Article:

Meng, F. orcid.org/0000-0002-9014-1231, Hawkin, J.L., Gast, L. et al. (13 more authors) (2025) End of life management for wind turbines. Nature Reviews Clean Technology. ISSN: 3005-0685

https://doi.org/10.1038/s44359-025-00097-3

End of life management for wind turbines

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Abstract

Global installed capacity of wind power reached 1,136 gigawatts (GW) in 2024 (representing 8.1% of total electricity generation) and continued installation of new capacity is needed to provide renewable energy. Effective end-of-life (EOL) management strategies are therefore needed to recover materials from wind turbines. This Review assesses current and emerging EOL practices, comparing the environmental and economic trade-offs across mechanical, thermal, and chemical recycling technologies. Wind turbines are built from a range of materials, including structural metals, concrete, composites, and magnetic materials, which have distinct recovery pathways and barriers. Structural metal recycling is well-developed and used commercially, but concrete recycling is more nascent and not competitive. Near-term scalable composite recycling technologies – including mechanical recycling and cement kiln co-processing - cannot recover the structural strengths of the original composite, but more advanced technologies – such as thermal fibre recovery and solvolysis - face energy, and economic barriers to wide-scale deployment. Magnet recycling can either preserve material in its intact form through shorter loop processes or recover valuable rare earth elements through longer loop processes. The size of the magnets could enable direct reuse of magnets, but it is complicated by changing designs. Further development of recycling and reuse pathways should be complemented by design that enables EOL management and materials circularity.

1 Introduction

Wind energy plays a vital role in global decarbonisation strategies and is projected to supply 35% of electricity by 2050 under the IEA's Net Zero Emissions Scenario[1]. Providing this wind energy requires rapid deployment of new wind farms, repowering of existing sites with larger turbines, and the phased replacement of ageing infrastructure. As of 2023, wind power capacity has reached 1,019 GW globally[2] and is expected to rise to 8,265 GW by 2050[1].

As global installed capacity grows, large volumes of decommissioned components and associated waste are expected. Wind turbines typically have a lifespan of 20–25 years[3,4], though some may be decommissioned earlier, around 15 years, due to economic factors[5], while others can remain operational for 35 years[6] or longer[7]. Early wind farms in Germany, Denmark, and Spain, and increasingly those in China and the U.S.[8], are now approaching end-of-life (EOL). Partial repowering and full repowering have increased installed capacity by an average of 158% in European projects without requiring new planning approval, but only around 7% of ageing capacity is currently being repowered[9,10], highlighting the need for EOL planning for the materials in wind turbines.

Wind turbines contain a diverse mix of materials, including bulk metals, rare earth elements (REEs), and composites (Figure 1), which vary in terms of their potential for circularity. Bulk metals such as steel, copper, and aluminium are technically recyclable[11], but not always recovered in practice due to dissipation, contamination, or inefficient separation at end-of-life. In particular, metals can be lost through dispersion in use-phase applications or because they are embedded within components that are difficult to access or economically recover during dismantling[12]. Composite materials like glass fibre- and carbon fibre-reinforced polymers (GFRP and CFRP) pose technical and economic recycling challenges due to their thermoset resin matrices[13,14]. Rare earth elements (REEs) in permanent magnets are high-value but difficult to recover[15]. Foundations, typically made from concrete, are rarely recycled due to cost and technical constraints; extracted and crushed waste concrete from all sources in Europe was estimated to replace around 10-25% virgin aggregates in 2015[16].

Despite technological progress in recycling these materials, commercially viable and scalable EOL management systems remain underdeveloped. A variety of blade recycling technologies—such as mechanical shredding[17], thermolysis[18,19], solvolysis[20–22], and cement kiln co-processing[23,24]—are available, but their uptake is constrained by energy intensity, infrastructure needs, and financial viability. These processes also vary by region due to differing regulatory environments and waste management infrastructure, and face challenges related to fragmented policies, the absence of harmonised decommissioning standards, limited traceability of material flows, and underdeveloped markets for recycled materials[25–27]. As a result, landfilling and incineration remain common disposal methods despite associated environmental and resource losses[28].

In this Review, we discuss wind turbine EOL management, evaluate the effectiveness and scalability of different recycling technologies, identify co-benefits and trade-offs, and discuss advances in materials, design, and regulation that support sustainable turbine decommissioning. We also highlight research gaps and propose opportunities to improve material circularity and reduce life cycle emissions in the growing wind power sector.

2 Materials usage and management

As wind energy capacity expands, both material demand and waste generation are expected to grow significantly, underscoring the importance of design and end-of-life planning. This section explores the material complexity of wind turbine designs, the scale of waste anticipated as turbines reach their EOL and the evolution of current design approaches. It focuses primarily on onshore wind turbines—which make up ~93% of global capacity as of 2022[29]—while highlighting differences in offshore designs. Designing systems for offshore applications is generally more challenging as marine environments are often harsh and sites are more remote from population centres and load demands, increasing design, construction and maintenance costs[30]. Offshore wind does, however, dominate the market in isolated cases, such as the UK, and is expected to experience significant growth globally over the next decades, becoming the dominant wind energy technology by 2050[31].

2.1 Design and materials

A modern commercial wind turbine is constructed of around 25,000 components[32], grouped into structural (foundations, tower, nacelle), mechanical (rotor, yaw, pitch, brake systems, gearboxes), and electrical systems (generator, cables, transformer) (figure 1). While horizontal-axis, three-bladed designs dominate globally[33,34], design choices such as generator type, tower material, and blade composition vary based on whether the turbine is onshore or offshore (Table 2), as well as local conditions and supply chains, technology capability and costs.

Some design choices have retained a high share of the market since the 1980s, such as horizontal axis three-bladed designs. Vertical axis and other blade configurations do exist, but have had limited commercial success[35,36] and are not considered in detail in this review. Other aspects of the design have developed as the capability for larger and more powerful turbines has increased. For example, the increasing blade lengths and forces through the turbine and offshore installations have led to (and been enabled by) increased use of lightweight materials such as reinforced composites and low-maintenance direct drive generators[33,37]. Although the majority of the installed base of wind turbines globally have gearboxes, direct-drive machines are becoming a preferred choice for higher power and offshore applications[37].

There are up to 45 named materials in wind turbine inventories[32,38,39], but the classifications and names differ across studies. For this review, materials are considered in six broad groupings: iron and steel, composites, rare earth elements (such as Neodymium), concrete, and other metals.

Across all wind turbine designs, structural materials—primarily steel and concrete—dominate total mass, accounting for approximately 90% [37,40,41]. The foundations and tower can account for around 35-50% of a turbine's production- and use- phase greenhouse gas emissions[42,43] owing to the large volumes of steel and concrete—both energy- and emissions-intensive materials[44]. Design approaches vary by manufacturer, introducing variation in material composition; typical 2 MW onshore wind turbines from Enercon[45], Vestas[42], Gamesa[46] include 73-84% concrete by mass and 14 - 24% steel.

Blades are predominantly composed of composite materials, with GFRP being the primary constituent in both onshore and offshore turbines[47]. CFRPs are selectively incorporated into blades longer than about 45 metres—typically in spar caps or load-bearing sections— where the increased stiffness enables longer, lighter and more slender blades with improved aerodynamic efficiency[48] (however, blades have been produced as long as 94 metres using entirely structural GFRP, without CFRP[49]). The CFRP comprises a relatively small weight fraction and the effect of weight saving on the rest of the structure can offset the increased cost of the CFRP compared to GFRP. However, CFRP production is highly energy-intensive (e.g. carbon fibre production alone requires 195–595 MJ/kg), with higher embodied emissions than either GFRP or steel (with emissions up to 10 times higher than steel parts and around 3-4 times higher than GFRP parts)[50–52]. Blade design trends suggest increasing adoption of CFRP, following the trend which saw carbon fibre use in blades increase from 800t in 2004 to over 30 kt in 2021[53]. Although CFRP-containing blades currently represent a minority of EOL waste today[47], this proportion is expected to rise as newer blades reach retirement.

Design choices, such as the generator configuration, can dictate the presence of specific materials. For example, turbines with permanent magnet synchronous generators (PMSGs) require rare earth elements such as neodymium, whereas geared generators typically do not (Figure 2). As the market share of generator technologies shifts, particularly with the increasing adoption of permanent magnet systems, the material intensity profiles are expected to evolve. Nonetheless, the overall dominance of structural materials in the mass composition is likely to remain consistent.

While both offshore and onshore turbines typically demand a similar portfolio of materials, the overall demands and proportion of those demands may vary. The main differences exist in the materials needed for structural components and the generator technology choice (see Table 2). Permanent magnet (PM) turbines were only introduced in offshore applications around 2005, but by 2018, 76% of the global market for offshore wind was met by PM designs, compared to around 20% for onshore applications[37]. The shares of concrete and steel used in offshore WTs can vary with different foundation designs - monopile and jacket designs require proportionally more steel, for example than gravity base or floating foundations – but material requirements are likely to be larger than comparable onshore designs to account for corrosion resistance and the higher forces from winds and waves[54].

While the exact composition of future waste materials from wind energy is hard to predict, increasing wind turbine waste is inevitable, given past and expected future growth[1]. Blade waste alone has been approximated to be around 3 Mt/yr by 2050[55] and total EOL wind-turbine materials could reach around 350 Mt/yr by 2050. This increase, rising from around 3 Mt/yr in 2025 is projected based on past capacity growth[31], estimated material intensities of past capacity[56] and assuming a design life of 25 years[3,4] (Figure 3 and SI). Under the net-zero emissions climate target[1] continued expansion of installed capacity is expected, and replacement of existing turbines reaching the end of their 20–25-year design life will compound this increase in EOL materials (Figure 3).

The composition and volume of material streams is also important. For example, composites and plastics have low mass density and therefore produce a large volume of waste. REE, such as neodymium (Nd) and dysprosium (Dy), are also a potentially important waste stream as wind turbines dominate energy sector demands for such materials[57,58]; without design and system changes, 11-26 fold increases in demand are estimated by 2050[59]. Improving the resource efficiency and end-of-life options for such materials is therefore essential to minimise broader environmental and social impacts.

2.2 Metrics to understand end of life

Effective EOL material flow management for wind turbines requires robust frameworks and metrics that assess impacts across four key dimensions: material efficiency, environmental performance, economic viability, and social acceptance. Material efficiency is a broad strategy aimed at reducing material use, minimising waste, and retaining resources throughout a product's life cycle[60]. It includes circularity strategies, such as recycling, reuse, and refurbishment, as well as design innovations that reduce material demand, substitute lower-impact materials, or extend product lifetimes[61].

Circularity, as a subset of material efficiency, focuses specifically on keeping materials, components, and products in productive use for as long as possible. It follows a hierarchy of approaches, with reuse and refurbishment prioritised over recycling, which is considered only once higher-value strategies are exhausted[62]. Recycling involves converting waste into new raw materials through mechanical, thermal, or chemical processes. In closed-loop recycling, recovered materials are reused within the same product system; open-loop recycling often results in lower-quality outputs and higher energy consumption. For example, crushing turbine foundations to produce recycled concrete aggregate (RCA) can displace virgin aggregate but still requires new cement, limiting the overall environmental benefit[16].

EOL material flow management is influenced by national and regional regulations governing decommissioning, recycling, and hazardous waste disposal, including rules targeting specific components such as electrical systems, oils, or foundation structures[63]. In the European Union, this is supported by directives such as the Waste Framework Directive and emerging regulations like the Ecodesign for Sustainable Products Regulation[41,64], which requires product passports and improved reporting for components, potentially including turbines. However, detailed bills of materials and end-of-life data are often not publicly disclosed by manufacturers or developers, limiting the capacity of researchers and policymakers to model recovery pathways. Industry-led initiatives, such as blade passport schemes, aim to close this gap by providing structural and material composition data[37,65]. Different strategies for EOL material flow management can be applied to components of wind turbines, according to the waste treatment options (Figure 4).

This section reviews the current methodologies for assessing the impacts of EOL processes for wind turbine systems, focusing on circularity indices, life cycle assessment (LCA), and financial cost evaluation metrics. These tools help identify the most effective circular strategies and highlight gaps in knowledge and practice, but they only provide meaningful decision support when they are considered within the context of the larger system, and each other. Trade-offs can exist between impacts, such as emissions and material circularity for example, and they each evaluate a narrow viewpoint. An appropriate decision-making framework, therefore, might include these metrics alongside qualitative considerations of the broader system, and logistical and practical challenges, such as relevant regulations.

2.2.1 Circularity approaches

Circularity can be measured through various metrics that evaluate material efficiency, and the environmental cost of returning materials to usable form. The prioritisation circularity strategy (Figure 5) guides our evaluation of wind turbine EOL pathways, from design innovations to end-of-use disassembly. For example, material efficiency can be improved through the use of cable-supported tower structures[66] and reduced concrete use in foundations (reducing material use), while modular steel designs that simplify recovery[67] can improve circularity. While circularity principles are a useful guide to minimise environmental impacts, they should be used alongside other frameworks, such as life-cycle analysis, to avoid adverse social and environmental impacts. For example, chemically recycling plastics could consume more water and increase toxicological effects on humans compared to virgin production[68]. Within the scope of this review, these broader effects are not considered in detail.

Material yield can be used as a metric to evaluate circularity[69]. It can be defined as the percentage of a component that a specific process can recycle into a new component – or more generally, the output material divided by the input material[70]. More advanced tools like circularity potential extend this by comparing the hypothetical availability of secondary materials from EOL processes with future material demands, for example, in turbine manufacturing[71]. The circularity potential has been used to model closed-loop scenarios, which assume materials from decommissioned turbines are recycled into new turbines[72]—not necessarily as the same atoms, but within the same material loop, such as steel scrap reused in new tower production. This interpretation of closed-loop recycling focuses on functional recovery and not strict material traceability.

The Material Circularity Indicator (MCI)[73,74] assesses the extent to which material flows are circular at a technology level. A similar approach, the Product Circularity Indicator (PCI)[75] is differentiated from MCI by including material losses in material production and manufacturing activities, thus providing greater emphasis on component reuse (compared to recycling). When applied to wind turbine blades[76], solvolysis—a process that could potentially recover both the resin and fibre composite fractions with a high material yield—has the potential to greatly enhance circularity compared to other EOL treatment options. However, challenges remain regarding its economic viability and environmental impacts.

The Circularity Index (CI)[77] builds on these circularity metrics, by considering two dimensions: the quantity of recovered material as a fraction of total material input (that is, the recycled content); and the quality of the recovered material, as defined as the amount of energy required to return the recovered material to its original quality, compared with the energy to make new primary material. This approach has been applied to a case study of the decommissioning of an offshore wind farm[78]. Applied to wind turbine materials, steel and aluminium score relatively well—CI values of 0.14 and 0.20, respectively—due to efficient recycling infrastructure and energy savings during remelting. In contrast, concrete, which dominates turbine foundations by mass, has a CI close to 0, as current downcycling practices recover little functional value and offer negligible energy benefits[77]. Increasing material reuse has been shown to be the most effective strategy for enhancing circularity across scenarios involving material demand reduction and EOL recycling for onshore wind turbines[41].

The Ecocircularity Performance Index extends this framework by integrating lifecycle environmental impacts (such as carbon emissions) alongside circular material flows[79]. A UK-based case study comparing transport technologies using the index found that a typical battery electric vehicle had an Ecocircularity Performance Index of 0.1, largely due to low material circularity (circularity index of 0.22) despite strong emissions performance (emissions index of 0.49). This example demonstrates that even systems with low environmental impact can perform poorly on material loop closure, highlighting the need for more nuanced metrics that go beyond recycling rates[80].

2.2.2 Life cycle environmental impacts

LCA can provide detailed evaluations, often focusing on key metrics such as greenhouse gas (GHG) emissions (presented as carbon dioxide equivalent) or considering a wider range of environmental impacts such as human and ecosystem toxicity, eutrophication, water use, and land occupation. LCA models have been developed for onshore[32,42,44,46,81] and offshore[43,78,82,83] wind turbines and plants, accounting for a range of environmental impacts across a broad cradle-to-grave perspective. Within these studies, activities related to decommissioning and material recycling and/or disposal are found to make a small contribution to overall impacts, for example, less than 2% across all life cycle impact categories[84]. However, this low contribution can be misleading. Many LCAs apply the cut-off allocation method[85], which excludes the benefits of displacing primary material production with recycled materials from the wind turbine system boundary. As a result, the circularity benefits, such as reduced energy and emissions from using secondary steel or glass fibres, are often unaccounted for or attributed to future products rather than the turbine itself[85].

In reality, the opportunity cost of failing to recover and reuse materials can be substantial. For example, in the case of composites produced from recycled carbon fibre, primary energy demand and greenhouse gas emissions can be reduced by ~90% relative to primary production[86]. However, such substitution effects are rarely captured. Furthermore, most LCAs rely on proxy data from turbine installation or generic infrastructure removal, rather than actual decommissioning operations[81,82,87]). Material fate assumptions—especially for blades—are highly uncertain, and recycling pathways (such as solvolysis vs. co-processing) can differ dramatically in environmental impact[88]. Although some LCAs have evaluated GHG savings from specific blade recycling case studies[89], more comprehensive assessments are needed that integrate operational decommissioning data, consider multi-loop and cross-sector recycling scenarios, and compare downcycling against upcycling options in terms of long-term circularity and environmental performance. Including such metrics would provide a more accurate picture of EOL contributions to sustainability outcomes.

2.2.3 Financial costs

Economic assessments of EOL options are critical for identifying commercially viable recovery strategies. Costs can be reported as per-tonne values, investment payback periods, or qualitative scales. For example, ORE Catapult uses a 3-step scale (low, medium, high) to describe cost implications for turbine EOL management[90].

Life cycle costing or techno-economic analysis provides more detailed insights into the costs of current and emerging EOL management options. For example, techno-economic analysis of blade recycling options shows that processes like solvolysis or thermolysis are often prohibitively expensive unless scaled and integrated into larger value chains[91–93]. The cost of landfill disposal per tonne of material serves as a baseline for comparison and remains the lowest-cost option. For example for blade waste, the cost of landfill can be less than $200/tonne, compared to costs up to $950/tonne for more advanced recycling technologies[92].

The EOL phase often accounts for a relatively small fraction of total turbine costs, but this can vary widely depending on location (such as onshore vs offshore), regulatory requirements, and material composition[91,93]. The financial viability of EOL options also requires consideration of the market value of recovered materials, like glass fibres, while considering the quality differences between recycled products and their virgin or conventional counterparts[92,94]. Net present value can inform EOL management decision-making and has been used to demonstrate the financial favourability of offshore wind farm life extension and repowering, in comparison with full and partial removal[9]. The economic viability is strongly tied to the development of consistent demand and regulatory support.

2.2.4 Other factors

The Technology Readiness Level (TRL) is a standard metric used to assess the maturity of recycling processes[95]. TRLs range from 1 to 9, with 1 indicating initial observations of basic principles and 9 representing fully commercialised technology. The US Department of Energy project Wind Blade Recycling Assessment uses a simplified TRL scale, categorising processes into low, medium, and high maturity based on their development stage: lab scale, pilot scale, and fully commercialised solutions[96]. Most solvolysis and high-quality wind turbine blade material recovery processes are at the pilot scale (TRL 4-6)[86], while mechanical grinding and co-processing in cement kilns are industrially deployed (TRL 7-9)[97].

The perception and acceptance of EOL recycling technologies for wind turbine blades are challenging to quantify but crucial for sustainable implementation. This area is underexplored yet understanding societal attitudes toward recycling solutions and the perceived severity of the EOL issue is vital. Integrated assessment methods that include social factors alongside technical, economic, and environmental performance can provide a more holistic view of technology acceptance and its potential impact on recycling practices.

By using circularity, life cycle, and financial metrics, researchers and industry professionals can comprehensively evaluate the viability and sustainability of recycling processes, ensuring a balanced consideration of technical maturity, environmental impact, economic cost, and societal acceptance. While landfilling is not a recycling process, it remains a default end-of-life option for some materials, particularly when recovery technologies are unavailable or prohibitively expensive. In certain cases, repurposing blade materials in construction (such as aggregate or structural elements) can offer a temporary extension of service life. However, without proper end-of-use tracking, such materials could ultimately still be landfilled at the end of the secondary application. As such, circular strategies must also consider material traceability beyond wind turbine applications to avoid unintended disposal[98].

3 Material reuse and recycling

Although recycling has been prominent in the literature, particularly for composites used in turbine blades[28], reuse and repurposing applications are gaining momentum. Blade repurposing in secondary structural applications, such as furniture and bridges[28], (**open-loop reuse**) component refurbishment and remanufacturing[52,99] (**closed-loop reuse**) can offer meaningful material savings and environmental benefits[100,101]. Partial-repowering strategies, which involve replacing nacelles and rotors while retaining towers or foundations, are becoming more common[102] and could represent a high-value circular solution if implemented (Figure 4), Partial-repowering is not, however, currently an established practice[103], except as for mid-life ‘upgrading’ to increase economic returns[102]. In the US, for example, many onshore wind projects have been partially repowered within ten years of operation, driven by access to tax credits[104]. Such strategies require rigorous assessment of structural integrity and site-specific conditions – reuse of foundations for repowering some sites could have a higher cost and environmental impact than new construction[103]. Alternative approaches, such as life-extension and full-repowering (using the site and grid connections but replacing turbines)[105] are increasingly recommended for wind-farm operators in some regions - for example, in Scotland[106] and in Denmark, where two offshore projects amounting for over 200 MW capacity were granted lifetime extensions of ten years in June 2025[107].

Recycling is another option for some EOL materials. However, the materials that are currently recycled from a wind turbine account for around 50-65% of the original material embodied energy, but only around 20% of the raw material economic value (shown in Figure 5), emphasizing that barriers to recycling exist. In this section, we review innovations and opportunities for the reuse and recycling of EOL material.

3.1 Steel

Steel is one of the largest material components in wind turbines, predominantly used in towers, foundations, and nacelle structures (Figure 1). For instance, a Vestas 15 MW offshore turbine contains approximately 1,261 tonnes of steel[108]. Steel's durability means it can often be reused directly, extending product lifecycles and reducing environmental impacts. The average life of steel products is about 40 years, exceeding that of wind turbines (20–25 years), which enables reuse in structural applications[109]. Some wind farms opt for remanufacturing turbines, extending operational life by up to 20 years and nearly doubling investment returns[109]. Given this volume, effective EOL recycling of steel is essential for reducing the environmental impact, particularly GHG emissions, of wind energy systems.

Steel recycling is a commercially mature process with substantial environmental advantages. For example, compared to primary steel production via blast furnaces, recycling in electric arc furnaces (EAFs) can reduce energy demand by up to 70% and GHG emissions by 58–70%[110]. Recycling one tonne of steel scrap can save 1.5 tonnes of CO_2, 1.4 tonnes of iron ore, 740 kg of coal, and 120 kg of limestone[109], compared to virgin steel.

Steel recovery rates vary by sector, reaching 85–90% in construction and automotive industries, though average post-consumer recovery is around 80%, with technical potential near 90% under a well-managed system[109,111]. Losses occur primarily due to oxidation, residual coatings or grout, and inefficient sorting of mixed scrap. Steel recycling from turbines poses distinct challenges compared to other sectors. Although turbine towers use high-quality low-alloy steels that are technically easy to recycle[112,113], real-world recovery is hindered by disassembly difficulties, long-distance transport, particularly from offshore sites, and material contamination. Towers can exceed 80–100 meters in length[39], requiring segmentation for transport and heavy lifting equipment during dismantling[114]. In offshore and floating offshore settings, these difficulties are amplified due to remote locations, weather conditions, and limited port-side infrastructure. As turbine designs trend toward larger units and more offshore deployment, the volume of steel per turbine is increasing, increasing both the circularity potential and logistical complexity[115]. Floating offshore turbines, in particular, introduce new constraints, including more complex foundation types (such as tension-leg platforms or semi-submersibles) that use greater quantities of embedded steel and are more difficult to recover intact[116].

The availability and proximity of recycling infrastructure, particularly EAF-equipped steelworks, influences the feasibility and carbon footprint of recycling. EAFs currently account for about 25% of global steel production[117,118]. However, many electricity-powered EAFs still operate using emissions-intensive electricity in countries such as India, South Africa and the Middle East, limiting immediate emissions savings by recycling in those regions[119]. In contrast, in countries such as Canada, Brazil, and France, which have cleaner electricity generation[119], substantially lower-carbon steel recycling is possible. Decarbonising EAFs by shifting to renewable electricity and incorporating hydrogen-based direct reduced iron could reduce emissions by up to 95%[120]. However, this transition is challenged by the continued reliance on fossil-based process heat, infrastructure limitations, and the energy-intensive nature of the smelting process, averaging 2 kWh per kg of recycled steel[121]. The projected growth in decommissioned capacity will correlate with regions with high renewable electricity generation and so could be a secondary material stream that could contribute to circular steel markets and provide stable feedstock for EAF facilities.

Advances in pre-processing technologies can increase recycling efficiency. For example, shredding, sensor-based scrap sorting, surface treatments can help maintain material quality by avoiding alloy contamination in mixed-metal streams[122], particularly from copper-containing generators and gearboxes. Methods to remove residual contaminants from liquid steel and to increase their tolerance in downstream processes are also possible approaches to manage contamination[123,124].

One challenge in the wind sector is that steel can be embedded in concrete foundations or be used in remote marine environments[106,114]. Integrating steel and cement recycling is being developed, where recovered cement paste is reused (substituted for lime) in steel recycling processes[125]. Extraction from offshore sites, especially when there is substantial saltwater corrosion of the steel, often incurs high pre-treatment and transport costs. These factors, combined with market volatility in scrap pricing can limit the economic viability of recovery[124].

LCAs consistently identify tower and foundation steel as major contributors to turbine embodied emissions[43]. Improving steel circularity—via enhanced dismantling logistics, clean material separation, and access to low-carbon recycling routes—is essential for reducing life cycle GHG impacts.

3.2 Composites

Wind turbine blades and nacelles are typically made of GFRP, most often with epoxy, though unsaturated polyester and other resins are used (depending on the manufacturer)[126]. CFRP composites have also been introduced for spar caps in longer blades[127]. Composite blades can be routinely maintained and repaired onsite to extend their life, or at higher cost, by transportation to a factory[128]. Large blade sections can also be reused in large structures such as footbridges, EV charging shelters and artistic furniture elements. The Re-Wind project has published a catalogue of suggested designs[129].

Resins used currently are almost all thermoset polymers[55], which makes the composites difficult to recycle. Thermosets have high heat and environmental stability, but do not melt or flow when re-heated and instead catastrophically degrade[130]. Moreover, recovered GF has a low value, and it is not easy to obtain valuable products from EOL composite resins (Figure 5). CF, however, has a much higher value than GF and its mechanical properties (especially stiffness) can be substantially maintained with several recycling processes, so the value in recycling is potentially higher than with GFRP recycling[131]. However, this potential is often reduced as the fibres are no longer continuous after the recycling processes, which limits applications and the potential properties of new composites containing recycled fibres[86].

3.2.1 Recycling processes

In current industrial practice, many GFRP EOL blades and nacelles still go to landfill, though where local regulations will not allow this (such as Finland and Germany) or the landfill taxes or public perception drives an alternative (such as the UK and USA), they might be shredded and used as refuse derived fuels in energy from waste plants, or recycled by cement coprocessing[132]. A small but rising quantity of shredded waste is mechanically recycled, and some blade parts are reused in new products[14,28]. Some companies might be close to commercialising thermolysis processes for

GFRP[133,134]. There is limited CFRP in current EOL turbines[135] but the CFRP recycling supply chain using thermolysis processes is now sufficiently mature to accept CFRP materials from turbines, subject to the economic viability of separating CFRP from other materials[136].

Mechanical recycling of composites by grinding has the lowest energy demand of the EOL processes (Table 1) [132]. While it results in lower value recyclate, it gains some value for the resin component as filler, without incinerating the resin to release CO_2[137]. Applications for the recyclate have been developed, such as in panels and construction products[28,138,139]. Mechanically ground recyclate can be extruded with virgin or recycled polymer to manufacture products[140].

GFRP blade waste can be co-processed in cement kilns with other fuels if shredded and blended with other waste-derived fuels to a solid recovered fuel specification. The aluminosilicate GF is recycled into cement clinker, replacing mined raw Although considered downcycling, this can save around 360 kg CO2e per t GFRP waste processed, where the energy recovered from the resin replaces coal for energy[141]. Closed-loop recycling of GF is being investigated by the DecomBlades consortium[142]. In this process, resin is removed from GFRP by pyrolysis and the GF is then milled, and introduced into new GF production by melting, substituting mined material at up to 5%[142].

Solvolysis and thermolysis methods are still in the lab or pilot phase[28] but have the potential to recover longer fibres, with the size of the process equipment limiting the recovered fibre length[22]. There is commercial interest in thermolysis and fluidised bed processes[133] despite the current low strength of recycled fibres. High temperature thermal processes cause damage to GFs, particularly above 300 °C [143] but post-treatment and re-sizing of fibres have been shown to result in strength restoration of thermally recovered GFs[144,145].

Low-temperature solvolysis processes can recover thermally sensitive recycled fibres such as E-glass without substantial damage to the fibre, as well as more effectively recovering matrix recyclates, which sometimes include monomers[22,146,147]. While potentially valuable for CFRP, a major disadvantage for the large volumes of GFRP is the relatively high energy demand of this process and the need for large, high-cost pressure vessels (a 15 MW wind turbine can contain up to 19 tonnes of epoxy in a single wind blade)[22]. Energy demand can be lowered by conducting resin degradation at lower temperatures and pressures with the use of catalysts[22]. Ambient pressure solvolysis removes the need for pressure vessels and opens up the potential for continuous processing, but the high cost and scarcity of the catalysts used for the degradation[148] and the low value of GF could offset any benefits and make such processes likely to be uneconomic[22]. In addition, technology to valorise the matrix recyclates into chemicals (other than fuels) requires development.

3.2.2 Thermoplastics

Unlike thermoset resins, thermoplastic polymers can be melted or more easily depolymerised through chemical or thermal processes, which enables a wide range of EOL secondary recycling and processing solutions[22,149]. While melt-processing of thermoplastics is not practical for large structures such as wind turbine blades, some thermoplastics can be used in the pre-polymer form with a comparable viscosity to uncured epoxy and cured at room temperature[150]. These infusible thermoplastics could be a potential “drop-in replacement” for thermoset polymers for wind blades[150]. For example, the ZEBRA project[151] has demonstrated the manufacture of wind blades of up to 77m in length with Elium™ thermoplastic acrylic polymers[152]. Thermal reshaping, thermal degradation, grinding, thermal depolymerisation and dissolution of the polymer matrix have been suggested as EOL recycling techniques, as well as shredding and 3D printing of co-extruded material[153] [154].

3.2.3 Separation and downsizing

Recycling strategies for CF will be challenging in some cases, particularly when CF is used in hybrid configurations or embedded with materials such as metallic meshes. Technologies are needed that are capable of recovering CF from mixed composite waste streams, including CF–GF hybrid laminates and multi-material core systems. For GFRP, mechanical recycling is currently the most viable short-term strategy for minimising GHG emissions due to its low energy demand and scalability[92]. However, its implementation is constrained by high economic costs. However, mechanical recycling is limited by the relatively high economic cost. These cost barriers could be mitigated by cross-sector recycling, which in turn could be accelerated with relevant waste codes to enable wider collection, such as proposed by industry associations[155]. In the longer term, process innovation is needed to enable efficient separation and recovery of high-value fibres, particularly from complex blade architectures.

A major challenge in turbine composite circularity, especially with larger blades, is mechanical downsizing. As cutting and shredding are costly and require special equipment, such downsizing approaches are a focus of numerous industrial research projects, including DecomBlades[126] and REFRESH[156], and are considered at length in a German Environment Agency report on dismantling and recycling standards for rotor blades[157].

3.3 Rare Earth Elements (REE)

Offshore wind turbines, particularly direct drive turbines, contain large quantities of sintered rare earth magnets based on an alloy of neodymium iron and boron (NdFeB)[158] (Figure 2, Figure S2-S3). At a much smaller scale of application, some onshore small-scale wind generators also use permanent magnet generators[159]. The magnets are used in the generators, typically on the rotating part of the machine. The neodymium is normally partially substituted with another light rare earth metal, praseodymium, and the magnets can also contain alloying additions of heavy rare earths including terbium and dysprosium[160].

The microstructure of sintered NdFeB magnets is primarily made up of ferromagnetic matrix phase grains ($Nd_2Fe_{14}B$) and a grain boundary phase containing around 90% neodymium[161]. The processing of rare earths, from mine to magnet, is a complex process resulting in environmental impacts and social impacts, with particular impacts in the mining and processing of magnetic materials (as a result of radioactive and non-radioactive contaminants[162]). There are a range of processes used to manufacture NdFeB magnets but the most common is a powder processing route used to produce sintered magnets which are the type used in wind turbines. During sintered NdFeB magnet production a powder is pressed and sintered containing the matrix phase grains ($Nd_2Fe_{14}B$) and the Nd rich grain boundary phase. During the sintering process the grain boundary phase forms a liquid. The grain boundary phase is particularly susceptible to corrosion and as such the magnets are typically laser welded into cans and embedded in epoxy resins to protect them against a salt spray environment[163], and hermitically sealed. The cans are then mechanically held inside of the wind turbine generator. There is a range of designs and in some cases the magnets are segmented into smaller magnets and potted and/or glued onto the rotating parts of the machine.

Removing magnets at EOL poses challenges, both in terms of reuse and recycling. Modules containing the magnets must be separated from the generator, and the magnets extracted from the cans and adhesives. Each module may contain multiple kilograms of NdFeB, which produce high magnetic fields and pose safety risks. Magnets are typically thermally demagnetised, but this can lead to contamination from epoxy resin. An alternative is to use a diminishing magnetic field to demagnetise, but this requires turbine-specific tooling. Hydrogen processing offers another option, reducing the magnets to demagnetised alloy powder.

3.3.1 Reuse

If the magnets are removed as whole pieces, then route back to market with the lowest environmental impact would be to reuse the EOL magnets or modules, most likely in alternative applications, such as magnetic resonance imaging[164], or even potentially in wind turbines [165]. More broadly, the possibility of reusing small electrical machines from other applications as the generator for small wind turbines has also been proposed[166]: whilst demonstrated to be possible, such applications are likely to be limited. Once magnets have been removed from the application they would have to be checked for signs of corrosion, and they would have to be tested to check the grade of magnet used in the application. It could be possible to reuse the material directly in another wind turbine. Where the magnets have been thermally demagnetised, the outside surfaces of the magnets could be removed to separate oxides and carbides[167]. However, there are concerns over quality control with this process. Moreover, the magnet grades used in turbines frequently change, so the magnets removed from an older wind turbine are unlikely to be suitable for direct replacement into a new wind turbine without specific design considerations for that material. For example, some wind turbine manufacturers use magnets that do not contain heavy REE[168,169].

Wind turbine magnets are more suited for reuse than smaller permanent magnets from other applications due to their larger size and relatively low surface-area-to-volume ratio. Possible reuse pathways involve demagnetisation, separation, cleaning, reshaping, and remagnetisation[170]. However, a large volume would need to be collected and matched to a new product that could utilise the grade to incentivise initiation of businesses and supply-chain infrastructure. Digital product passports[126] could support reuse by documenting chemistry and grade.

3.3.2 Recycling

If reuse is not possible, materials from NdFeB magnets can be recovered using short, medium or long loop processes[171,172,15]. These processes can rely on chemical separation by hydrometallurgy or with the use of ionic liquids to produce oxides (long-loop), remelting[173,174] to produce strip cast alloy or melt spun ribbons (medium-loop), or magnet-to-magnet (short loop) approaches where the magnets are used directly to produce new magnets from an alloy powder[175] (Figure 6). In general, the recycling market is relatively immature compared to recycling of other metals[15].There are also alternative pyrometallurgical[176] and electrochemical[177] approaches, but these are less mature than the commercial approaches discussed in this section (Supplementary Table 1).

Short-loop (or magnet-to-magnet) processes directly convert EoL magnets to new magnets with minimal loss of raw materials. EoL magnets are demagnetised, pulverized, milled, and re-sintered into new magnets[178,179]. In one short-loop method, hydrogen can be used directly to separate NdFeB magnets from wind turbine components (sections of turbines or canned material) in a process named Hydrogen Processing of Magnetic Scrap(HPMS)[180]. HPMS results in a powder that is non-magnetic allowing for easy handling, and also allows for easy separation of the coatings. In another method, the magnets must be thermally demagnetised inside the components and any coatings mechanically removed, before the uncoated magnets are processed in hydrogen to reduce the material to a powder[167], as with HPMS. This powder can be directly remanufactured into new sintered magnets by degassing, jet milling, aligning, pressing and sintering[179,181,182]. The short loop process avoids many of the complex and energy-intensive processes outlined for primary production including hydrometallurgy, metal winning and alloy production.

The short loop process needs careful control of impurities from the starting materials and the magnets will require some level of blending to modify the grade and to aid with the sintering behaviour of the material[15]. During primary production of NdFeB magnets, the material picks up oxygen during each stage of manufacture. This oxygen is concentrated in the grain boundary phase, which has to melt to allow for liquid phase sintering. Therefore, if magnets are made without additions they tend to be porous, which affects the magnetic properties of the material. By blending in rare Earth hydride powders (typically 2-5 atomic percent of neodymium hydride (NdH_2)) it is possible to re-sinter magnets with full density and to separate out the grain boundary phase either chemically or by cyclone separation[183] and then to fully replace this phase. This process allows for higher grade magnets to be remanufactured than previously thought using these direct methods.

Medium-loop and long-loop approaches include more processing stages that can increase the environmental and economic costs. The medium loop process involves remelting the extracted magnets back into an alloy, making it possible to reduce the oxygen content of the starting magnets by removing this in the slag phase[184] and to blend elements into the alloy. Remelting processes can include book mould casting, strip casting or melt spinning. Book mould and strip casting can be combined to produce alloys for sintered magnet manufacture, whereas book moulding and melt spinning are combined to produce nanocrystalline flakes which can be used in resin-bonded or hot-pressed magnets[182].

Long loop processes chemically extract individual rare earths as oxides from the magnets[15,185]. The main advantage of the long loop process is that individual rare earths can be separated and therefore magnets can be remanufactured with an exact composition. Industrially, long loop processes typically can be classified as either a complete leaching process or a selective leaching process (Supplemental Table 1). Selective leaching involves crushing of scrap magnets, oxidative roasting, and acid leaching in hydrochloric acid. Sodium chlorate and sodium hydroxide are then introduced to remove iron from the solution and individual REEs are removed via solvent extraction. The REEs can then be fed into a metal-winning process[186] and the metals cast into alloys, which are manufactured into new magnets using the same processes as those used for short loop recycling[15]. The complete leaching process is similar to the selective process, except that whole magnets are directly leached and there is no oxidation step.

Hydrometallurgical recycling of NdFeB magnets is the most common industrial method used to recycle magnets today, as illustrated by the compilation of commercial projects compiled in Supplementary Table 1: there are commercial processing plants using hydrometallurgical processes, such as in China and Vietnam. The use of ionic liquids to separate rare earths is also being developed and pilot facilities have been built[187,188] (Supplementary Table 1). Often acid leaching and/or solvent extraction processes are used in conjunction with ionic liquids. However, this technology is not well developed compared to conventional hydrometallurgical separation of rare earths and this technology has yet to be fully commercialised[187].

3.3.3 Environmental impact

LCAs for recycling methods vary widely and benchmarking is challenging due to differences in the recycled product form (oxide, alloy, magnet). Generally, the short loop process has been shown to produce a recycled magnet with less than 80% of the total GHG emissions of primary production of NdFeB magnets. Recycling magnets via hydrogen decrepitation can reduce energy demand by

88% compared to primary production[189]. An LCA[171] comparing five different recycling routes for NdFeB magnets found the short loop process are less damaging to the environment in all categories including air pollution, toxicity and GHG emissions. It should be noted that this analysis assumed that the magnets were demagnetised, and the surface coating was removed from the magnets prior to hydrogen decrepitation. Therefore, a higher environmental impact will be observed compared to when HPMS is applied directly to the scrap applications (without thermal demagnetisation and surface grinding). With each additional processing step needed during recycling (remelting, metal making and hydrometallurgy) a cumulatively higher environmental impact is observed. For example, the chemicals used in leaching and solvent extraction add to the toxicity, and metal winning and casting use large amounts of energy.

Ultimately, a mix of recycling routes is likely. Wind turbine magnets can be reused or short-loop processed owing to their large volume and uniform composition. Short-loop recycling lowers environmental impact and cost, while long-loop recycling enables grade modification. Blending both approaches offers a path to higher-performing and more sustainable recycled magnets.

3.4 Concrete

Current onshore wind turbine designs depend heavily on concrete, which accounts for approximately 70% of the total mass of onshore turbines (primarily within the foundations)[46,190,191]. Early offshore foundations also had a high reliance on concrete (they were mostly gravity fixed-bottom foundations), though more recent designs are typically situated in deeper water and dominated by steel-based designs (monopile and jacket fixed bottom foundations)[106,192]. The future distribution between steel and concrete used for offshore wind foundations is unclear because there are a variety of suggested future designs, including hybrid or floating foundations, which could use either material[192].

Although specific concrete embodied energy and emissions are relatively low[193], the large volume of concrete used means it contributes around 6% and 12% of overall wind turbine embodied energy and emissions, respectively (Figure 5). The majority of environmental impacts of concrete production occur during cement-making, and more specifically clinker-making (the primary component of cement)[194]. More than half of the emissions in cement-making are process emissions from the thermal decomposition of limestone in clinker-making, while the remainder are mostly from combustion of fossil fuels, needed for the high kiln temperatures[195].

Despite this importance, foundations are sometimes excluded from turbine manufacturers' analyses[108] as they are site-specific. Where concrete is included in analyses such as LCAs, waste concrete is often assumed to be landfilled[41] although common practice is to leave underground infrastructure (such as foundations and connecting cables) in place[104,114], when regulation allows. Concrete reuse is not an established practice today[103] but onshore foundations can, in principle, be reused, having potential for a design lifetime of around 60 years[103], around three times the current turbine lifespan[3,4]. Reuse and lifetime extension of concrete components might be more difficult for sites with corrosive conditions or repeated free-thaw[196–199]. Faster degradation can occur in high-chloride (such as marine environments and offshore turbines[198]) or in high-sulphate environments (such as for onshore turbines close to areas of high fertilisers use[199]), unless foundations can be designed to be adequately resistant. The actual reuse of concrete foundations, however, remains uncertain because newer, larger turbine models often require different foundation designs or enhanced load-bearing capacity, reducing compatibility with existing foundations.

Combined with the challenges of ownership changes, high costs, and trust issues, these limitations contribute to the limited practice of reuse in current repowering projects[103,200,201]. Designing foundations for extended life is also possible but logistically difficult for three reasons: future turbine designs are unknown, there could be contractual and insurance challenges if the connection components considered in certification of the new turbine are not be compatible with existing foundations, and current subsidy schemes generally do not incentivise the increased upfront costs of larger foundations[103]. Similarly, repowering onshore foundations can cost between 2 and 3 times more than a new foundation (Figure 4)[103]. Offshore concrete structures can have design lives of over 50 years[202] but rely on adequate protection and testing to avoid degradation[203]. In cases of concrete degradation, material recovery through crushing or thermal processing could still be feasible, provided contamination (such as from chlorine or sulphate) is adequately managed[192].

Removing foundations for potential recycling, however, has potentially high environmental and logistical challenges. The details differ markedly between different foundation designs, and whether turbines are situated onshore or offshore. Onshore gravity foundations can be extracted by breaking the foundations down into sections but require heavy machinery, such as steel cutting equipment, hydraulic breakers and excavators[204]. Onshore turbines supported by deeper concrete piles can be difficult to remove because their design relies on friction; they might break during extraction, exposing reinforcement and requiring contingency measures to excavate or cap snapped parts (to minimise environmental contamination)[204]. Offshore removals also resource-intensive, due to the remote and challenging environmental conditions, requiring specialised equipment, underwater demolition, and careful environmental monitoring[116,205], contributing to high costs. Furthermore, as with offshore deployment, removal of large components can be constrained by vessel availability, port space, and sea conditions[206,207]. Some researchers have proposed leaving offshore foundation structures in place to minimise disruption to marine life and act as artificial reefs for ecosystems[208,209]) - this approach is unlikely to be detrimental, but the evidence to support many ecological benefits is currently inconclusive[210]. Concrete in floating foundations might be more easily recovered since the turbine platform could be towed to shore without specialised vessels, but extracting concrete from anchors could be more challenging[211].

Closed-loop recycling of concrete would require each component material to be separated and recycled individually, which is technically challenging. Instead, the most common approach to recycling waste concrete is a form of open-loop recycling, in which concrete is crushed to create RCA. This downcycled material is a subgrade aggregate (one with low value and relatively poor mechanical properties)[212] but, after processing and combination with cement and higher quality aggregates, it can be used for new construction concrete[213,214]. Most RCA, however, is used in lower strength applications, such as road construction and earthworks (around 80-100%), replacing around 10-25% virgin aggregates in Europe[16]. Although using RCA could reduce landfilling costs and high mass aggregate transportation, the overall environmental impacts of producing RCA for structural concrete could be around 20-30% greater than producing crushed natural stone[16]. This impact is largely because the low-quality aggregate can require a higher cement fraction; use of RCA in place of gravel for road construction, in contrast, could reduce overall environmental impacts[16]. Concrete has also been explored as a potential sink for recycled composite waste. Shredded wind turbine blades could be incorporated, potentially alongside RCA, into concrete to divert composite waste from landfills[213,215]. Although effective in allowing producers to meet recycling and reuse targets and potentially a higher quality aggregate than RCA alone[213], this approach has minimal potential for reducing the environmental impacts of concrete, which mostly are from clinker-making.

Although it is not economically lucrative, it is also possible to extract and use the cement binder from the crushing process[125]. Fines are produced alongside RCA and contain a mixture of Portland cement and supplementary cementitious materials, together with finely crushed aggregate and other contaminants. These could be used as Non-Portland Cementitious Materials (NPCMs), replacing materials such as blast furnace slag and coal fly ash, which are used currently but could become more limited in supply as other sectors decarbonise[216]. The clinker-substitution rate is, however, limited to around 25%[217]. Emerging technologies aim to extract the cement paste from the fines and reclinker the material at high kiln temperatures to drive off water and CO_2. These thermoactivated cementitious materials have potential for higher clinker-substitution rates, and novel approaches, such as the novel electric cement recycling process[125], could substantially reduce both emissions and energy demands. The reclinkering process is, however, both technically and economically challenging[218] – the thermochemical processes are not yet well understood[219], with unavoidable contamination of recovered cement paste adding complexity[125].

Material efficiency approaches to managing future concrete waste are likely to be more impactful than those of reuse and recycling. Innovative solutions are emerging that aim to reduce the initial material demand for foundations, such as using additive manufacturing to optimise material usage[220] or modular precast elements to also improve constructability and disassembly[221]. Current trends suggest, however, increased use of concrete in future wind turbines[192]

Regulations on concrete foundation decommissioning vary between jurisdictions, shaping both current practices and future opportunities. Within Germany, for example, full removal of the foundation is required in some states, while others allow partial removal to a depth of 1.5 metres[63]. Such policy variability presents a challenge for harmonised EOL strategies across regions.

4 Design for circularity

Circular design in the wind turbine industry involves integrating strategies across the entire lifecycle—from material selection and manufacturing to servicing and EOL management—to reduce waste and maximise resource efficiency. These strategies include modular architecture, design for disassembly, recycling, and the early-stage incorporation of recyclable, recycled or short fibre-reinforced structures into components such as blades[222]. Blade designs should also support CF spar removal for recycling and incorporate recycled carbon fibre content ab initio. However, commercial uptake of recycled content remains limited due to economic constraints and quality degradation during recycling[130]. Recycled materials tend to suffer losses in performance[223], making them less attractive to manufacturers. Enhancing the value proposition of recycling will therefore require innovation in recycling processes, development of high-performance secondary materials, and policy mechanisms to support stable supply-demand dynamics.

In the case of fibre-reinforced composites, resin selection is central to circularity. Mechanical grinding methods are resin-agnostic and can retain carbon in durable products, enabling long-term carbon sequestration[137]. However, for chemical recycling routes such as solvolysis or thermolysis, resin chemistry heavily influences recyclability[22]. Current industrial research focuses on several options. Existing epoxy resins can be chemically recycled through catalysed solvolysis, as explored in the CETEC project[224,225]. Alternatively, new resin systems, such as Swancor's EzCiclo[226] are formulated to improve solvolysis efficiency at EOL. Thermoplastic resins like Elium, used in the ZEBRA project[227], enable both melt processing and thermal or chemical recycling. Bio-based resins also allow thermal recycling, including fluidised bed and cement kiln co-processing, where the organic fraction contributes energy to the process without adding to fossil carbon emissions[228].

However, these advances in resin systems apply only to new blade designs and do not offer solutions for managing the large volume of legacy blades made with traditional epoxy or polyester thermoset resins, which continue to dominate EOL waste streams.

Thermally reversible thermoset resins, such as covalently adaptive networks or vitrimers[228–230], have also been proposed for potential use in composites but their long-term network reversibility allows creep. Early commercial examples include recyclable resins that contain degradable bonds or functional groups (acetals, imines, disulfides, Diels-Alder adducts, boronic esters and others). These are designed to be intrinsically susceptible to solvolysis and so can be degraded much more efficiently, often generating more valuable matrix recyclates. One such example is Recyclamine-epoxy system from Aditya Birla Chemicals, which aims to improve the recyclability of epoxies by incorporating acetal groups within the polyamine hardener[231]. However, utilization of these materials is limited to research, with minimal demonstration[232].

Reducing impacts of resin also depends on reducing process emissions and shifting to renewable or bio-based precursors. Fossil-based epoxy production results in cradle-to-gate emissions of 3–8 $kgCO_2e$ per kg, while bio-based alternatives have the potential to be net negative cradle-to-gate and achieve as low as –2 $kgCO_2e$ per kg when fossil-intensive pathways such as epichlorohydrin are avoided[233]. Recyclable thermosets derived from renewable feedstocks are being investigated (for example, innovations through polyester covalent adaptable networks)[234]. Nevertheless, solvent-based recovery of chemicals from resins remains both economically and environmentally costly and is limited in practice[235].

Designing for circularity also requires addressing the quality and end uses of recycled fibres and matrix materials. Inclusion of recovered fibre structures or substructures in original component design, particularly in blades, can help close material loops[222]. These closed-loop recycling processes could include incorporating recyclable epoxy or thermoplastics, facilitating disassembly, and ensuring fibre alignment and integrity for high-performance reuse. Studies[222] have proposed the production of outer body shells and shear web skins using recycled CF; however, due to their structural performance requirements, spar caps are manufactured from virgin CF. The discontinuous nature of recycled CF results in fibre volume fraction requirements of up to 40%, which do not give sufficient mechanical performance for closed-loop applications[94]; therefore, continuous fibre alignment is needed to achieve the mechanical properties required for spar cap applications.

5 Summary and future perspectives

Effective EOL management of wind turbines is becoming increasingly critical as the global installed capacity of wind power continues to grow. While recycling bulk metals, such as steel, is commercially mature and environmentally beneficial[236], challenges remain in disassembly, contamination, and geographic mismatches between scrap supply and processing capacity. In contrast, concrete recycling and less developed. Downcycling to recycled aggregate is common, but higher-value options such as reclinkering and recalcination remain pre-commercial. Offshore foundations, due to rebar corrosion and underwater complexity, are particularly difficult to recover. Nonetheless, top-block reuse and modular design offer new avenues for circularity in concrete systems.

GFRP remains the most challenging material class for EOL. Economic feasibility remains a challenge. Mechanical recycling is currently the most viable method, especially for GFRP, and demonstrates the lowest GHG emissions among recovery technologies, although it often yields lower-value products[92]. kiln co-processing is a practical, scalable recycling solution for GFRP and can be environmentally beneficial, compared, for example, to incineration for energy recovery[28],[100] (Table 1).

Advanced processes such as solvolysis and thermolysis enable higher recovery value for CFRP and are vital to valorising offshore turbine blades, which increasingly incorporate carbon fibres. Further development is required to reduce energy consumption and high-value applications of recyclates need to be identified. A cross-industry approach, where composite waste from wind, aviation, marine, and other sectors is aggregated, could increase available waste volumes and enhance the economic case for advanced recycling. To enable this effort, legislation will be needed to ensure that material fractions from different industries are effectively tracked and pooled, creating more predictable feedstock supply and supporting investment in scalable recycling infrastructure. Digital material passports are gaining attention as tools to improve transparency and traceability across the turbine lifecycle[126]. These passports document material composition and recyclability, potentially enabling more effective disassembly and recovery strategies. However, their implementation remains limited, with few large-scale examples across the wind energy sector[10].

For typical onshore, geared turbines, current recycling and reuse practices recover only around 25% of the total material mass**,** substantially due to the concrete foundations, which are not economically recoverable, and recover materials accounting for around 60% of the embodied energy for materials (Figure 5). Design for circularity is emerging as a key enabler of sustainable wind turbine systems. Strategies include the use of modular components, material passports, recycled content, and low-carbon alternatives such as hydrogen-based steel or bio-based resins. Early integration of EOL considerations—particularly disassembly and recyclability—into component and system design is essential to reducing lifecycle emissions and material losses. The successful commercialisation of high-value recovery processes depends on strengthening end-markets for recyclates. Expanding the market for secondary materials, particularly CFRP and recovered REEs, can increase EOL material recovery value substantially, especially in larger, direct-drive turbines, but will require demonstration case studies, standardised quality metrics, and industry-wide collaboration.

Policy frameworks are essential to support this transition. Regulatory drivers such as the EU Ecodesign for Sustainable Products Regulation and national mandates can incentivise innovation and material recovery. Stronger data transparency, particularly through material tracking systems and digital product passports, will be essential for accountability and lifecycle planning. Standardised decommissioning protocols, circular design guidelines, and robust supply chain coordination are equally critical. Collectively, these strategies can help recover the materials in wind turbines as they continue to be a key part of a low-carbon energy system.

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Acknowledgements

The authors would like to acknowledge support from the National Key Research and Development Program of China (no. 2022YFB4202101), the National Natural Science Foundation of China (no. 52388101, 52225902, and 72161147003), and the Guangdong Institute of Chinese Engineering Development Strategies (2025-GD-04), the Royal Society ISPF - International Collaboration Awards (ICA\R1\231046), Saudi Aramco (189360), the EPSRC funded RECREATE (REcycling CRitical Elements in Advanced Technologies for the Environment) project (EP/Y53058X/1) and from the European Union funded Harmony Project (EC-GA 101138767/IUK10094315).

Competing interests

The authors declare the following competing interests: A.W. is a director of Hypromag Ltd., a company specialising in the recycling of rare earth magnets. A.K.P. is Head of Materials and Sustainable Scaling at Vestas. The other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions

All authors contributed to the conceptualisation of the study. Methodology was developed by F.M., L.G., and S.J. Formal analysis was conducted by F.M., L.G., S.J., A.K.P., J.H., and G.H. The original draft of the manuscript was written by F.M., L.G., and S.J. All authors contributed to reviewing and/or editing the manuscript prior to submission.

Key points

- Metals like iron, steel, and copper have established recycling routes, but logistical, contamination, and regional infrastructure challenges still affect recovery rates. Rare earth elements and composite materials remain difficult to recover at scale.
- Mechanical recycling of glass fibre-reinforced polymers is currently the most viable short-term solution to minimise environmental impact, but cement kiln co-processing could be more scalable economically in some areas. Thermal fibre recovery and solvolysis offer greater material recovery potential but face energy, cost, and scalability barriers, such as uncertain recyclate markets.
- Emerging thermoplastic composites offer improved recycling options but long-term durability and scalable recycling routes are not yet proven or established.
- The scale-up of emerging processes for recovering rare earth elements in magnets and carbon fibre from turbine blades could increase wind turbine end of life material value. However, economic viability remains uncertain.
- Decisions about EOL management of wind turbines should be guided by robust environmental, economic and circularity metrics, which capture trade-offs across different recovery pathways, including energy use, emissions, and material quality.
- Developing robust supply chains and markets for secondary materials, supported by strong policies and regulations, is crucial for the commercial viability of recycling processes.

Figures and Tables

Table 1 - Overview of fibre-reinforced polymer (FRP) recycling and end of life processes.

Process	**TRL (1-9)**	**Fibre strength retention[a]**	**Suitable for**	**Type of value retention**	**Primary energy demand[b] (MJ/kg FRP)**
Landfill[86]	9	n/a	Carbon fibre (CF), glass fibre (GF)	None, but long-term storage of resin carbon	1.1
Incineration[28,237]	9	n/a	GF	Primarily energy recovery, in some cases mineral residue used in aggregates	1.7
Re-use[100]	9	100%	CF, GF	Full value retention, depending on structural value of application	not known
Recycling by mechanical grinding to fine filler [86,238]	9	n/a	GF, CF	Low value filler	0.7-1.9
Recycling by mechanical grinding with fibre retention [239]	9	Substantial strength loss (varies)	GF, CF	Resin as filler (or matrix with thermoplastic resins) and some reinforcing value from fibres	0.3-1.6
Cement kiln recycling[237]	9	n/a – recycled into cement	GF	Efficient energy recovery and replacement of mined raw material	1.3
Thermolysis recycling CFRP [86,238]	9	95%+ is achievable, but typically retention is lower in commercial processes	CF	Fibre retention, syngas and/or oils recovered (limited in practice) or resins combusted for energy recovery	32 (Newer processes might be lower)
Thermolysis recycling (GFRP) [86]	7	Substantial strength loss (varies), can be mitigated with fibre regeneration	GF		32
Fluidised bed recycling (CFRP) [51,86,94]	6	50-75%	CF	Fibre retention and energy used to power process (excess	10.4

Fluidised bed recycling with fibre regeneration (GFRP) [92]	6	~80%	GF	energy depends on resin content)	13 (for 60% wt fibre content GFRP)
Solvolysis recycling [22,86]	8	95%+	CF, GF	Fibre retention and monomers from resin, limited in practice	38.4 but varies by process
Pressolysis recycling (CFRP) [240]	5	95%+	CF (GF research in progress)	Fibre retention and potential monomers from resin, research in progress	not known
Virgin glass fibre[237,241,242]	-	-	-	-	13.0 - 54.3
Virgin carbon fibres[237,241]	-	-	-	-	171 - 998
Virgin resins [237,241]	-	-	-	-	84.4 - 107.9

[a]Fibre strength and primary energy demand (PED) values will vary substantially with process parameters and with resin content, so they should be treated as a guide only. [b]Primary energy demand values do not include downsizing or the benefits of recovered material. [c]Virgin material values are included for comparison.

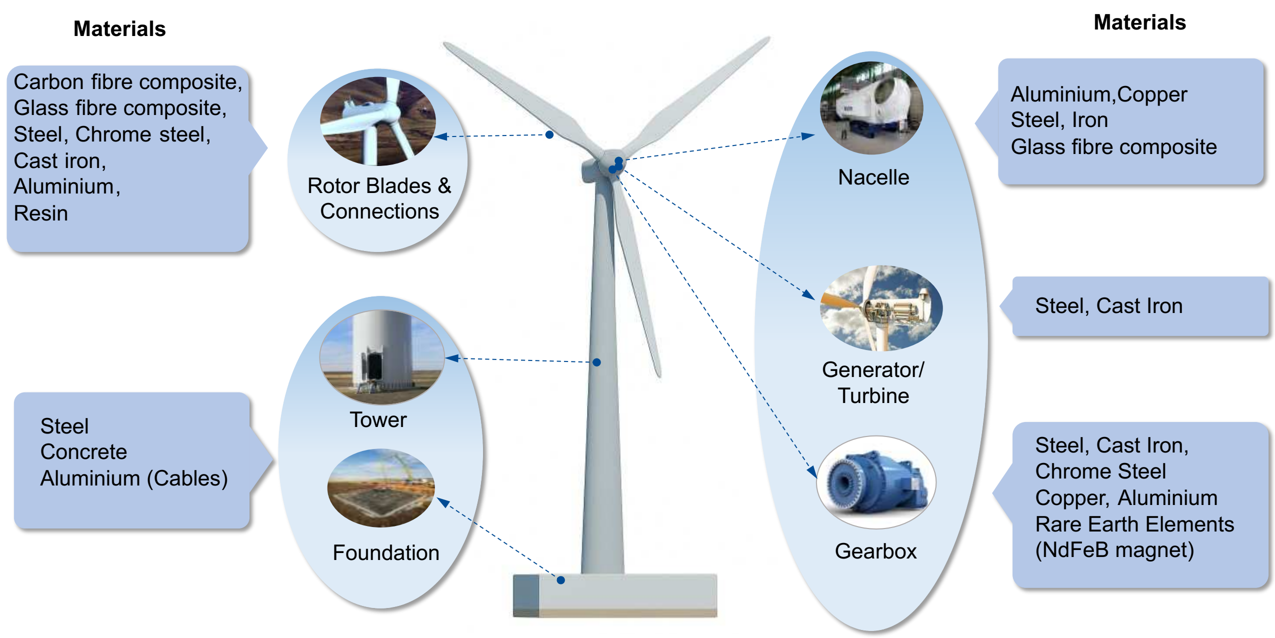


Figure 1 Wind turbine material composition and recycling
The main components—foundation, tower, rotor, nacelle, gearbox, and generator—and their associated material inputs of geared and direct drive wind turbines. Common materials include steel, aluminium, concrete, copper, and composites such as glass fibre-reinforced epoxy polymers

and carbon fibre-reinforced epoxy polymers. The multi-material composition of modern turbines creates challenges and opportunities for end-of-life material recovery.

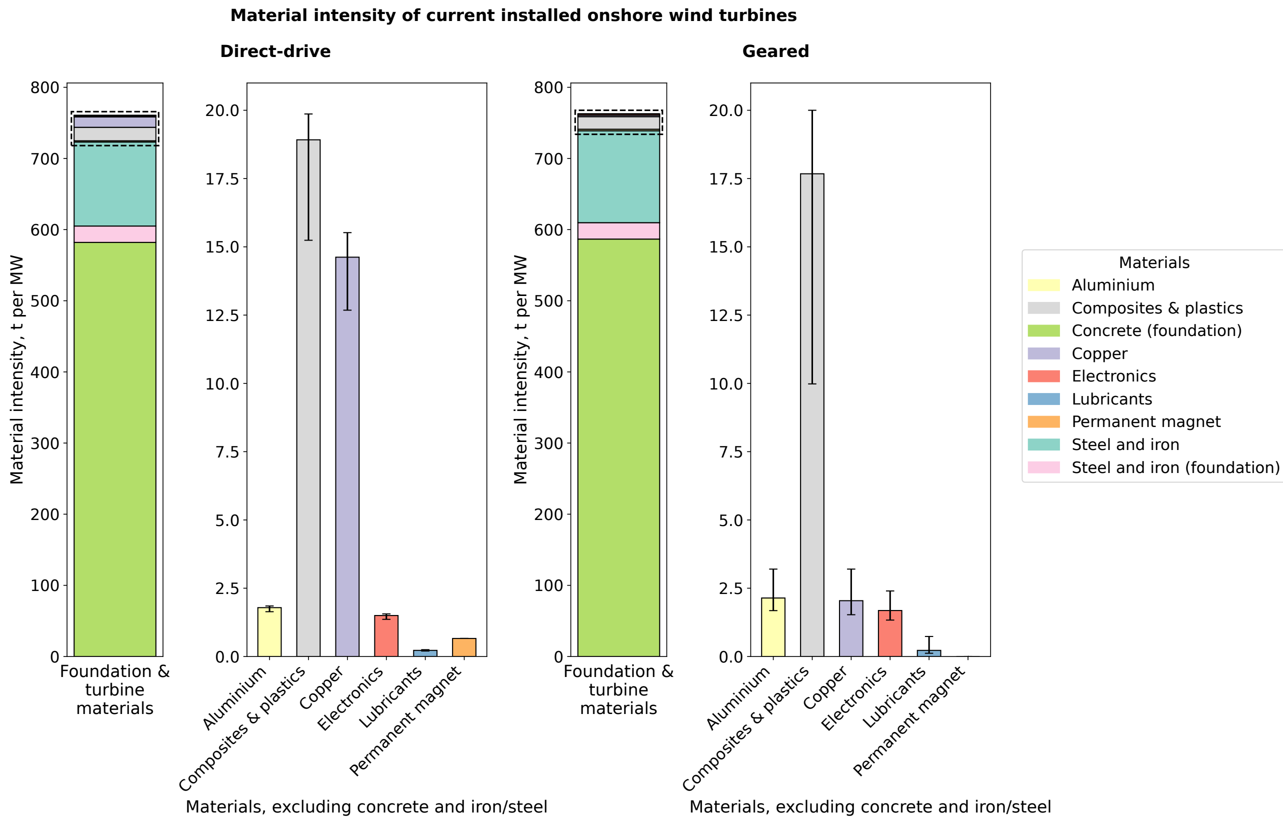
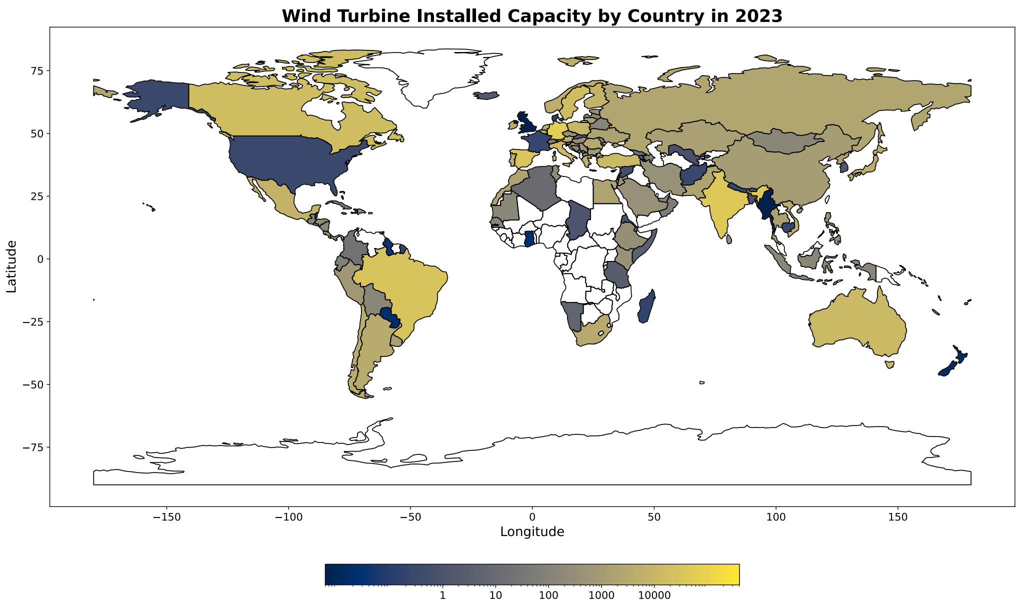
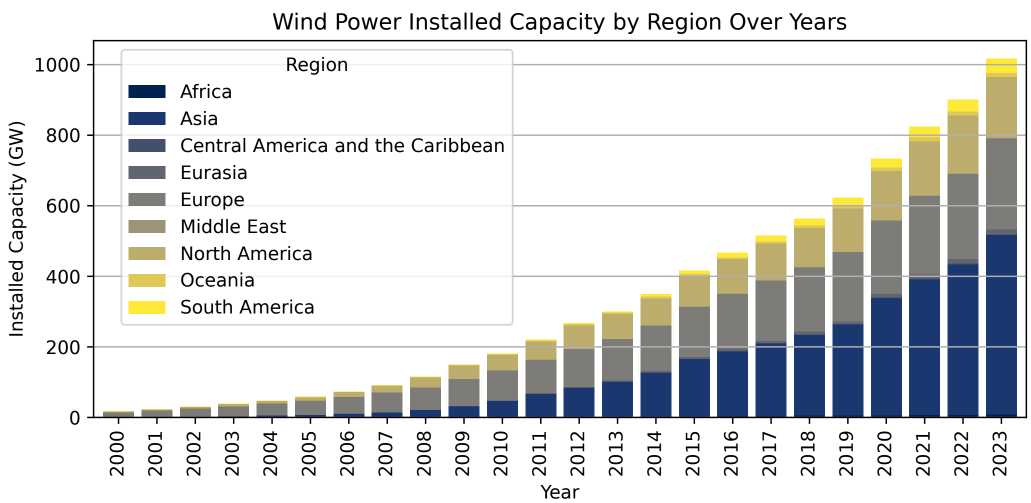


Figure 2 **Material intensity of onshore wind turbines by generator type.**
Comparison of median material intensity values (t/MW) for direct-drive (left) and geared onshore wind turbines (right) installed between 1989 and 2018. Data are derived from 92 wind turbines across 31 series by 15 manufacturers, with power ratings ranging from 0.15 to 3 MW (Ref[40]). Bars represent different material categories, including foundation and turbine materials (left), and excluding concrete and steel (right). Generator design influences the composition and quantity of material use, with implications for both environmental impact and end-of-life material recovery. Notably, direct-drive systems use more rare earth elements and copper, while both designs rely on steel and concrete. Total material intensity estimates vary across sources due to different assumptions and averaging methods[37].


Wind Turbine Installed Capacity by Country in 2023
Latitude
Longitude
75
50
25
0
−25
−50
−75
−150
−100
−50
0
50
100
150
1
10
100
1000
10000


Wind Power Installed Capacity by Region Over Years
Installed Capacity (GW)
Year
Region
Africa
Asia
Central America and the Caribbean
Eurasia
Europe
Middle East
North America
Oceania
South America
0
200
400
600
800
1000
2000
2001
2002
2003
2004
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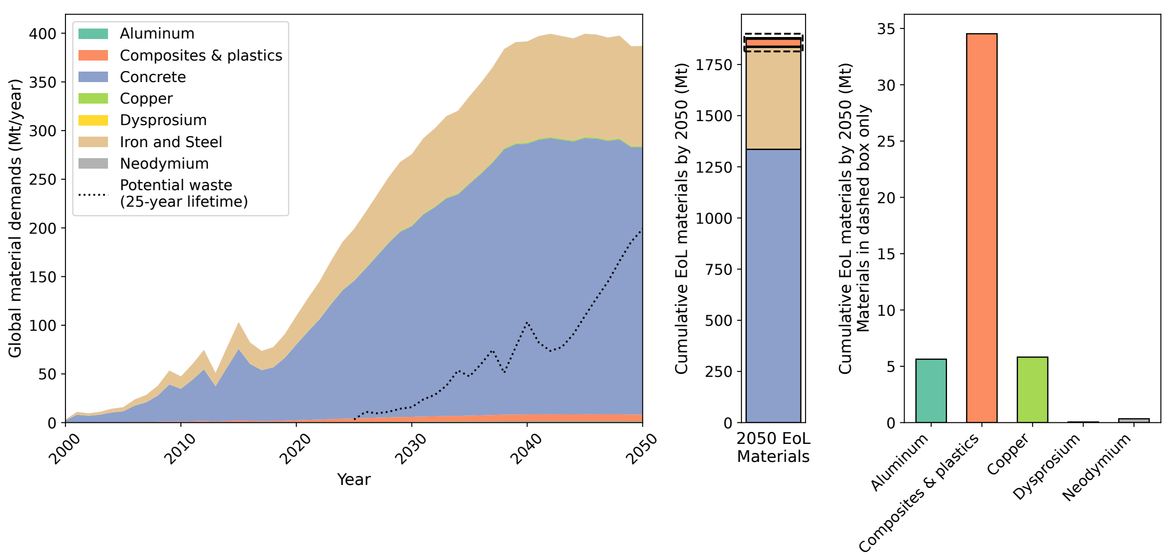
Global material demands (Mt/year)
Year
Aluminum
Composites & plastics
Concrete
Copper
Dysprosium
Iron and Steel
Neodymium
Potential waste
(25-year lifetime)
0
50
100
150
200
250
300
350
400
2000
2010
2020
2030
2040
2050
Cumulative EoL materials by 2050 (Mt)
0
250
500
750
1000
1250
1500
1750
2050 EoL
Materials
Cumulative EoL materials by 2050 (Mt)
Materials in dashed box only
0
5
10
15
20
25
30
35
Aluminum
Composites & plastics
Copper
Dysprosium
Neodymium

Figure 3 **Global growth in wind capacity and associated material waste through 2050.**
a| Installed wind turbine capacity (in MW) in 2023, based on IRENA data[8]. Data not available for places mapped in white (see Supplementary Information). b| Regional growth of wind capacity (in GW) from 2000 to 2023, based on IRENA (2024)[8] and the IEA Net Zero Emissions Scenario[1]. c| Annual material demands required for capacity growth and resulting waste after a 25-year design life (left graph from 2000-2050) and cumulative materials from end of life wind turbines by 2050 (middle graph for total, right graph for detailed breakdown of materials other than concrete and iron and steel). Data for c is based on historical and future capacity growth given by the IRENA ReMap scenario from ref [31] and material intensity data for onshore and offshore wind from ref [56]. Potential waste is estimated to result only from materials needed for capacity increases, assuming a design life of 25 years. Gravel (used for anchoring and ballast in offshore applications[56]) is not included in this figure. The numerical data for these figures are provided in Supplementary Information. Total waste material could reach around 200Mt/yr by 2050, equivalent around 6% of global construction and demolition waste produced in 2016[243]. This estimate is highly dependent on turbine design assumptions. The information presented in c assumes that onshore and offshore wind turbines maintain a high dependence on concrete. Current offshore designs often use monopile substructures with a strong dependence on steel, rather than concrete[244], therefore an alternative projection based on direct-drive monopile offshore wind turbine designs is given in Supplementary Figure 4.

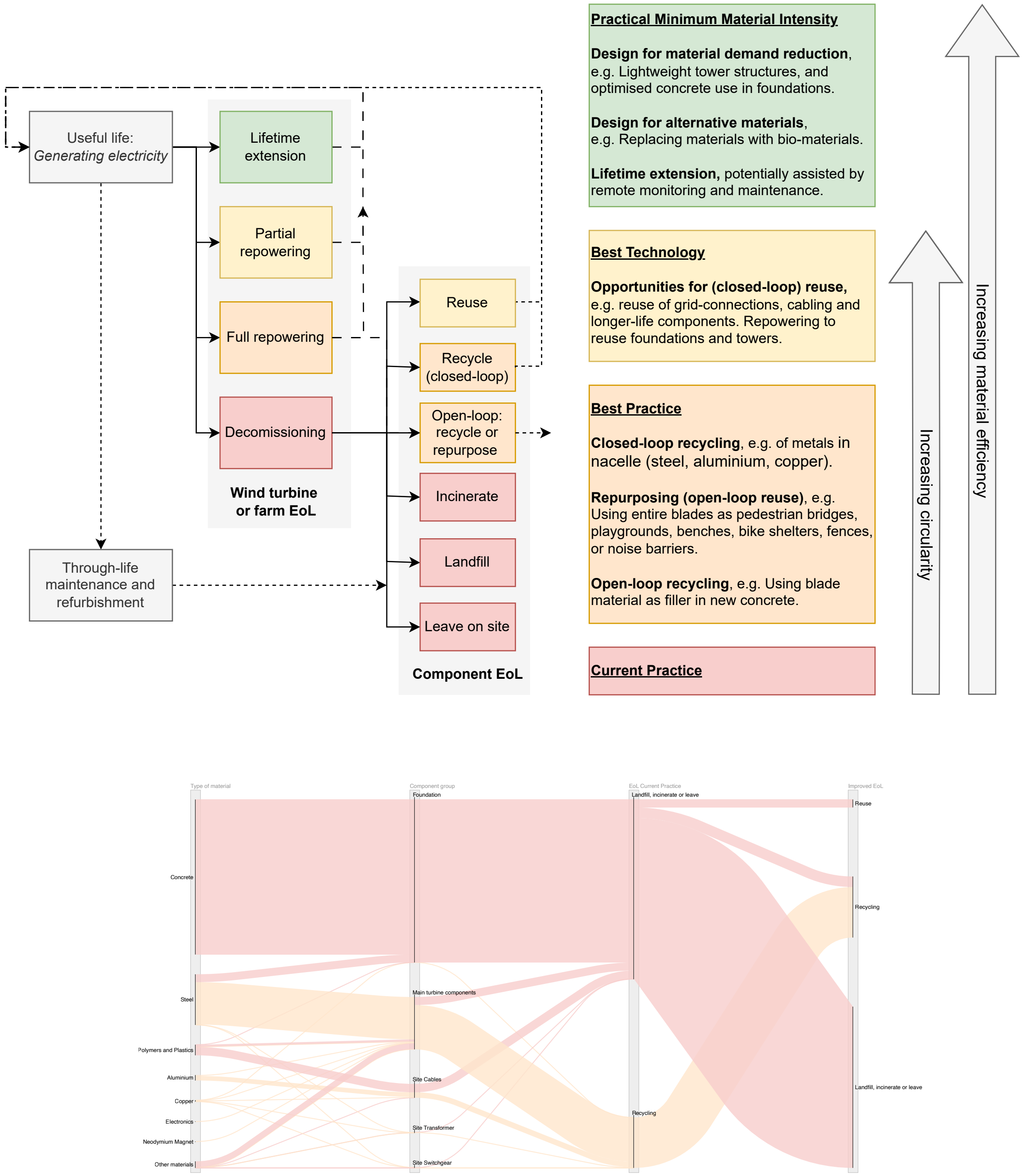

Figure 4 **End of life options and material flow pathways for wind turbines.**
a| Key in-sector material efficiency strategies to reduce environmental impacts of wind-powered electricity generation, including lifetime extension, partial or full repowering, and decommissioning with various end of life options. b| Sankey diagram of turbine material flows. Based on data in ref[41] for Vestas V-90 turbines to identify how different wind turbine materials are currently managed at EOL, and how these could be improved by increasing reuse and recycling for each material type.

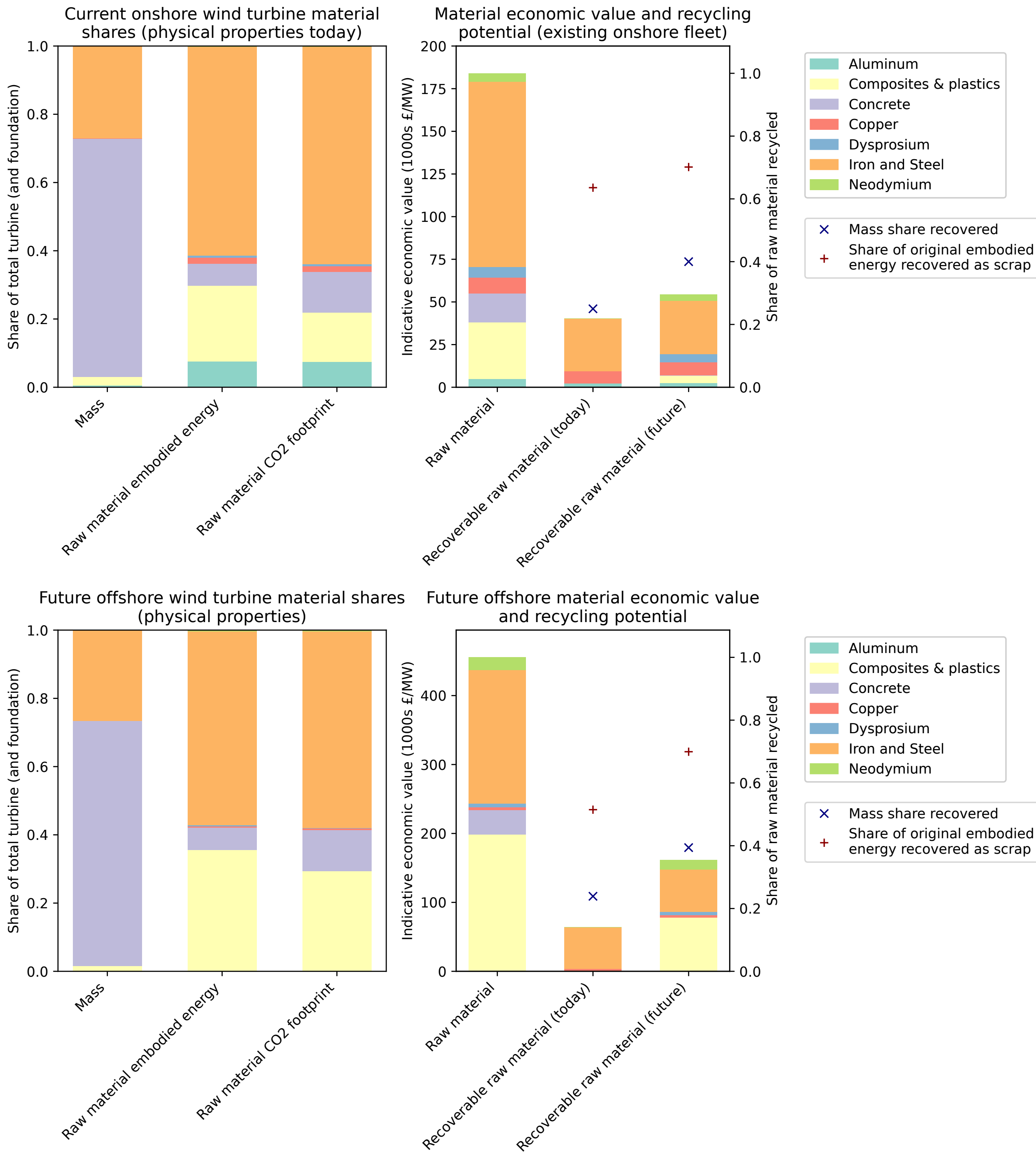

Figure 5 **Material composition and relative economic value indicators for wind turbines.** Onshore and offshore wind turbine materials in terms of their mass share, embodied energy, CO_2 footprint, raw material economic value, and current and future recycling economic value. Concrete dominates the mass distribution and iron and steel have large environmental impacts and costs.

Polymers, composites and aluminium also have substantial environmental impacts despite their low mass fraction. The economic share of these materials could be higher than shown because manufacturing costs are not included in the figure and these materials have large price uncertainty due to immature markets[245] with potential for increases due to competing demands[58] and composites have been assumed to be only 50% recoverable (compared to around 90% for other materials). See the supplemental information for data sources and values.

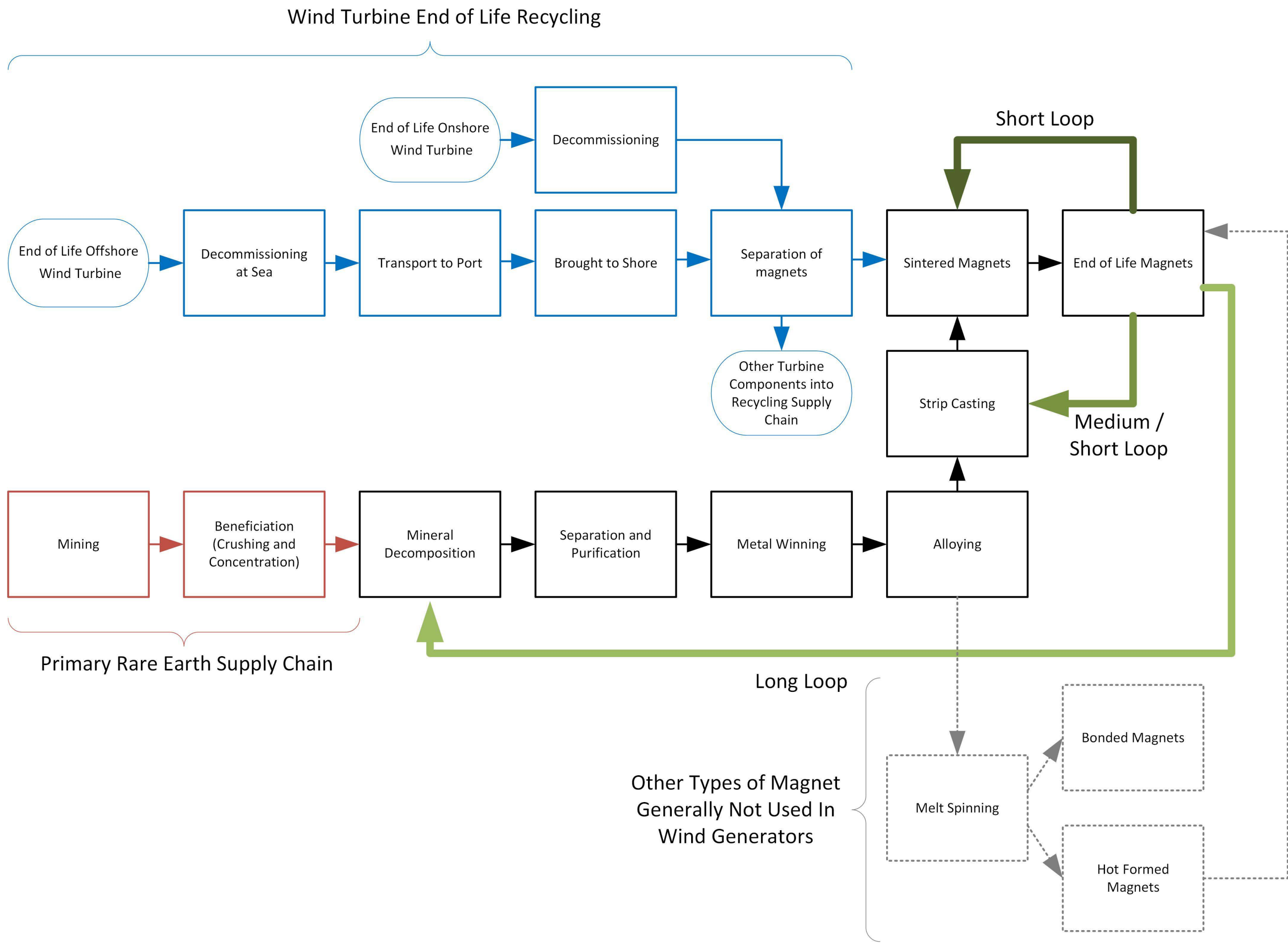

Figure 6 **Recycling options for separated NdFeB magnets.**

The process of recycling magnets from wind turbines, the supply of primary materials into the wind turbine magnet supply chain, and possible routes for production of recycled magnets from wind turbines to alternate applications. There are three different process routes for magnets – short, medium and long loop recycling. The longer the loop, and the more steps required to recycle the magnet, the greater the impact in terms of carbon, resource inputs and energy.

Box 1 | Drivetrains and generators

Wind turbines are typically classified based on their drivetrain and generator system, with four main configurations widely used in commercial deployment: direct-drive + electrically excited synchronous generator (DD-EESG), direct-drive + permanent-magnet synchronous generator (DD-PMSG), gearbox + permanent-magnet synchronous generator (GB-PMSG), and gearbox + double-fed induction generator (GB-DFIG)[37,246,247] (see the figure). The selection of the generator type is driven by system size, site conditions, and OEM design strategies.

Gearbox versus direct-drive systems

Gearbox-based turbines (GB-DFIG, GB-PMSG) use a mechanical gearbox to match rotor and generator speeds, enabling the use of smaller, faster-spinning generators. These designs are compact and cost-effective but increase maintenance due to wear-prone components.

Direct-drive systems (DD-PMSG, DD-EESG) eliminate the gearbox, improving reliability and reducing maintenance, especially for offshore applications. However, they require larger generators and incur higher upfront costs.

Generator principles

Synchronous generators (SGs) rotate at grid frequency and include permanent magnet synchronous generators (PMSGs) and electrically excited synchronous generators (EESGs). PMSGs are highly efficient and compact but rely on rare earth elements (REEs) such as neodymium and dysprosium, making them expensive and geopolitically sensitive[248]. EESGs avoid REE use by using copper windings and excitation systems but are heavier and require more complex controls[249].

Induction generators (IGs) operate asynchronously relative to the grid and include squirrel cage (SCIG), wound rotor (WRIG), and doubly-fed (DFIG) types. DFIGs dominate onshore markets due to their cost-efficiency and partial converter control, though they offer limited fault tolerance and weaker frequency support. SCIGs and WRIGs are rarely used in modern commercial turbines[246,250].

Material and environmental implications

Rare earth magnets used in PMSGs pose critical material concerns; a 10 MW DD-PMSG turbine can contain >500 kg of NdFeB magnets[251]. Copper demand is especially high in EESG and PMSG systems due to rotor windings and excitation coils[252]. Steel use is concentrated in gearbox components and nacelle structures, contributing to embodied emissions but offering strong recycling potential.

Glossary

Circularity: *A systemic approach aimed at retaining the value of materials, components, and products in the economy for as long as possible.*

Material yield: *The share of input material to a process, which is used within the final product from that process*

Recycled Concrete Aggregate: *The material obtained by crushing and processing waste concrete, which can be used in place of natural aggregates (such as sand, gravel and crushed stone) in new concrete production.*

End Of Life*: when components or systems have reached the end of their initially-intended design lifetime, or which would be classified as too damaged for further use without non-routine repair.*

Circularity potential: *The quantity of material required for a product, which could be sourced from secondary material supply.*

Material circularity indicator: *A measure of how effectively a product's materials are kept in use by evaluating the proportion of virgin material input, the amount of unrecoverable waste generated, and how long and intensively the product is used compared to industry norms, resulting in a score between 0 and 1 that reflects its circularity.*

Product circularity indicator: *A measure of circularity that builds on the Material Circularity Indicator to evaluate product circularity between 0 (completely linear) and 1 (perfectly circular); it considers manufacturing stages to include material losses during manufacture and the uses of recycled and reused materials/components within the circularity evaluation.* [75]

Solvolysis: *A chemical reaction where a solvent acts as a nucleophile, cleaving chemical bonds.*

Pyrolysis: *Thermal decomposition of organic matter in the absence or near absence of oxygen; it produces a range of products including gases, liquids (oils), and solids (char).*

Thermolysis: *the chemical decomposition of materials through the application of heat, but without combustion, which can include pyrolysis, fluidised bed, gasification and other processes.*

Circularity index: *A percentage measure, where 100% indicates perfect circularity, calculated as the product of a measure of material quantity (α, the ratio of recovered EOL material against total material demand) and one of material quality (β, the ratio of energy needed for material recovery against energy required for primary material production).*

Ecocircularity Performance Index: *An advanced circularity metric that incorporates both material inflow/outflow dynamics and lifecycle environmental impacts*

Cut-off allocation: *A method used to manage multifunctional processes in life cycle analysis where, for example, the burdens of initial production are allocated to the first life and those of recycling allocated to the second use,* with no credit given to the first life for the avoided impacts of recycling.

Net present value: *The value of all future cash flows, discounted to the present to account for the time value of money in techno-economic analysis.*

Material efficiency: *The pursuit of approaches (including circularity) to reduce the material intensity (the amount of material production and processing) required to provide material services*

Lifetime extension: *Analysis and monitoring to extend design life with minimal additional material demands.*

Partial repowering: *Replacing some turbine components to increase generation efficiency; generally uses existing towers and foundations.*

Full repowering: *Replacing turbines with new ones to increase turbine capacity, using existing grid connections.*

Decommissioning: *Removing wind turbines from a project (without replacement) and restoration of the site.*

Material demand reduction: *Approaches to minimise overall material demands (and therefore waste generation).*

Closed-loop recycling: *the transformation of waste into new raw materials, which could be used in place of the original function or application*

Open-loop recycling: *the transformation of waste into new raw materials, which could not be used in place of the original function or application*

Closed-loop reuse: *Using a component or material again as parts in other wind turbines to supply its original designed function.*

Open-loop reuse: *Use of a component or material in another application, requiring minimal processing; typically, the material properties and design requirements are lower than needed for the original function.*

Table of contents summary

Wind turbine retirement will result in large end of life materials flows that must be managed. This Review discusses material reuse and recycling options for composites, steel, rare earth elements and concrete.