use the seabed bearing capacity and develop flanges for monopiles that will reduce the depth of either the concrete or steel monopile • Develop sectional post-tensioned concrete monopiles to replace large, welded steel counterparts	• Reduce needed capital costs to create manufacturing facilities for large components • Facilitate compliance with the Jones Act • Develop a U.S.-specific monopile solution that is better adapted to U.S. water depths and manufacturing constraints

RD&D Technological Innovation	Potential Impact
Develop a life cycle assessment tool to iteratively assess the sustainability and circularity performance of proposed foundation technology design innovations	• Facilitate early planning, forward thinking, and optimization of emerging foundation designs (i.e., modular foundations) • Improve understanding for businesses about the potential values and trade-offs of their design decisions

3.2 Tower

Wind turbine tower masses range from 40% to 80% (excluding the foundation). The wind turbine tower is the primary structural component that connects the foundation to the nacelle and supports the gravitational load from the mass of the nacelle and rotor components. The towers are usually constructed using a steel tubular design, but steel lattice structures and concrete tubular structures have been deployed to a lesser extent. As the wind turbine height increases, the length of the tower section and the wall thickness also increase, which significantly increases the mass. The relationship is a second order or square that leads to significantly higher tower mass ratios for turbines with taller towers of the same rated power.

3.2.1 Material Breakdown for Towers

Wind turbine towers are made of more than 95% carbon-based steel along with other ancillary subcomponents, such as access components (e.g., doors, ladders, and platforms), electrical components (e.g., electrical cables, lighting), and paint and other coatings (e.g., anticorrosion coatings, cable sheathing).

Land-based wind turbine towers have a steel material intensity of 50,000–150,000 kg/MW, whereas offshore wind turbines use more steel in the tower and foundation totaling 250,000–300,000 kg/MW (REMPD 2023). The steel structural components are usually made of ASTM A572 Gr 50 in North America or S355 in Europe. The typical compositions of the A572 Gr 50 and S355 are shown in Table 6. These steel grades are the most commonly deployed in wind turbine towers today.

Table 6. Mass Composition of Steel-Grade ASTM A572 and S355 in North America and Europe, respectively.

Note: Values are a mass percentage per metric tonne of steel (%/metric tonne).

Grade	Carbon	Manganese	Phosphorus	Vanadium	Nickel	Cobalt	Sulfur	Silicon	Copper
A572 Gr 50	0.23	1.35	0.04	0.06	0.015	0.05	0.05	0.4	-
S355	0.2	1.6	0.025	-	-	-	0.025	0.55	0.55

As discussed in Section 1.2.1, the United States has a low production capacity for the critical materials nickel and cobalt. In the high-deployment scenario, 240–550 million kg of nickel and 0.3–0.6 million kg of cobalt are cumulatively needed from 2020 to 2050. Adopting efficient decommissioning and metal recycling pathways to eliminate or minimize the loss of these critical elements is essential to securing the future U.S. wind energy supply chain.

3.2.2 End-of-Life Management Practices for Towers

Figure 8 summarizes the steps taken when a wind turbine tower reaches its end of life. The steps reported here represent the most adopted practices gleaned from interviews with decommissioners and metal recyclers in the United States for land-based wind turbines.

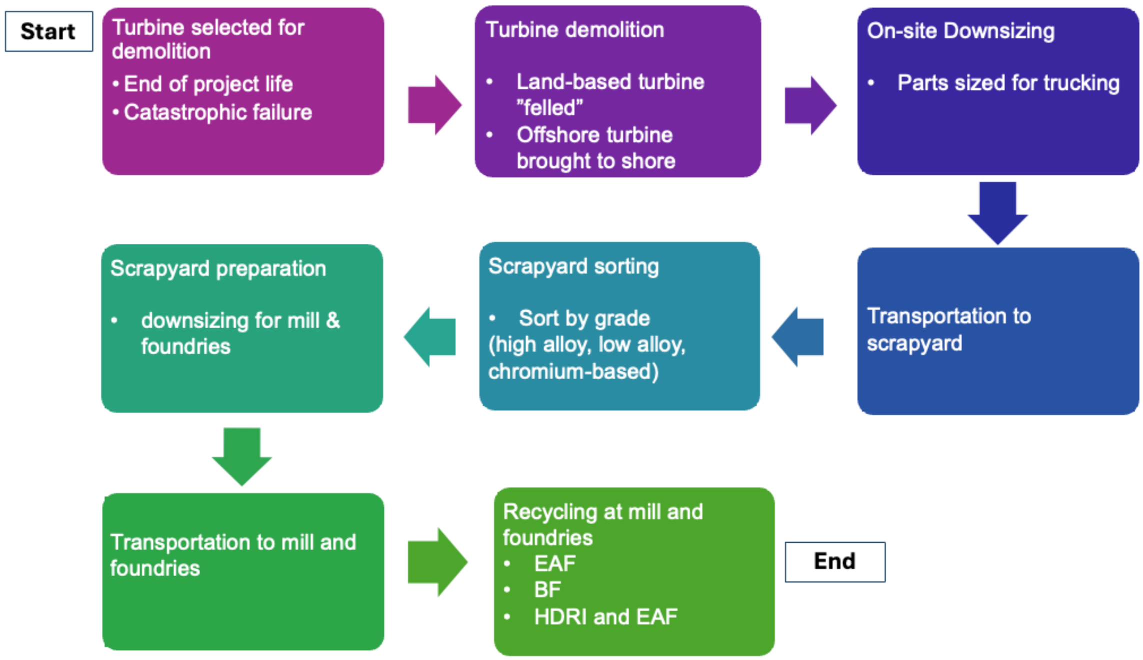

Figure 8. Steps for wind turbine tower decommissioning and subsequent steel recycling pathways. *Figure by Peter Wang, ORNL.*

EAF = electric arc furnace; BF = blast furnace; and HDRI = hot direct reduced iron.

Decommissioners start the disassembly process by making a large incision near the base of the wind turbine. This incision will facilitate the tower toppling onto the ground in the following step. Ropes are strapped around different regions of the tower diameter, and heavy machinery is used to pull these ropes and topple the entire tower to the ground. This practice is reported to be the most cost-effective option to date because it requires minimal time and crew members on-site (4–6 members per turbine). Yet, it is also destructive because other components will break after they hit the ground (e.g., generators, nacelle, drivetrain). Upon the request of the owners, blades are sometimes decommissioned separately for further processing. However, it is common for wind turbine blades to topple along with other components. As a result, decommissioners might be responsible for their disposal, which typically means composites are sent to waste management or incineration facilities.

Metal and nonmetal components are then sorted. Steel-based components from the tower, nacelle, and bedplate of the drivetrain and generator are separated from other components because they are deemed to be the most valuable. Nonmetal parts, such as blades, are typically trucked and sent for storage or disposal in landfill as of 2023 (detailed discussion about end-of-life blade management is discussed in section 3.6). Metal parts are then trucked to scrapyards where steel scrap is further sorted by grade: carbon-based steel, electrical steel, cast iron, and high-alloy steel. Each steel grade is either sold to a steel mill processing plant to be included as part of the steel furnace input (e.g., electric arc furnace [EAF]) or sold overseas, such as in the case of electrical steel. As of 2024, the United States does not have the capacity to produce electrical steel, which hinders the ability to recycle it at the end of life.

Structural (i.e., carbon) steel that comprises wind turbine towers is "downsized" by mills to fit their feed-size standards of 2-ft-by-4-ft pieces. Downsizing methods may include shears, crushers, shredders, flatteners, hydraulic hammers, impact breakers, guillotines, drop balls, or cutting the component with torches, such as an oxygen lance, carbon-arc powder, inert-gas cutting, or plasma-arc (Essadiqi 2003; Fenton 1998). The geometry and material of the component as well as the steel furnace type and size determine the downsizing method. Scrap preparation beyond sorting and downsizing may also include de-tinning, de-zincing, blasting, and other methods to clean scrap and remove potential contaminants such as corrosion, oils, coatings, or organic impurities (Futas et al. 2022; Fenton 1998). A scrapyard's processes for scrap are dictated by the specifications of the steel mill that will buy the scrap. Scrap brokers often connect scrap collectors and processors to steel mills and foundries, playing an intermediary role in helping processors locate markets for their scrap and providing consumers with a supply of the ferrous products needed for their manufacturing operations (Essadiqi 2003; Fenton 1998).

3.2.2.1 Existing steel recycling practice: economic and environmental benefits and challenges

Recovered and cleaned steel scrap can be introduced into a steelmaking furnace to make new steel, closing the steel material loop. The U.S. steel industry is well-developed; in 2018, 87 million metric tonnes of crude steel were produced. There are two main steelmaking technologies: primary steel production through blast furnace basic oxygen furnace (BF-BOF) using predominantly iron ore reduction, and secondary steelmaking via an EAF using steel scrap but that could also use direct reduced iron. The U.S. steel production capacity is up to 67% EAF. EAF process input can be up to 100% steel scrap from end-of-life products and systems, whereas the BF-BOF process can accept up to 30% by mass of steel scrap, with the balance coming from direct reduced iron processes.

3.2.2.1.1 Economic benefits of steel recycling

In general, primary steel is more expensive than secondary steel. As of August 2023, BF-BOF steel cost $1,300/metric tonne, whereas EAF steel cost $800/metric tonne. Steel scrap offers significant economic savings to steelmakers.

The cost of steel recycling is difficult to gauge as steel scrap is a commodity that is subject to market supply and demand. As of 2023, decommissioners sell structural steel scrap from towers to the scrapyard at roughly $200 per metric tonne. Often the decommissioner will provide a rebate back to the owner for the value of the scrap that is sold, so the owner receives a higher discount on decommissioning if scrap prices are high. The scrapyard will then downsize and sort the steel at $30–$60 per metric tonne (as of 2023) and finally sell the scrap to a steel mill at $300-$400 per metric tonne (as of 2023). The steel mill will then process the steel at a cost of roughly $200 per metric tonne and sell it at $800–$1,200 per metric tonne on average (as of 2023).[38]

3.2.2.1.2 Environmental benefits of steel recycling

The iron and steel industry is one of the largest contributors to U.S. GHG emissions. As of 2020, the industry contributed 7% to total U.S. GHG emissions and 8% of total fuel used in the manufacturing sector (DOE 2022b; Energy Information Administration 2021). Table 7 shows a life cycle emission comparison between primary and secondary low-alloy structural steel used in wind turbine towers via BF-BOF and EAF, respectively.

[38] Steel scrap average selling prices are obtained from the following source: https://jrsadvancedrecyclers.com/scrap-metal-prices/ and verified with interviewed steel recyclers who provided actual bids for land-based turbines of 3-5 MW sizes.

Table 7. Life Cycle Emission Comparison Between BF-BOF and EAF Low-Alloy Structural Steel Production Used in Wind Turbine Towers

Environmental Metric	GHGs	Embodied Energy	Human Toxicity, Noncancer	Human Toxicity, Cancer	Water Consumption
Unit	kg CO_2 eq./metric tonne	MJ/metric tonne	kg 1,4-dicholorbenzene (DCB)/metric tonne (noncancer)	kg 1,4-DCB eq./metric tonne (cancer)	m^3/metric tonne
Low alloy, steel, BF-BOF	3,180	30,100	15,200	0.213	0.029
Low alloy, steel, EAF	1,240	14,900	1,870	0.001	0.009

EAF steel manufacturing has up to 61% lower life cycle GHG emissions, 50% lower embodied energy, 88%-99% lower human toxicity, and 71% lower water consumption. The wind energy industry could lower its life cycle environmental impacts by using secondary steel, when available.

The largest contributor to life cycle GHG emissions and energy use of steelmaking is direct energy consumption, especially process heating by natural gas and coke, which alone contribute to more than 63% of direct energy use. In the United States, natural gas is the most common heating source for the iron and steel industry, contributing more than 36% to the total energy mix used as of 2018 (DOE 2022b). Using clean energy sources to power steelmaking processes is an important step in reducing life cycle impacts.

Decarbonizing steel processing will dramatically reduce the carbon footprint and life cycle emissions of the wind energy industry. To reach the net-zero goal, life cycle GHG emissions need to be cut by 70%–80% or between 200 and 300 kg CO_2 eq./metric tonne of steel. When this occurs, life cycle GHG emissions could be reduced by 60%-70% to reach 2–6 g CO_2 eq./kWh. To reach this goal, several technology innovations are undergoing research and development, such as hydrogen-based direct reduced iron EAF, molten oxide electrolysis, biofuels, and energy efficiency measures (DOE 2022b).

We estimated life cycle GHG emissions for dismantling, shredding, separating, transporting, and steel scrap-melting operations to be less than 500 kg CO_2 eq./metric tonne of steel.[39] Dismantling and shredding operations yield 110-120 kg CO_2 eq./metric tonne of steel, transporting yields 20–25 kg CO_2 eq./metric tonne of steel, and scrap melting yields 270–300 kg CO_2 eq./metric tonne of steel. The environmental impacts of end-of-life activities for tower dismantling could be reduced by using more energy-efficient shredding equipment and sustainable transportation fuels. However, on-site decommissioning activities still contribute slightly to life cycle GHG emissions when compared to material recycling processes.

3.2.2.1.3 Steel recycling challenge: alloying element losses

Although steel recycling is a well-established practice that offers economic and environmental benefits, the dilution and subsequent loss of critical alloying elements such as nickel and cobalt during steel recycling

[39] We collected data for process steps from the life cycle inventory (Worldsteel 2021). Few assumptions about data inputs for energy consumption of decommissioning equipment were modified based on personal communication with Benson Steel. On-site equipment and machinery were assumed to run on diesel.

operations is a major hurdle to supply chain security. Every metric tonne of structural steel used in wind towers comprises between 11 and 20 kg of nickel, 4 to 6 kg of cobalt, and 50 to 60 kg of manganese. As mentioned earlier, we identified cobalt and nickel as critical minerals to U.S. wind energy supply chains. Therefore, loss of nickel and cobalt during steel-melting operations leads to an increase in mining raw materials and U.S. imports to supplement the lost fractions and restore steel functionality.

Alloying elements can be lost during recycling for reasons including mixing with other steel grades that introduce impurities, melting of steel scrap, and precipitation of alloy elements in slag or fly ash in end-of-life operations (Reck et al. 2008; Yellishetty et al. 2011; Ohno et al. 2017; Nakajima et al. 2013). Depending on the type of steel being recycled, between 5% and 14% of nickel content could be lost during steel-melting operations; up to 15% of all produced nickel becomes undesirable impurity in carbon steel cycles (Reck et al. 2008, 2010; Nakamura et al. 2017; Pauliuk et al. 2017). Steelmakers add raw nickel as fresh feed to recoup those losses.

Potential solutions for recycling steel from wind turbines and the adjacent supply chains are provided in Section 3.2.4.

3.2.3 Decommissioning and Recycling Metrics for Towers

Table 8 provides the decommissioning and recycling metrics identified for steel towers. Future tower recycling technologies should perform better than the metric values indicated here, allowing for more sustainable end-of-life practices for wind turbine towers.

Table 8. Metrics for Existing Decommissioning and Recycling for Tower Steel

Metric	Value	Unit
Percentage that goes to landfill	<5	%
GHG emissions	1,200–3,200	kg CO_2 eq./metric tonne
Embodied energy	14,900–30,000	MJ/metric tonne
Water use	0.01–0.03	m^3/metric tonne
Human toxicity	Cancer: 0.001–0.2; Noncancer: 1,870–15,200	kg 1,4- DCB eq./metric tonne
Cost of recycling	500–660	$/metric tonne
Market selling price	800–1,200	$/metric tonne
Material yield	>97	%
Material quality ratio	0.80–0.95	Relative to loss of nickel and chromium
TRL	9	1–9
Critical material use	Nickel: 11–20; cobalt: 4-6	kg/metric tonne

3.2.4 RD&D Needs, Gaps, and Opportunities for End-of-Life Management Practices for Towers

There are many opportunities for fundamental and applied research to improve recycling rates, cost-effectiveness, and environmental sustainability of steel recovery and recycling pathways from wind turbine towers. See Table 9 for priorities for RD&D priorities for improving end-of-life practices for towers and the projected impacts of implementing those innovations.

The following potential solutions may help address challenges with recycling steel from wind turbine towers:

- Create material labels for different steel grades in wind turbine components. Although interviewed decommissioners reported that simple sorting is usually conducted to salvage the value of dismantled steel components, particularly the tower, they also expressed that the practice is not optimized, and scrap buyers usually have low pricing margins due to mixed grades of scrap. Some decommissioners reported that on-site steel sorting adds appreciable time and cost. One way to reduce steel grade mixing, which often leads to downcycling and loss of critical alloying elements, is for plant owners to keep a material passport for each component and subcomponent in their plant. This passport can later be used by decommissioners to streamline their dismantling operations and efficiently separate and sort different grades of steel. Send steel scrap to EAF plants instead of BF-BOF (whenever feasible). The EAF process typically involves fewer steps and operates at lower temperatures than primary steel production through BF-BOF. In addition, EAF slag is often richer in nickel and other alloying content, which could make subsequent refining and separation operations more cost-effective and with better yield.
- Avoid steel melting and embrace re-rolling and reusing towers. Alloying element loss is inevitable during steel-melting operations. Alternative options could include reusing towers by segmenting them into sections and reassembling them at another site for similar scale wind turbines or re-rolling steel into another diameter to fit wind turbines of different sizes. Rolling operations retain alloy element content and reduce the process steps needed to recycle steel.

Table 9. RD&D Needs, Gaps, and Opportunities for End-of-Life Practices for Towers and Potential Impacts of Investments

RD&D Technological Innovation	Potential Impact
Develop research programs that demonstrate reuse of wind turbine towers such as re-rolling techniques	• Reduce demand on virgin steel and its subsequent critical alloy element needs.
Develop a labeling system for wind plant components and subcomponents that documents different steel grades, quantities, and their respective location	• Provide a useful guide to decommissioners to reduce time, cost, and environmental impacts of dismantling activities • Enable more efficient recycling of alloy steel grades through proactive sorting and separation at plant end of life, preserving loss of critical material alloys
Develop research programs that enable cost-effective and environmentally friendly nickel and chromium alloy recovery from steelmaking slag	• Reduce losses of critical alloying elements in waste management facilities or undesirable contamination in other steel grades
Develop research programs that aim to substitute nickel and chromium with noncritical elements such as nitrogen	• Reduce the demand of critical materials for wind energy systems
Fund research programs that aim to increase steel impurity tolerances, material use efficiency, and operational/process circularity	• Enable blending of highly contaminated steel scrap grades (e.g., copper) as well as manufacturing 100% steel scrap in electric arc furnace models • Enable recycling of critical materials (e.g., zinc) impurities from galvanized steel grades used in towers

3.3 Nacelle

The nacelle houses, supports, and protects the drivetrain, generator, some power electronic components, and supporting systems for wind turbines. We investigated the drivetrain, generator, and power electronic components separately and present the discussion and results in subsequent sections. In this section, the nacelle components considered include the cover (i.e., gondola or canopy), bedplate (i.e., base plate, rear, or subframe), hub, and spinner (i.e., nose cone, rotor cover).

3.3.1 Material Breakdown for the Nacelle

Figure 9 and Table 10 summarize the material and mass breakdown of the different subcomponents of the nacelle structure (Ancona and McVeigh 2001).

Table 10. Material Breakdown of the Nacelle Subcomponents

Nacelle Main Subcomponent	Material
Bedplate	Cast iron (front) and high-alloy steel (rear)
Hub	Spheroidal graphite cast iron
Cover	Polyethylene-based reinforced glass-fiber composite
Spinner (i.e., nose cone)	Polyester-based reinforced glass-fiber composite

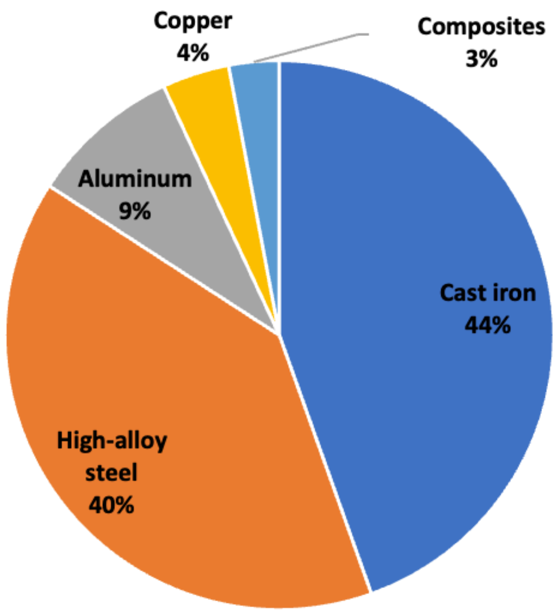

Figure 9. A typical material and mass breakdown of a nacelle. *Figure by Amiee Jackson, ORNL.*

The mass of the nacelle increases disproportionately to the size of the wind turbine. A nacelle for a typical land-based 5-MW turbine weighs 270 metric tonnes, whereas a nacelle for a 15-MW turbine weighs up to 1,600 metric tonnes (Gaertner et al. 2020; Desmond et al. 2016; Bortolotti et al. 2019; Bak et al. 2013; Bredmose et al. 2020; Peeringa et al. 2011; D'Souza and Bachynski-Polić 2022; Ashuri et al. 2016; Jensen and Natarajan 2014; Chaviaropoulos et al. 2017).

3.3.2 End-of-Life Management Practices for the Nacelle

Decommissioners interviewed in the United States indicated that there is no unique decommissioning procedure for the nacelle and that it is typically dismantled along with the wind turbine tower. Steel-based subcomponents (e.g., bedplate, drivetrain subcomponents) are deemed to offer the highest economic resale value to decommissioners, therefore nacelles are partially disassembled to remove ferrous components. Composite components, such as the nacelle cover and spinner, are more challenging to recycle or reuse. Generally, recycling processes for blades could also apply to the nacelle cover and spinner. In the following sections, we discuss material recycling pathways for each nacelle subcomponent: cover, spinner, bedplate, and rotor hub.

3.3.2.1 Nacelle Cover

Nacelle covers protect internal components from weather and environmental hazards while accommodating design constraints for manufacturing, assembly, transportation, installation, maintenance, and repairs. Covers also support anemometry, wind speed and direction measurement, auxiliary equipment for tracking performance of various components, and communications systems. In addition, the nacelle cover protects internal components from lightning damage.

Comprising significantly less mass than the bedplate and hub, the nacelle cover is typically made of a glass-fiber composite sandwich structure (composite polyvinyl chloride [PVC]/polyethylene [PET] foam). The glass-fiber composite is made from woven or chopped E-glass fibers,[40] PET, and styrene (D'Souza, Gbegbaje-Das, and Shonfield 2011). The most common material combination is glass fiber, which may be a woven or chopped strand mat depending on its structural role, and polyester resin with a polyester gelcoat. Common processes for the nacelle cover include resin infusion molding and spray molding.

Some nacelle designs also incorporate carbon fiber in the main structures for increased stiffness and lower weight (Bayati et al. 2016; Bledzki et al. 2020). Carbon fibers are more costly and carry up to 4 times life cycle GHG emissions than glass fibers per kilogram (see Section 3.6.4). With existing destructive wind turbine decommissioning practices and use of lower-quality glass composites, recovering carbon fibers could become a major challenge for such nacelle designs. Developing alternate nacelle designs that show high performance and eliminate the need for carbon fiber could be one way of avoiding wasteful disposal or incinerating valuable carbon fibers in nacelle structures. An example of this could include using natural fibers (e.g., flax, hemp) to fully or partially substitute carbon fibers (Pilkington 2021; Anandjiwala and Blouw 2008).

Currently, there is no effective technology for recycling nacelle covers and spinners, and they are generally incinerated at energy recovery facilities. In theory, wind turbine blade recycling technologies (e.g., mechanical, pyrolysis, and solvolysis) could be used for processing nacelle composite subcomponents (i.e., covers and spinners). However, nacelle composites are generally made from shorter chopped fibers, which are unlike the higher-quality, longer fibers used in blades. This challenge compels existing small-scale composite recyclers that adopt pyrolysis or solvolysis process models to avoid processing mixed composite streams from blades and nacelles. Mechanical recycling of a nacelle's low-quality composites for use as a filler in low-strength applications (e.g., plywood sheet replacements, consumer electronics covers, acoustic insulations) may offer the best near-term prospect for avoiding wasteful disposal or hazardous incineration of this component.

3.3.2.2 Nacelle Spinner

The nacelle spinner protects the rotor hub internal components from weather and environmental hazards while allowing access for maintenance and repairs. It is typically made from glass-fiber-reinforced polyester (D'Souza, Gbegbaje-Das, and Shonfield 2011). Like nacelle covers, the most common material combination includes glass fiber, which may be a woven or chopped strand mat depending on its structural role, and polyester resin with a polyester gelcoat. The typical fiber-to-resin ratio is 50:50 for polyester resins (Bak 2011). The manufacturing process for spinner covers is similar to the one used for composite nacelle covers, which involves resin infusion and resin transfer molding (Bak 2011; Boehm 2014).

[40] E-glass fibers are a synthetic composite reinforcement developed to provide electrical insulation.

3.3.2.3 Bedplate

The bedplate transfers loads from the rotor to the yaw bearing and provides a rigid mount for both the generator and gearbox to prevent misalignment. It must also accommodate lifting points for final assembly of the full wind turbine system. Bedplates are made mainly of cast-iron material (e.g., EN-GJL-150 grade, ISRI Grade 252). For a typical 5-MW land-based wind turbine, the bedplate weighs approximately 70 metric tonnes. Figure 10 shows the bedplate mass variation with turbine nameplate capacity. Future bedplates for larger turbines may become heavier and could need more specialized and high-power disassembly equipment (Crawford 2009; Fingersh, Hand, and Laxson 2006; Fullenkamp and Holody 2014; Bortolotti et al. 2019; Gaertner et al. 2020; Ashuri et al. 2016; Stehouwer and Zinderen 2016; Dabrowski et al. 2015; Smith 2012; Klair 2013; Andersen et al. 2014; Pehlivan 2013).

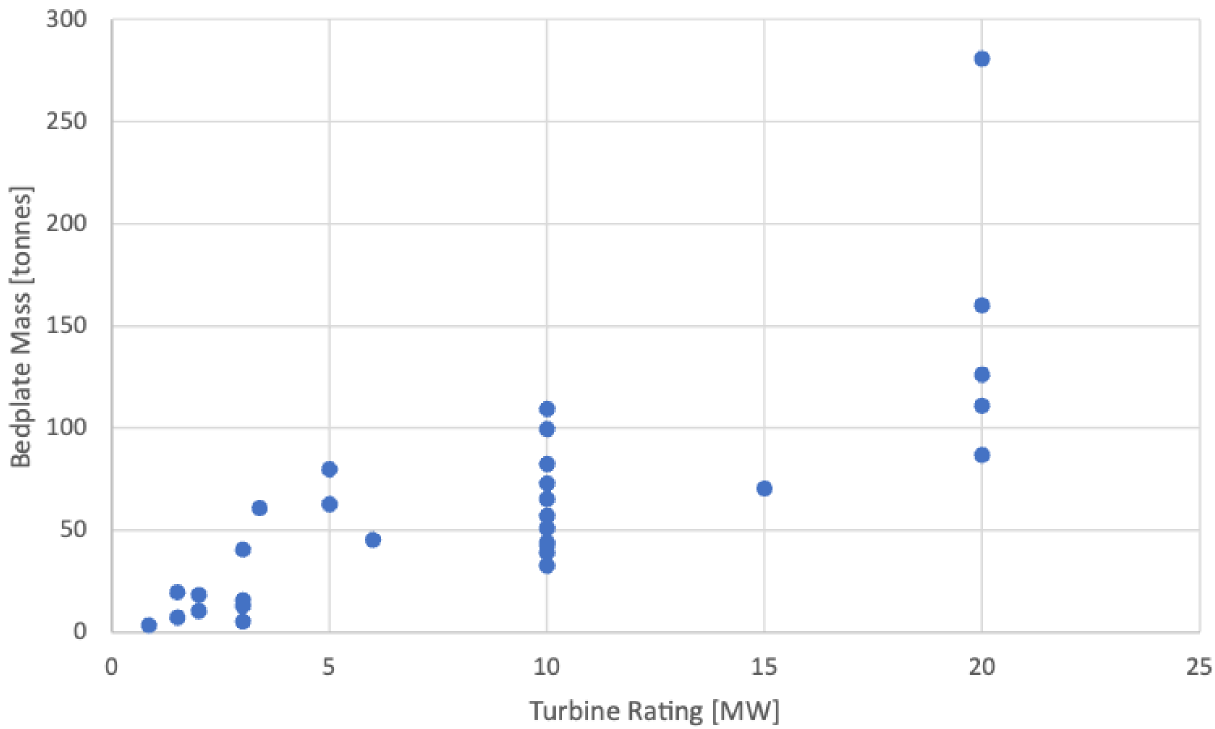

Figure 10. Bedplate mass vs. turbine nameplate capacity. *Figure by Amiee Jackson, ORNL.*

Bedplates are made primarily of ferrous materials (mainly cast iron) and therefore are typically separated and sold in scrapyards instead of being disposed of or incinerated. The iron or steel grade dictates the final selling prices of these materials. Bedplates are priced between $47 and $70 per 100 pounds in scrapyards. In the scrapyards, the bedplate material is reduced according to specifications of steel mills or foundries that will buy the scrap from scrap brokers. Similar process steps as those discussed in Section 3.2.1.1 for steel scrap preparation and size reduction apply for ferrous nacelle components.

Cast-iron scrap is often re-melted in cupola and electric induction furnaces in sand-casting foundries to produce new cast-iron products. Cupola furnaces are the most conventional method for re-melting scrap at rates of 100 metric tonnes/hour in continuous operation (Lacaze, Dawson, and Hazotte 2021). Electric induction furnaces produce synthetic cast iron from steel waste at scrap melting rates of 20 metric tonnes/hour in batch operation. Electric induction furnaces are typically more energy efficient because they use electricity in their operation, whereas cupola furnaces burn coke (Lacaze, Dawson, and Hazotte 2021).

3.3.2.4 Rotor Hub

The rotor hub is generally made of spheroidal graphite iron (e.g., EN GLS 400 18 LT), a specific type of cast ductile iron with high-yield strength, ultimate tensile strength, creep resistance, and high-cycle fatigue resistance to fulfill its purpose throughout the 20- to 30-year design life. The hub connects the rotor blades and the main shaft. The hub mass for a typical 5-MW land-based turbine is about 50 metric tonnes. Figure 11 shows the hub mass variation with turbine nameplate capacity rating. Similar to bedplates, future hubs for larger wind turbines may become heavier and could need more specialized, high-power disassembly equipment. The recycling pathway for hub spheroidal graphite cast-iron grade is like that of the cast iron used in bedplates (i.e., separated and sold in scrapyards, and then the cast-iron scrap is re-melted in cupola and electric induction furnaces in foundries to produce new cast-iron products).

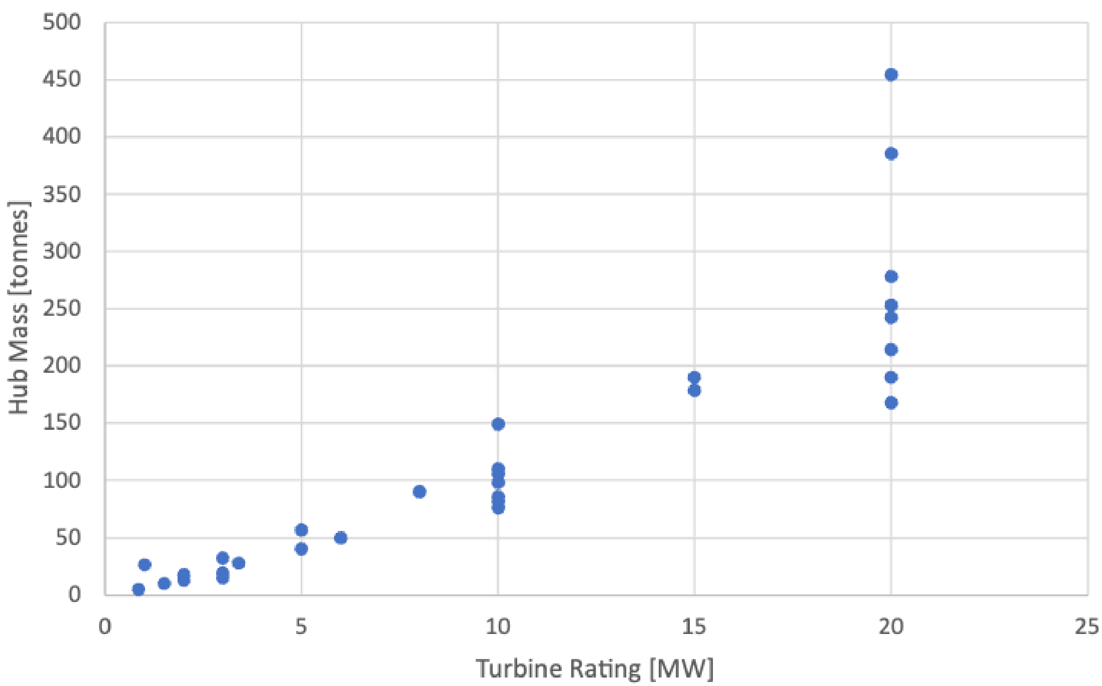

Figure 11. Hub mass vs. turbine nameplate capacity rating. *Figure by Amiee Jackson, ORNL.*

3.3.3 Decommissioning and Recycling Metrics for Nacelle Materials

Metrics reported for decommissioning and recycling nacelle materials are based on available data for cast-iron and composite parts (Table 11). Metrics for other steel-based subcomponents (rear parts of the bedplate) are found to be like those reported in Section 3.2.3 for steel-based tower components. Future decommissioning and recycling technologies for nacelle materials should ideally perform better across this metrics space than the metric values indicated here, allowing for more sustainable end-of-life practices for nacelle materials.

Table 11. Metrics for Existing Decommissioning and Recycling Technologies for Composite and Cast-Iron Materials in the Nacelle

Metric	Value	Unit
Waste disposal percentage	>50	%
GHG emissions	Composite: 100–200; cast iron: 700–1,200	kg CO_2 eq./metric tonne
Embodied energy	Cast iron: 9,000–21,000	MJ/metric tonne
Water use	Cast iron: 0.1–0.3	m^3/metric tonne
Human toxicity	Cast iron: cancer: 0.001–0.2; noncancer: 1,870–15,200	kg 1,4-DCB eq./metric tonne
Cost of recycling	Composites: 60–100; cast iron: 500–700	$/metric tonne
Market selling price	Composite: unknown; cast iron: 250–300	$/metric tonne
Material yield	Composite: N/A; cast iron: >95%	%
Material quality ratio	N/A	Material-specific ratio
TRL	9	1–9
Critical material use	N/A	kg/metric tonne

3.3.4 RD&D Needs, Gaps, and Opportunities for End-of-Life Management Practices for the Nacelle

There are many opportunities for fundamental and applied research to improve recycling rates, cost-effectiveness, and environmental sustainability of materials recovery and recycling pathways for wind turbine nacelles. Table 12 provides the RD&D priorities for improving end-of-life practices for nacelle materials and the potential impacts of implementing these innovations.

Table 12. RD&D Priorities for End-of-Life Practices for Nacelle Components and Potential Impacts of Investments

RD&D Technological Innovation	Potential Impact
Develop and demonstrate nacelle cover and spinner designs made with alternate biodegradable or natural fiber like flax, hemp, or bagasse (the dry fibrous material that remains after crushing sorghum or sugarcane to extract juice) and biodegradable or recyclable resin systems (e.g., thermoplastics) and their accompanying processing development and optimization	• Reduce life cycle environmental impacts associated with hazardous incineration of chlorinated composite waste streams by up to 50%–80% • Overcome technical and economic challenges of reclaiming and recycling low-quality composites
Demonstrate novel nacelle manufacturing routes that enable advanced manufacturing and process automation	• Reduce material manufacturing losses by up to 30%–50% • Reduce labor and cycle times for high-throughput nacelle processing
Develop alternate nacelle designs that eliminate the sandwich composite structure in favor of lightweight stiffener-based designs	• Reduce material use in larger wind turbine designs in the future for lightweighting purposes
Demonstrate mechanical recycling approaches for existing epoxy-based nacelle composite structures in high-value secondary applications	• Improve the recyclability of mixed composites
Develop minimally intrusive nacelle disassembly approaches that retain the nacelle cover structure	• Enable further reuse of nacelle covers for future wind turbines

3.4 Drivetrain

The wind turbine drivetrain comprises the main shaft, main bearing, gearbox, and yaw and pitch bearings. Although the generator is housed in the drivetrain, it is analyzed in a separate section.

3.4.1 Material Breakdown for the Drivetrain

3.4.1.1 Gears, Shaft, and Bearings

Gears and bearings are made of forged chromium-molybdenum steel, also known as high-alloy steel, grade ASTM 4140 alloy steel (Otai SpecialSteel 2023; Nejad et al. 2022; Sethuraman, Venugopal, and Mueller 2013). Chromium and molybdenum comprise up to 0.1% and 0.25% by weight of high-alloy steel. Both alloys are identified as critical minerals (DOE 2023a). Using high-alloy steel in gears and shafts provides structural strength, corrosion resistance, and durability to withstand harsh environmental conditions at the top of the wind tower as well as support for heavy components and equipment such as generators. Some bearings might contain small amounts of other materials such as brass or plastic composites because the bearing elements are separated by a cage or spacers that may be made of brass or plastic.

Rolling-element bearings are the most used in wind turbine technologies. Main bearings are often subjected to large fluctuations in load and thus experience failures due to skidding, surface fatigue, and wear and abrasion. Some reliability studies show that bearings could experience up to 30% failure rates during a 20-year turbine life (Hart et al. 2020). As wind turbine size increases, larger-diameter bearings could become harder to lubricate and maintain. A knowledge gap exists regarding the impact of increasing bearing diameter size on its lifetime and failure rate. Conventional International Organization for Standardization (ISO) standards 76 and 281 and technical specification 16281 might not be sufficient to study these effects; thus modifications and developments to these standards are pivotal for understanding failure rates of bearings and planning their end-of-life management accordingly.

Lightweighting of the bearings and shaft is an important step to increasing the recyclability of drivetrains in larger turbines in the future as it can minimize the cost of waste transportation and recycling. One solution for this challenge is to use cast iron instead of high-alloy steels (Chen et al. 2014; Herrmann et al. 2016; Kirsch and Kyling 2021). Cast iron could be up to 8% lighter than high-alloy steel and does not contain critical minerals such as chromium or molybdenum. In addition, up to 20% of material intensity could be saved in rotor shaft design (Kirsch and Kyling 2021). Additional benefits include lower life cycle GHG emissions of cast iron than high-alloy steel due to its lower smelting temperature (Jensen 2019; Zhu, Keoleian, and Cooper 2023).

3.4.1.2 Gearbox and Lubricating Oils

A gearbox is part of the drivetrain, which connects the low-speed shaft to the high-speed shaft to increase rotational speeds in the generator to produce electricity. The gearbox housing is made of carbon-based or low-alloy steel (REMPD 2023).

Lubricating grease and oils play a critical role in the operational efficiency of gearboxes and pitch bearings because they minimize wear and tear (Sinha et al. 2014; Schwack et al. 2020). Depending on the wind turbine size, between 200 and 1,500 liters of lubricant may be required, and it is replaced at least once every 2–3 years, and in some cases every year (Exxon Mobil 2021; Treyer and Bauer 2013). A 2-MW land-based turbine uses about 1,150 kg of lubricant oil. Most commonly used oils are synthetic petroleum-based polyolefins saturated with hydrogen (Mobil 2022; Cuffari 2019).

Our analysis shows that production and disposal of lubricating oils cause life cycle GHG emissions of 1.1-1.4 kg CO_2 eq./kg and 3.29 kg CO_2 eq./kg, respectively, contributing less than 1% to life cycle GHG emissions of the full wind power plant. On the other hand, gear oils have been a source of potential occupational safety and health risks because of increased fire hazards and spillage during maintenance and decommissioning (Gul, Guneri, and Baskan 2018; Zhang et al. 2019; Sun et al. 2019). Development of nontoxic, biodegradable, and low-carbon lubricant oils could decrease health risks associated with wind turbine operation and decommissioning (Sotavento 2023; IKV Tribology 2023).

3.4.2 End-of-Life Management Practices for the Drivetrain

Interviewed decommissioners confirmed that separation and recycling of shafts, bearings, and gears is an existing, profitable practice. They occasionally pay a rebate to wind power plant project owners, the amount of which is not fixed, but a margin of 20%–50% of sold value by decommissioners to scrapyards is communicated (see Section 3.2 for further details). Different practices and remelting pathways between scrap processors exist. For example, some scrapyards could view chromium-molybdenum steel as more valuable than low-alloy steel in towers, thus offering a higher buying price of $250-$400 per metric tonne from decommissioners instead of $200 per metric tonne as of 2023. Other interviewed decommissioners state that their local scrapyards redeem the same value for both grades of steel. Scrapyards control a fraction of steel market prices, but generally steel recycling is a profitable industry in the United States.

Existing lubricant oil disposal practices include either reprocessing and reconditioning in refining facilities or incineration with energy recovery.[41] Grease is more difficult to filter and is typically sent directly to incineration. Developing safer oil filtration systems and collection tanks is one way to prevent unintended oil spillage accidents during wind turbine decommissioning.

3.4.3 Decommissioning and Recycling Metrics for the Drivetrain

Table 13 summarizes the decommissioning and recycling metrics for lubricating oils and high-alloy steels used in the drivetrain. Future decommissioning and recycling technologies should ideally perform better than the metrics values indicated here, allowing for more sustainable end-of-life practices for drivetrain materials.

Table 13. Metrics for Existing Decommissioning and Recycling Technologies for the Major Drivetrain Materials

Metric	Oils and Grease	High-Alloy Steel	Unit
Percentage that goes to landfill	<1	<1	%
GHG emissions	1.11–3.29	4,880–5,100	kg CO_2 eq./metric tonne
Embodied energy	80–160	72,300–75,000	MJ/metric tonne
Water use	49.4–213	78.3–75.0	m^3/metric tonne
Human toxicity	Cancer: 7.2–10.0; noncancer: 3,180–4,300	Cancer: 643–650; noncancer: 76,660–78,000	kg 1,4-DCB eq./metric tonne
Cost of recycling	Data not available	500–660	$/metric tonne
Market selling price	N/A	2,000–2,600	$/metric tonne
Material yield	>98	>99	%
Material quality ratio	N/A	Uncertain	% loss in chromium or molybdenum
TRL	8–9	9	1–9
Critical material use	N/A	Chromium: 1–1.5 molybdenum: 2.5–2.8	kg/metric tonne

[41] This information was obtained via interviews with experts at Argonne National Laboratory, Rymax, and Fuchs.

3.4.4 RD&D Needs, Gaps, and Opportunities for End-of-Life Management Practices for the Drivetrain

There are many opportunities for fundamental and applied research to improve recycling rates, cost-effectiveness, and environmental sustainability of materials recovery and recycling pathways from wind turbine drivetrains. Table 14 provides the RD&D priorities for improving end-of-life practices for drivetrain components and the potential impacts of implementing these innovations.

Table 14. RD&D Priorities for End-of-Life Practices for the Drivetrain and Potential Impacts of Investments

RD&D Technological Innovation	Potential Impact
Demonstrate and test high-alloy steel substitute in rolling bearings for cast iron	• Eliminate demand for chromium and molybdenum critical minerals • Reduce drivetrain weight by at least 8% • Reduce life cycle GHG emissions of drivetrain bearings by 40%–60%
Develop standardized lifetime testing for large-diameter bearings	• Provide reliability data to plan maintenance and decommissioning operations
Develop research programs that demonstrate modular drivetrain designs such as by additive manufacturing of stages and their subsequent performance and reliability testing	• Enable cost-effective part-by-part installation and disassembly • Enable shorter repair time for parts and overall turbine downtime • Increase subcomponent accessibility that could increase repairability and recyclability
Develop effective oil collection and recovery systems and approaches that shield oils from neighboring components and the field environment	• Reduce ignition risks during harsh environmental conditions or destructive disassembly approaches • Reduce or eliminate occupational health risks by preventing spillage through controlled handling
Research and develop novel oil formulations that have low hydrogen content, are reusable, nontoxic, biodegradable, and use low-fatigue oils	• Reduce white etching of bearings and component replacements • Reduce life cycle human toxicity impacts by avoiding hazardous incineration

3.5 Generators and Rare Earth Permanent Magnets

A wind turbine generator is located in the drivetrain and uses the mechanical energy created by the turning of the wind turbine blades to create electrical voltage that is then converted and delivered to the grid. Figure 12 shows the different parts of a wind turbine generator. These generators have three main components: a rotor (made of electrical steel, wound copper coils, and may include rare earth permanent magnets), a stator (made of electrical steel and magnets), and housing elements for the generator (made of high-alloy steel). Electrical steel, rare earth elements, and some alloying elements (i.e., cobalt) are identified as critical materials according to DOE's critical materials list (DOE 2023a). Rare earth elements (e.g., dysprosium, neodymium, praseodymium, and terbium) and cobalt are classified as critical in the short and medium terms as well as to

U.S. supply disruption and global shortage (DOE 2023a). Wind turbine generators have the most concentrated presence of critical materials among all other wind power plant components; therefore, developing a robust domestic recycling capability for their parts is key to securing the U.S. wind energy supply chain.

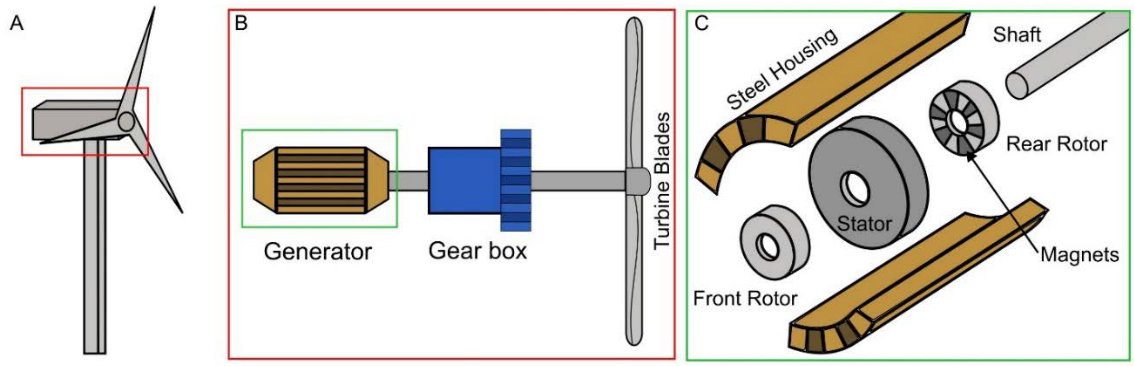

Figure 12. Structure of a typical wind turbine generator including A) wind turbine, B) drivetrain interior, and C) generator parts. *Figure by Willey Kemp, ORNL.*

3.5.1 Material Breakdown for Generators

The most common type of wind turbine generators deployed today in the United States are gearbox doubly-fed induction generators in land-based wind turbines, which do not require any rare earth permanent magnets. This generator type requires a gearbox to translate lower-speed rotation of turbine blades to the higher rotation speeds required for the generator. Globally, nearly 30% of installed wind turbines use direct-drive permanent-magnet synchronous generators (PMSGs), primarily for offshore turbines due to their lighter designs, more efficient performance, and lower maintenance needs (and thus costs) in comparison to gearbox doubly-fed induction generators (Osmanbasic 2020). About 70% of today's global installed wind turbines use high-speed geared generators (mainly low PMSG), and around 2% use direct-drive electrically excited synchronous generators (European Commission et al. 2020).[42]

3.5.1.1 Rare Earth Permanent Magnets

Certain types of wind turbine generators use rare earth permanent magnets (e.g., PMSGs and low-PMSG high-speed geared generators), which are made exclusively of neodymium iron boron (NdFeB) magnets. The composition and type of rare earth elements used in NdFeB magnets depend on the magnet type (sintered vs. bonded) as well as the type of generator. Direct-drive PMSGs require 180 kg/MW of neodymium, 17 kg/MW of dysprosium, and 7 kg/MW of terbium, whereas high-speed geared generators only require 12 kg/MW of neodymium, 2 kg/MW of dysprosium, and 0 kg/MW of terbium (European Commission et al. 2020).

Offshore wind turbines, especially at larger scales beyond 8 MW, use direct-drive PMSGs because of their high energy density and turbine efficiency considerations (Barter et al. 2023; Sethuraman et al. 2021). Domestic and global deployment of offshore wind power plants is expected to grow by up to sevenfold through 2035, which will trigger significant demand for rare earth elements. The United States pledged to deploy 30 GW of offshore wind energy by 2030; of which, 15 GW for floating offshore applications (The White House 2021). Potential circular pathways to meet an expected surge in rare earth permanent magnet

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[42] Generally, wind turbine generators are classified as direct drive or gearbox (i.e., geared). Direct-drive generators could be further classified as permanent-magnet synchronous or electrically excited synchronous. Gearbox generators are typically classified as mid or high speed. High-speed generators could either be a low permanent-magnet synchronous generator or electromagnet. Today, high-speed geared generators (with low permanent magnets) are the most commonly used for land-based wind turbines globally.

demand in the wind industry include using magnet designs with less rare earth magnets (e.g., bonded magnets), recertifying and reusing waste magnets to give them second lives in turbines, and scaling up magnet-to-magnet recycling and building out a sustainable recycling infrastructure to recover rare earth elements from permanent magnets.

Table 15 summarizes the variation in magnet composition between sintered and bonded magnets. Magnets are produced mainly via sintering and jet milling of microcrystalline magnetic powders (or sintered) or through the use of polymer resin bonding of nanocrystalline or ultrafine structured magnet powders (Ding et al. 2015; Ma et al. 2002). Nearly all wind turbine generators deployed globally and in the United States use sintered magnets with well-established manufacturability and performance. Bonded magnets offer some advantages compared to sintered magnets, such as simpler and less energy-intensive manufacturing processes (e.g., injection molding, extrusion), and reduced material waste due to reduced machining. However, the presence of polymer resin lowers magnetic properties (Schafer et al. 2023; Zhang et al. 2009). Ongoing research efforts are taking place to improve magnetic properties of bonded magnets.

Table 15. NdFeB Magnet Composition of Sintered and Bonded Magnets

Permanent Magnet Type	Neodymium (%)	Iron (%)	Dysprosium (%)	Praseodymium (%)	Boron (%)	Other
NdFeB (bonded)	16–25	71–2	0–1.2	0–4.9	0.9	-
NdFeB (sintered)	28–30	62–69	0–1.2	0–4.9	0.9	Aluminum, niobium (0.28), gallium (0.3)

Other magnet types such as samarium cobalt are also reported to be a potentially suitable alternative (Palz 2013). However, samarium-cobalt magnets have lower magnetic properties (e.g., energy product) and a higher manufacturing cost, which resulted in NdFeB magnets being more widely deployed (Pyrhönen et al. 2010; Zhou et al. 2021). However, samarium cobalt exhibits higher resistance to corrosion and higher demagnetization temperatures.

3.5.1.2 Electrical Steel

Electrical steel (commonly known as silicon or transformer steel) is an iron-silicon alloy that has up to 6.5% by weight of silicon including other materials such as carbon and aluminum. This type of steel is commonly used in the cores of electromagnetic equipment such as motors, generators, and transformers. In wind power plants, it is present in generators and transformers. Although electrical steel is an engineered material, it has been identified as a critical material (DOE 2023a). The United States contributes less than 1% of total global exports for electrical steel, and its manufacturing capacity is limited to about 2,000 metric tonnes/yr as of 2020 (REMPD 2023). Electrical steel production is highly specialized and cannot be easily substituted with other materials. Existing research efforts to develop alternate materials, such as soft magnetic composites, is limited. However, these materials have considerable potential in reducing scrap losses in traditional electrical steel production as well as higher brittleness, which might improve access to copper windings for easier recyclability at the end of life (Alatalo, Lundmark, and Grunditz 2011; Shokrollahi and Janghorban 2007).

Electrical steel intensity in wind energy is estimated to be 1,500–5,300 kg/MW for land-based wind turbines and 2,700-3,600 kg/MW for offshore wind turbines (REMPD 2023). In the high-deployment scenario (see Eberle et al. 2023), which uses the all-options deployment projection that achieves 100% clean electricity by

2035 and aims for a net-zero emissions economy by 2050 (Denholm et al. 2022), about 3.3 million metric tonnes of electrical steel is needed from 2020 through 2050 (REMPD 2023). Generators fail and require replacements every 5–10 years because of exposure to harsh environmental conditions (Dao, Kazemtabrizi, and Crabtree 2019). However, precise generator reliability data in the United States are limited; therefore, we found it difficult to calculate accurate generator waste estimations. Assuming a conservative 10-year operational lifetime and a lower and higher electrical steel use in the future deployment scenario, the United States is expected to have a waste stream of about 264,000-671,300 metric tonnes of electrical steel cumulatively through 2050. Average annual electrical steel waste is estimated to be 103,000 metric tonnes from 2025 through 2040. When comparing the average annual electrical steel waste estimation to 2020 U.S. production capacity, we find that the current ability to recycle electrical steel is not feasible unless the nation expands its electrical steel manufacturing capacity.

3.5.2 End-of-Life Management Practices for Generator and Permanent Magnet Materials

3.5.2.1 Generator Decommissioning and Disassembly

There are different ways in which decommissioners could disassemble and harvest wind turbine generators, depending on wind turbine size, decommissioning budget, and specific requirements by project owners. Most of the interviewed decommissioners reported that the generator is typically lowered to the ground using cranes or other specialized equipment to minimize damage to internal components and maximize their resale value. However, some decommissioners still use more generic approaches like toppling for small turbines or for low-budget decommissioning projects. Typically, generators are viewed to be the most valuable wind turbine component to decommissioners and project owners.

The first step after a generator is lowered to the ground is to mechanically harvest permanent magnets that are mounted onto the surface or in pockets. Pocketed magnets are generally harder to harvest and typically broken when pulled out, scratching the inner cavity. Broken magnets or scratched components cannot be reused in a second life and must be sent to a material reclamation facility, sold at a lower value, or disposed of, depending on cost trade-offs of the project location. Magnets typically have the highest selling value among other generator components and were the focus of analysis in this report.

3.5.2.2 Sorting and Recycling Steel Grades

Virtually all steel in the generator can be economically recycled today. Different generator subcomponents are separated and sorted by their steel grade (e.g., low-alloy steel in generator housing and high-alloy steel in the rotor). Existing practices mainly involve separating steel parts into low and high alloy. Interviews with recyclers revealed that electrical steel, although it has more economic value, is not separated from other high-alloy parts in the nacelle such as bearings. Electrical steel scrap is typically mixed with other high-alloy scraps in scrapyards, losing its inherent magnetic properties. However, low- and high-alloy steel scrap, including electrical steel, is sold in scrapyards and then distributed to respective steel mills where specific blends are optimized for different steel grades (similar to the steel recycling operations discussed in Section 3.2, Section 3.3, and Section 3.4). As domestic manufacturing capacity for electrical steel expands, more incentive will be present to separate this stream and send it to specialized electrical steel manufacturing plants for recycling.

A major challenge to recycling steel is scrap contamination with nonferrous metals during disassembly, sorting, and shredding operations. Copper, from windings, is the most common contaminant and accounts for 0.25%-0.3% by weight of scrap content (Daehn, Cabrera Serrenho, and Allwood 2017; Nakamura et al. 2017). High-grade steel should typically have less than 0.02% copper content. Copper contamination renders steel scrap as low quality. Mixing scrap grades dilutes other critical alloying elements such as cobalt and nickel. Retaining steel composition is a major challenge in existing end-of-life disassembly and scrap collection practices. Developing copper-tolerant steel grades is one promising pathway to retaining steel composition at the end of life, reducing loss of critical alloying elements and minimizing the associated environmental impacts of sourcing raw materials to recoup alloy element losses (Lowder, Seetharaman, and Yalamanchili 2022).

3.5.2.3 Rare-Earth Permanent Magnet Recycling

Figure 13 illustrates the life cycle stages for permanent magnets in wind turbine generators as well as possible end-of-life processing pathways depending on the state of recovered magnets. In addition to the material recovery (i.e., metallurgy), direct reuse and magnet-to-magnet recycling offer alternative end-of-life management pathways for permanent magnets. The choice of end-of-life recycling pathway for rare-earth permanent magnets depends on the magnet type (sintered vs. bonded), its composition, and protective coating (epoxy vs. metal plated).

Direct reuse involves reusing the same magnet sizes in a similar generator class. This practice is not widely deployed because stringent performance requirements must be validated before reusing magnets. However, some original equipment manufacturers have started to implement magnet testing programs. Developing standardized tests for end-of-life magnets for reuse is an existing gap that must be filled to enable improved circularity of rare earth elements.

Magnet-to-magnet recycling involves reprocessing magnetic powders in spent magnets to make new magnets that exhibit properties similar to virgin magnets. This technique allows reuse of constituent rare earth elements without expensive and energy-consuming purification of individual renewable energy elements. The process also alleviates demand on mining operations and the need to build capital-intensive refining operations. Magnet-to-magnet recycling requires spent magnets to be pristine (i.e., not broken) and free of contaminants. From an environmental perspective, several studies have shown that this type of recycling avoids 11 metric tonnes of CO_2 eq. and has up to 46% less direct energy consumption per metric tonne of recycled magnet than virgin sintered magnet production (Zakotnik et al. 2016; Jin et al. 2018).

Magnet-to-magnet recycling process steps include demagnetization, coating removal, hydrogen decrepitation, jet milling, sintering, cutting, and annealing to produce new magnets. New magnets can be cut into any size; therefore, this process is suitable for producing magnets for all wind turbine generators.

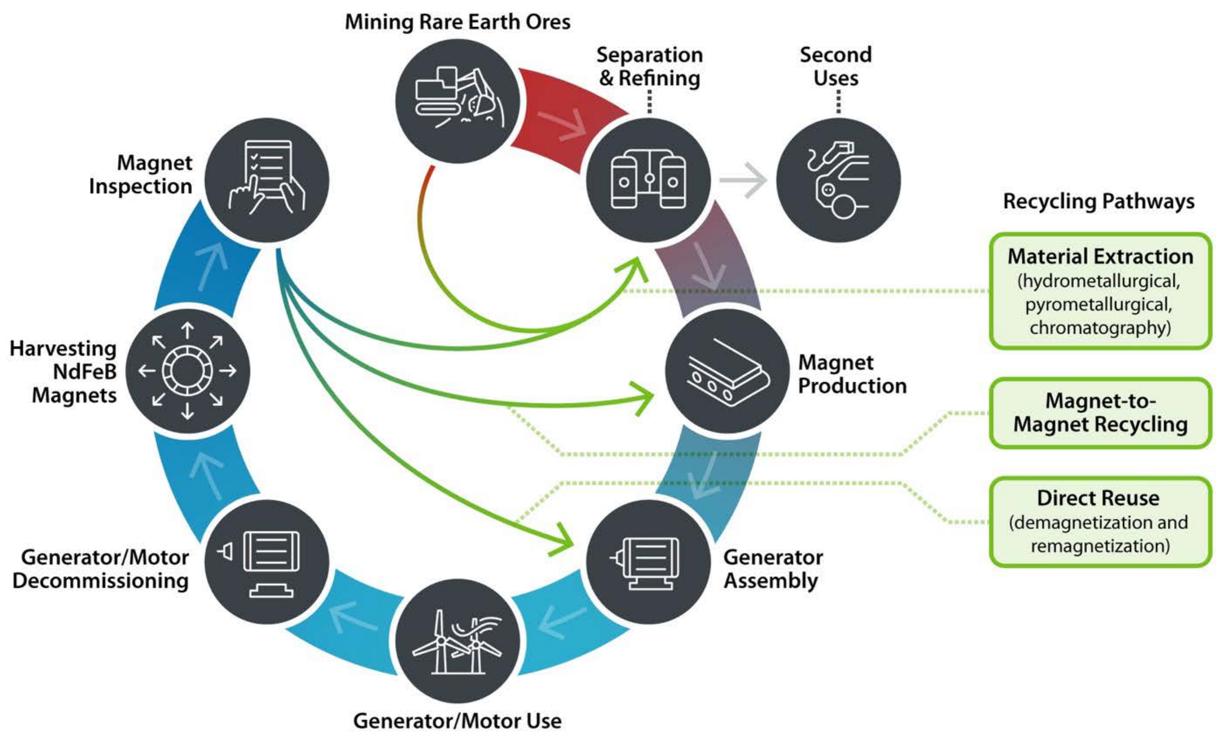


Figure 13. Life cycle stages and circularity pathways for rare-earth permanent magnets in wind turbine generators. *Image created by Christopher Schwing, NREL*

DOE's *America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition* (2022a) calls for government agencies to coordinate and expand programs and perform market analysis and technological commercialization of clean energy materials, including use of recycling. In addition, this strategy report calls for using the Defense Production Act to support a domestic rare earth magnet market that spans multiple supply chain stages. DOE's corresponding Rare Earth Permanent Magnets: Supply Chain Deep Dive Assessment (Smith et al. 2022) details China's dominance of all stages of the NdFeB magnet supply chain: increasing from 58% of the global rare earth mining (first stage) to 92% of global magnet production (third stage). The report states that the United States could facilitate magnet recycling and fill supply chain gaps by establishing research, development, demonstration, and deployment in magnet recycling techniques and aid for companies in the recycling field.

Several proposed recycling methods to recover pure rare earth elements (e.g., neodymium or dysprosium) or rare earth oxides have been actively investigated. Some recycling methods are suitable only for sintered permanent magnets (e.g., hydrogenation disproportionation desorption recombination or hydrogen decrepitation) or bonded magnets (solvent extraction/ionic liquid separation and cryomilling) or both (e.g., alkali baking) (Dai et al. n.d.; Delogu et al. 2022; Gandha et al. 2019; Önal, Riaño, and Binnemans 2020).

The hydrogen decrepitation process crumbles the magnetic alloys with hydrogen gas to form hydrides and renders the material extremely friable (easily crumbled) and easy to mill to the required particle size (McGuiness et al. 1986). Hydrogen disproportionation desorption recombination might be done afterward to further refine the grain size. Hydrogen decrepitation recovers magnet powder from magnet alloys (Nakayama and Takeshita 1993). Process yield for the hydrogen decrepitation recycling process is estimated at 96%.

In the hydrometallurgical process, magnet powders are completely dissolved in a dilute acid solution and output nearly all the dissolved iron in the ferrous state. During this process, the magnets are demagnetized, fractured, crushed, and milled. Then, the milled powder undergoes mechano-chemical grinding with sulphate-based chemicals, and is water leached. The resulting product then undergoes precipitation, filtration, calcination, dissolution, and then moves on to the split anion extraction process for rare earth extraction. The rare earth recovery rate of the hydrometallurgical route is 86%. Although the yield is not as high as with hydrogen decrepitation, it should be noted that the output from the hydrometallurgical process is rare earth oxides, whereas the output in hydrogen decrepitation is magnet powder (including iron and boron).

In the dissolution process, the magnet is demagnetized, then polyamide leaching is performed. Next, the powder mixture is filtered through a membrane to recover the precipitate and remaining leachate. The precipitation removes any ionic metals from the solution. Lastly, unwanted particles formed by the previous step are removed via a second filtration. Process yield for polyamide leaching exceeds 99%.

In alkali baking, demagnetized magnet powder is milled and separated by a sieve. The powder is treated with a diluted sodium hydroxide solution at relatively low temperatures for short durations in a closed polytetrafluoroethylene cell at ambient pressure. The resulting product is washed and dried and then leached in a versatic acid solution. Over 95% of all rare earths are recovered in this process. After precipitation stripping and calcination occurs, a mixed rare earth oxide with 98% by weight purity can be produced.

Novel recycling concepts, such as ligand-assisted displacement chromatography, have the potential to dramatically reduce capital- and energy-intensive solvent extraction methods needed for rare earth element separation and purification (Ding, Harvey, and Wang 2020). Traditional solvent extraction methods require thousands of settler mixers to refine crude rare earth oxide mixtures using toxic acids at high temperatures (Riaño and Binnemans 2015; Dong et al. 2016).

3.5.2.4 Rare Earth Recycling Innovations From the Critical Materials Institute

A novel way to recover rare earth elements known as acid-free dissolution recycling was invented by the Critical Materials Institute (CMI). This new method allows for rare earth elements to be separated from wind turbine generators and other electronics parts such as those in cell phones and computer disk drives (DOE 2023b). CMI and the Idaho National Laboratory also developed a new electrochemical recovery approach to reclaim rare earth elements, including from NdFeB magnets, as oxides. Commercialization at a pilot plant in Nevada has yielded about 200 pounds of rare earth oxides and other precious metals (Lister 2022).

Ames Laboratory, working with the Idaho National Laboratory, Oak Ridge National Laboratory, and CMI, have recently developed a new extraction agent based on diglycolamide and process to separate rare earth elements from ore, mine tailings, and electronics parts with much greater efficiency than other extraction methods (Stamberga et al. 2020).

Case Western Reserve University, Ames Laboratory, Lawrence Livermore National Laboratory, Idaho National Laboratory, and CMI are using high-temperature molten salts in the electrowinning process to recover pure neodymium from ore.[43]

[43] For more information, see https://engineering.case.edu/news/scientists-developing-climate-friendly-method-process-rare-earth-minerals.

3.5.2.5 Results of Life Cycle Assessment and Techno-Economic Analysis of Magnet Recycling Processes

3.5.2.5.1 Life Cycle Impact Assessment of Magnet Recycling Processes

Delogu et al. (2022) reported detailed LCA results for material extraction recycling processes: hydrogen decrepitation, hydrometallurgical, ionic liquid with polyamide, and alkali baking. This work was presented as part of the NEOdymium-Iron-Boron base materials, fabrication techniques and recycling solutions to HIghly REduce the consumption of Rare Earths in Permanent Magnets for Wind Energy Application (NEOHIRE) project (Berzi et al. 2019). We collected life cycle inventory (LCI) data as part of process development and demonstrations for this project and determined those data to be reasonably comparable to potential future U.S. magnet recycling process inputs and outputs with few variations. We compiled the process data from Delogu et al. (2022) and changed some of the inputs to represent U.S.-relevant results (e.g., grid mix, sourcing of materials, and scopes of materials selection in the life cycle inventory databases). Figure 14 summarizes life cycle GHGs for four different magnet recycling processes.

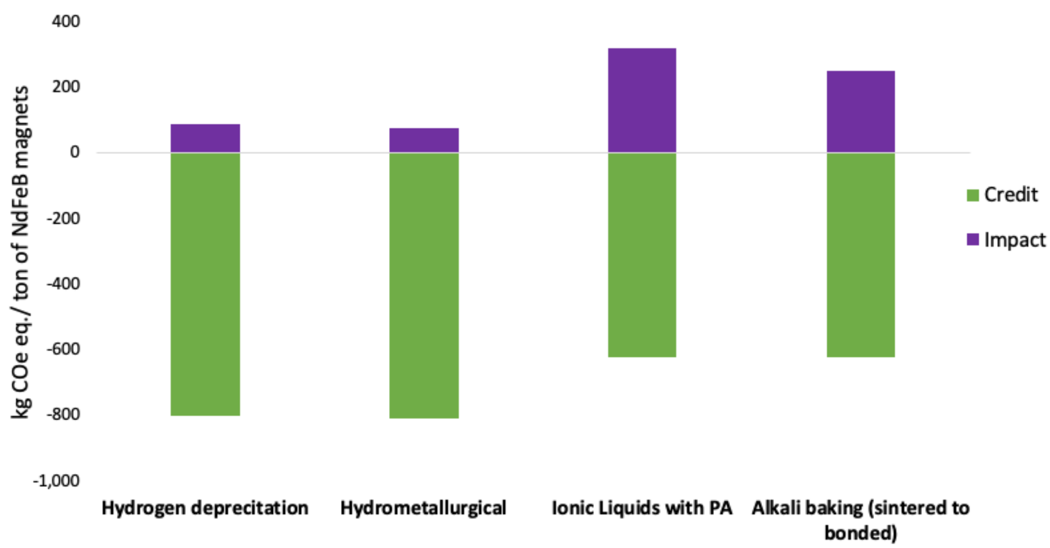


Figure 14. Life cycle GHG emissions of rare earth element material extraction pathways of NdFeB magnets in wind turbine generators. *Adapted from Delogu et al. (2022).*

Note: PA refers to the polyamide solvent used.

Results show that the benefits of all recycling processes for offsetting the need to mine for raw rare earth element materials, represented as credit in Figure 14, exceed the impacts of material and energy consumption used. Dissolution recycling pathways, namely ionic liquids with a polyamide solution and alkali baking, release more life cycle GHG emissions than hydrogen decrepitation and hydrometallurgical routes. More than 90% of GHG impacts for dissolution are associated with acid leaching and stripping precipitation. Reducing solvent use and energy consumption of stripping operations could improve the sustainability of dissolution processes for processing the potential future bonded magnet waste stream. In the hydrogen decrepitation process, electricity consumption in the decrepitation step alone contributes about 61% to life cycle GHG emissions. Direct electricity consumption is estimated to be 50 MJ/kg of magnet. For the hydrometallurgical route, mechano-chemical grinding, acid leaching, and calcination are the largest contributing factors to life cycle GHG emissions.

3.5.2.5.2 Techno-Economic Assessment of Magnet Recycling Processes

We considered three permanent-magnet recycling pathways for the recycling cost estimation using the TEA model developed by the Laboratory for Sustainable Manufacturing at Purdue University, a member of CMI. The model provides support to the economic feasibility for a new technology at its development stage (TRL 4-6) by identifying cost bottlenecks and evaluating alternative approaches (e.g., different feedstock, material, and sequential process flow settings). We obtained both preliminary and comprehensive TEA results, with the focus on the former type on technology production cost and the detailed financial analysis (i.e., break-even point, net cash flow, and payback period) in the latter type.

We generated recycling cost estimates for three potential permanent-magnet recycling pathways: hydrometallurgical (sintered permanent magnet), hydrometallurgical with split anion extraction (sintered permanent magnet), and ionic liquid dissolution (bonded magnets) using the bill-of-materials data from Delogu et al. (2022). The first two recycling pathways are similar, but the third considers the recycling cost of extracting neodymium and dysprosium rare earth metals via a split anion extraction pathway using rare earth oxides obtained at the end of the hydrometallurgical recycling process. The rare earth oxides from the hydrometallurgical recycling process can be used for injection molding and/or manufacturing new permanent magnets.

Figure 15 shows the disaggregated recycling production cost estimates from the Laboratory for Sustainable Manufacturing model for three recycling pathways based on operation assumptions of 260 working days per year, 1 shift per day, and 8 hours per shift. Recycling production cost is in the range of \$6.53/kg–\$15.33/kg of recycled magnet. Direct cost—comprising materials, electricity, utility, and direct operating expenses—has the largest share of total cost for all three analyzed magnet recycling processes. The hydrometallurgical pathway, without split anion extraction, was found to have the lowest cost of recycling among the three examined recycling processes. In the split anion extraction process, the cost of extracting rare earth metals (\$4.46/kg) could be offset by the revenue from selling pure rare earth elements instead of rare earth oxides, which would be recovered without conducting the split anion extraction process along with the hydrometallurgy process. Of the three permanent magnet recycling processes, the most expensive is the ionic liquids process (\$15.33/kg). In this process, electricity usage is the largest factor in the high cost, accounting for 30% of the total cost and 66% of the direct process cost.

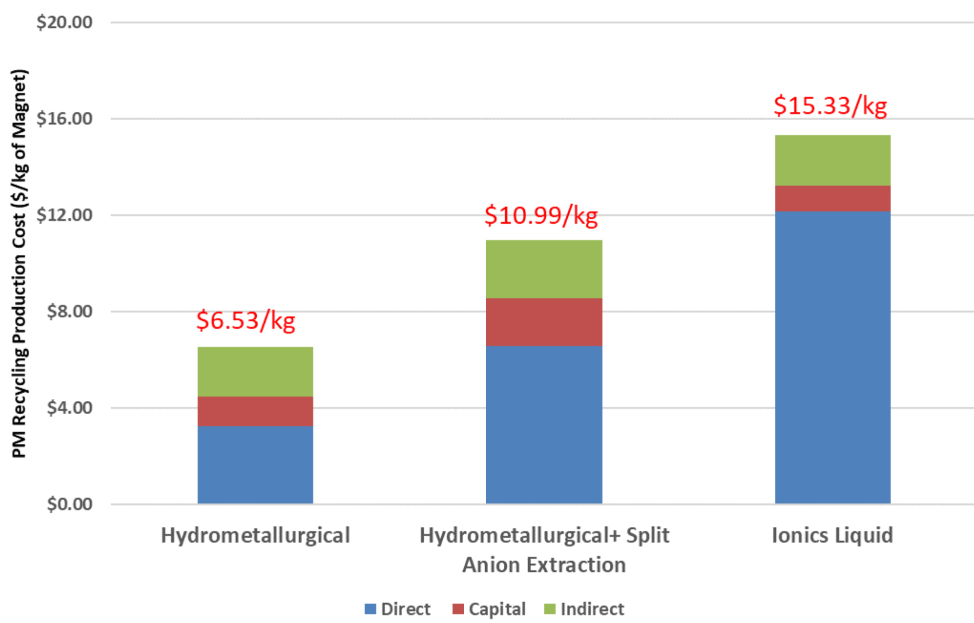


Figure 15. Estimated permanent magnet cost of recycling ($/kg). *Figure by Sujit Das, ORNL.*

Recycling production cost estimates for the acid dissolution recycling pathway for bonded magnets using the Laboratory for Sustainable Manufacturing cost model also validated the earlier poor economics reported by Dai et al. 2016. A significantly higher recycling cost of ~$200/kg of magnet than the estimates of the other three technology pathways considered here are mainly due to both the larger amount and cost of reactants such as tripodal nitroxide ligand and potassium bis(trimethylsilyl)amide in addition to the high capital investment necessary for the ReTriNox (rare earth element$_2$ – O_3) reactor used for synthesis and isolation of rare earth oxides. The value of recycled end products such as neodymium trioxide (Nd_2O_3) and dysprosium trioxide (Dy_2O_3) does not break even with the high recycling cost.

The recovery of rare earth elements from waste magnets is potentially profitable depending on the production cost as a function of the concentration of the target product in the feedstock (Ding, Harvey, and Wang 2020). The analysis shows that waste magnets are promising feedstocks for producing dysprosium, neodymium, and praseodymium, with a potential profit of about $5/kg of waste magnet at an average production cost range of $4–$8/kg feedstock. However, the reported rare earth oxide recovered amount of 47 milligram/kg of magnet at $150/kg under the most economical hydrometallurgical process (Delogu et al. 2022) is close to the estimated production cost of $6.53/kg. Yet, it will not cover the full production cost, which includes a significant share of administrative, marketing, financing, and research and development costs. Selling recycled rare earth elements from permanent magnets in open markets has been uneconomical in the industry today. To improve the economic value of recycling these materials, magnet manufacturers need to ensure a safe, reliable stream of material in the long term versus cheaper material available in the short term. In many efficient recycling streams, such as those for lead and aluminum, a large portion of income for the recycling companies comes from contracts with the manufacturers of the materials they are recycling. Guaranteed revenue from metal manufacturers and economies of scale make these recycling streams economically feasible.

3.5.3 Decommissioning and Recycling Metrics for Rare-Earth Permanent Magnets

Table 16 provides a range of decommissioning and recycling metrics for four rare-earth permanent-magnet recycling pathways: hydrogen decrepitation, hydrometallurgical, ionic liquids with polyamide, and alkali baking. Future recycling technologies should perform better than the metric values indicated here, allowing for more sustainable end-of-life practices for permanent magnets. As mentioned earlier, this section only focuses on recycling rare earth permanent magnets, not other generator materials.

Table 16. Metrics for Existing Select Permanent-Magnet Recycling Processes

Metric	Unit	Hydrogen Decrepitation	Hydrometallurgical	Ionic Liquids w/ Polyamide	Alkali Baking
Percentage that goes to landfill	%	N/A			
GHG emissions	kg CO_2 eq./metric tonne	-710	-735	-300	-370
Embodied energy	MJ/metric tonne	Poor data quality			
Water use	m^3/metric tonne		Poor data quality		
Human toxicity	kg 1,4-DCB eq./metric tonne		Poor data quality		
Cost of recycling	$/metric tonne	150 (estimated from Fraunhofer IFAM Germany)	653	153	170 (estimated from AIST Japan)
Market selling price	$/metric tonne	Neodymium oxide: 100-120; dysprosium oxide: 300-500 (as of 2020–2022)			
Material yield	%	99	96	99	99
Material quality ratio	% loss in rare earth purity	<1	5–20	1–5	1–5
TRL	1–9	5/6	6/7	3/4	3/4

3.5.4 RD&D Needs, Gaps, and Opportunities for End-of-Life Management Practices for Rare Earth Permanent Magnets

There are many opportunities for fundamental and applied research to improve recycling rates, cost-effectiveness, and environmental sustainability of materials recovery and recycling pathways from wind turbine generators and rare earth permanent magnets. Table 17 provides the RD&D priorities for improving end-of-life practices for rare earth permanent magnets and the potential impacts of implementing those innovations.

Table 17. RD&D Priorities for End-of-Life Practices for Rare Earth Metal Permanent Magnets and Potential Impacts of Investments

RD&D Technological Innovation	Potential Impact
Develop and demonstrate scale-up of hydrogen decrepitation recycling for waste sintered magnets	• Enable a domestic magnet recycling infrastructure that would allow for recovering and reusing rare earth elements and avoiding exporting waste magnets overseas
Develop and demonstrate low-operating-cost and green-solvent hydrometallurgical magnet recycling pathways	• Reduce market entry cost barriers • Reduce life cycle GHG emissions associated with solvent production and disposal
Develop and demonstrate large-scale magnet refining processes with dramatically reduced operating costs and solvent use in the short and medium terms (e.g., ligand-assisted or continuous/ion exchange chromatography)	• Replace capital-intensive liquid-liquid extraction refining processes to reduce the cost of entering the market in the United States • Enable processing of waste magnet streams in rare earth ore refining operations • Reduce/eliminate toxic solvent waste streams and their subsequent life cycle impacts; lower life cycle GHG emissions by up to 50%-80% compared to baseline solvent extraction techniques
Develop standard magnet testing procedures to characterize magnet properties for direct reuse	• Reduce need to recycle in the short and medium terms, allowing time to scale up the magnet recycling infrastructure • Reduce life cycle GHG emissions associated with magnet transportation and recycling operations
Develop and demonstrate additive manufacturing pathways for bonded magnets to achieve on-par performance with sintered magnets	• Reduce swarf material losses in traditional sintered magnet production • Dramatically reduce capital and operating costs of magnet production and recycling • Eliminate energy-intensive process steps (e.g., jet milling) to reduce life cycle emissions of recycling operations
Develop and demonstrate hybrid recycling processes (e.g., alkali baking) for sintered and bonded magnets in the medium and long terms	• Reduce capital and operating costs of developing separate recycling designs for sintered and bonded magnets • Streamline magnet recycling operations for higher raw material throughput
Demonstrate large-scale freezer grinding recycling pathways in the medium to long term when bonded magnets gain market share	• Enable recovery of high-quality magnet powder for reuse
Develop and demonstrate modular generator designs	• Enable easier access to internal generator components during on-site repair • Enable piecewise module replacement instead of entire generator replacement • Reduce demand on generator primary materials (e.g., electrical steel, rare earth magnets)

3.6 Wind Turbine Blades

Blades represent the largest volume of wind turbine materials that are currently going to waste management facilities (Cooperman, Eberle, and Lantz 2021). Wind turbine blades are massive components. They are classified as plastic waste because they comprise fiber-reinforced polymers and often contain polymeric foam. Wasteful disposal of these composites eliminates the opportunity to recover the embodied energy in the blades and the chance to reduce life cycle emissions of primary materials. These relatively inert materials pose minimal near-term environmental risk, and the volume projections of wind turbine blades reaching end of life represent a small percentage of total waste in the United States (Cooperman, Eberle, and Lantz 2021). However, there can be regional constraints, such as lack of specialized disassembly equipment and costly transportation, that overwhelm waste management facilities in rural areas with large wind power plants.

To avoid these issues, some European countries like France have banned sending wind turbine blades to landfills, and current lobbying may extend this ban throughout Europe (Wind Europe 2020). Ultimately, the question remains if these durable wind blade materials could serve a better purpose if recovered for downstream markets. Various recycling approaches exist for separation and recovery of these materials (Beauson et al. 2022) but are currently cost-prohibitive in the United States compared to other parts of the world. In addition to the economic challenges for recycling domestic wind turbine blades, the environmental impacts of recycling these materials remain uncertain.

In addition to the economic challenges for recycling domestic wind turbine blades, it is important to understand the associated environmental impacts of recycling these materials based on well-defined sustainability metrics. Two of these metrics are quantifying GHG emissions and recovered mass yields from different recycling approaches in comparison to wasteful disposal. The objective of these comparisons and analyses is to identify challenges and opportunities for improved material recovery from decommissioned wind blades through technology assessments of existing and emerging recycling approaches.

3.6.1 Material Breakdown for Blades

Wind turbine blades vary in size, but current blades being decommissioned weigh more than 7 metric tonnes per blade. This makes them a relatively small contributor to overall turbine mass, which can be well above 200 tonnes. Even with this small mass, wind turbine blades have been found to contribute 10%–15% of total wind turbine life cycle GHG emissions (Razdan and Garret 2022). Primary material acquisition and its subsequent manufacturing are the largest contributors to life cycle GHG emissions of the blade component (Liew 2021). Wind blades are primarily made of fiber-reinforced polymer composites such as fiberglass and in some cases carbon-fiber reinforcements, epoxy and vinyl ester resin systems, and core materials that use balsa wood and PET/PVC foam materials. Using these materials makes wind turbine blades both lightweight and durable to withstand environmental and performance stress. However, their durability is a significant challenge when attempting to recycle wind blades at the end of life.

3.6.2 End-of-Life Management Practices for Blades

Current recycling processes require shredding the composite materials as a precursor to material separation. Furthermore, it can be energy-intensive to separate the constituent fiber and resin materials for recycling. These technical and economic challenges cause most wind turbine blades to be disposed of after reaching the end of their operational lifetime. In the United States, the cumulative amount of end-of-life wind blade waste that could go to waste management facilities by 2050 is estimated to be over 2 million metric tonnes (Cooperman, Eberle, and Lantz 2021).

Several approaches have been proposed for repurposing, recycling, and recovering end-of-life wind turbine blade materials. Comparing these approaches through both qualitative and quantitative analysis is important to understanding the technical, environmental, and economic trade-offs associated with each one. The following sections describe different recycling approaches as well as independent quantitative assessment for blade decommissioning, recycling, and secondary market assessment for recovered material. The quantitative analysis includes data gathering, process modeling, and LCA. The combined results of this analysis are then used to compare GHG emissions, recovered mass yields, and other useful metrics.

Figure 16 highlights the broad range of end-of-life approaches proposed for wind turbine blades. Approaches higher in the pyramid are presumed to be more sustainable with increased material recovery and reduced processing requirements. Preventative approaches include lifetime extension, design for disassembly, and the use of recyclable materials representing approaches for improved blade design. Recyclable thermoplastic-based resin or other thermoset-based separable resin systems are advancements that enable easier composite separation. Developing recyclable resin systems has been actively investigated, and major wind turbine manufacturers have already used them in new blade generations (General Electric [GE] 2022; Cousins et al. 2019). However, given the 20- to 30-year operational life of wind turbine blades, blade waste in the near term will be primarily made of glass-reinforced epoxy composites, and is therefore the primary focus of the assessment in this report.

Figure 16 shows end-of-life approaches for existing wind turbine blade materials. The list begins with repurposing, which includes a wide range of novel concepts but is most associated with cutting blades into segments that can be used as structural components such as beams or poles (Nagle et al. 2022). The simplicity of repurposing for structural applications means that only a small amount of energy is required to downsize and transport the blade segments. Additionally, repurposing the materials in their original composite form makes further repurposing or recycling possible going forward. However, these advantages involve some uncertainties. One issue is that the structural health of end-of-life wind turbine blades is highly variable and requires qualification through advanced inspection. This qualification could prove challenging to construction applications where properties such as strength are critical and need to meet established standards such as building codes.

In addition to repurposing, various recycling processes exist for recovering wind blade materials including mechanical, chemical, and thermal approaches. Mechanical recycling is a general term covering varying degrees of mechanical size reduction and sometimes pulverization for composite materials to be used as filler material in downstream applications. In the context of this report, the term mechanical recycling is used to denote approaches limited to size reduction and separation with minimal subsequent processing required to generate recyclable material. Within mechanical recycling, size reduction usually involves some combination of cutting, shredding, and grinding to obtain chunks of fiber-rich composite mixtures, and resin-rich powders. These materials can be used in different applications, most notably as reinforcement or filler in other materials. For example, fiber-rich materials can be added to sheet or bulk molding compounds used to create paneling or boxes. In another example, resin-rich powder can be added as a filler material for mortars used in construction applications. Across these applications, environmental and economic impacts of adding recycled wind blade materials remains uncertain. Some applications claim an increase in properties such as strength, but others report negligible or even a negative impact. The value of adding mechanically recycled material to these products depends on the specific application.

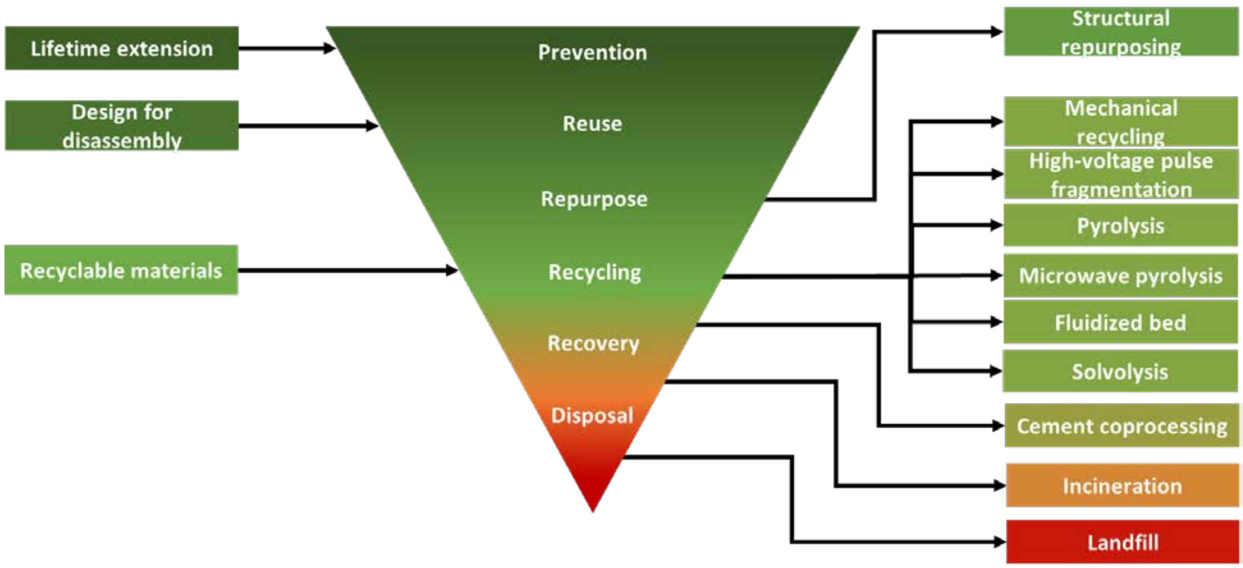


Figure 16. Approaches for increasing circularity of wind turbine blade materials. *Figure adapted and expanded from existing literature (Nagle et al. 2020)*

Another approach to separate materials is high-voltage pulse fragmentation. In this approach, wind blade composite pieces are placed in a dielectric liquid and cycled through a series of high-voltage electrical pulses. The electrical pulses disintegrate the material, allowing for the separation and collection of fibers. Compared with mechanical grinding, high-voltage pulse fragmentation has been shown to produce cleaner, longer fibers (Mativenga et al. 2016). This approach remains at a lower TRL than mechanical recycling. High-voltage pulse fragmentation may also be used as an initial size reduction step in the future before other subsequent recycling processes, such as pyrolysis or solvolysis.

The remaining recycling approaches in Figure 16 rely on thermal or chemical mechanisms to separate resin from fibers. Pyrolysis is one of the most widely discussed in literature and is currently in the initial stages of commercialization (DOE 2022c). In pyrolysis, the composite is raised to an elevated temperature between 400°C and 600°C in a mostly inert environment. At this temperature, the resin is decomposed into oils and gases that can be separated from the fibers and other fine solids. The oils and gases can be sold as products or reused directly within the pyrolysis process as fuels to offset the thermal energy load. The quality of fibers obtained from pyrolysis varies and is based on considerations such as tensile strength and surface characteristics. Many pyrolysis systems employ subsequent regenerative steps that help remove char from the fiber surface and improve fiber quality.

Two alternative thermal recycling approaches are microwave pyrolysis and fluidized bed. Microwave pyrolysis heats the composite via microwave irradiation. Using microwaves allows for uniform heating of the composite, which has the potential to reduce unwanted charring on the fiber surface. In a fluidized bed recycling approach, a bed of silica sand is fluidized via hot air, allowing for rapid heating of the composite. While both approaches have potential benefits, neither has been performed at full scale within the United States. A pilot-scale microwave pyrolysis facility has been developed in Sweden to demonstrate the feasibility of separating fiberglass from wind turbine blade composite materials. The project resulted in significant technical development of a continuous microwave pyrolysis process and has provided solid groundwork for further development of the approach.

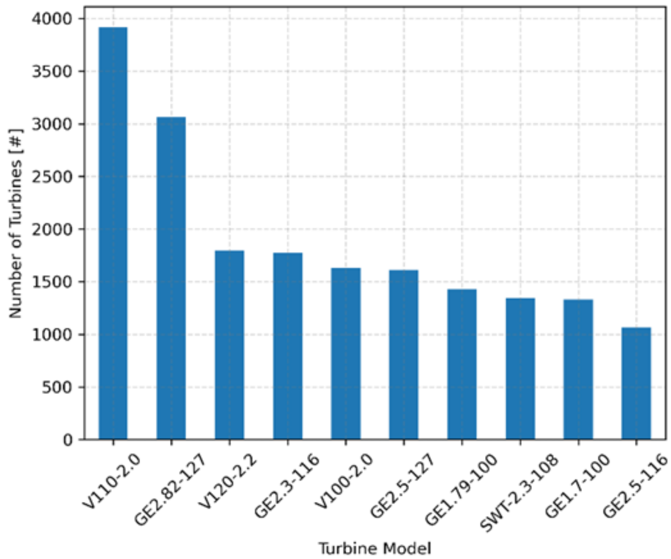
Chemical recycling of wind turbine blades includes numerous approaches each with their own unique combination of chemicals, pressure, and thermal energy. In solvolysis, one of the most frequently discussed approaches, a solvent is applied at an elevated temperature and pressure to dissolve the resin and separate out fiberglass. The mix of solvents that is most effective varies for different resin systems, but some examples include acetone, ethanol, propanol, and water (Oliveux, Dandy, and Leeke 2015). Solvolysis has the potential to reduce the energy needed to separate resin and fiberglass compared to thermal approaches such as pyrolysis. However, the manufacturing, handling, and recovery of solvents in a continuous full-scale process would also require a large amount of energy and add significant complexity related to concerns with toxicity and safety. As a result, most chemical recycling solutions are focused on future wind turbine blade materials where recovery of recyclable resin is a high priority (as opposed to combusting these resin systems in pyrolysis processes).

The final recycling approach shown in Figure 16 is cement coprocessing, in which shredded wind turbine blade material is fed into a cement kiln where the resin is burned as fuel, and the fiberglass can be directly substituted for feedstock materials required to make clinker, the key material in cement production (solid material that is an intermediary product in the manufacture of Portland cement). Given that the resin is directly combusted for energy recovery and only the fiberglass portion of the blade is recycled, cement coprocessing is often considered to fall somewhere in between recycling and recovery. One advantage of this approach is that the fiberglass material does not need to go through a calcination step before entering the cement kiln. As a result, cement coprocessing not only offsets the use of virgin materials, but also the energy and direct CO_2 emissions associated with calcination. Because of these advantages and the large demand for alternative fuel and feedstock materials within cement production, cement coprocessing is currently the most widely deployed solution for recycling wind turbine blades in the United States. However, the amount of wind blade material going to cement coprocessing is still smaller than the amount going to waste disposal facilities.

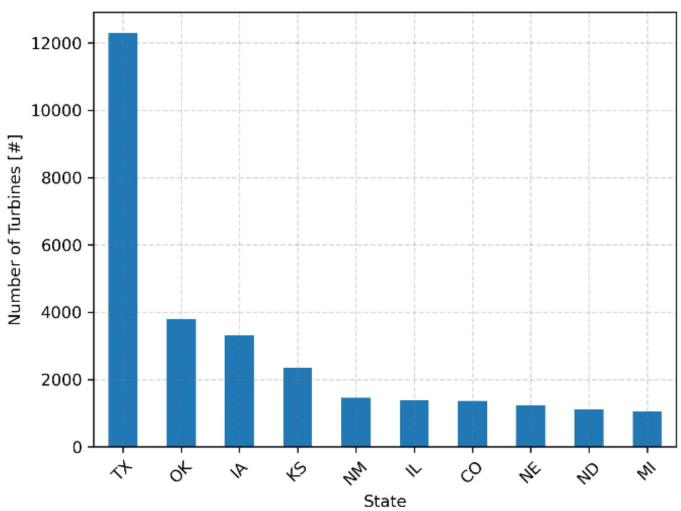
Of the approaches described earlier, we analyze five in this report: cement coprocessing, mechanical recycling, pyrolysis, microwave pyrolysis, and solvolysis. We selected these approaches based on their current prevalence in the U.S. wind turbine blade recycling market, the availability of data required to perform the analysis, or their novel technical features. The high-voltage pulse fragmentation and fluidized bed approaches also have their own unique limitations and advantages, which should be analyzed in future efforts.

3.6.2.1 Wind Turbine Model Definition

We assessed the wind blade material recovery and recycling processes using a reference wind turbine that represents a common wind turbine model in the United States being decommissioned in the near term. Repowering wind turbines is an activity that replaces wind turbine blades prior to the end of their design life and can occur as early as 7–9 years after installation. Repowering is motivated by opportunities to increase energy capture with longer blades and because of favorable tax incentives. With consideration of repowering activities and the understanding that domestic blade recycling efforts are currently nascent but are expected to accelerate during the next 5–10 years, we chose the reference wind turbine model from those having been installed within the past 10 years. A distribution of the 10 most frequently used wind turbine models installed from 2013 to 2023 in the United States is shown in Figure 17, which also includes a distribution of the 10 states installing the largest number of wind turbines over this period. Based on these data and feedback from the Industry Advisory Board, we selected the GE 1.x-100 wind turbine models with 48.7-meter blades and fiberglass spar caps for project analysis.



(a) Top 10 wind turbine models installed



(b) Top 10 states with the most wind turbine installations

Figure 17. Distributions of wind turbine model and installation location from the past 10 years (2013-2023). *Figure by Michelle Williams, SNL.*

We developed a material breakdown of the reference blade model to represent the constituent material mass in the blade. In some recycling processes, the organic materials are combusted and produce various byproducts while supplementing the required thermal energy based on the respective heating values. The material distribution of this reference blade is considered generally representative of similarly sized blades with a fiberglass spar cap (as opposed to a carbon-fiber spar cap), epoxy resin system, balsa core material, and metal lightning protection system. The developed material distribution was confirmed by the Industry Advisory Board, in which the various mass percentages are generally representative of the reference blade type, shown in Table 18.

Table 18. Reference Wind Turbine Blade Properties Used in the Recycling Analyses

Property	Value	Unit	Mass Percentage
Turbine capacity	1.7	MW	N/A
Blade length	48.70	meters (m)	N/A
Total blade mass	9,000	kg	100%
Blade fiberglass mass	5,283	kg	58.7%
Blade resin mass	2,401	kg	26.7%
Blade balsa mass	416	kg	4.6%
Blade gelcoat mass	180	kg	2.0%
Blade adhesive mass	450	kg	5.0%
Blade metal mass	270	kg	3.0%

3.6.2.2 Decommissioning Baseline Development

Wind turbine blades are designed to last for 20 to 30 years, and a tremendous amount of work has been performed to maximize that lifetime. The materials within them are highly engineered to minimize costs and maximize functional life. To remain competitive in the market and maximize profit, owner-operators have indicated that they often decommission older but still-functioning blades and replace them with new blades (known as repowering) approximately every 7–9 years (after only 23%-45% of the design life of the materials in the blade). Another source for premature blade decommissioning results from damage and failure of the blade. Common sources of blade failure include lightning strikes, leading-edge erosion, manufacturing defects, and damage during transportation. Although there is growing interest and significant development in advanced, nondestructive characterization methods for finding and repairing damage in blades, it is often difficult to identify in the field. For example, damage on the inside of a blade from lightning strikes can be impossible to detect using current technology without someone physically climbing onto the blade. As a result, damage is often missed by owner-operators until irreparable failure occurs. A third reason for blade decommissioning is that materials reach the end of their design life. In the United States, some blades can remain installed and be nonoperational for months to years before being decommissioned.

The typical decommissioning process flow for the United States is displayed in Figure 18. The highest value recovery of the blade is for direct reuse in another turbine for sustainable energy generation. Industry partners indicate that this approach is not often done for domestic utility-scale wind turbine blades (multimegawatt turbines) but is more common in the distributed, or small (i.e., a wind turbine owned by a local community that is less than 1 kilowatt) wind industry. Additionally, wind blades at end of life can be repurposed into semistructural or structural applications, such as bridges. However, most repurposing efforts are not industrialized at this time and the structures would need to be recycled at the end of the repurposed life, which may be further complicated by the newly designed/built structure.

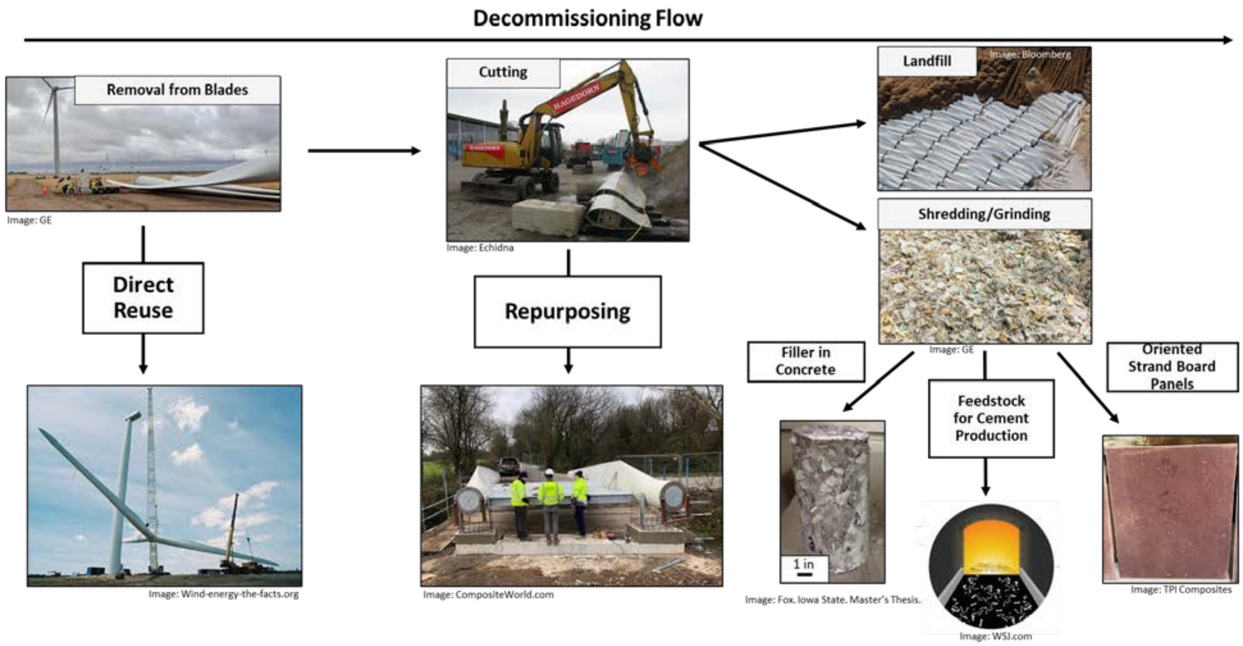


Figure 18. Decommissioning process flow for U.S.-based wind turbines. *Diagram by Evan Sproul, SNL. Images in diagram from various sources.*

Photos from upper left (GE.com), top middle (Echinda.com), upper right (GE.com), bottom left (wind-energy-facts.org), bottom middle (Compositeworld.com), middle right (Fox et al. 2016), lower left to right (wsj.com), Bloomberg.com.

3.6.2.3 Location of Wind Turbines Being Decommissioned

The number of wind turbines being installed in the United States is increasing significantly. For example, in 2020, 42% of new electricity generation capacity was from wind energy. The state with the greatest wind power capacity is Texas, where more than a quarter (27%) of all U.S. wind capacity is located. Texas alone has more than 40,000 MW of wind power capacity, which is nearly 20% of its overall electricity generation in 2021. In addition, that same year Texas had more than 40 wind-related manufacturing facilities across the state. As such, the baseline case in this analysis considers blades being decommissioned from wind power plants located in Texas. A limitation of this model is that travel distances will need to be accounted for when considering blade recycling in other locations, and transportation can contribute heavily to the final costs and environmental impacts.

3.6.2.4 Blade Disassembly Techniques

Wind turbines are often installed in remote locations to access quality wind resources, which can make decommissioning difficult. Removing wind turbine blades while minimizing environmental impacts and costs can involve many steps and engineering perspectives and is thus an expensive process. The current leading techniques used to remove blades from towers include disassembly using a crane, toppling with a pulley system and heavy machinery, or controlled demolition via explosives. These techniques are summarized as follows.

3.6.2.4.1 Crane Technique

Because wind turbine blades are secured to the rotor at the root using numerous bolts, they can be nearly as time-consuming to remove from the rotor as when installed to the turbine. For this reason, the blades can be brought down attached to the rotor itself and then removed on the ground. Afterward, the blade is often cut perpendicular to its length into sections that are more easily handled and transported. This step is often performed using heavy equipment with a large saw attached as the blades are too large and difficult to cut manually. In some cases, blades are then shredded either at the site or transported in sections to a recycler where they are then shredded. Some recyclers have indicated that it is possible to stack the blade sections such that they can meet the maximum weight permissible on the truck, thereby avoiding shredding at the site. However, others have indicated that using mobile shredding units to break down blades into smaller pieces would make transportation easier. Currently, renting or purchasing mobile shredders is expensive, so it is more common for blade sections to be transported via truck rather than as shredded material. One consideration during shredding is the metal content of the lighting protection system. Separating the metal from other blade materials is challenging, leading to increased wear and tear on shredding systems, as well as metal contamination in composite material streams intended for recycling. Resolving this issue will be critical for reducing the contamination of composite recycling streams and enabling recycling of the metal in the lighting protection system.

3.6.2.4.2 Pulley System

In some cases, crane access or availability can delay decommissioning. As a result, another technique that has been employed is a pulley system. In this process, the top of the tower (including the rotor and blades) is secured to a pulley system. The entire tower is then pulled down using heavy machinery to make it fall. The blades, nacelle, and rotor are often fractured during this process, resulting in small pieces and chunks of the blades and other components flying off into the surrounding area. This process is more time-intensive and laborious than the crane technique and is less likely in locations where the terrain typically allows for crane access.

3.6.2.4.3 Controlled Demolition

Like the pulley system, explosives may be used to bring down a full wind turbine when a crane is not available or unable to access the site. This approach may be more cost-effective than using a crane, but is often considered a last resort. As with the pulley system, the goal of this approach is to topple the turbine but does result in chunks of the blades and components flying off into the surrounding area, which must be remediated before the project is complete. This is a time-intensive process but has been used in the United States in special circumstances where other options were not possible.

Considering the three options that are known in the U.S. market for decommissioning blades, it is most likely that for Texas it will be possible to get a crane to the site. Furthermore, feedback from recyclers indicated that disassembling an intact blade is preferred to ensure high material quality for the recycling process. As a result, the analysis in this section is based on a scenario in which a blade is disassembled with a crane and cut into 10-meter segments on-site. Blade sections destined for disposal at a landfill would be packed on a truck without further downsizing, whereas blades destined for recycling would go through an additional shredding step, occurring either on-site before transportation or at a recycling facility. The shredding process results in a mixed material stream that is recyclable using a few technologies currently available at industrially relevant scales. If it were possible to separate the materials in this mix either through smarter disassembly/decommissioning techniques or through plastic separation after shredding, this could increase the value of the recovered material streams.

3.6.2.5 Life Cycle Assessment of Wind Turbine Blade Recycling Approaches

We performed a LCA in accordance with guidance from ISO14040 and 14044 (2006a, 2006b). Based on this guidance, the four standard phases of LCA are 1) goal and scope definition, 2) LCI analysis, 3) life cycle impact assessment, and 4) interpretation and decision-making. Within this specific LCA, the primary goal was to compare the GHG emissions of multiple wind turbine blade recycling approaches. In addition, we estimated mass yields, embodied energy, and water consumption as secondary metrics. The system boundary is consistent across all recycling approaches. The boundary begins when a blade reaches its end of life and ends when it has been transformed into a new material intended for remanufacturing. To enable a reasonable scope for this analysis, life cycle stages outside of the system boundary such as blade manufacturing and remanufacturing of recycled materials have been excluded from the LCA.

Including these other manufacturing life cycle stages in future analysis would place the end-of-life results within the context of the full life cycle of a wind turbine blade. Remanufacturing would impact both the emissions of the recycling process and the substitution credit given to recycled products. However, the large up-front emissions of manufacturing a wind turbine blade would likely dilute the comparative analysis between recycling approaches. It is noted that remanufacturing is not required for material recovery processes that generate a direct substitute for a raw material of the second-life application, as is the case for cement coprocessing.

The primary functional unit considered in this analysis is one kilogram of recycled material leaving the system boundary. However, because disposal in a landfill does not result in any recycled material, comparisons are initially shown on a per-blade basis. Primary LCI data were sourced from the process modeling discussed in Appendix B. Secondary LCI data were sourced from Ecoinvent 3.9.1 (Wernet et al. 2016). When possible, we selected Ecoinvent LCI data based on specific geographic regions within the United States. If these data were unavailable, we selected “rest-of-world” or “global” options to represent the best possible approximation. Within Ecoinvent we selected “cut-off unit process” data to avoid any duplicate accounting for recycling processes. Once LCI data were collected, we performed a life cycle impact assessment using climate change emissions factors from the EPA’s Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (version 2.1), water consumption factors from the ReCiPe2016 methodology,[44] and cumulative energy demand as defined by Ecoinvent (Huijbregts et al. 2017; Wernet et al. 2016).

3.6.2.5.1 Mass Yield Analysis

We used mass flows from primary LCI data to compare the mass yields for each recycling approach. Figure 19 displays the blade mass yields for each approach considered. All five recycling approaches lose 5%–6% of material because of system inefficiencies. These include dust lost to the environment during downsizing and the metal present in lightening protection systems that is assumed to be removed from the blade and sent to the landfill. Four of the approaches include incinerating organic material within the system boundary. This method begins with the initial incineration of the resin when it is heated, as well as recirculating certain oils or gases for secondary combustion to provide thermal energy back into the process. In addition to this incineration, pyrolysis and microwave pyrolysis also result in an export of some oil or gas, which is not used within the system boundary. The remaining solid recycled materials are then split into two categories. One is the primary solid recycled material, which comprises either recovered fiber or cement clinker. The other is secondary solid material, which comprises powders resulting from the recycling processes.

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[44] A life cycle impact assessment method, called ReCiPe2008, provides consistent environmental impacts of many products; human health, ecosystem quality, and resource scarcity were the three areas of protection in ReCiPe2008 (Goedkoop et al. 2009). The same three areas of protection were selected for implementing the ReCiPe2016 methodology.

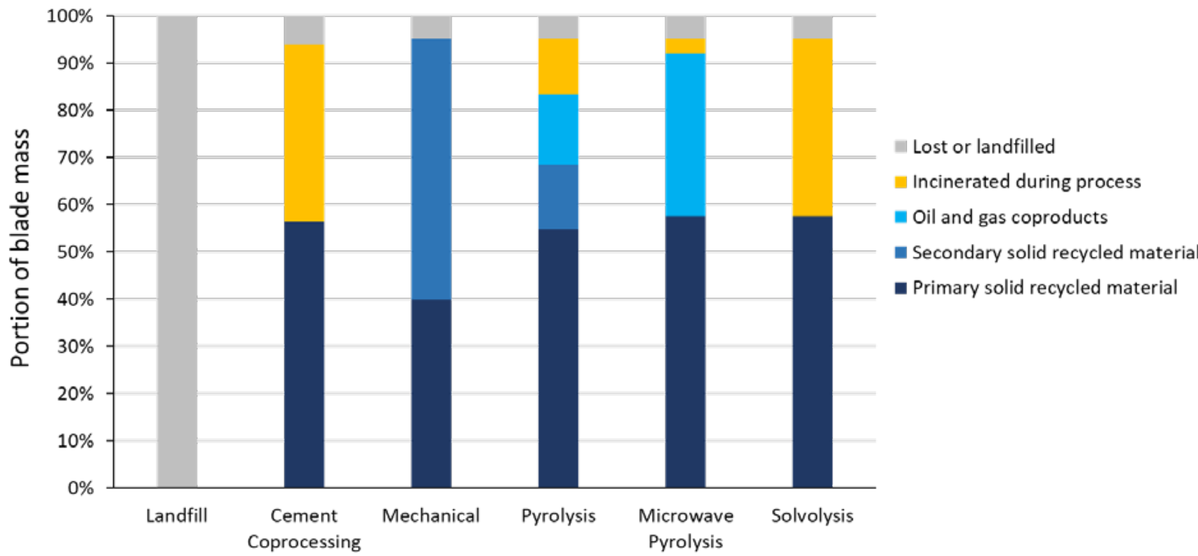

Figure 19. Wind turbine blade mass yields through different approaches. *Figure by Evan Sproul, SNL.*

3.6.2.5.2 Life Cycle Credits for Recycled Materials

To account for potential benefits of recycled materials, we applied substitution credits based on the mass of cement clinker, fiberglass, powders, oils, and combustible gases produced during recycling. The amount of credit given to a recovered material was based on the physical properties of the recovered material compared to the physical properties of a similar virgin material. Table 19 shows the credit applied for each recycled material. We assumed cement clinker to meet all requirements for standard quality clinker and that it receives a credit equal to the emissions of producing an equivalent amount of standard cement clinker. Recovered fiberglass received a credit based on the emissions of producing virgin fiberglass. However, that credit was weighted by the estimated tensile strength of recovered fiberglass compared to the tensile strength of virgin fiberglass. Recovered oil or gas received credit based on standard production of light fuel oil and natural gas. These credits were assumed proportional to their higher heating value. Recovered powders are treated as filler materials and assumed to have properties equivalent to mortar used in construction processes. Therefore, these filler materials received a credit equal to the emissions of producing virgin mortar.

Table 19. Credits for Producing Clinker, Fiber, Filler, Oil, and Gas

Approach	Recovered Material	Credit Material	Criteria	Credit High	Credit Baseline	Credit Low
Cement coprocessing	Clinker	Clinker	All properties equal	100%	100%	100%
Mechanical	Fiberglass	Virgin fiberglass	Tensile strength	80%	50%	30%
Mechanical	Filler	Construction mortar	All properties equal	100%	100%	80%
Pyrolysis	Fiber	Virgin fiberglass	Tensile strength	90%	80%	50%
Pyrolysis	Filler	Construction mortar	All properties equal	100%	100%	80%
Pyrolysis	Oils	Light fuel oil	Heating value	83%	80%	77%
Solvolysis	Fiber	Virgin fiberglass	Tensile strength	90%	80%	50%
Microwave Pyrolysis	Fiber	Virgin fiberglass	Tensile strength	90%	80%	50%
Microwave Pyrolysis	Oils	Light fuel oil	Heating value	82%	82%	82%
Microwave Pyrolysis	Gases	Natural gas	Heating value	97%	72%	60%

Other emission credit allocation techniques based on factors such as economic value of recovered products, market volumes of end applications, and exact material substitutions in specific end products are examples that could be more relevant when examining the benefits of recycling. However, data on the selling prices of recycled materials, volumes of secondary markets, and use of recovered products in specific applications are highly uncertain.

3.6.2.5.3 Baseline Life Cycle GHG Results

The baseline results for GHG emissions of recycling approaches and landfill disposal are shown in Figure 20. These results show the positive GHG emissions from decommissioning, size reduction, transportation, and recycling or disposal. They also show an estimate for emission credits due to substituting recycled materials for cement clinker, virgin fiberglass, mortars, light fuel oil, and natural gas based on a material's physical properties. The sum of the positive emissions and the negative credit represent the net GHG emissions of each recycling approach. To compare net emissions to disposal in a landfill, the results are shown per one 48.7-m wind turbine blade weighing 9,000 kg entering the system boundary.

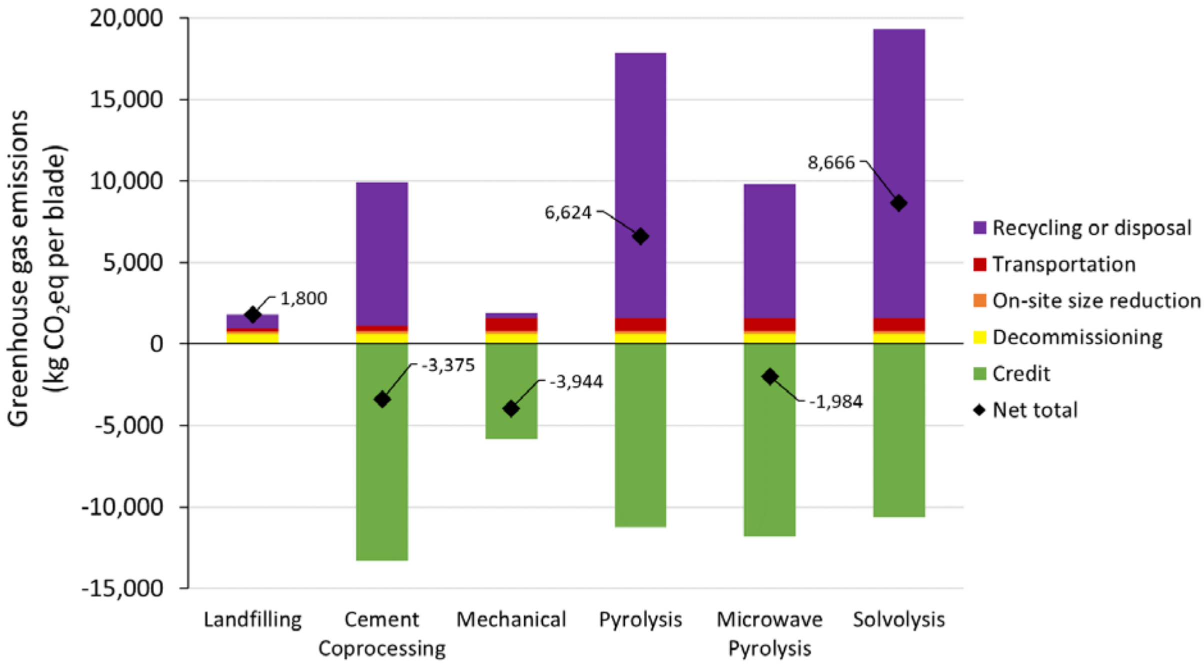

Figure 20. Life cycle GHG emissions of recycling approaches compared with wasteful disposal.
Figure by Evan Sproul, SNL.

The net GHG emissions of cement coprocessing, mechanical recycling, and microwave pyrolysis are negative, meaning the credit for producing recycled materials is greater than the emissions of the recycling process itself. The other processes result in net-positive GHG emissions, meaning that the GHG emissions of recycling a wind turbine blade are greater than the modeled credit for recycled material. Two of the recycling approaches—pyrolysis and solvolysis—have higher predicted net GHG emissions than those of disposal in a landfill for the specified blade design (see Section 3.6.2). The GHG emissions presented in Figure 20 largely align with similar analyses (Pender et al. 2023; Liu et al. 2019). However, there is still significant uncertainty regarding several input parameters, including the amount and type of energy used in recycling. An uncertainty analysis of the LCA results capturing the range of results for each recycling approach is presented in Section 3.6.6.

When considering the full life cycle of a wind turbine blade, the overall emissions associated with manufacturing a wind turbine blade of this size are estimated to be 45,000-50,000 kg CO_2 eq per blade (Liu and Barlow 2016). Therefore, GHG emissions of all proposed recycling approaches are significantly less than the total blade manufacturing GHG emissions. Blade recycling presents an opportunity to reduce life cycle GHG emissions of blade materials, should recovered materials become technically and economically feasible for reuse to make new blades and/or valued-added applications outside the wind energy industry.

3.6.2.6 Size Reduction and Transportation Scenario Analysis Results

The baseline GHG emissions sourced from decommissioning, on-site size reduction, and transportation are small compared to the recycling process in four out of six recycling approaches. Across the approaches there is a small but notable difference in transportation emissions due to truck packing efficiency and transportation distance. Building off these baseline GHG results, we developed a set of alternative scenarios to compare different methods of size reduction and transportation by truck. The primary considerations of these scenarios were the method of size reduction, the packing efficiency of downsized material onto the truck, and the transportation distance. In six of the scenarios, the method of downsizing material is limited to cutting material into 10-m-long segments. In the remaining two scenarios, the same cutting operation occurs, but the material is then fed into an on-site mobile shredder. The way in which a blade is cut or shredded directly impacts how efficiently it can be loaded onto a truck for transportation. The scenarios developed in this LCA include considering four different packing efficiencies on the truck. These efficiencies represent how much of the truck's 16,000-kg mass payload can be filled by blade mass.

The first three packing efficiencies are 25%, 50%, and 75% based on segmenting the blades. A low efficiency of 25% represents a scenario in which the blade segments are not packed efficiently and the volumetric constraints of the blade limit how much blade material is loaded onto the truck. A higher efficiency of 75% represents a scenario in which blades are cut and stacked in an efficient manner on the truck, reducing the volumetric constraints and increasing the amount of mass that can be loaded onto it. The likelihood of low or high packing efficiencies depends on the portion of the blades fitting together neatly and the range used in this analysis reflects feedback from various industry advisors. For shredding, we used a 100% efficiency to represent the likely scenario in which material can be condensed and will take up the full mass payload of the truck.

Once material is loaded on the truck, the final consideration is the distance of transportation. The current challenge in evaluating transport distance is that few blade recycling locations exist within the United States. Therefore, there are no historical distances that can be used to gauge the impacts of transporting the blades. As a result, we considered two generic transportation distances in these scenarios to represent an upper and lower bound. The first distance of 200 kilometers (km) represents a nearby end-of-life destination, most likely associated with a landfill or cement coprocessing facility. The second distance of 1,000 km represents transportation to a theoretical dedicated wind turbine blade recycling facility. While this distance remains uncertain, the current scenario of 1,000 km aligns with larger distances of transport to current pilot-scale facilities.

Figure 21 shows the GHG emissions of the size reduction and transportation scenarios considered. Across all scenarios, truck transportation has the largest share of GHG emissions. Consequently, the packing efficiency and transportation distance have a significant relative impact on GHG emissions. However, this impact is far more pronounced for longer distances, as with the 1,000-km scenario. This means that on-site shredding may be more important to reduce GHG emissions if recycling facilities are located further away. Evaluating these emissions along with economic considerations would help identify the trade-offs between different size reduction approaches as well as an optimal solution for a given location.

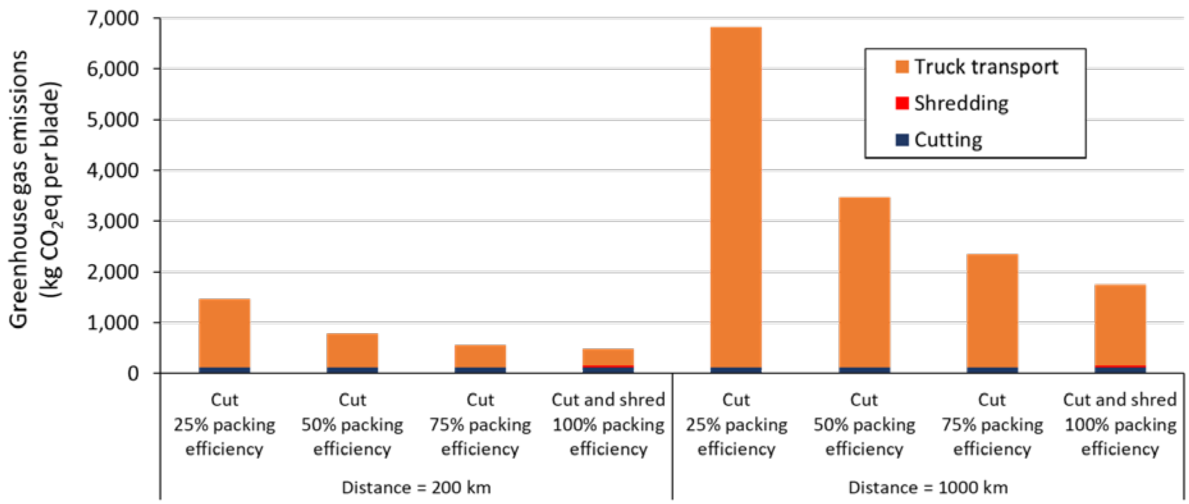

Figure 21. Life cycle GHG emissions from eight different downsizing and transportation scenarios. *Figure by Evan Sproul, SNL.*

3.6.2.7 Uncertainty Analysis Results

After developing size reduction and transportation scenarios, we considered the next two scenarios: an overall optimistic and conservative scenario. We developed these scenarios to capture the simultaneous effect of adjusting all process model input parameters to their best or worst value. While these scenarios are unlikely to represent real-world outcomes, they are useful in defining likely upper and lower bounds of uncertainty for each technology. Net GHG emission results from the optimistic and conservative scenarios are shown in Figure 22, with a functional unit of one kilogram of solid recycled material. These results show the total cumulative uncertainty of net GHG emissions for each recycling approach, and inherently account for the mass yield of solid recycled materials (primary and secondary solid materials from Figure 19). Within the figure, all approaches show a wide range of uncertainty due to the breadth of different approaches available in literature. While the general trends across recycling approaches remain similar between the baseline, optimistic, and conservative scenarios, some findings do change depending on the scenario considered. For example, the conservative bound of cement coprocessing has net-positive GHG results due to a conservative assumption regarding cement kiln fuel mixtures. In this scenario, the fuel of the kiln is assumed to be 43% natural gas, meaning that the incineration of a blade has a lower effect on GHG emissions than in the baseline scenario where more coal is used in the kiln. In another example, pyrolysis shows the potential for an optimistic net negative result. This result is dictated by an optimistically low input for pyrolysis energy consumption (10 MJ/kg) and a high value of the recovered fiber (100%). Based on the wide uncertainty bands for pyrolysis and solvolysis, we also performed a sensitivity analysis to identify which individual input parameters are most sensitive to uncertainty. Figure 23 displays the top six most sensitive parameters to uncertainty. In both approaches, energy consumption and fiber yield are highly sensitive to uncertainty.

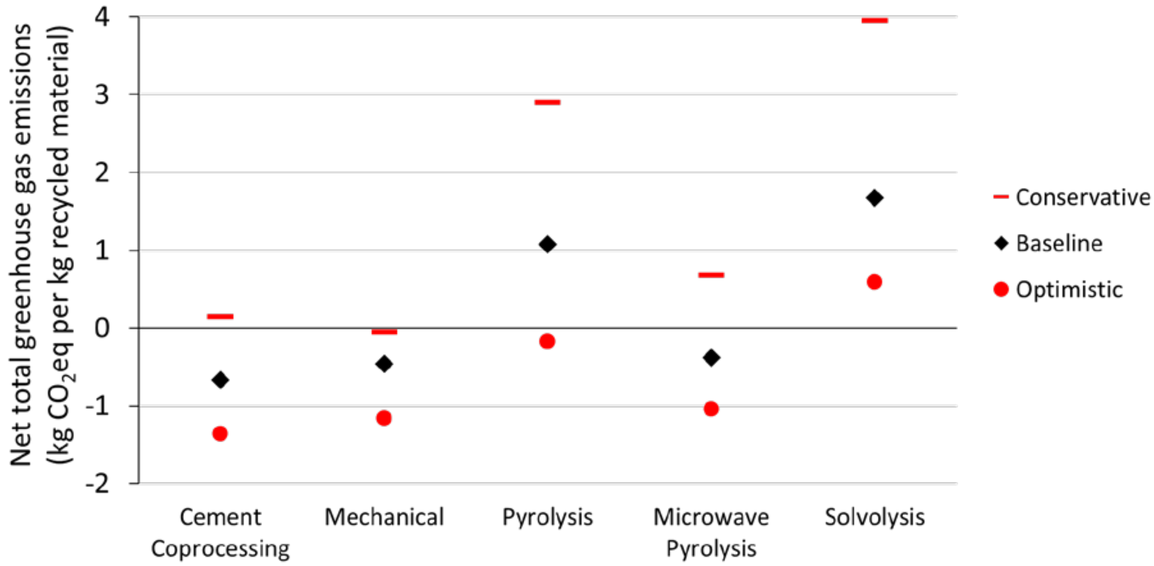

Figure 22. Optimistic and conservative scenario net GHG emissions compared with the baseline results. *Figure by Evan Sproul, SNL.*

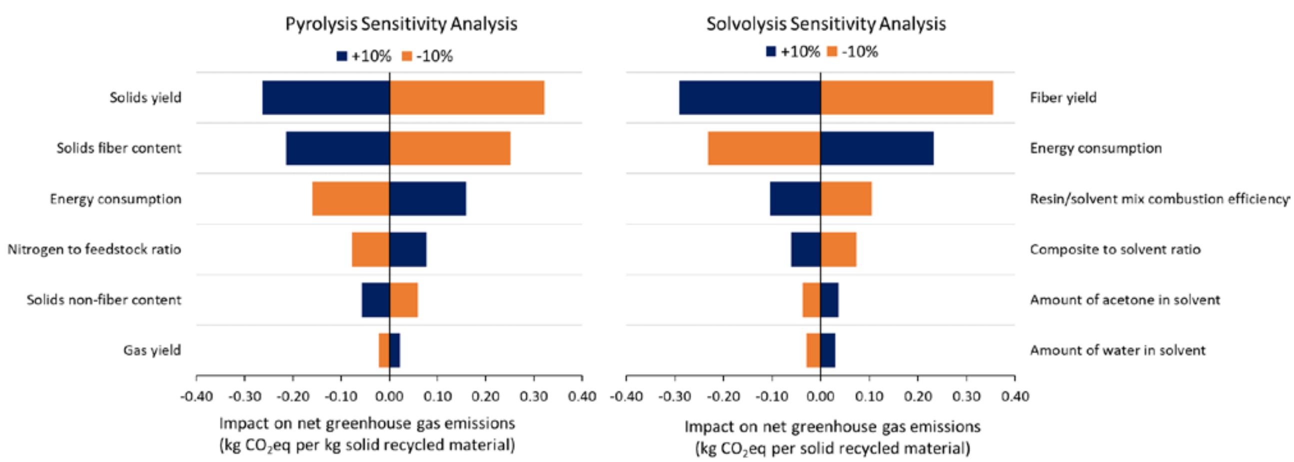

Figure 23. Sensitivity analysis of adjusting individual input parameters by 10%. *Figure by Evan Sproul, SNL.*

3.6.2.8 Low-Carbon Energy Scenario Analysis Results

The final two scenarios we considered focused on low-carbon energy sources for both electricity and thermal energy. The first scenario looks at the potential emission reductions based on electricity being supplied by a projection of the 2035 U.S. electrical grid mix (Cole et al. 2021). The second scenario considers this same electrical grid mix, but also analyzes the impact of introducing a low-emission fuel source such as green hydrogen or biomethane for all thermal energy demand. Based on data from Ecoinvent, this fuel source is estimated to have emissions of 0.015 kg CO_2 eq per MJ of heat delivered, which aligns with optimistic estimates for green hydrogen production via renewable energy (de Kleijne et al. 2022). Figure 24 shows the impact of a 2035 electrical grid mix that is mostly decarbonized and the additional impact of low-emission fuel sources. The 2035 electrical grid reduces GHG emissions by 1%–23% across different recycling approaches. The largest impacts are on mechanical recycling and microwave pyrolysis, which experience reductions of

12% and 23%, respectively. Simultaneously adding a low-emission fuel for thermal energy results in a total reduction of emissions ranging from 0%–44% across the recycling approaches. The largest reductions appear in solvolysis and pyrolysis, which are reduced by 40% and 44%, respectively. Meanwhile, no reduction occurs for cement coprocessing because thermal energy GHG emissions come from incinerating the wind turbine blade resin. Across all approaches the decommissioning, on-site size reduction, and transportation steps are estimated to operate via standard diesel power and are not impacted by the 2035 grid or low-emission fuel scenarios.

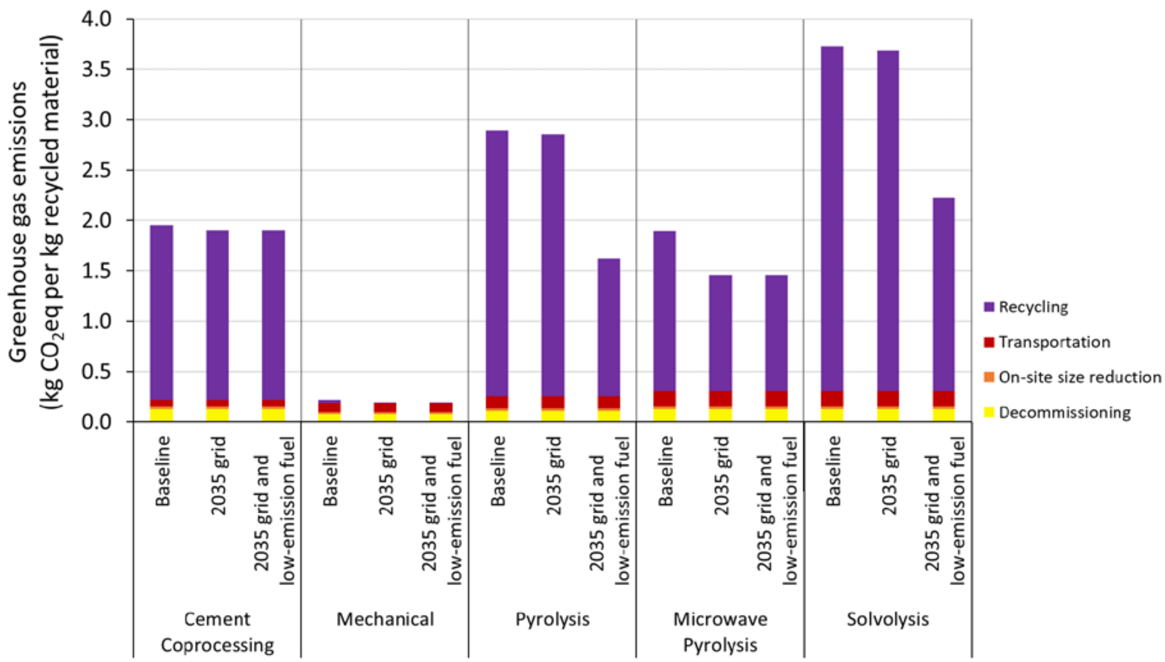

Figure 24. GHG emissions for different recycling approaches with a 2035 grid mix and low-emission fuel source for thermal energy. *Figure by Evan Sproul, SNL.*

3.6.3 Decommissioning and Recycling Metrics for Blades

Table 20 summarizes each blade recycling approach: cement co-processing, mechanical recycling, pyrolysis, microwave pyrolysis, and solvolysis. GHG emission results of the previous sections are included, along with other metrics defined within the LCA. We defined the ranges for each metric via the conservative and optimistic LCA results. Negative results indicate that the credit for recycled materials exceeds the burden of the recycling process. Currently, economic metrics including the cost of recycling and selling price of the recycled materials are not included, as that information is often proprietary or based on limited data. However, future work will include an independent assessment of these economic metrics through techno-economic analysis. Future decommissioning and recycling technologies for blades should ideally perform better than the metric values indicated here, allowing for more sustainable end-of-life practices for wind turbine blades.

Table 20. Metrics for Existing Blade Decommissioning and Recycling Approaches

Metric	Units	Cement Coprocessing	Mechanical Recycling	Pyrolysis	Microwave Pyrolysis	Solvolysis
Net greenhouse gases	kg CO_2 eq per metric tonne of recycled component	-1,360 – -30	-1,164 – -58	-177–2,899	-1,042–676	593–3,949
Net embodied energy	MJ per metric tonne of recycled component	-25,000–-12,000	-16,000–1,000	-6,000–35,000	-29,000–-3,000	-7,000–47,000
Net water consumption	m^3 per metric tonne of recycled component	-1–3	-7 – -2	6–18	9–16	-9–5
Cost of recycling	$/metric tonne	Data	Withheld[45]			
Recycled material selling price	$/metric tonne	Data Withheld[37]				
Process yield	%	55%–57%	95%–99%	60%–80%	60%–80%	58%
Recycled material quality	Material-specific (i.e., purity, tensile strength)	100% (clinker)	30%–80% (fiber tensile strength)	50%–90% (fiber tensile strength)	50%–90% (fiber tensile strength)	50%–90% (fiber tensile strength)
Technology readiness level	1–9 scale	8/9	8/9	7/8	4	

3.6.4 Assessment of Secondary Markets for Recovered Blade Material

3.6.4.1 Environmental and Economic Salvage Value of Blade Materials

Secondary markets are industries that reuse recovered fibers (e.g., glass and carbon fibers) and resins (if feasible) from blade recycling processes to create new end products. Identifying large-volume, environmentally conscious, and profitable secondary markets that accept recovered blade materials is pivotal to sustaining the blade recycling industry. Reusing fibers and resin materials in these secondary applications could retain economic value and has the potential to offset fractions of life cycle emissions resulting from

[45] Authors determined the data for cost of recycling and recycled material selling price metrics not to be of reasonable certainty at the time of this study. Such data could include but are not limited to labor and cycle times, material value in secondary markets, U.S. market supply and demand dynamics, and other regional and economic factors relevant to U.S. geography. Some data collected are proprietary and do not reflect broader recycling technology performance. In Part 2 of this report series, we will release a detailed technoeconomic assessment of the blade recycling technologies including relative impacts of key factors affecting these economic metrics.

primary material production. This potential is shown in Table 21, which summarizes the life cycle environmental impact metrics and selling prices for major blade materials in current and future blade designs. Existing blade designs are made primarily of epoxy-based glass-fiber-reinforced composited and balsa wood. Future blade designs may have more carbon fibers, especially in spar caps, to assist in lightweighting of longer blades while maintaining performance. Additionally, future blades could be made of separable thermoplastic resin systems that are acrylic-based, such as Arkema's Elium. Blade materials have environmental and economic trade-offs that may help prioritize recovery of some materials. Examining the impacts of these potential future blade designs on their recyclability is beyond the scope of this study and will be communicated in Part 2 of this report series.

Table 21. Life Cycle Environmental Impact Metrics and Current Selling Prices for Major Blade Materials in Current and Future Blade Designs

Primary Production Metrics	GHGs	Embodied Energy	Human	Toxicity	Water Consumption	Selling Price
Units	**kg CO_2 eq./kg**	**MJ/kg**	**kg 1,4-DCB/kg (Noncancer)**	**kg 1,4-DCB eq./kg. (Cancer)**	**m^3/kg**	**Selling Price ($/kg)**
Glass fibers	3.18–4.10	48.8	11.40	0.03	5.99	1.87–3.00[46]
Carbon fibers	13.80	231	2.61	0.01	2.00	30.00
Epoxy resin	7.08	135	2.23	0.07	0.43	3.63
Acrylic recyclable resin	7.04	120	0.12	0.03	0.12	6.83

In existing wind turbine blade designs, epoxy resin has about twice the life cycle GHG impacts per kilogram as virgin glass fibers. Nonetheless, life cycle human toxicity and water consumption for glass fibers are many times higher than those of epoxy or acrylic resin systems. These impacts are driven primarily by upstream hazardous incineration of waste byproducts and subsequent wastewater treatment from material production facilities. Thus, recovering and recycling glass fibers from existing and future blades is important to reduce toxicity and water consumption in the wind energy industry. However, from a cost viewpoint, epoxy resins are up to twice as expensive as glass fibers, depending on the material supplier. Furthermore, the price of separable acrylic resin systems is nearly double that of epoxy resin systems. Therefore, manufacturers may have significant interest in recovering and reusing resin systems at the end of life for wind turbine blades.

[46] The price of glass fibers ranges according to the different fabric orientations required for blade assembly and manufacturing (e.g., uni, bi, and triaxial). Selling prices of fiber and resin materials were obtained from Bortolotti et al. (2019). We corresponded with blade original equipment manufacturers and these current prices, although slightly higher, do not vary significantly from the values reported in the referenced study.

3.6.4.2 Impact of Blade Recycling Processes on Reusability and Sustainability of Recovered Materials

None of the processes modeled in this analysis can recover thermosetting epoxy resin. In cement coprocessing, resin is incinerated with energy recovery and thus permanently lost. In pyrolysis, the resin is converted to gases or oils that are incinerated for energy recovery or sold as downcycled coproducts. In the solvolysis process, epoxy resin is permanently damaged by breaking covalent ester bonds of the polymer chain due to its thermosetting nature and only monomers are left behind that were modeled to be separated and incinerated for energy recovery (Bodaghi, Park, and Krawczak 2022; Meyer zu Reckendorf et al. 2022). Table 21 shows that the selling price of resin is up to four to six times higher than the cost of glass fibers; yet the use of fiber and resin is similar. Because epoxy resin systems cannot be recovered and resold, profit margins of traditional, large-scale recycling processes of current blade designs are significantly reduced (Beauson et al. 2022; Oliveux, Dandy, and Leeke 2015). Recovering resins improves revenue resulting from recycling process operation compared to obtaining cost credit of energy recovery. Emerging recyclable epoxy curing agents or recyclable epoxy-based resins, such as Recyclamine by Aditya Birla, may help recover epoxy resins by using a solvolysis treatment that is more benign and retains resin polymeric structure than using traditional solvents (La Rosa et al. 2018; Aditya Birla 2023).

Thermoplastic resins, particularly acrylic-based, have become a viable choice for wind blade manufacturers due to their low glass transition temperature, compatibility with pultrusion processes, and recyclability. Prior work demonstrated the feasibility of recovering near-virgin properties of glass fibers and acrylic resin suitable for reuse using chemical dissolution followed by polymer extrusion (Jagadeesh et al. 2022; Cousins et al. 2019). The next generation of wind turbine blade designs may offer reduced labor and cycle times that contribute substantially to the cost of blade production, offer a more modular design to overcome larger blade transportation logistics, and enable full recyclability of blades (Blok et al. 2018; Bortolotti et al. 2019, 2023).

While both pyrolysis and solvolysis of thermoset-based composites have relatively high recovery yield for glass fibers, the quality of recovered fibers has been shown to deteriorate. Glass fibers recovered at operating temperatures of traditional or fluidized-bed pyrolysis show a loss of up to 80% of their tensile strength (Pickering et al. 2000; Oliveux, Dandy, and Leeke 2015). Additionally, on-site shredding operations during blade decommissioning can result in short, discontinuous fibers, further reducing performance and compatibility with subsequent composite processing techniques used in a wide range of end-product applications (e.g., automobile parts, marine equipment, medical instruments, consumer electronics). Similarly, harsh reagents (e.g., acids and abrasives) and operating conditions of high-yield solvolysis processes of epoxy-based composites have been shown to reduce tensile strength and stiffness of recovered glass fibers (Mattsson et al. 2020; Buggy, Farragher, and Madden 1995; Gonçalves, Martinho, and Oliveira 2022).

Existing research gaps include developing processes that reduce the operating temperature of pyrolysis and solvolysis processes, as well as using green solvents in solvolysis approaches that still enable high-quality fiber recovery (Tapper et al. 2019; Oliveux, Bailleul, and Salle 2012; Prinçaud et al. 2014). On the other hand, chemical dissolution of thermoplastic-based composites has demonstrated full-length fiber recovery with near-virgin fiber qualities (Cousins et al. 2019). Using milder solvents, such as acetic acid instead of nitric acid, and low-temperature operation of the thermoplastic dissolution process retains fiber quality and performance. Table 22 summarizes the process yield and life cycle GHG impacts of different recycling options for current and future wind turbine blade designs.

Table 22. Summary of Process Yield and Net Change in Life Cycle GHG Emissions of Pyrolysis and Solvolysis for Recovered Fibers and Resin Systems

Blade Type	Thermoset (Epoxy-Based)		Thermoplastic (Acrylic-Based)
Recycling Process	**Pyrolysis**	**Solvolysis**	**Solvolysis**
Glass fiber yield (%)	95	95	99
Carbon fiber yield (%)	N/A	N/A	95
Resin yield (%)	N/A (combusted)	N/A (decomposed)	90
Recycling Process	**Pyrolysis**	**Solvolysis**	**Solvolysis**
GHG impact per kg of recovered fiber	4.2	3.83	0.93
GHG impact per kg of recovered resin	N/A	N/A	3.08
Change in GHG compared to virgin glass fiber (%)	+32	+20	-243
Change in GHG compared to virgin resin (%)	N/A	N/A	-56%

Recycling epoxy-based composites using baseline pyrolysis and solvolysis yields higher life cycle GHG emissions than primary glass fiber production. High energy consumption and using large volumes of energy-intensive solvents are the main contributors to outsized life cycle GHG impacts for pyrolysis and solvolysis recycling processes. As a result, these processes diminish any potential life cycle environmental benefits from reusing fibers in other applications. This result also excludes transportation and further processing of recovered fibers in their secondary market application. Findings are subject to significant variation upon changes in assumptions about process operating conditions and LCA modeling choices. Additional research is needed to quantify life cycle GHG impacts of innovative recycling concepts of epoxy-based systems. However, in the medium and longer terms, using thermoplastic resin systems in wind turbine blade manufacturing could help improve recyclability of fibers. However, the economic impacts of this design change are outside the scope of this study.

3.6.4.3 Applications for Recycled Fibers

The U.S. composite market volume was estimated to be 1.9 million metric tonnes as of 2022, worth $17.8 billion (IBIS World 2022). Wind energy contributes less than 10% of the total demand of the composite industry, whereas automobiles, aerospace, defense, and construction have the largest market share. A wide range of applications that use fiber-reinforced composites also exist in medical instruments, consumer electronics, and sports equipment (Duflou et al. 2012). Some products and parts, such as blade shells and automobile door skins, require high-quality continuous fiber (Puri, Compston, and Pantano 2009; Bortolotti et al. 2019). However, most composite products use intermediate composite pellets, which are made by infusing chopped fiber with an appropriate resin, such as polypropylene and polyamide, that can then be used as an input to composite manufacturing processes (e.g., extrusion, resin transfer molding) to yield the final product shape (Potter 2023). These applications can use discontinuous fibers but still meet strength and stiffness requirements depending on performance needs. Polypropylene and polyamide are thermoplastic-based composite materials and are the most used. Table 23 summarizes the fiber content, life cycle GHG emissions, strength, stiffness, and cost range of polyamide and polypropylene intermediate materials.

Table 23. Cost, GHG Emissions, and Material Quality Comparison Between Polyamide and Polypropylene Intermediate Composite Materials

Secondary Fiber Market	Fiber Content (% wt.)	GHG Emissions (kg CO_2 eq./kg)	Strength	Stiffness	Cost	Potential Applications
Polyamide intermediate materials	20–70	7.3–9.2	High	High	Medium	Automotive parts, machinery, sports equipment
Polypropylene intermediate materials	10–60	3.4–6.8	Medium	Medium	Low	Medical instruments, food packaging, consumer electronics, automotive parts

Polyamide intermediate materials are often used for high-performance consumer applications (Wei et al. 2022; Balaji, Rudd, and Liu 2020; Hassan et al. 2022), and thus might require higher fiber content and quality. On the other hand, polypropylene intermediate materials could be used in applications that do not require high strength or stiffness, such as food packaging or automobile parts (e.g., acoustics). Life cycle GHG impacts are generally higher for polyamide composites than polypropylene counterparts because polyamide resin manufacturing is more energy-intensive than polypropylene (Banerjee and Ray 2022). However, specific fiber content and additives used in various composite types affect which manufacturing method requires more energy.

A few scalable techniques have been demonstrated to regenerate lost fiber properties from thermal recycling approaches, such as pyrolysis, through chemical etching and postsalinization (Yang et al. 2015; Thomason et al. 2016). These techniques have demonstrated near-full recovery of lost tensile strength, interfacial shear strength, and surface morphology of glass and carbon fibers. Existing research gaps include demonstrating scalability, sustainability, and profitability of these fiber regeneration pathways. Baseline pyrolysis already shows inferior life cycle GHG performance compared to primary fiber production. Therefore, investments in reducing the energy consumption and ancillary fiber regeneration steps are needed to sustain thermal recycling business models.

Tailoring recovered fibers from wind turbine blade recycling processes to meet performance requirements for individual applications is a challenge for those involved in the wind energy supply chain. From a blade recycler’s perspective, investing in additional steps to reprocess recovered fibers needs to be justified by guaranteeing a customer base that has a sustained demand for fibers. From a secondary market perspective, there are more complications to consider for accepting recovered fibers including the state and quality of the fiber, steadiness of supply, ability to meet product performance standards, and cost competitiveness with primary fiber production. Secondary industries are also risk-averse because there are no standard tests or protocols for products with recycled fiber or resin content to assure consumer confidence. Developing standard recovered fiber testing procedures similar to International Electrotechnical Commission or ASTM standards is important to imposing a technical benchmark for reusing fibers in secondary applications.

Organizing consortiums of composite manufacturers, blade recyclers, and researchers is one impactful way to iterate on recycling process design and product development that could facilitate fiber reprocessing and reuse in secondary applications. An example of this is the European Union's FiberEUse project that aims to show a large-scale demonstration for fiber applications in three areas: thermal recycling, mechanical recycling, and inspection, repair, and remanufacturing for high-performance applications (Yan et al. 2020). The project seeks to overcome the main bottlenecks for each blade recycling pathway. For example, in thermal recycling, optimizing low-temperature pyrolysis, recovering long fibers, resizing recycled fibers, and improving pyrolysis process parameters to reduce operating costs are the four key challenges for fiber reuse in automotive parts such as clutch pedal and front-end carrier. In mechanical recycling, optimizing and automating mechanical grinding to lower operating costs and developing low-cost and environmentally friendly fiber surface finishing techniques (e.g., ultraviolet curing) are important steps toward reusing recovered fibers in consumer products (e.g., kitchen panels, orthopedic parts). The United States could benefit from similar efforts that optimize recycling operations for specific end-use markets.

Additional modeling and analysis work is needed to examine the consequential economic and environmental implications on specific secondary applications. Such work could shed light on the magnitude recycling credits taken under different market maturity scenarios and trade-offs in fiber property, application, and cost of recycling.

3.6.5 RD&D Needs, Gaps, and Opportunities for End-of-Life Management Practices for Blades

There are many opportunities for fundamental and applied research to improve recycling rates, cost-effectiveness, and environmental sustainability of recovery and recycling pathways for wind turbine blade materials. Table 24 provides the RD&D priorities for improving end-of-life practices for blade materials and the potential impacts of implementing those innovations.

Table 24. RD&D Priorities for End-of-Life Practices for Blades and Potential Impacts of Investments

RD&D Technological Innovation	Potential Impact
Reduce energy consumption of pyrolysis and solvolysis recycling processes	• Reduce GHG emissions • Lower costs
Create specific products for sufficiently high-volume markets using mechanically recycled materials	• Increase likelihood of market adoption • Enable mechanical recycling
Demonstrate microwave pyrolysis at a larger scale in the United States	• Increase likelihood of electrified pathway for blade recycling • Reduce net GHG emissions

RD&D Technological Innovation	Potential Impact
Increase quality of fibers recovered through pyrolysis, microwave pyrolysis, and solvolysis	• Increase likelihood of market adoption • Increase revenue for recyclers • Reduce net GHG emissions
Define optimal logistics for blade decommissioning and transportation to facilitate recycling, considering on-site shredding	• Reduce net GHG emissions • Reduce costs • Increase recycled material quality and/or throughput
Investigate improved methods of blade segmenting such as water and laser cutting, as well as intelligent separation of high-value blade components like carbon fiber	• Reduce costs • Increase recycled material quality and value • Increase throughput and supply chain scale-up
Increase understanding of material recovery and secondary markets for reversible thermoset and thermoplastic materials	• Increase adoption of recyclable polymers in wind energy • Increase revenue for recyclers
Develop cost estimates for recycling processes and selling prices for recycled materials	• Quantify the economic metrics for comparing recycling processes • Identify market opportunities for recycled materials
Increase certainty of life cycle assessment through continued collaboration with recyclers	• Increase confidence in environmental performance of recycling
Analyze recycling processes and secondary markets for increased carbon-fiber content	• Identify additional recycling technologies that are suitable for conductive fibers • Assess the opportunity for recycling higher-value carbon-fiber materials
Characterize emerging recycling processes, such as high-voltage pulse fragmentation and fluidized bed	• Identify opportunities and challenges for emerging technologies compared to existing recycling processes
Increase understanding of the timeline for decommissioned wind turbine blades based on volume, location, and constituent materials	• Assist recycling companies to strategically locate future facilities • Reduce logistics cost and GHG emissions for blade recycling
Quantify the recycled material quality and mechanical performance	• Increase certainty in emissions credit and market suitability • Identify opportunities for various recycling processes and specific market applications
Standardize material qualification for mechanical recycling processes with structural applications	• Improve certainty in mechanical performance • Assist with market adoption for more circular recycling processes
Characterize the benefits and opportunities for front-end design approaches to reduce	• Increase sustainability of wind blade materials • Generate higher value for end-of-life wind blade materials

RD&D Technological Innovation	Potential Impact
environmental impacts from wind blade materials and enable greater resource recovery at end of life	
Identify opportunities for wind turbine supply chains to increase recycled content	• Increase circularity of wind turbines • Create markets for recycled content

3.7 Power Electronics, Substations, and Cables

Power electronic systems refer to solid state parts that can convert, distribute, and control electricity flow generated from wind turbine generators to the grid interface and their ancillary cables. These parts may include, but are not limited to, the following:

- Alternating current (AC)/direct current (DC) and DC/AC inverters (i.e., converters)
- Power transformers
- Capacitors
- Sensors (e.g., anemometer)
- Heat sinks and thermal interface components
- Transistors (e.g., metal oxide semiconductor field-effect transistors and insulated gate bipolar transistors
- Diodes
- Printed circuit boards
- Array and export cables.

3.7.1 Material Breakdown for Power Electronics, Substations, and Cables

High-fidelity material composition data of power electronic systems used in wind power plants are scarce in existing literature and tools. For example, a 4-MW land-based wind power plant could use up to 8,000 different power electronic components (Razdan and Garret 2022). However, these components, which are typically housed in the nacelle, are relatively small and contribute only about 1% of total power plant mass for land-based systems (Bonou, Laurent, and Olsen 2016). Offshore wind power plants have substations that contain a higher number of electronic components that are larger in size. These substations could weigh up to 2,000 metric tonnes and may need to process extra-high voltages to obtain an efficient and reliable grid interface (Chen, Guerrero, and Blaabjerg 2009; Zhang and Tolbert 2010).

An independent survey of major electronic components for wind power plants and analogous electric vehicle power electronics shows that aluminum, copper, silicon, silver, palladium, steel, and compo sites are the primary materials used (Bulach et al. 2018; Razdan and Garret 2022). Semiconducting materials, predominantly silicon, comprise between 15% and 30% of total power electronics mass, and are used in many components such as transistors, printed circuit boards, transformers, and inverters (Chen, Guerrero, and Blaabjerg 2009). This material estimation is uncertain and additional research is needed to trace material composition of power electronic systems in wind energy. Aluminum is used primarily in housing casings and cables. Copper and other precious metals, such as palladium and silver, are used in connectors.

3.7.2 End-of-Life Management Practices for Power Electronics Materials

Disassembled and recovered end-of-life power electronic systems are often classified as e-waste, which is similar to consumer electronics (Kang and Schoenung 2005). This waste stream is often sent to material recovery facilities where material is sorted into different categories, such as reusable and hazardous parts (e.g., lead, cadmium, or mercury content). These parts are often separated and sold to other electronic manufacturers or sent to hazardous incineration facilities. The remainder metal parts are then reduced in size and different separation techniques are applied, such as magnetic and eddy current, to sort ferrous and nonferrous metals. Density separation is used to separate out plastics, such as PVC and PET, such as in the case for cables, which are later typically incinerated (Li et al. 2017). Components with a high metal content, such as aluminum housing or circuit boards, could be easier to recycle with mechanical means rather than solvent-intensive chemical means (Li et al. 2007). After mechanical or chemical extraction, individual metals are sent to their respective processing facilities such as aluminum and copper smelters and EAF steel plants.

To date, recycling semiconductor materials is a challenge to the electronics and renewable energy industry (Ikhmayies 2020; Guo et al. 2021). The semiconducting industry is nascent in the United States and recycling is being actively investigated with small-scale semiconductor recyclers trying to scale-up various mechanical, thermal, and chemical process models. Recovery of high-grade instead of metallurgical-grade silicon using cost-effective techniques is currently the most significant challenge for profitable silicon recycling (Deng et al. 2019; Heath et al. 2020). Silicon is deemed a critical material, and its high-value recycling could be prioritized in the near future to cope with the rising volume of electronic waste.

Diodes and transistors also contain critical materials such as gallium arsenide or gallium nitride. Several targeted hydrometallurgical techniques have been demonstrated at the lab scale for gallium (de Oliveira, Benvenuti, and Espinosa 2021; Zhan et al. 2020). These demonstrations rely on combined thermal and chemical leaching approaches to increase gallium recovery yields. Gallium compounds exhibit refractory characteristics that could complicate its separation and subsequent processing.

3.7.3 Decommissioning and Recycling Metrics for Power Electronics Materials

Life cycle inventory data appear to be extremely scarce for power electronic components used in wind energy systems. Yet, these systems should not be marginalized as widespread deployment of wind energy begins. Except for semiconductor materials, environmental benefits to recycling these systems have been reported in a few studies arising mainly from recycling nonferrous metals. Up to 10,000 kg CO_2 eq. were avoided per metric tonne of recycled power electronics (Fraunhofer 2023). It is important to note that the impacts of silicon and silicon carbide recovery were not analyzed in this report due to time constraints. However, because both are critical materials and power electronics are known to have higher failure rates than the rest of the components, future research would help address material intensity and recyclability of replacing silicon with silicon carbide.

Recycling power electronic components is generally profitable in the United States (EPA Recycling Economic Information 2020). The cost of recycling power electronics, including transportation and material processing, to extract mainly aluminum and copper is on average $800-$950 per metric tonne. Selling prices of subcomponents are $1,000–$1,500 per metric tonne, excluding material assembly and installation. Specific prices for individual components were difficult to find and require a more detailed assessment. Data transparency for power electronic components in LCA and TEA studies could resolve this gap in the future. In addition, future research and development for production and recycling of silicon carbide and gallium nitride materials in wind energy power electronics is a priority.

3.7.4 RD&D Needs, Gaps, and Opportunities for End-of-Life Management Practices for Power Electronics Materials

There are many opportunities for fundamental and applied research to improve recycling rates, cost-effectiveness, and environmental sustainability of materials recovery and recycling pathways from power electronics. Table 25 provides the RD&D priorities for improving end-of-life practices for power electronics components and the potential impacts of implementing those innovations.

Table 25. RD&D Priorities for End-of-Life Practices for Power Electronics and Potential Impacts of Investments

RD&D Technological Innovation	Potential Impact
Quantify materials used for power electronic systems and trace their intensity evolution	Fill existing data gaps for more robust LCA and TEA
Prioritize research and development of high-performance materials, such as silicon carbide, in future power electronics	Enable deployment of larger wind turbine systems with cost and weight savings
Develop research programs on reliability and durability that enable longer lifetimes of power electronic components	Reduce the need to recycle power electronics as frequently and reduce logistics cost of such recycling (e.g., disassembly, replacements, transportation, recycling)
Develop innovations that emphasize high-yield recovery of critical materials in power electronic systems	Reduce future demand on critical materials in wind balance-of-system applications

3.7.4.1 Potential Impacts of Substituting Silicon With Silicon Carbide in Future Power Electronics

As wind turbine designs gets larger, limited space and weight require increasing efficiency of power electronic components to reduce associated costs of equipment cooling systems and transmission as well as reduce electricity conversion losses. Using silicon carbide instead of traditional silicon has been demonstrated to exhibit superior material properties, such as faster switching, higher-voltage transmission loads, faster heat dissipation, and better tolerance to harsh operating conditions (Zhang and Tolbert 2010; PowerAmerica 2018). These characteristics could offer a wide range of cost and performance advantages, especially for offshore wind energy systems (Tiwari et al. 2018). Silicon carbide could be used as a substitute for silicon in inverters and transistors, which could also improve balance-of-system costs and overall wind levelized cost of energy (reve 2019). Silicon carbide is a critical material according to the 2023 DOE Critical Materials and Minerals List (DOE 2023). Although the current silicon carbide market comprises less than 4% of the total power semiconductor market, the market share is expected to increase over the next few years (Bauer et al. 2023). The United States is currently the world leader in the production of wafers per year of silicon carbide substrates. However, silicon carbide chip production is evenly split between the United States, Japan, and Europe (Horowitz, Remo, and Reese 2017).

Most silicon devices are manufactured from high-purity, industrial-grade silicon by growing silicon ingots through the Czochralski process at about 1,425°C. Silicon carbide is traditionally produced via the Acheson process, which involves heating quartz sand and petrol coke in a furnace to around 2,500°C. Energy consumption and life cycle GHG emissions for silicon carbide could thus be higher than traditional silicon (Horowitz, Remo, and Reese 2017). However, considerable uncertainty exists in the process model data used for LCA and there is a lack information on the impacts of design changes and efficiency gains between both systems. As a result, comparative life cycle assessment of silicon carbide and silicon including these factors is encouraged. Decarbonizing silicon carbide production via dramatically reduced energy consumption technology innovations is a priority to reducing the environmental impact of emerging power electronic systems. An example of this is the RECOSiC process developed at the Fraunhofer Institute of Ceramic Technologies, which consumes 80% less energy than the Acheson process (Diaz 2021).

4 Community Planning and Social Impacts

4.1 Community Planning

Though recycling is often thought of as an activity occurring at the end of a wind energy project's useful life, the planning and coordination efforts that determine whether a project and its components will be fully recycled typically begin earlier in the project's life or even before it is proposed. Factors such as local and state regulations and policies; project developers' perception and approaches regarding recycling; project location; proximity to recycling solutions; processing costs; and availability of recycling solutions are all influential in shaping how much recycling will occur. The key aspects of regulatory or developer decision-making that can impact how much of a given wind project is recycled (i.e., project recyclability) include standards at the state and local level for removing underground components, developer/owner requirements for recycling blades and other composite materials, and the standards or requirements within wind project decommissioning plans.

Authority over wind energy activities—including end-of-life activities—can be at the state or local level, or a combination thereof, and depends on location, with each state or local authority developing their own standards and regulations. This approach can create patchwork regulations, making it challenging for project developers to ensure consistency across their portfolio. Additionally, this lack of consistency could cause project developers/owners to determine that a community or state's end-of-life standards are too restrictive for wind energy deployment.

Decommissioning standards within ordinances/regulations often define removal depth requirements for underground infrastructure (e.g., cables and foundations). These requirements often consider land type and use with some areas requiring full removal and others requiring partial removal to a depth of 3–5 feet. Land-lease agreements may also include language related to the removal of underground infrastructure. Regardless of how removal depth requirements are established, partial removal of underground infrastructure is more common than full removal for reasons such as cost and reducing disturbance to the land. One consequence of leaving these components partially in place, however, is that it limits the total recyclability potential of a project. Even if full removal occurs, there is no guarantee within local or state regulations that the infrastructure will be recycled, though the materials within these components are generally considered more easily recyclable than composite materials.

While state and local decommissioning standards often address removal of underground infrastructure, they do not typically address whether those materials are disposed of or recycled. Additionally, local decommissioning requirements do not typically address whether blades or other composite components are recycled when they reach their end of life. Thus, in the absence of regulations or requirements, project developers tend to have full control over recycling decisions for these components. Developers and blade manufacturers with recycling commitments or other internal sustainability goals or policies thus play a significant role in encouraging the development of recycling solutions and capabilities. However, not all developers are committed to composite recycling and instead choose wasteful disposal, as it is generally the lowest cost and most readily available processing method for composite components. While landfill bans at the state and local level could force industry to find or create more recycling solutions for these components, this patchwork of bans has the potential to relocate wind energy waste to other communities and/or states that accept those materials.

In addition to decommissioning standards for underground infrastructure and landfill bans, states and/or local communities can require decommissioning plans from owners/developers as part of the siting and permitting processes for a new wind energy project. Decommissioning plans normally focus on priority community concerns issues like financial surety (financial guarantees that ensure decommissioning/project removal can be conducted regardless of the financial viability of the project owner) and component removal, but state or local governments may also require that plans include additional details about how components are processed when they reach end of life. For example, some communities have required developers to include language about blade recycling within these plans. Additionally, decommissioning plans often include cost estimates for the various activities that are part of the decommissioning process. These estimates are used during the surety process to ensure financial guarantees cover the costs of decommissioning activities and should reflect blade recycling costs if they are included as part of the decommissioning plan. States and local communities can require project developers/owners to update estimates and sureties to reflect changes in cost and decommissioning practices at a defined frequency (typically every 3-5 years).

Most state and local end-of-life regulations have focused on decommissioning and associated activities, without considering repowering. Thus, the processing methods for components that have reached their end of life due to repowering are not typically defined within state or local wind energy regulations or decommissioning plans. Instead, the repowering process often requires new or renewed permits. Some state or local authorities may use this midlifetime permitting process as an opportunity to ensure that blades and other composite components are not disposed of locally or that they are recycled.

Because recycling-related decisions are made throughout and beyond the lifetime of a single wind energy project, there are many opportunities for communities and participating landowners to engage with project owners/developers and state agencies with permitting authority that can impact the overall recyclability of a wind energy project. These opportunities can include hosting public meetings during project development or updating local/state wind energy regulations; establishing decommissioning requirements and waste management standards; and hosting public meetings during project siting and permitting processes for a new project or for the repowering of an existing project. Finally, landowners that are hosting wind turbines on their land may engage with developers about end of life and recycling during land-lease negotiations.

4.2 Social Aspects of Recycling Wind Systems

Recycling activities have positive social impacts, such as creating jobs and conserving natural resources, but also negative ones, such as generating dust, noise, and traffic, which often disproportionally affect disadvantaged communities (Symanski et al. 2023). The main stakeholder categories impacted by recycling are local communities, workers, and society as a whole (Ardolino et al. 2023). For instance, plastic recycling can affect the health and safety of workers and local communities and provide economic development opportunities for local communities and the broader society (Ardolino et al. 2023). In the United States, recycling programs also often create environmental justice[47] challenges for consumers as many households in disadvantaged communities may lack access to affordable (or free) recycling programs (Karasik et al. 2023).

Social impacts and environmental justice issues are interrelated. The sustainability concept, for instance, addresses social impacts and asserts that efforts to protect the environment also need to ensure that benefits and burdens of sustainability are equitably distributed (Griggs et al. 2013). Environmental justice is a basic human right, which guarantees that people have agency over environmental decisions that impact their lives. In addition, addressing environmental justice concerns could improve the social acceptance of a new technology

[47] Environmental justice is defined by U.S. government in **Executive Order 14096**, *Revitalizing Our Nation's Commitment to Environmental Justice for All*, 88 Fed. Reg. 25251 (April 21, 2023), as the just treatment and meaningful involvement of all people, regardless of income, race, color, national origin, Tribal affiliation, or disability, in agency decision-making and other Federal activities that affect human health and the environment so that people: (i) are fully protected from disproportionate and adverse human health and environmental effects (including risks) and hazards, including those related to climate change, the cumulative impacts of environmental and other burdens, and the legacy of racism or other structural or systemic barriers; and (ii) have equitable access to a healthy, sustainable, and resilient environment in which to live, play, work, learn, grow, worship, and engage in cultural and subsistence practices. Full text from executive order can be accessed here: https://www.govinfo.gov/content/pkg/FR-2023-04-26/pdf/2023-08955.pdf .

or policy. When people feel that they are not considered in the development of a new project—regardless how virtuous this project is for the environment—they may reject it. This reaction is especially the case when the project is perceived to be unfair to a certain segment of the population. Addressing social impacts and environmental justice aligns with the U.S. government's ambitions, such as the Justice40 Initiative, which sets a goal that 40% of the overall benefits of certain federal climate, clean energy and other investments flow to disadvantaged communities that are marginalized by underinvestment and overburdened by pollution.[48]

Social acceptance of wind turbines is a growing area of research (Batel 2020). In most states, local governments have at least some authority over wind project siting, so continued expansion of wind energy deployment requires the willingness of communities to host wind turbines (Bessette and Mills 2021). Prior research focused on identifying and evaluating the impact of various factors that can shape how potential host communities and/or other impacted communities respond to wind energy development. Some of the key factors that have been identified include concerns about living near wind turbines (e.g., noise disturbance, visual impacts), local socioeconomic impacts (e.g., landowner payments, tax revenues, property values), concerns about wildlife impacts from project operations, and perceptions of fairness and trust in planning and decision-making processes (Rand and Hoen 2017). Additionally, a growing number of research efforts have considered how social acceptance may change throughout a wind projects' life cycle; for example, communities may oppose or support decisions to repower or decommission projects (Windemer 2023).

Understanding the links between social acceptance of wind energy and energy justice is another growing area of research, as equity and community perceptions are key to shaping community response and acceptance to wind energy. For example, Walker and Baxter (2017) found that acceptance is contingent on the communities' perception of how fair the benefits and burdens of wind energy are distributed.

Beyond fair processes and distribution of benefits and burdens, it is important to consider how concepts like community identity, relationships with places (i.e., place attachment), and sense of ownership over wind energy projects can shape both social acceptance and perceptions of equity (Gill et al. 2023). Given that large-scale wind energy deployment requires the approval of host communities, it is imperative to address the social, economic, and environmental impacts of wind energy, including recycling.

4.2.1 Overview of Social Impacts and Environmental Justice

Some scholars have proposed extending the definition of "environmental justice" to include criteria for equity based on age, gender identity, disability, or sexual orientation (Calderón-Argelich et al. 2021; Sotolongo et al. 2021). However, environmental justice definition in Executive Order 14096 is most encompassing and detailed used (See footnote 47). Others concentrated on the fair distribution of environmental benefits, departing from the more common focus of environmental burdens (Choi et al. 2020). Thus, given the multiple definitions of environmental justice, choosing one has distinct implications for its formulation, implementation, and assessment. However, over the years, scholars have converged toward a common framework that evaluates environmental justice in the following areas: distributive justice, procedural justice, recognition justice, and structural justice[49] (See and Wilmsen 2022). The DOE Equity Action Plan defines "energy justice" as the goal of achieving equity in both the social and economic participation in the energy system, while also remediating

[48] The Justice40 Initiative was established in Executive Order 14008: Tackling the Climate Crisis at Home and Abroad. 86 Fed. Reg. 7619 (January 27, 2021). Full text of Executive Order 14008 can be accessed here: https://www.federalregister.gov/documents/2021/02/01/2021-02177/tackling-the-climate-crisis-at-home-and-abroad#p-163

[49] Distributive justice addresses the just allocation of resources, goods, and opportunities. Procedural justice addresses the fairness in processes for resolving disputes and allocating resources. Recognition justice addresses the recognition of human dignity and the effects of social hierarchy. Structural justice addresses institutions and systems and strives for them to function so that large groups of people are not disadvantaged.

social, economic, and health burdens on those historically harmed by the energy system ("frontline communities") (U.S. DOE Equity Action Plan 2023). Similar definition is adapted from Initiative for Energy Justice Workbook (Baker 2019). Environmental justice, energy justice, and climate justice are intrinsically intertwined. The social and environmental impacts of technologies are more closely related to distributive justice.

As mentioned earlier, social metrics are needed when assessing the sustainability of a technology (Griggs et al. 2013). Consequently, several of the 17 United Nations' sustainable development goals focus on social impacts (Carlsen 2022). The first goal, for instance, aims to reduce poverty worldwide, whereas the fifth goal promotes gender equality. The third and sixth goals focus on delivering clean water and air to all.

At a smaller scale, organizations (e.g., companies, nongovernmental organizations) may tackle social impacts under their corporate sustainability reporting activities. Frameworks and standards, such as the Global Reporting Initiative, Sustainability Accounting Standards Board, and ISO 26000 can guide companies in their efforts to positively contribute to sustainability—including its social aspects. The Sustainability Accounting Standards Board standards have identified the total recordable incident rate and percentage of the workforce under bargaining agreements as relevant social impact metrics for the waste management industry (Sustainability Accounting Standards Board 2023). This reporting increases transparency and accountability regarding the social burdens of companies' activities, which also help to address distributive environmental justice. In another example, the Global Reporting Initiative asks companies to evaluate—among many other sustainability indicators—the social and environmental impacts of their supply chains (Giannarakis 2023).

Tools such as social LCA (S-LCA), and TEA can be used to evaluate the social impacts of a technology. For example, the United Nations Environment Programme's S-LCA guidelines have an entire section regarding impacts on local communities, with indicators assessing topics such as the respect of Indigenous rights, the provision of safe and healthy living conditions, and local employment opportunities (Desai 2020. Regarding the social benefits (or positive impacts) a technology can have, Norris et al. (2021) proposed the Sustainability and Health Initiative for NetPositive Enterprise handprint framework, which quantifies positive environmental and social impacts.

4.2.2 Social Impacts of Composites and Rare Earth Elements Recycling

As this report demonstrates, more research into wind turbine blades (mainly made of fiber-reinforced composites) and permanent magnets recycling is needed. Next steps would include research and demonstration but also analysis work. Analysis may help guide technical decisions toward the most efficient or clean process and assess potential environmental impacts before they occur. Ideally, such analysis would also investigate social and economic impacts and address environmental justice.

4.2.2.1 Composites

We found only one S-LCA study for composites. Pillain et al. (2019) used input-output tables and the social hotspot database (a website that provides data to assess and manage the social risks of supply chains, such as labor rights, human rights, and health and safety) to calculate the impact of carbon-fiber-reinforced plastic recycling on direct and indirect employment (i.e., a positive social impact). However, we note that more research is needed to evaluate other social aspects of carbon-fiber-reinforced plastic recycling. While social LCA studies on composites recycling are sparse, several have assessed the social impacts of plastic recycling. Because composites are made of thermoplastic or thermoset plastic resins, plastics recycling studies are the closest proxy for examining social impacts of composite recycling. For example, one study looked at different end-of-life options for hard-to-recycle plastics waste from products such as electric and electronic equipment, vehicles, and buildings (Ardolino et al. 2023). Also, for composites, such plastic waste streams are complex to recycle, requiring advanced recycling solutions like dissolution and precipitation, supercritical fluid extraction, and catalytic pyrolysis. Overall, the study found that mechanical recycling and the supercritical fluid end-of-life options could bring the most social benefits to workers, local communities, and society because they pose limited risks for workers to be exposed to accidents, pose a low risk of exposing local communities to health impacts, create direct and indirect jobs, and contribute positively to environmental sustainability and the economy. Conversely, sanitary waste management and substandard options such as illegal dumping and open burning could cause the most adverse social impacts. Dissolution, precipitation, and catalytic pyrolysis are believed to bring social benefits, such as job creation, but pose greater risks to the health and safety of local communities than mechanical and supercritical fluid recycling due to emissions that are released into water and air. Finally, we note that the export of plastic waste needs to be tackled. Most countries outside Europe lack sufficient management of plastic waste.

In a Dutch study on recycled high-density polyethylene (HDPE) non-beverage bottles, Papo and Corona (2022) found that the social risks of recycling are higher than producing virgin plastic. Most social impacts occur outside of the Netherlands due to waste exports to countries that lack sufficient recycling practices, such as Pakistan or India. For all stakeholder categories and indicators within them—except for the workers' health and safety, local employment, and migration indicators—the recycled HDPE performs worse than its virgin counterpart. However, when focusing on direct impacts only (i.e., occurring in the Netherlands), recycled HDPE performs better than virgin HDPE. While the study provides an initial assessment of the social impact of HDPE recycling, we note that the Product Social Impact Life Cycle Assessment database (PSILCA) used to conduct the S-LCA only contains a generic recycling activity rather than a specific plastic recycling one. Thus, social impacts due to other types of waste, such as electronic waste, could be skewing the social impact results of HDPE recycling. Conversely, a specific virgin plastic manufacturing activity exists in the PSILCA database, creating a discrepancy in the comparative assessment of virgin versus recycled plastic.

4.2.2.2 Rare Earth Elements

Werker et al. (2019) performed a comparative S-LCA of NdFeB permanent-magnet production through three different supply chains: magnet production in Japan using rare earth oxides from the United States (Mountain Pass), magnet production in Malaysia using rare earth oxides from Australia (Mount Weld), and magnet production in China using rare earth oxides from Australia (Bayan Obo). Using PSILCA, we compared the three options using 49 quantitative and semiquantitative social impact categories affecting five stakeholder types: workers, participants in the supply chain, society, local communities, and consumers. The results show that the U.S. supply chain causes the least social impacts. The treatment of raw materials and magnet production phases of the life cycle cause the highest social impacts—particularly in China. For the U.S. supply chain, corruption, bribery, and violation of Indigenous rights were identified.

Overall, the U.S. value chain presents opportunities to reduce the social impacts of permanent-magnet manufacturing, although those benefits would occur outside of the country. Moreover, we note that switching production routes could also create unintended consequences. For example, while the magnet itself could be considered more sustainable, local supply chain participants involved in magnet production in other countries could lose their businesses, causing unemployment and negative impacts on the economic development of local communities. Overall, rare earth element mining is considered a threat to sustainable development because extraction and treatment of raw materials can cause local health and safety issues, and work conditions within the magnet production supply chain are often unsatisfactory.

Mining and production in local areas with stringent health and safety regulations, such as Mountain Pass in the state of California, will likely mitigate these negative social impacts. In addition to fewer social impacts, rare earth element mining in Mountain Pass for magnet manufacturing could also offer opportunities for magnet manufacturing and recycling efforts (Smith, Riddle, Earlam, Iloeje, and Diamond 2022). Along those lines, Jin et al. (2018) developed a multi-objective optimization method to find the optimal locations of four reverse supply chain actors (e.g., collection centers, end-of-life product dismantling facilities, NdFeB magnet recycling facilities, and sales points). They used this optimization method to score each location (using indicators such as labor supply, quality of life, and population) to assess the social impact of the reverse supply chain candidate. The solution offering maximum social support identifies that dismantlers would be valuable in North Carolina, Utah, and Nebraska as human resources and business support are abundant in those states. We note, for instance, that Utah ranked first on various social indicators such as labor supply, regulatory environment, and education. Overall, circular economy strategies such as recycling can help lessen the social impacts of permanent-magnet manufacturing. According to Bonfante et al. (2021), permanent-magnet recycling and reuse could contribute to the United Nations Sustainable Development Goal 11: Sustainable Cities and Communities and 12: Responsible Consumption and Production.

4.2.3 Perspectives

Adding environmental justice metrics to current wind turbine recycling analyses could steer science and decision-making toward more justice-oriented goals and help fulfill some of the current U.S. administration objectives (e.g., the Justice40 Initiative). Given the high social impacts of current permanent-magnet supply chains, developing a reverse supply chain based on the recycling and reuse of wind turbine permanent magnets presents a clear opportunity. Due to the high value of rare earth oxides and their high concentration in permanent magnets, costs could be lowered by up to 70 times if those components were recycled (Amato et al. 2019). Plastics and composites are at a lower monetary value, but their substandard management causes many social impacts, such as health and safety issues.

On the contrary, developing a recycling industry for wind energy systems could create higher-paying jobs and significantly improve health and safety conditions for local communities and workers. However, when deciding on what end-of-life option should be supported, multicriteria decision analysis or multiobjective optimization techniques may be needed to avoid any potential conflicts among social, economic, and environmental benefits.

5 Short, Medium, and Long-term RD&D Priorities

Section 3 of this report identified several research, development and demonstration (RD&D) priorities to enhance the recyclability and reusability of all major components in a wind energy system. This section will now introduce a time-phased prioritization framework of the previously introduced RD&D priorities. This framework is intended to aid stakeholders in planning for domestic investments.

We define the short-term (2024–2026), medium-term (2026-2035), and long-term (beyond 2035). The short-term reflects immediate recycling technology needs to end wasteful disposal of wind-energy-related materials and deployment of more sustainable materials, where available, that could facilitate component recyclability. Medium-term priorities reflect broader goals including increasing supply security for critical materials and reducing life cycle emissions caused by decommissioning, disassembly, and recycling technologies. Long-term priorities are tied to a grander circular economy vision for the U.S. wind energy sector including design for disassembly, circularity (i.e., recyclable materials, separable subcomponents), and reliability as well as cross-sector integration and optimization of recycling technologies.

These goals and priorities are not independent, and progress in one area will likely affect progress and impact of other areas. For example, a long-term effort to develop certification standards for using recycled fiber in blade manufacturing may be directly supported by research programs for regenerating performance of recycled fibers from blade recycling processes in the short and medium terms. The goal of organizing RD&D priorities by timeframes is not to discourage investment in any specific research areas on any particular timeline. Instead, it aims to help stakeholders and decision-makers understand the potential progression and impacts of different RD&D areas, enabling them to meet evolving needs and priorities in the clean energy transition.

Table 26. Key RD&D Investment Priorities for the Circular Economy of Wind Energy Systems

RD&D Priorities for Recyclability of Primary Materials/Wind Energy System Components	**Short Term (Now through 2026)** **Goal:** Reducing wasteful disposal of hard-to-recycle wind energy system components (i.e., blades, permanent magnets)	**Medium Term (2026–2035)** **Goal:** Optimizing the role of recycling in secure, cost-effective, and environmentally sustainable wind energy deployment to meet U.S. decarbonization goals	**Long Term** **(Beyond 2035)** **Goal:** More robust integration and optimization of cross-sector circularity and decarbonization for wind energy systems
Composites and Polymers/Blades and Nacelles 	• Develop research programs for intelligent blade cutting and segmenting (e.g., water and laser jetting methods). • Develop targeted blade decommissioning protocols to segment blade regions based on respective potential value. • Prioritize investing in Re-X before recycling approaches for waste blades (i.e., reuse, repair, remanufacture) to meet relevant regional and community needs. • Develop research programs for regenerating recycled fiber performance from	• Develop research programs for scaling manufacturing methods for blades to enable modular wind turbine blade designs. • Prioritize developing and scaling low-temperature, solvent-based recycling pathways for blades to recover pristine separable resin materials. • Support establishment of regional end-of-life blade service centers for on-site blade repair for reuse and waste collection. • Develop research programs to foster innovations in material design for blade reliability. • Develop research programs that	• Develop certification standards for using recycled fiber and/or shredded composites in targeted blade performance areas (e.g., core, shear webs). • Develop research programs that demonstrate blade prototyping and performance testing. • Develop and demonstrate use of natural or bio-based fiber and resin materials to replace petroleum-based composites. • Optimize cross-industry composite

	pyrolysis, mechanical, and solvent-based recycling methods for targeted end-use composite applications. • Support replacing baseline thermoset composites with thermoplastic and/or polyamine-based epoxy resin materials in blade manufacturing.	optimize material properties, manufacturability, and reliability of adhesive joints for different resin systems in blades.	recycling process designs to reduce cost of transportation, cost of recycling, and life cycle emissions of mixed composite waste streams. • Develop testing and certification standards for reuse of end-of-life blades in second-life applications.
Rare Earth Permanent Magnets/Turbine Generators 	• Develop large-scale demonstrations of hydrogen-decrepitation and magnet-to-magnet recycling of waste magnets. • Develop recertification standards for retired magnet testing procedures to qualify for reuse. • Develop demonstrations for magnet reuse in second-life applications (i.e., distributed wind systems). • Develop research and demonstrate solutions for rare earth element-free superconducting generators as well as generator designs that eliminate use of terbium and/or reduce use of dysprosium in sintered and bonded magnets.	• Develop research programs for scaling additive manufacturing methods for bonded magnets. • Develop research programs to support technology innovations that radically reduce operating costs and increase use of greener solvents for rare earth metal refining technologies.	• Develop and deploy hybrid (sintered and bonded) permanent magnet recycling technologies. • Develop and demonstrate the use of modular generator designs.

Steel and Its Alloying Elements/Towers, Nacelles, Drivetrains 	• Establish standardized decommissioning protocols with improved sorting of different steel alloys. • Demonstrate whole tower reuse in new plant buildup.	• Develop and demonstrate feasibility of targeted alloying element recovery from steel scrap. • Develop research programs that demonstrate light weighting and modularity of tower designs. • Develop on-site treatment for elimination of alloy elements from steel scrap (e.g., zinc). • Support the procurement and use of low embodied carbon concrete, asphalt and steel in wind turbine construction and wind-related manufacturing processes that qualify for IRA funding.	• Develop and demonstrate feasibility of recycling electrical steel scrap in production facilities.
Foundations and Substructures 	• Implement decommissioning strategies that trim the top off the base followed by capping. • Prioritize partial demolition instead of full recovery.	• Develop demonstrations for low-cost, easy-access decommissioning technologies for offshore substructures with emphasis on fixed-bottom technologies for full foundation recovery. • Support the use of low embodied carbon concrete and asphalt in wind turbine systems as defined in Inflation Reduction Act (IRA).	• Develop and demonstrate modular designs for land-based foundations.
Other Systems-Level Priorities	• Develop a national standard for reporting environmental product declarations	• Expand access and U.S. manufacturing capacity of minimally intrusive disassembly	• Develop mobile on-site recycling solutions to reduce costs and emissions of

	with standardized tools and harmonized data sources. Support reporting of emission hotspots and waste handling strategies. • Develop material passports for wind power plants including material intensity, grade, and properties with intellectual property protection measures. • Strategically site new recycling technology capacity based on optimized regional variations (e.g., tipping fees, workforce, location of material suppliers' component manufacturing facility).	equipment for blades and towers. • Develop research programs that demonstrate technological solutions for high-yield, intelligent separation of silicon carbide and gallium nitride in power electronic systems.	component disassembly and transportation.

6 Conclusions

This report identifies RD&D needs and priorities for end-of-life management and subsequent recycling of major wind energy system components to build an efficient, cost-effective, and environmentally responsible U.S. infrastructure for wind energy systems. The report responds to the Energy Act of 2020 and Bipartisan Infrastructure Law, which directs DOE's Wind Energy Technologies Office to develop a wind energy recycling RD&D program. In this work, we quantified the technical, environmental, and economic metrics of candidate recycling technologies for each major wind system component to inform the selection of alternate materials, designs, and manufacturing processes that could promote a circular, resource-conserving economy for wind energy systems.

We found that the existing U.S. recycling infrastructure is likely capable of processing projected decommissioned materials volumes through 2050 for concrete aggregate,[50] iron, and steel found in foundations, access roads, towers, and some parts of the nacelle, drivetrain, and gearbox. These recyclable portions of the end-of-life stream represent about 90% of the weight of wind power plants. Although recycling capacity for these materials appears sufficient, future investments in steel and concrete decarbonization, as well as development of modular foundation designs, could likely reduce life cycle GHG emissions and other environmental and human health impact categories (e.g., cumulative energy demand, human toxicity, and life cycle water consumption) associated with wind project decommissioning, facilitate site excavation efforts, and promote efficient use of materials.

The primary component materials that are currently not recyclable in the United States are fiber-reinforced composites found in wind turbine blades and nacelle covers, as well as rare earth permanent magnets and electrical steel found in generators. Not being able to recycle these materials represents a vulnerability to the U.S. and global wind industry in terms of sustainability as well as burdening existing supply chains to meet future wind deployment targets. To address this vulnerability, short-term investments could be directed toward developing a dedicated recycling infrastructure at scale for blades and permanent magnets, and expanding the domestic production capacity for electrical steel. The latter would also improve recyclability of waste electrical steel materials present in generators because having domestic facilities that manufacture electrical steel could provide an opportunity for reusing recovered electrical steel in the primary production process after necessary scrap cleaning and size reduction steps. Large-scale demonstrations of cement co-processing and mechanical recycling in the short term offer recycling pathways that have environmental and sometimes economic advantages over disposal, depending on significant variations in regional factors.

In addition, if blade manufacturers and wind original equipment manufacturers prioritize using recyclable resin systems in planned blade production capacities, this practice could enable the commercialization of more environmentally sustainable and potentially more cost competitive blade recycling process designs such as pyrolysis or chemical dissolution for blades. Compared to cement co-processing, mechanical recycling, and other repurposing activities prioritized in the short term, dedicated blade recycling pathways, including pyrolysis and chemical dissolution, use significantly less net life cycle energy and reduce GHG emissions, water consumption, and human toxicity levels if downstream markets for recovered materials are well-developed. Recovered fibers and resins have the potential to be used as value-added recycled content in a wide range of secondary market applications if recycling process designs are optimized to develop targeted material quality profiles for the downstream applications. More detailed examination of the value of recovered

[50] The weight of concrete in foundations and access roads is included in the calculated weight of wind power plants.

materials from blades and specific priorities for optimizing recycling process design is communicated in part 2 of the wind energy recycling assessment report.

Recovery of resins increases process profit margins and lowers life cycle energy and GHG emissions compared to primary production of petroleum-based resins. Reusing fibers and resins in value-added applications in secondary markets outside the wind industry is a pivotal step in reducing life cycle emissions and increasing economic competitiveness of pyrolysis and solvent-based recycling pathways. Future investments would help develop research programs that can optimize quality profiles of recycled materials for target end products. Additional modeling and analysis would help to quantify estimated life cycle and cost impacts of specific end-use applications.

In the short term, expanding magnet-to-magnet recycling and hydrogen decrepitation magnet recycling may help retain the use of critical rare earth elements in permanent magnets. Aligning these magnet recycling pathways with efforts from original equipment manufacturers to recertify used magnets for reuse could ease short- and medium-term U.S. rare earth supply chain vulnerability for the wind energy industry. Medium-term investments would help develop higher efficiency and power density, as well as more reliable electronic devices such as inverters to reduce the magnitude of their waste. In addition, developing standardized testing for retired wind turbine blades and magnets offers multiple benefits, such as increasing industry confidence in reuse of recovered materials and enabling component remanufacturing for a second life.

The United States is expected to benefit from secure access to, or expanded manufacturing capacity of, disassembly equipment, particularly cranes, to meet its decommissioning needs in the medium term. A shortage of cranes might drive unsustainable decommissioning practices that could diminish the salvage value of primary materials used and encourage wasteful disposal. Improvements to end-of-life collection and sorting practices and decarbonizing manufacturing of steel and concrete have significant potential to maximize the value of recyclates, reducing the loss of critical alloying materials and lessening the life cycle environmental impacts of recycling these materials.

The projected waste volumes of wind energy systems required at the highest plausible deployment scenario are not likely to pose outsized threats to U.S. wind industry competitiveness or create any adverse environmental impacts to domestic waste management systems. Careful planning of a future U.S. recycling infrastructure and making the RD&D investments prioritized here offer great potential to conserve national resources; avoid the burden on local waste management facilities; reduce pollutant discharges to air, water, and soil; and ease potential material supply chain vulnerabilities in the United States. These efforts ultimately ensure secure domestic wind energy deployment and keep the United States on track to meeting its ambitious climate goals.

In summary:

- The existing U.S. recycling infrastructure could cost-effectively and sustainably process over 90% of projected wind turbine waste by mass into value-added products through 2050 under a high-deployment scenario.
- The United States could benefit from expanding its recycling infrastructure for fiber-reinforced composites in wind turbine blades and nacelles, as well as for select critical materials such as rare earth elements in permanent magnets, electrical steel in generators, and alloying nickel and cobalt in steel structures.
- Increasing and verifying the quality of recycled fibers for high-value applications in secondary markets outside the wind energy industry are critical to enhancing consumer confidence in recycled products as

well as improving their economic competitiveness and reducing emission impacts of recycling composites from blades and nacelles.

- Wind turbine original equipment manufacturers and blade manufacturers would likely be well served to begin implementing thermoplastic-based blade designs, or other recyclable-by-design resin systems, because they can be recycled using pyrolysis and chemical dissolution; such processes could recover higher-quality fibers and/or resins that further increase profitability of blade recycling operations.
- Nascent rare earth element magnet recycling technologies show lower environmental impacts and lower production cost than rare earth element ore mining. However, magnet recycling alone is unlikely to meet rare earth element demand from wind deployment through 2035 due to low-waste volumes in the near term coupled with projected fast wind energy deployment. Our analysis identifies value in scaling magnet-to-magnet recycling pathways and developing cross-technology sorting techniques to concentrate rare earth element content in the waste stream. Additionally, research programs and commercialization projects that focus on using polymer-bonded magnets, recycled magnets, and modular generator designs could bring substantial benefits to meeting wind energy deployment by the 2030s.
- State-level regional factors, such as landfill tipping (disposal) fees, transportation distances, and differing capabilities in local workforce and material demand play a critical role in the environmental sustainability and cost-competitiveness of recycling technologies. As a result, we prioritize strategic siting of material-level recycling technologies to adapt to regional variations.
- A shortage of minimally intrusive disassembly equipment, such as cranes, might encourage unsustainable decommissioning practices that could diminish the salvage value of primary materials used and incentivize their hazardous disposal. The United States could benefit from securing access to, or expanding its manufacturing capacity of, disassembly equipment, particularly cranes, to meet its decommissioning needs in the medium term (2026–2030).

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Appendix A. Energy Act of 2020 Wind Recycling, Development, and Demonstration Program Language

Section 3003 (b)(4) of the Energy Act of 2020 (42 U.S.C. 16237 (b)(4)): WIND ENERGY TECHNOLOGY RECYCLING RESEARCH, DEVELOPMENT, AND DEMONSTRATION PROGRAM

(A) IN GENERAL.—In addition to the program activities described in paragraph (2), in carrying out the program, the Secretary shall award financial assistance to eligible entities for research, development, and demonstration, and commercialization projects to create innovative and practical approaches to ***increase the reuse and recycling*** of wind energy technologies, including—

(i) by increasing the efficiency and cost effectiveness of the ***recovery of raw materials*** from wind energy technology components and systems, including enabling technologies such as inverters;

(ii) by ***minimizing potential environmental impacts*** from the recovery and disposal processes;

(iii) by advancing technologies and processes for the ***disassembly and recycling*** of wind energy devices;

(iv) by developing ***alternative materials, designs, manufacturing processes***, and other aspects of wind energy technologies and the disassembly and resource recovery process that enable efficient, cost effective, and environmentally responsible disassembly of, and resource recovery from, wind energy technologies; and

(v) strategies to ***increase consumer acceptance*** of, and participation in, the recycling of wind energy technologies.

(B) DISSEMINATION OF RESULTS. —The Secretary shall make available to the public and the relevant committees of Congress the results of the projects carried out through financial assistance awarded under subparagraph (A), including—

(i) ***development of best practices or training materials*** for use in the wind energy technology manufacturing, design, installation, decommissioning, or recycling industries;

(ii) dissemination at industry conferences;

(iii) coordination with information dissemination programs relating to recycling of electronic devices in general;

(iv) demonstration projects; and

(v) ***educational materials***.

(C) PRIORITY. —In carrying out the activities authorized under this subsection, the Secretary shall give ***special consideration to projects that recover critical materials***.

(D) SENSITIVE INFORMATION. —In carrying out the activities authorized under this subsection, the Secretary shall ensure proper security controls are in place to protect proprietary or sensitive information, as appropriate

Appendix B. Data Sources for Life Cycle Assessment and Techno-Economic Analysis

As described in the main body of this report, the authors use tools from life cycle assessment (LCA) and techno-economic assessment (TEA) to quantify the environmental and economic metrics of recycling technologies provided in Table 2. We first developed process models for select recycling technologies that we determined were priorities. Using material and energy balances, we developed process models for the inputs (e.g., material flows, energy consumption) and outputs (e.g., air pollution emissions, discharges to water and soil). We used a unified scale of one metric tonne of material as the basis for the analysis.

These process models served as the basis for subsequent LCA and TEA modeling and analysis work, as well as the foreground data for LCA. Foreground data refer to mass, energy, and emission flows that are part of the recycling process. Examples include:

- Finished materials that are required as part of the recycling process, such as materials in the waste component, subassembly, or subcomponent
- Other raw materials used as part of the recycling process (e.g., solvents)
- Electricity and heat consumption
- Generated co- or byproducts.

Background data refer to mass, energy, and emission flows that are part of the supply chain of the inputs and outputs identified in the foreground data. Examples of background data include the upstream processes that are required to extract and process raw materials and manufacture processed materials used in the foreground systems. Background data are used in this report mainly for LCA (see next section).

While reviewing available data for material and energy balances that make up the process models, we observed significant differences in the availability and certainty of various materials and components. The first step in our data collection effort involved compiling literature review results for available technologies to develop process models that align with the baseline 1.5-megawatt wind turbine design. We determined this to be the most installed model in the early 2000s.

Following the literature review, we relied on data provided by industry members (e.g., recyclers, decommissioners, original equipment manufacturers, and project owners), where feasible. We conducted interviews and collected data on topics including cement co-processing for blades, employing a hydrometallurgical recycling process for magnets, and steelmaking in an electric arc furnace. Some data obtained are proprietary and sometimes used to represent a range of metric values. We modeled upper, mid, and lower ranges of input data obtained from industry, where feasible.

If industry outreach data were not available or informative for a specific recycling process, we used established tools and concepts in process engineering and design to model the scale-up of the recycling process under consideration, including equipment sizing, energy consumption, raw material needs, scrap losses, consumables, or by- or coproducts.

Data Sources for Life Cycle Inventories

Using the process models developed for candidate recycling technologies of interest, we used life cycle inventory (LCI) data generated for LCA to estimate background material for the foreground material, energy, and emission entries in process models. Whenever possible, we sourced LCI data from publicly available data sources that closely align with the temporal and spatial resolution of each foreground material (e.g., U.S. Life Cycle Inventory Database,[51] Federal LCA Commons[52]). We selected data to model material and energy flows with a U.S. supply chain focus. If U.S.-relevant selections were not available, we used global averages of supply chain assumptions. All LCI choices complied with Renewable Energy Materials Properties Database (REMPD) LCI data selection choices (see Appendix C in Materials Used in U.S. Wind Energy Technologies: Quantities and Availability for Two Future Scenarios (Eberle et al. 2023) for exact material choices). For materials such as rare earth elements (e.g., neodymium, dysprosium) and silicon carbide that are not modeled in REMPD, we used the Critical Material Life Cycle Assessment Tool for our analysis.[53] Purdue University developed this tool with support from the Critical Materials Institute, an Energy Innovation Hub funded by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy.

Modeling product recycling in LCA is a complex problem, especially when products are not reused for novel purposes or are completely transformed into other materials. This issue in LCA introduced the concept of allocating impacts where the environmental impacts could be calculated in various ways. While the International Organization for Standardization 14040 and 14044 standards provide reasonable guidance on these issues, some recycling concepts studied here introduced unique cases that are more challenging to model and analyze (e.g., repurposing wind turbine blades as tower poles or bike shades and reusing fiber in low-value vs. high-value applications that are made of materials with similar quality). We excluded these decision points and instead relied on material quality as a reasonable first-order estimation for crediting or offsetting life cycle emissions.

If material quality data were not readily available, we applied economic allocation, distributing emissions based on the economic value of the recycled product.

[51] https://www.nrel.gov/lci/
[52] https://www.lcacommons.gov/
[53] https://ecn-deviis.ecn.purdue.edu/CMLCAT