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MATERIAL STREAMS FROM **WIND ENERGY** DECOMMISSIONING TO 2050

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Contents

Abstract

This report provides a comprehensive assessment of decommissioned material waste streams from the wind energy sector in the EU until 2050, based on total wind installations in the EU until 2023. Our research focuses on 15 materials, including structural materials, electronic materials, the composite materials present in blades, and materials present in the permanent magnets; and explores each of these materials' recyclability. By developing a robust decommissioning model and analysing the material intensities of various wind turbine components, we strive to provide a detailed picture of the quantities and types of materials that will be decommissioned in the coming years. The findings of this study will enable policymakers, industry stakeholders, and researchers to better anticipate the EU's recycling needs and develop effective strategies for managing the growing volume of wind energy waste streams.

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Executive summary

Policy context

Wind energy plays a crucial role in achieving the EU's climate targets, enhancing industrial competitiveness, and reducing the cost of energy. It is expected to grow even further in the coming decades, in the context of the Renewable Energy Directive (RED III; EPC, 2023).

This report addresses the projected material waste streams from the wind energy sector in the EU until 2050, to support and inform the implementation of the Waste Framework Directive and the Critical Raw Materials Act. Together, these aim to ensure that the wind energy sector promotes circular practices and can rely on resilient value chains for critical raw materials.

Main findings

Decommissioning Model On the basis of our analysis, we have developed a robust decommissioning model, which estimates the median lifetime of onshore wind energy capacity to be around 32 years, and offshore wind energy capacity to be around 37 years. This suggests that decommissioning may occur later than the wind turbines' design lifetime, with significant implications for the prediction of decommissioned material streams and the development of end-of-life management strategies.

Heavy Structural Materials Concrete and steel are expected to be the largest contributors to wind energy waste streams, with intensity waste streams anticipated to reach the megatonne scale by 2050. However, these waste streams would only represent less than 2% of the EU's overall end-of-life material streams for concrete and for steel, and they are expected to be readily accommodated within existing recycling infrastructure.

Rare Earth Elements Our analysis highlights the importance of critical raw materials such as rare earth elements (REEs) and boron, which are used in the manufacture of permanent magnets in wind turbines. Strengthening collection, disassembly, and recycling for REEs will be crucial to reducing waste and minimising environmental impacts, and to increasing the availability of secondary REE materials to meet the EU's growing demand.

Blade Materials The recycling of wind turbine blades is a significant challenge due to the complexity of the materials used. Our analysis highlights the need for research and development to improve the recyclability of existing blades, as well as the design of new blades with recyclability in mind. By investing in innovative recycling solutions and designing new blades for recyclability, the wind industry can reduce waste and minimize environmental impacts.

1 Introduction

1.1 Context and objectives

As the world transitions towards a low-carbon economy, wind energy has emerged as one of the cheapest renewable resources to replace fossil fuels. In fact, wind power has already surpassed 1 TW of global capacity, with the EU holding a substantial share of 220 GW, including 201 GW of onshore wind and 19 GW of offshore wind (EC-JRC, 2024). In 2023, this wind capacity contributed 17.5% of the EU's electricity generation, making Europe the continent with the highest share of wind electricity. However, as wind installation continues to grow globally, it is essential to assess (and eventually address) the sustainability of wind energy beyond its operational lifetime.

This issue is becoming increasingly pressing as the EU's wind energy fleet expands, with the amount of decommissioned waste expected to grow substantially. The revised Renewable Energy Directive (RED III) raises the binding target for renewable energies to 42.5% by 2030, with a goal of reaching 45% (EPC, 2023), which should drive continued growth in the European wind industry sector. It is therefore essential to consider the opportunities for reducing waste and promoting sustainable materials management in this sector.

The Waste Framework Directive sets a hierarchy for waste management, with prevention as the preferred option, followed by reuse and recycling, and recovery and disposal as the least desirable outcomes (EPC, 2008). In the context of wind energy, prevention of waste can take the shape of designing turbines and components with reduced material usage, designing components with longer lifetimes (or easier maintenance) to reduce the need for replacement, or designing turbines for easier disassembly at the end of their life. Reuse, on the other hand - which involves the direct use of components or materials in their original form without significant processing or transformation - can be an option for some wind turbine components, if they are still operational when the wind turbine is decommissioned. The third option in the waste hierarchy, recycling, involves the processing of materials to extract valuable resources which can then be used to manufacture new products. Recycling is a critical pillar when promoting circularity in the wind energy sector, and can be applied to many of the materials within the turbines. Finally, energy recovery and disposal are considered lower down in the waste management hierarchy, and they are options that should only be considered when reuse and recycling are not feasible. Overall, circularity in the wind sector can thus be achieved through various strategies, including minimising waste generation during the design phase, reuse of decommissioned wind turbine components, or recycling of the materials that compose the turbines.

To support the development of a circular economy, the EU has established policies and regulations that promote the responsible management of raw materials. The 2024 Critical Raw Materials Act (CRMA) sets a benchmark for the EU's consumption of critical raw materials by 2030, including a target of 25% of Strategic Raw Materials (SRMs) to come from recycled sources (EPC, 2024). According to the CRMA, SRMs are materials that are crucial for the development of strategic technologies, including wind energy. CRMs on the other hand, are defined as materials that are both essential for the development of emerging technologies, such as renewable energy technologies, and are subject to supply chain risks. Specifically, the wind energy sector relies on several critical materials, including manganese and aluminium, which are classified as CRMs, and copper, which is considered a SRM. Additionally, boron and rare earth elements (REEs) play a crucial role in the sector, falling under both CRM and SRM categories due to their essentiality for emerging technologies and potential supply chain risks (EC-JRC, 2023).

This report aims to provide a comprehensive assessment of the decommissioned material waste streams from the wind energy sector in the EU until 2050, based on the total wind installations made in the EU until 2022. Our research focuses on 15 materials, including structural materials, composite materials present in the blades, and REEs present in the permanent magnets; and explores their recyclability. By developing a robust decommissioning model and analysing the material intensities of various wind turbine components, we strive to provide a detailed picture of the quantities and types of materials that will be decommissioned in the coming years. The findings of this study will enable policymakers, industry stakeholders and researchers to better anticipate the EU's recycling needs and develop effective strategies for managing the growing volume of wind energy waste streams.

1.2 Methodology

1.2.1 Material intensity per wind turbine type

In order to calculate the material waste streams, we need to consider the quantity with which these materials are present in the wind turbines, i.e. the material intensity of the various materials. In the following section, we develop these material intensities, specifically considering the different wind turbine configurations. We note that our analysis is focused on wind turbines and their foundations.

Table 1. Material intensity estimates for wind turbines, in kg/MW, per wind turbine type.

Material	Range	Type C GB-DFIG	Type D-EE DD-EESG	Type D-PM DD-PMSG	Type E E-PMSG	Type F F-SCIG
Concrete	300 000 - 500 000	400 000 ± 100 000				
Steel	90 000 - 130 000	110 000 ± 20 000				
Aluminium (Al)	150 - 1 900	1 400 ± 500	150 – 500	550 ± 150	1 400 ± 500	1 600 ± 150
Chromium (Cr)	410 - 510	460 ± 50				
Copper (Cu)	650 – 6 200	800 – 1900	5 700 ± 500	2 200 - 4 600	900 ± 250	850 ± 150
Iron (cast)	16 000 - 22 000	19 000 ± 3 000				
Manganese (Mn)	650 - 950	800 ± 150				
Molybdenum (Mo)	90 -110	100 ± 10				
Nickel (Ni)	370 - 490	430 ± 60				
Zinc (Zn)	5 150 - 5 750	5 450 ± 300				
Polymers	3 900 - 5 500	4 700 ± 800				
Glass/carbon composites	6 000 - 9 000	7 500 ± 1.500				
Boron (B)	0.2 - 7	0.5 ± 0.3		5 ± 2	0.8 – 1.8	0.3 – 1.2
Dysprosium (Dy)	1 - 21	2 ± 1		17 ± 4	4 ± 3	1 - 4.7
Neodymium (Nd)	6 - 210	12 ± 6		180 ± 30	50 ± 20	7 – 34
Praseodymium (Pr)	0 – 35	0		35	4	0
Terbium (Tb)	0 - 7	0		7	1	0

Source: Mc Govern, 2024. Note: The foundations of the wind turbines are included.

Wind turbines can be classified into six sub-technology types, labelled from A to F, which differ in terms of generator type and system design (Telsnig, 2020; Carrara, 2025). These sub-technology types can be characterised as follows: types A, B, and C employ gearbox systems, with a squirrel cage induction generator (SCIG – type A), wound rotor induction generator (WRIG – type B), or doubly-fed induction generator (DFIG – type C). Types D-EE and D-PM are direct-drive (DD) turbines, i.e. without a gearbox, utilising electrically excited (EE) generators or permanent magnet (PM) generators. Finally, types E-PM and F are hybrid drive train systems that integrate both a gearbox and a full power converter, together with either a PM generator (type E-PM) or a SCIG (type F).

Sub-technologies A and B were mostly installed between 1990 and 2007, when the annual capacity additions remained below 7 GW. Currently, they only represent 3.5% of the onshore fleet and 1.4% of the offshore fleet installed in the EU. We therefore focus the remainder of our analysis on the other sub-technology types, from C to F, which are more representative of the current wind turbine fleet.

The material content of these sub-technology types can vary significantly. This is especially the case for REEs, where, for example, the amount of neodymium required for each type of wind turbine ranges from 12 ± 6 kg/MW for type C to 180 ± 30 kg/MW for type D.PM. Similar variations are also observed for other materials, such as aluminium and copper. For other materials, such as concrete, steel or nickel, the material intensity is found to be independent of the wind turbine type.

The overall material intensity table is presented in **Table 1**; it is based on the work of Carrara *et al.* (Carrara, 2020) and was subsequently updated in 2024 (Mc Govern, 2024). In the following sections, we consider the decommissioning waste streams from the heavy structural materials (concrete and steel); from the materials supporting the steel in terms of properties and coating (manganese, molybdenum, chromium, nickel and zinc); and from the structural and electronic materials (aluminium and copper). Furthermore, we also consider the decommissioning material streams coming from the permanent magnets (boron, dysprosium, neodymium, praseodymium and terbium) and from the blades (glass-carbon composites).

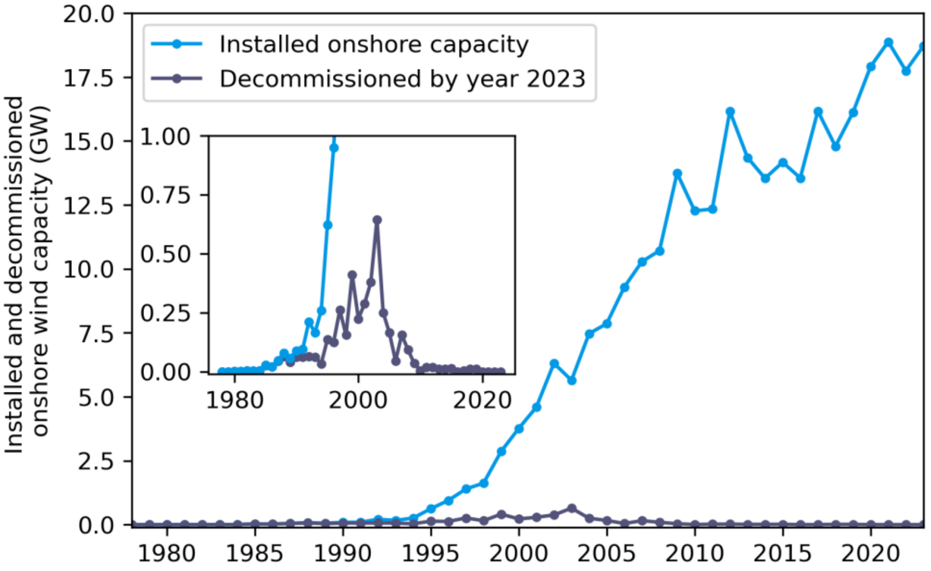
1.2.2 Decommissioning model

To predict the decommissioned material streams from wind energy, we need to build a robust model of the decommissioning of wind turbines. Our model relies on a comprehensive dataset of European wind turbine installations and decommissions, sourced from Wood Mackenzie (Wood Mackenzie, 2024). This dataset takes into account a total of 50 758 wind farm projects that were installed in Europe between 1978 and 2023, including 2 580 projects that were decommissioned by the end of 2023.

Figure 1 displays the annual onshore wind capacity additions in Europe from 1978 to 2023 (in blue), and the decommissioned capacity curve (in purple). We find that European wind installations remain below 1 GW/yr until 1997 and are then followed by a substantial increase, reaching 10 GW/yr by 2007 and almost 19 GW/yr by 2023 (18.7 GW/yr).

The decommissioned capacity curve shows the amount of wind capacity that was installed in a given year and is decommissioned by our reference year, 2023. Between 1978 and 1990, this decommissioned capacity aligns closely with the installed capacity for each year (see inset of **Figure 1**), indicating that most of the wind capacity from this period has been decommissioned. From 1990 onwards, the decommissioned and installed capacity curves diverge, which means that a significant portion of the wind capacity installed after 1990 has not yet been decommissioned, and is therefore still in use as of 2023.

Figure 1. Annual capacity additions of onshore wind between 1978 and 2023 in Europe, and associated decommissioned capacity by 2023.



Source: JRC, 2024.

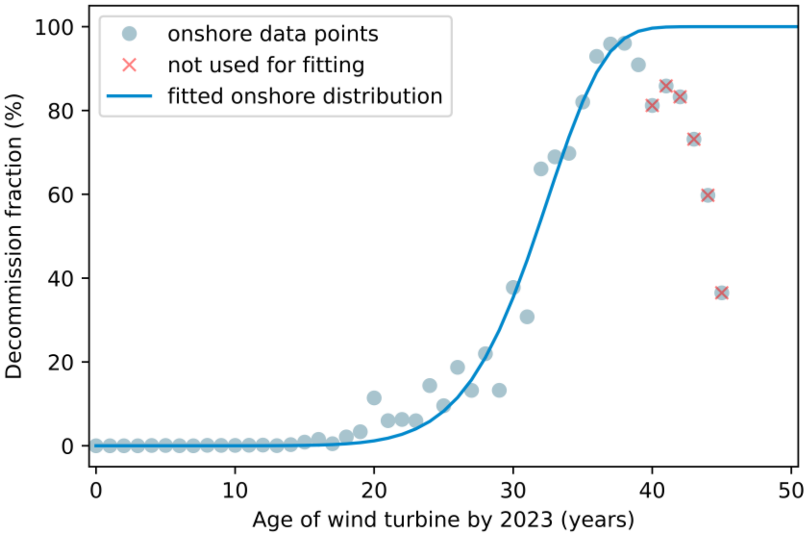
The data shown in **Figure 1** is employed to build a decommission fraction, as described in the work from Bech Abrahamsen (2024), where

$$Decommission\ fraction = \frac{Wind\ capacity\ installed\ in\ year\ y\ and\ decommissionned\ by\ 2023\ [GW]}{Wind\ capacity\ installed\ in\ year\ y\ [GW]}$$

This calculation yields the decommissioning fraction, in percentage, as a function of the year of installation. We then present each of these datapoints as a function of the age of the wind turbine operation. The resulting decommission function data points are shown as light blue dots in **Figure 2**.

We anticipate that the decommission fraction will exhibit a characteristic shape with three distinct phases. Initially, the curve is expected to remain low, as few wind turbines are decommissioned within the first 5-10 years of operation. As the turbines age, the decommission fraction should increase, indicating that the probability that wind turbines are decommissioned increases as these get older. Finally, after a certain number of years, the curve should reach 100% decommissioning, indicating that all wind turbines of a given age (e.g., 45 or 50 years) have reached the end of their life. **Figure 2** confirms this expected pattern, with an initial decommission fraction of 0-5% for turbines under 19 years old, and followed by a significant increase in decommissioning between 20 and 39 years. However, our onshore data deviates from this pattern after 40 years, with a notable drop in the decommission fraction. We attribute this discrepancy to a mathematical artefact resulting from the low rate of wind capacity installations before 1983 (below 5 MW/yr), which can therefore lead to errors in the estimation of the decommissioned curve. Furthermore, the reliability of the data from the 1980s may be compromised due to incomplete digitisation, underreporting, or loss of records by 2023, which can also contribute to a sub-100% decommission curve. Our analysis thus suggests that the decommission fraction curve follows the expected pattern, with the exception of the 6 data points corresponding to wind turbines aged over 40 years in 2023. These exceptions are attributed to an artefact, and are excluded from the following fitting procedure.

Figure 2. Decommissioning fraction as a function of wind turbine age and fitted Weibull distribution.



Source: JRC, 2024.

Following the methodology of Bech Abrahamsen (2024), we fit a Weibull distribution function to the decommission fraction curve, as shown in dark blue in **Figure 3**. The Weibull distribution is a commonly used model for describing the failure rates of complex systems (Jardine, 1987; Pascovici, 2009), and has been applied in various studies to model the decommissioning of wind turbines (Zimmermann, 2013; Chen, 2021). Specifically, the fitting procedure yields the scale parameter (λ) and the shape parameter (k), where λ gives information about the timing of decommissioning, and k is an indication on the speed of the decommissioning slope. Here we find λ = 32.9 ± 0.2 and k = 8.9 ± 0.6, where the fit is statistically significant[1] (see footnote for technical details on the fit quality). Together, the two parameters result in a median lifetime of 31.6 years for European onshore wind energy capacity.

Onshore wind turbines have a design lifetime of 20 years – here, our model thus suggests that the design lifetime shouldn't be used as a proxy for the decommissioning time, and that decommissioning might in fact take place later than the design lifetime. Indeed, we find that the median lifetime of 32 years calculated from our model is higher than in other studies where decommissioning is fixed between 20 and 25 years. However, it is consistent with the findings of Bech Abrahamsen (2024), who reported a median lifetime of 29 years for onshore wind turbines in Denmark. Our findings, along with those of Bech Abrahamsen (2024), thus indicate that the decommissioning process may actually occur over a longer timeframe than previously assumed. This has significant implications for the prediction of decommissioned material streams, and for the development of end-of-life management strategies for wind energy infrastructure.

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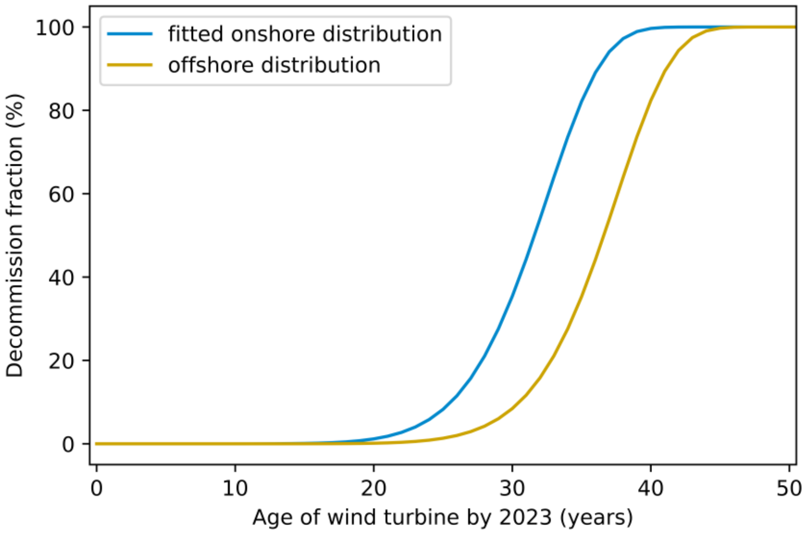
[1] The fit is statistically significant, with a mean squared error (MSE) of 0.0024, a root mean squared error (RMSE) of 0.0487, and an R-squared value of 0.9772. The F-statistic is 1628.79, and the p-value is essentially zero, indicating that the relationships between the variables are unlikely to be due to chance.

Building on this onshore decommissioning model, we develop an offshore decommissioning model that accounts for both the similarities and differences in design lifetime and decommissioning rates between onshore and offshore wind turbines. Specifically, onshore wind turbines have a design lifetime of 20 years, while their offshore counterparts have a lifespan of 25 years. We thus adjust the onshore Weibull distribution function by setting an offset of 5 years, and fix the scale parameter λ to 37.9 years for offshore wind. Furthermore, we assume that the decommissioning of onshore and offshore wind will take place with a similar speed. To obtain the same decommissioning speed, we calculate the shape parameter (k). We find that k = 10.4, and fix this parameter for offshore wind - the impact of this assumption is further evaluated in **Box 1**. Finally, with λ and k, we can calculate the median lifetime of offshore wind energy, and find that it is equal to 36.6 years. The offshore distribution function is shown in yellow in **Figure 3**, where, as expected, the decommission fraction curve increases later than its fitted onshore equivalent.

In summary, our analysis provides a comprehensive understanding of the decommissioning patterns of onshore and offshore wind energy capacity. We estimate the median lifetime of onshore wind energy capacity to be around 32 years, while offshore wind energy capacity has an estimated median lifetime of around 37 years. These results set the basis for the calculation of the total wind capacity to be decommissioned in the EU by 2050.

Figure 3. Decommissioning fraction of onshore wind turbines (fitted according to the fitting procedure) and of offshore wind turbines.



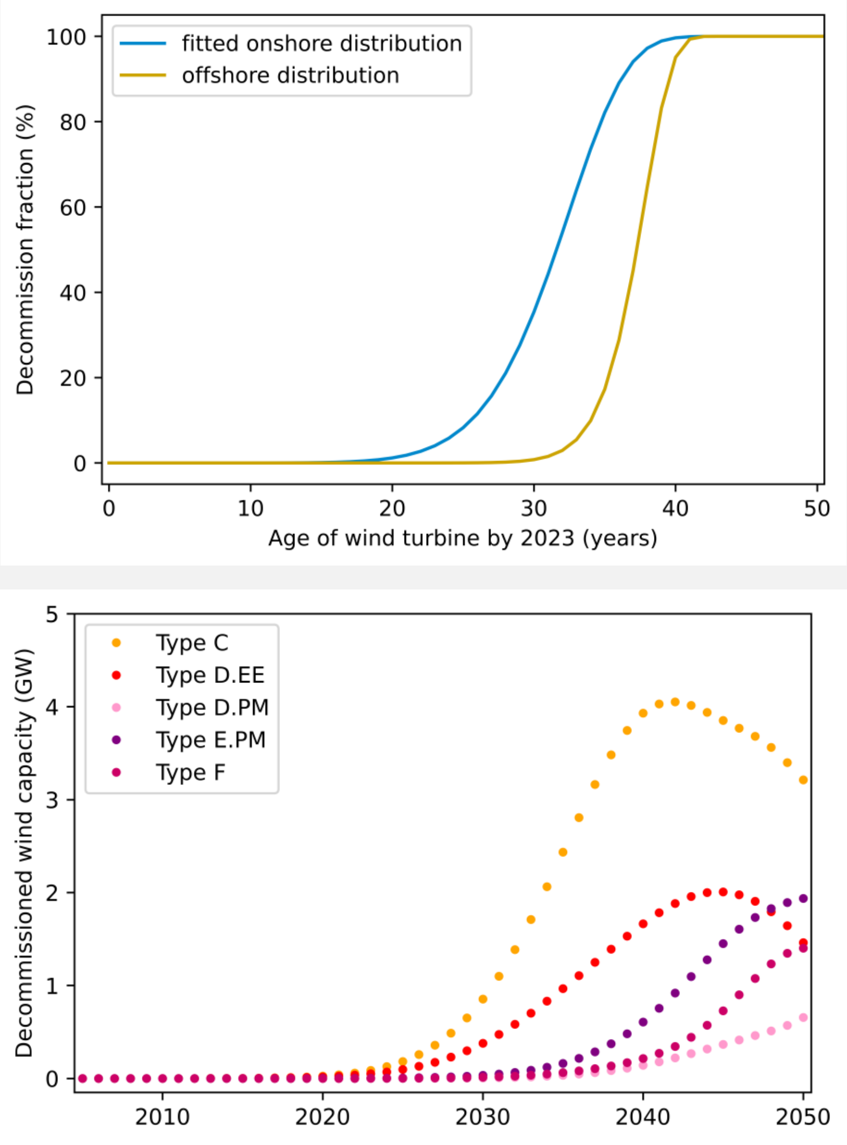
Source: JRC, 2024.

It is worth noting that our analysis focuses on decommissioning, which involves the complete removal of wind turbines, and does not account for repowering, a process where older turbines are either replaced with new, more efficient turbines at the same location, or partially upgraded by exchanging specific components (e.g., keeping the tower and foundations of the wind turbine, but replacing the generator and blades with updated versions that improve performance). Due to the limited availability of data on repowering activities, we are not able to incorporate this process into our models, and our analysis might underestimate some material waste streams occurring during these repowering events. As a result, our analysis could provide a conservative estimate of the material streams coming from the wind energy sector.

Box 1. Offshore model – effect of the assumption on decommissioning speed

Alternatively, it is also possible to assume a faster decommissioning rate for offshore installations compared to onshore installations. Indeed, specialised vessels with heavy lifting characteristics are required for decommissioning operations (Topham, 2019). In order to minimise the vessels costs for decommissioning, which represent as high as 80% of the total decommissioning expenditure for offshore wind (Judge, 2019), it may be advantageous to decommission multiple turbines from a single offshore farm simultaneously. By setting a shape parameter (k) of 20.7 for offshore wind (i.e., double of $k_{onshore}$), we test the hypothesis of a higher decommissioning speed. As expected, the offshore decommission fraction raises more rapidly, and the median lifetime increases to 37.3 years. However, by comparing **Figure 4** and **Figure 6**, we see that the differences in the overall decommissioning capacity curves would remain minimal; and that this assumption therefore would only have a negligible impact on the overall decommissioned wind capacity.

Figure 4. Decommissioning fraction of onshore wind turbines and of offshore wind turbines, considering a rapid decommissioning process (top); and corresponding decommissioning annual capacity curves for total wind installations in the EU between 2005 and 2050 (bottom).



Source: JRC, 2024.

1.2.3 Existing wind capacity to be decommissioned by 2050

Building on the decommissioning models and on the categorisation of wind turbines according to their specific sub-technology type, we can now construct the various projected decommissioned wind capacity curves per wind turbine type, for both onshore and offshore installations. The decommissioned capacity curves are based on installations made in the EU until 2023, and are calculated until 2050.

Figure 5 presents the onshore wind installations in the EU between 1990 and 2022, together with the estimated decommissioned wind capacity in the EU between 2020 and 2050, for all wind turbine types. The probability density function for decommissioning as a function of the time since installation of the wind capacity is also shown in the inset of the decommissioning curves.

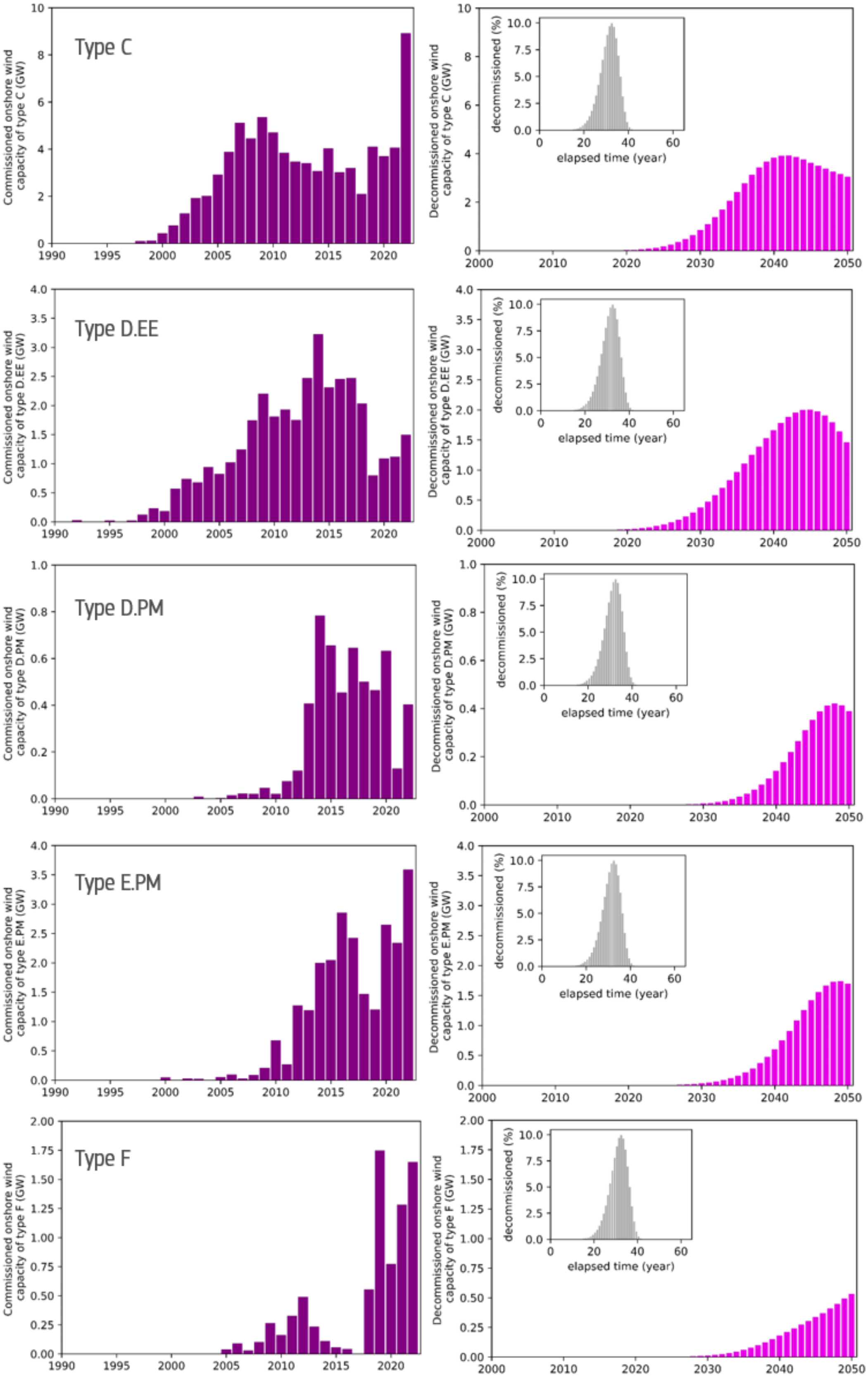
We find that the decommissioned onshore wind capacity of type C remains relatively low between 2000 and 2030, with less than 0.1 GW being decommissioned per year. However, this figure steadily increases to reach 1.0 GW/yr by 2030 and 3.0 GW/yr by 2040, peaking at 3.4 GW/yr in 2045 before decreasing to 2.9 GW/yr by 2050. In contrast, the decommissioning curve for wind turbines of type D.EE follows a similar trend, but with a lower overall intensity, reaching a maximum of 1.6 GW/yr in 2045 and 1.4 GW/yr in 2050. The decommissioning curve for wind turbines of type E.PM is both lower and delayed, with a peak of 0.3 GW/yr reached in 2050. Meanwhile, the decommissioning curve for wind turbines of type D.PM remains low between 2020 and 2030, but then steadily increases to reach 0.6 GW/yr in 2040, continuing to rise to 1 GW/yr in 2045 and reaching 1.2 GW/yr by 2050. Finally, the decommissioning curve for wind turbines of type F is similar to that of type D.PM, growing to a maximum of 0.4 GW/yr in 2050.

Figure 6 presents the offshore wind installations in the EU between 1990 and 2022, together with the estimated decommissioned wind capacity in the EU between 2020 and 2050, for all wind turbine types. Overall, we find that the annual decommissioning capacities of offshore wind have a lower rate than their onshore counterparts (due to the lower capacity installations) and, also, that offshore decommissioning activities increase later (due to the later offshore wind installations compared to onshore installations). Wind turbines of type F show the highest decommissioning activity, with a projected rate below 0.1 GW/yr in 2040 and peaking at 0.6 GW/yr in 2050.

These decommissioning curves are shown in **Figure 7**, for both onshore decommissioning activities, offshore decommissioning activities, and the total of both onshore and offshore decommissioning activities. We find that the largest decommissioned capacity is from wind turbines of type C, followed by wind turbines of types D.EE and E.PM, and finally by turbines of type F and D.PM. The first wind turbines to be decommissioned are also those of type C and D.EE, due to the large onshore installations taking place already before 2005, compared to the more recent development of the other wind turbine sub-technologies.

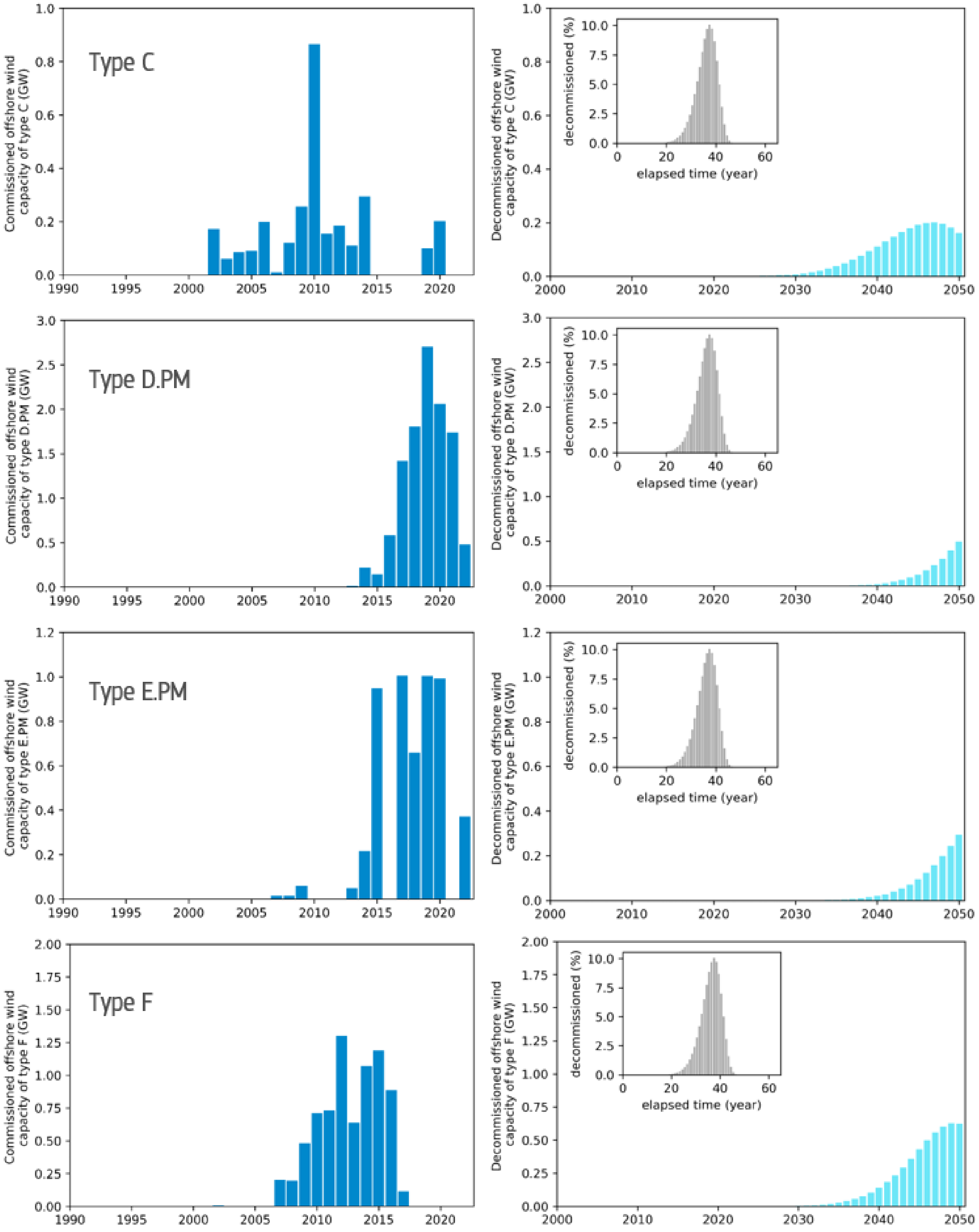
The final step in our methodology involves calculating the total decommissioned material streams by multiplying the decommissioned capacity curves for each wind turbine type by their corresponding material intensities. The resulting material streams are then aggregated to obtain the total decommissioned material stream, providing a comprehensive picture of the materials that will be generated from the decommissioning of wind energy infrastructure in the EU.

Figure 5. EU onshore wind annual installations from 1990 to 2022 (left) and the corresponding decommissioning annual capacity curves from 2000 to 2050 (right), for wind turbines of type C, D.EE, D.PM, E.PM and F.



Source: JRC, 2024.

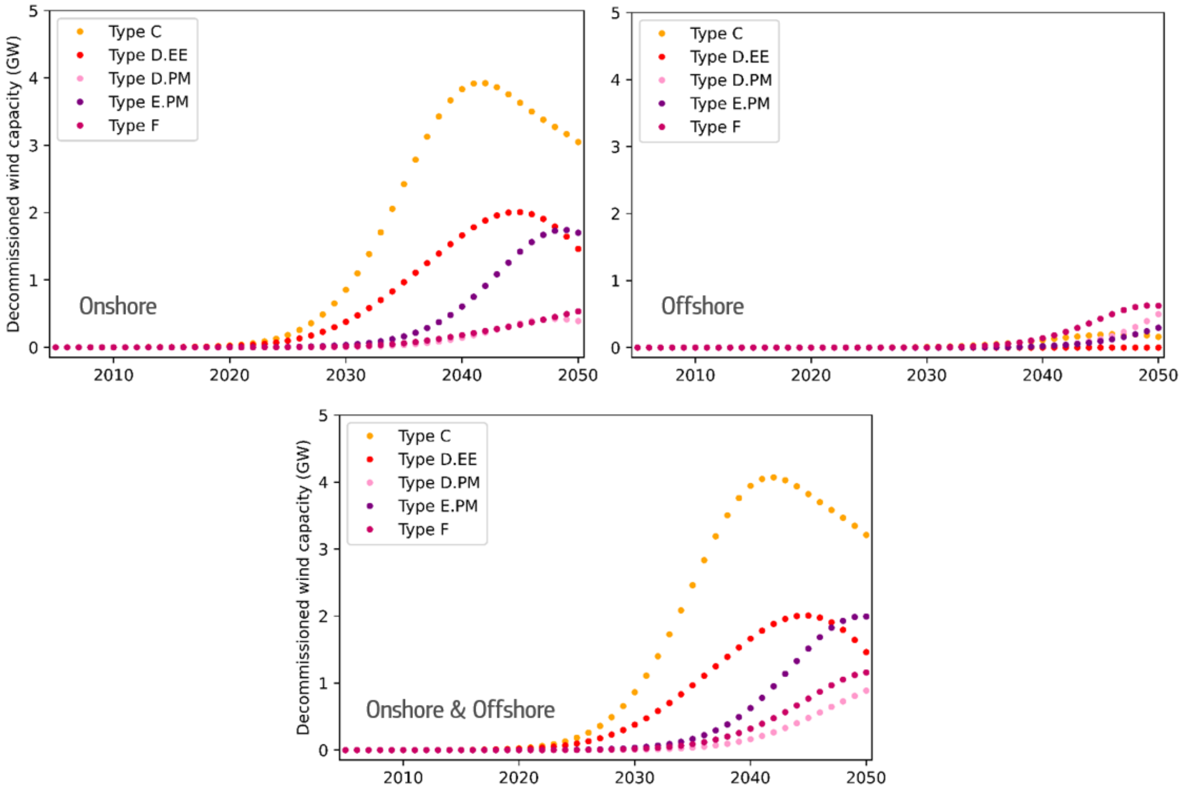
Figure 6. EU offshore wind annual installations from 1990 to 2022 (left) and the corresponding decommissioning annual capacity curves from 2000 to 2050 (right), for wind turbines of type C, D.PM, E.PM and F.



Source: JRC, 2024.

In agreement with the recent work from Foster *et al.* (EC-JRC, 2025), we also find that validating our results (e.g. by comparing, for the period between 2000 and 2023, our predicted decommissioned capacity against collected data for the same time frame) is particularly challenging, due to the absence of such data. Our work thus attempts to provide the best estimation possible for the decommissioning of wind energy in the EU, and the corresponding decommissioned material streams.

Figure 7. Decommissioning annual capacity curves for onshore wind (top left); offshore wind (top right); and total wind installations (bottom) in the EU between 2005 and 2050.



Source: JRC, 2024.

Finally, we note that the material streams presented in this report are the reflection of the decommissioned wind energy capacity that was installed until 2022, i.e. that any further addition in wind energy installations in the EU (as is expected from the ambitious REPowerEU targets) will result in increased decommissioned wind capacity in the future, and thus larger material waste streams. Considering the respective probability functions for decommissioning of onshore and offshore wind, and their median lifetimes of 32 years and 37 years, we find that additional wind capacity installations from 2023 will start to have an impact for the decommissioned material streams only 20 to 25 years later, i.e. only in 2043-2048, and that they will have maximal impact in 2045-2050. Consequently, installations of wind capacity in the EU after 2023 will only have a negligible contribution to the decommissioned material streams before 2040, and will have a larger impact only after 2045.

2 Heavy structural materials – concrete and steel

2.1 Role of concrete and steel in wind turbines

Concrete and steel are the primary structural materials used in wind turbines, playing a crucial role in their construction and operation. Concrete forms the foundation and tower base, while steel is used in the tower, rotor hubs, and other components. Together, these two materials provide the necessary strength and stability to support the turbine's operation, enabling it to withstand various environmental conditions and maintain its structural integrity. Due to their abundance and availability, as well as the well-diversified supply chains, the CRMA does not recognise concrete and steel as critical raw materials (CRM) or strategic raw materials (SRM) (EC-GROW, 2023).

The steel used in wind turbines comes in various types, each with its own specific applications. The foundation of a wind turbine, for example, is primarily made of concrete, but also contains carbon steel, High-Strength Low-Alloy (HSLA) steel, and stainless steel. Carbon steel is the dominant type of steel used in the foundation, with HSLA steel added for extra strength and durability, and stainless steel is used for corrosion-resistant components, such as anchor bolts and reinforcement. The nacelle and hub of a wind turbine may use a combination of stainless steel, carbon steel, and alloy steel for components such as gears, bearings, and shafts. Wind turbine blades, on the other hand, are typically made of fiberglass-reinforced polymer (FRP) with steel reinforcement, such as carbon steel or stainless steel, for added strength and stability.

2.2 Intensity and recyclability of concrete and steel

Concrete and steel are the dominant materials in wind turbine systems, with a weight intensity of 400 000 kg/MW for concrete and 110 000 kg/MW for steel, as shown in **Table 1** (Mc Govern, 2024). The high recyclability of both of these materials is a key factor in the overall recyclability of wind turbines, which is estimated to be 85-95% (Vestas, 2024; Siemens Gamesa, 2024; Nordex, 2024).

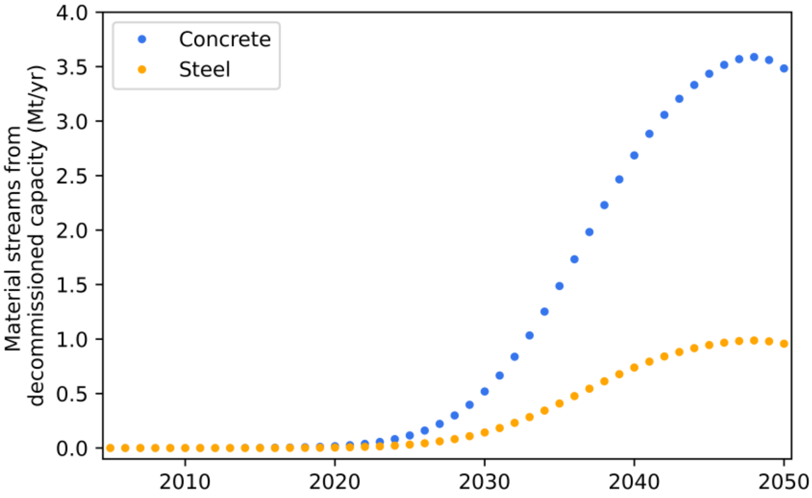
Concrete foundations can be reused for new wind turbine installations, the most circular option (Gast, 2024). Alternatively, they can be demolished and recycled into different forms: recycled concrete aggregate (RCA) for use in new concrete or road construction (Cristobal Garcia, 2024) is the most widely used recycling approach. However, recycling concrete into cement paste for the production of new cement would yield greater environmental benefits (Caro, 2024; Marmier, 2023; Krour, 2022). In contrast with reuse and recycling, landfilling is the least sustainable option. The EU estimates that of the 450-500 million tonnes of construction and demolition waste (C&DW) produced in Europe each year, approximatively one third consists of concrete (CEMBUREAU, 2016). This is equivalent to 150-165 Mt/yr of concrete waste generated annually in the EU. More recently, Caro *et al.* reported the annual flow of concrete in C&DW in the EU to represent 224 Mt in 2020 (Caro, 2024).

Steel waste (commonly labelled steel scrap) can be recycled into secondary steel, which reduces the demand for primary steel production. The steel used in wind turbine foundations, typically in the form of rebars in reinforced concrete, can be easily separated. Additionally, specialised steels used in wind turbines can also be recycled. In fact, over 90% of end-of-life stainless steel is currently collected and recycled into new products, highlighting the effectiveness of steel recycling practices in the EU (EuRIC, 2022). The production of steel scrap in the EU is actually higher than the domestic demand for steel scrap: between 2020 and 2023, the EU consumed 75-90 Mt/yr of its own steel scrap, imported 4-5.5 Mt/yr, and exported 17.5-19 Mt/yr; which resulted in net exports of 13-15 Mt/yr (Eurofer, 2024). There is therefore no steel scrap shortage in the EU.

2.3 Decommissioned concrete and steel material streams

As the largest materials in wind turbine systems, concrete and steel are expected to generate significant waste streams. Our analysis shows that the waste streams from these two materials will reach the megatonne scale in the EU by 2050, with concrete at 3.5 Mt/yr and steel almost at 1 Mt/yr. The decommissioned material streams from concrete and steel are presented in **Figure 8**.

Figure 8. Decommissioned concrete and steel material streams in the EU, coming from wind capacity installed by 2023.



Source: JRC, 2024.

The concrete waste stream increases slowly between 2010 and 2020, from 100 t/yr to 17.1 kt/yr, followed by a more consistent increase between 2020 and 2030, when it reaches 518.8 kt/yr. A significant growth occurs between 2030 and 2045, followed by a slight decrease and a stabilisation in 2050 at 3.5 Mt/yr. While this is the largest waste stream for wind turbines, it would still only represent a minor contribution (close to 2%) to the overall concrete waste stream currently generated in the EU, which is estimated to be between 150-160 Mt/yr and 224 Mt/yr (CEMBUREAU, 2016; Caro, 2024).

The steel waste stream exhibits a similar trend, with a slow increase from 2010 to 2020 (from 27 t/yr to 4.7 kt/yr), followed by a steady rise in the subsequent decade (reaching 142.7 kt/yr of decommissioned steel in 2030). This is followed by a rapid growth phase until 2045, after which the steel waste stream stabilises at 958 kt/yr in 2050. Although steel is the second largest waste stream generated by decommissioned wind turbines, the predicted decommissioned volume is relatively small compared to the current consumption of steel scrap in the EU (between 75 and 90 Mt/yr for 2020-2023) and also small compared to the level of EU exports during the same period (between 17.5 and 19 Mt/yr). As a result, the steel waste stream from the wind energy sector will likely be readily absorbed by the existing steel scrap ecosystem, either for domestic use or for exports, and is not expected to pose a significant challenge to the overall steel recycling practices in the EU.

In conclusion, the material streams from concrete and steel waste will increase significantly in the coming decades, but are expected to remain manageable within the existing recycling infrastructure. This is a positive outcome, as it suggests that the EU can continue to support the growth of the wind energy sector while minimising its environmental impacts.

3 Materials supporting steel properties: alloying elements and coating

3.1 Role of alloying elements and coating in wind turbines

Alloying elements (AEs) play a crucial role in enhancing the strength, corrosion resistance, and durability of steel used in wind turbines. The primary AEs used in wind turbine steel include manganese, chromium, molybdenum, and nickel, where each of the AEs serves a specific purpose.

- Manganese is used to improve the strength, toughness, and weldability of steel, particularly in HSLA steels used in wind turbine foundations and towers.
- Chromium enhances the corrosion resistance and strength of stainless steel used in wind turbine components, such as rotor hubs and towers.
- Molybdenum increases the strength, toughness, and resistance to fatigue and corrosion of alloys used in wind turbine components, such as gears, bearings, and fasteners.
- Nickel is used to improve the corrosion resistance, strength, and durability of steel.

Additionally, to the AEs, zinc is used as a corrosion protection coating for steel components, and is present for example on the surface of the tower or on the foundations of wind turbines.

From this list of elements, only manganese is classified as a CRM; it is however not considered as an SRM, which is a classification reserved for battery-grade manganese. It is interesting to note that nickel used for steel production is neither considered a CRM nor a SRM, as these classifications are reserved for battery-grade nickel. Chromium, molybdenum and zinc are not listed as CRMs.

3.2 Intensity and recyclability of alloying elements and coating

The weight intensity of AEs in wind turbines varies. Zinc has the highest weight intensity, with 5 450 kg/MW, followed by manganese (800 kg/MW), chromium (460 kg/MW), nickel (430 kg/MW), and molybdenum (100 kg/MW, see **Table 1**).

While it is theoretically possible to recover some AEs from steel (Peaslee, 2005), the efficiency of recovery varies depending on the type of steel and the specific AE. For example, nickel and chromium can be recovered from stainless steel to a significant extent (Chen, 2022), although the recovery rate is lower for other types of steel. Molybdenum is only partially recoverable, and manganese is particularly challenging to recover as it tends to oxidise to MgO, resulting in poor recoverability (Reuter, 2019). In practice, the recovery of AEs from steel scrap is thus more complex than the recycling of steel itself, and the efficiency of AE recovery can vary significantly.

In the automobile industry for example, several challenges have been identified, such as the contamination by impurities or other elements that can affect the recovery of AEs (Ohno, 2015), and the proper sorting and separation of steel scrap by AE content, which is crucial for maximising recovery rates. The complexity of products can also affect the recyclability of AEs, as it can lead to a reduced collection rate and/or a reduced disassembly rate. Additionally, the recycling of AEs also depends on the availability in terms of the specific recycling facilities and infrastructure required, which can affect the amount of recycling of AEs locally, and on economic factors such as the processing costs and market fluctuations, which may not always make recycling the most economically viable option. However, there are also opportunities for improving AE recovery, such as advances in sorting and separation technologies, where new technologies (such as sensor-based sorting and advanced magnetic separation) can improve the efficiency and accuracy of steel scrap sorting (Gu, 2021). Advances in recycling processes, such as the use of plasma arc furnaces, can also improve the recovery of AEs and reduce energy consumption (Changming, 2018).

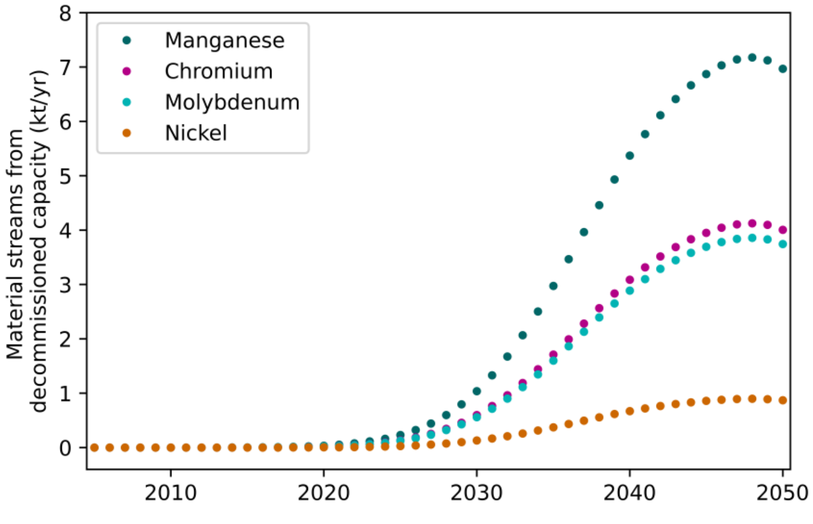
Unlike the recovery of AEs, zinc and zinc products can largely be recycled, with a recovery rate of 80% of recoverable zinc, and secondary zinc accounting for approximately 30% of the yearly zinc consumption in Europe (Cusano, 2017; EEA, 2019). Specifically, the zinc present in the galvanised steel sheet can volatilise and be recovered, enabling the effective recycling of both the zinc and the steel (Antrekowitsch, 2014).

Overall, the recycling of zinc in the EU thus takes place with a high efficiency rate, while the recovery of AEs from steel scrap is more complex, with efficiency and feasibility varying depending on the specific element and recycling process (Reuter, 2019). As the demand for AEs continues to grow, it is essential for the EU to develop and implement effective strategies for improving AE recovery and recycling, such as investing in R&D, improving infrastructure, and promoting best practices among industry stakeholders.

3.3 Decommissioned waste streams from alloying elements in steel (manganese, molybdenum, chromium and nickel) and zinc coating

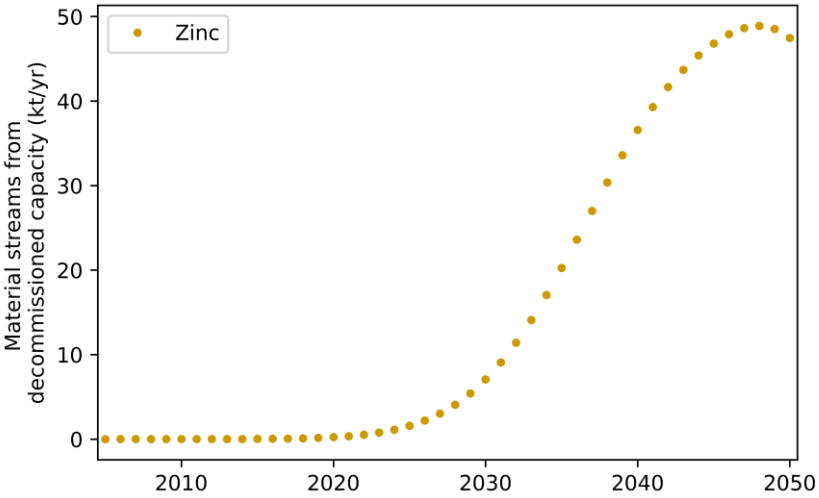
The decommissioned waste streams of zinc and AEs are shown in **Figure 9** and **Figure 10**. The decommissioned manganese stream increases from 0.2 t/yr to 34 t/yr between 2010 and 2020, to 1 kt/yr in 2030 and 7 kt/yr in 2050. The chromium waste stream increases from 0.1 t/yr to 20 t/yr between 2010 and 2020, to 0.6 kt/yr in 2030 and 4 kt/yr in 2050. Molybdenum shows a similar increase in decommissioned waste stream to chromium, but reaches a slightly lower value of 3.7 kt/yr in 2050. For nickel, the material waste stream is lower than for the other AEs considered, and evolves from 130 t/yr to 871 t/yr between 2030 and 2050 (**Figure 9**). Due to its higher material intensity, zinc has the largest decommissioned waste stream, reaching 7.1 kt/yr in 2030 and 47.5 kt/yr in 2050 (**Figure 10**).

Figure 9. Alloying material streams coming from decommissioned wind capacity installed by 2023; for manganese, molybdenum, chromium and nickel.



Source: JRC, 2024.

Figure 10. Zinc material stream coming from decommissioned wind capacity installed by 2023.



Source: JRC, 2024.

To reduce waste, the wind industry should therefore maintain its high recycling rate of zinc, even as the waste stream of zinc increases between 2030 and 2050. At the same time, the industry will need to invest in new technologies and infrastructure to handle the increasing waste streams of AEs, and develop more efficient and effective recycling processes.

4 Structural and electronic materials – aluminium and copper

4.1 Role of aluminium and copper in wind turbines

Copper and aluminium are both essential materials in the wind turbine system. Copper is present in all of the electrical components of the wind turbine system, including the generator and transformer, as well as the wiring, cabling, and connections. Aluminium is present both as an intermediate structural material, such as in the nacelle casing, and in the electrical components, for example for cabling and wiring purposes.

Compared to copper, aluminium offers several benefits for wind turbine electrical systems, including lower costs, a higher strength-to-weight ratio, better corrosion resistance, and versatility in terms of shape and size. As a result, aluminium is often the preferred choice for wind turbine electrical systems. However, copper remains a crucial material in applications where high conductivity is essential, such as generator windings and transformer windings, due to its superior electrical properties.

Aluminium is classified as a CRM in the CRMA list of 2023, due to its combined economic importance and high supply risk. While copper does not meet the CRM thresholds (notably in terms of supply risk, as the supply of copper is well diversified), it is still classified as a SRM due to its importance for the electrification of strategic technologies in the EU (EC-GROW, 2023).

4.2 Intensity and recyclability of aluminium and copper

Aluminium and copper exhibit intermediate weight intensities in wind turbine systems, ranging from 150 to 1 900 kg/MW for aluminium, and 650 to 6 200 kg/MW for copper (see **Table 1**). The significant variability in these intensities can be attributed to differences in generator type, electrical system design, and component selection across the various wind turbine models. For example, direct-drive turbines require more copper for their generators and power converters, resulting in higher weight intensities. In contrast, geared turbines may use more aluminium in their mechanical components.

Aluminium and copper are both highly recyclable, which is particularly valuable given their classification as CRM (aluminium) and SRM (copper).

In the EU, aluminium recycling rates are substantial, with close to 70% of the scrap collected and recycled, resulting in approximately 3 Mt/yr of recycled aluminium (EuRIC, 2022). This highlights the effectiveness of aluminium recycling practices in the EU. Currently, part of this recycled aluminium scrap is exported outside the EU. By consuming recycled aluminium scrap domestically, the EU could reduce its reliance on primary aluminium imports. Globally, secondary production accounts for twice the volume of primary production.

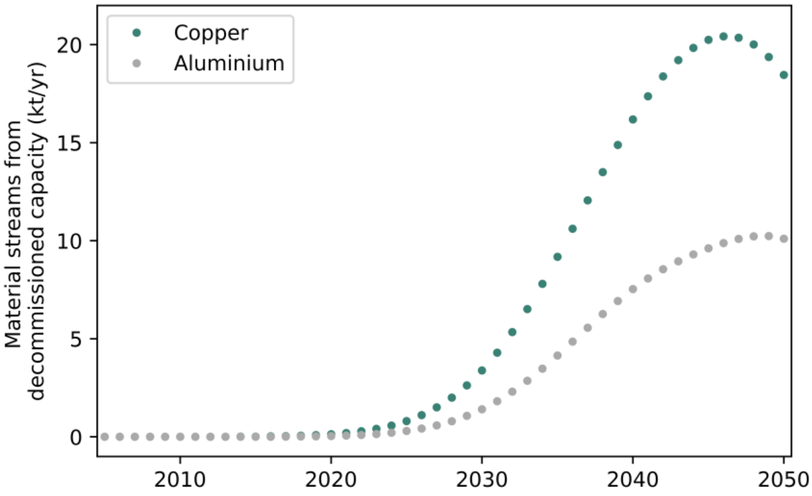
Copper recycling in the EU is also notable, with more than 60% of scrap collected and recycled, amounting to around 1.6 Mt/yr of recycled copper (EuRIC, 2022). The EU's limited natural copper deposits will make recycling more and more crucial for meeting domestic demand, to avoid reliance on external supply. Currently, the EU remains a net exporter of secondary copper scrap, but the situation could change if the demand for copper increases significantly in the EU.

In summary, the recyclability of aluminium and copper, combined with their significant recycling rates in the EU, highlights the potential for closed-loop recycling to minimise waste. However, these secondary material streams are only partly consumed in the EU, while the rest is exported. To support the independence of the EU in terms of its material sourcing, domestic consumption could be strengthened.

4.3 Decommissioned aluminium and copper material streams

The decommissioned waste streams of aluminium and copper show a slow increase between 2010 and 2020, from less than 1 t/yr to 42 t/yr for aluminium, and from 1 to 131 t/yr for copper (see **Figure 11**). The increase then gains momentum, reaching a stream of 1.4 kt/yr in 2030 for decommissioned aluminium and 3.4 kt/yr in 2030 for decommissioned copper. The material streams further increase until 2050, when they reach 10.1 kt/yr for decommissioned aluminium and 18.5 kt/yr for decommissioned copper.

Figure 11. Copper and aluminium material stream coming from decommissioned wind capacity installed by 2023.



Source: JRC, 2024.

Assuming recycling rates of 70% for aluminium and 60% for copper (EuRIC, 2022), the decommissioned material streams would yield secondary waste streams of 1 kt/yr of aluminium and 2 kt/yr of copper by 2030, and 7.1 kt/yr of aluminium and 11.1 kt/yr of copper by 2050. In comparison to the current secondary waste streams of 3 Mt/yr of recycled aluminium and 1.6 Mt/yr of recycled copper, these contributions would be relatively minor, accounting for less than 1% of the total waste streams currently generated in the EU. Even by 2050, when the decommissioned material streams reach their maximum, they would still represent only 0.2% of the secondary aluminium stream and 0.7% of the secondary copper stream. However, it's essential to note that our material waste projections remain conservative, as they do not account for repowering, and that the actual values may be higher. On the other hand, the growing demand for copper and aluminium in the coming decades will likely keep the relative weight of the wind sector's contribution to the overall secondary waste streams relatively low.

In conclusion, the wind sector's contribution to the secondary material streams of aluminium and copper is expected to remain limited in the coming decades, potentially accounting for less than 1% of the total. Nevertheless, it is crucial to maintain and potentially increase the high collection and recycling rates for these materials, particularly given their classification as CRM (aluminium) and SRM (copper). As the wind sector's waste streams grow until 2030 and 2050, strengthening collection and recycling efforts will help reduce waste and decrease the demand for virgin materials. By doing so, the EU can promote a more circular and sustainable economy, mitigate supply risks, and support its objective of securing a domestic and sustainable supply of CRMs.

5 Permanent magnet materials – rare earth elements and boron

5.1 Role of rare earth elements and boron in wind turbines

Rare earth elements (REEs) and boron are used in the manufacturing of permanent magnets, which are present in the permanent magnet generators of wind turbines of type D.PM and E.PM.

Specifically, neodymium-iron-boron (Nd-Fe-B) magnets owe their magnetic properties to the combination of REEs and iron. The structure of these magnets typically consists of a tetragonal crystal lattice, where neodymium (Nd) is the primary rare earth element responsible for creating the magnetic field. Iron (Fe) serves as the primary magnetic phase, while boron (B) stabilises the crystal structure and enhances the magnetic properties. Dysprosium and praseodymium are often added as secondary REEs to improve the magnet's coercivity and thermal stability. Dysprosium, in particular, helps to mitigate the loss of magnetic field strength at high temperatures, while praseodymium contributes to the magnet's overall magnetic field strength. Finally, terbium may also be used in smaller amounts to further enhance the magnet's resistance to demagnetisation.

Although REEs and boron only represent a small fraction of the overall weight of the wind turbine, their critical role in enabling the functionality of permanent magnets gives them a strategic importance for the development of wind turbines with permanent magnet generators. Notably, boron and REEs are classified as SRMs, due to their use in strategic technologies and the expected growth in future demand; and as CRMs, due to their high economic importance and limited global supply. The supply risks associated with REEs are particularly pronounced, with China accounting for 85% of global processing for Light REEs concentrates (LREEs) such as neodymium and praseodymium, and a staggering 100% of global processing for Heavy REEs concentrates (HREEs) such as dysprosium and terbium. This level of concentration poses a significant threat to the long-term independence and security of the wind energy sector, as it creates a high degree of vulnerability to supply chain disruptions and geopolitical tensions. The boron market is also under-diversified, with Turkey accounting for 48% of global extraction of boron concentrate, which may lead to supply chain vulnerabilities (EC-GROW, 2023).

The use of REEs and boron in wind turbines is thus crucial for their efficient operation, but their limited global supply and high economic importance pose significant challenges for the wind energy sector, highlighting the need for effective recycling and waste management strategies.

5.2 Intensity and recyclability of rare earth elements and boron

The quantity of REEs required for wind turbines differs significantly depending on the turbine design, with dysprosium ranging between 1 and 21 kg/MW, neodymium between 6 and 210 kg/MW, praseodymium between 0 and 35 kg/MW, terbium between 0 and 7 kg/MW, and boron between 0.2 and 7 kg/MW (**Table 1**). As expected, the larger intensities correspond to the wind turbines of types D.PM and E.PM.

There are two main pathways for the recycling of permanent magnets: short-loop recycling, where the permanent magnets are reprocessed into new magnets; and long-loop recycling, where the magnets are chemically decomposed into the rare earth oxides and boron concentrate, and further purified into the individual concentrates. An advantage of long-loop rare earth recovery is that it offers flexibility in sourcing, as primary mineral feedstocks can be used to supplement the process if needed. Additionally, the ability to produce isolated rare earth oxides that can be sold into various application markets beyond magnets helps to support business models during the initial stages of magnet recycling stream development (IDTechEx, 2024). On the other hand, short-loop recovery could be cheaper, as it prevents the expensive purification step.

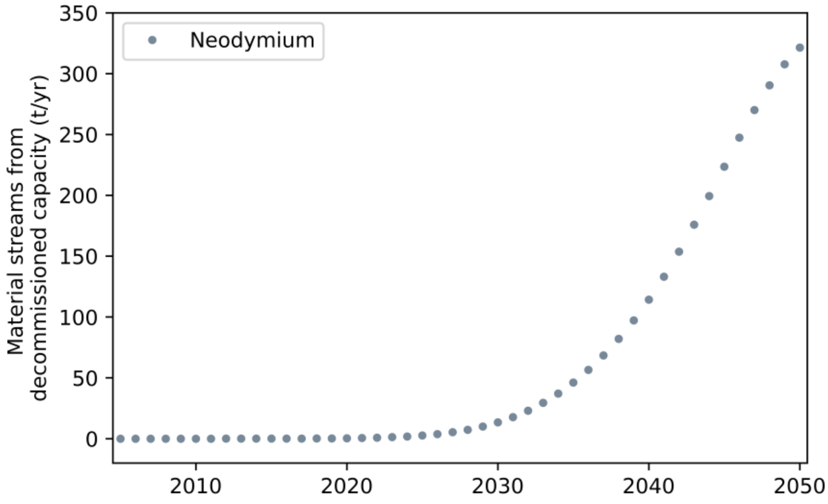
Currently, the recycling of REE material streams from decommissioned wind turbines is limited, with only an estimated 1% of the REEs present in permanent magnets being recovered (Eggert, 2016; Jowitt, 2018). In contrast, theoretical estimates suggest that permanent magnets from wind turbines could be reprocessed into secondary material streams with an overall efficiency of 75%, calculated by combining a collection efficiency of 90%, a disassembly efficiency of 90%, and a recycling efficiency rate of 92% (Schulze, 2016). Nevertheless, the economic viability of recycling REEs and boron is currently constrained by the high cost of reprocessing these materials into secondary streams, which often exceeds the cost of importing virgin primary materials (Jowitt, 2018). Additionally, the current recycling infrastructure is limited, even if pilot projects may scale to industry. To overcome these challenges, the EU is exploring initiatives to strengthen the recycling of these materials, such as developing more efficient recycling technologies and creating incentives for the use of secondary materials, in order to reduce the sector's reliance on primary materials and mitigate supply chain risks. For instance, the SUSMAGPRO initiative funded by Horizon Europe is focused on recycling and reusing neodymium-containing magnets from waste, creating a shorter recycling loop with a higher recovery rate (25%) and increased yield compared to conventional methods (EC-JRC, 2024).

Between 2000 and 2022, the world's cumulative consumption of REEs in products was equivalent to 3 Mt, with permanent magnets accounting for 52% or 1.6 Mt of the global total demand (Chen, 2024).

5.3 Decommissioned rare earth elements and boron material streams

The decommissioned waste streams of REEs and boron show a slow increase between 2020 and 2030, followed by a more significant growth between 2030 and 2050.

Figure 12. Neodymium material stream coming from decommissioned onshore and offshore wind capacity installed by 2023.



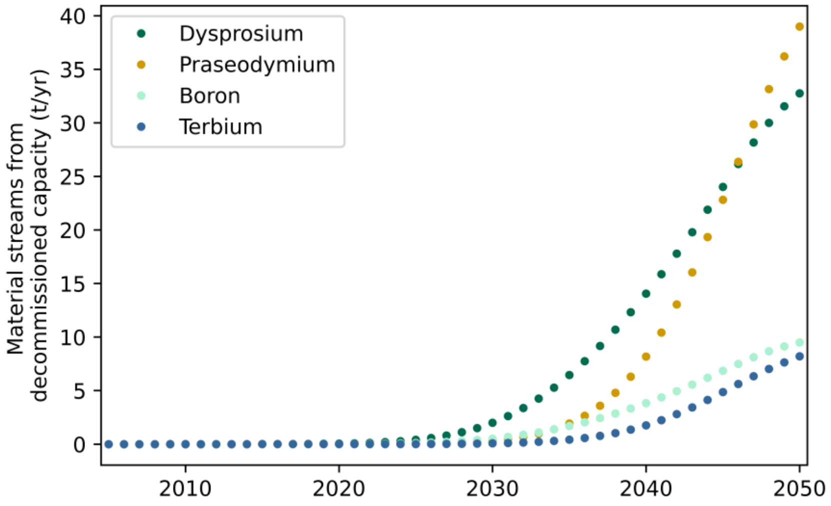
Source: JRC, 2024.

We note that the material streams presented in **Figure 12** and **Figure 13** are shown individually, per element (e.g., the neodymium material stream). However, in practice, when the permanent magnets are collected and recycled, it is as a whole permanent magnet, containing a mixture of rare earth oxides and boron concentrate, which can further be processed through either short-loop recycling (with no separation or purification stage of the elements) or long-loop recycling (in which case each material stream is isolated and purified).

The largest decommissioned material stream corresponds to neodymium, reaching 13 t/yr in 2030 and 321 t/yr in 2050 (see **Figure 12**). Dysprosium is the second material waste stream to grow, reaching 2 t/yr in 2030 and 33 t/yr in 2050 (see **Figure 13**). It is followed by praseodymium, which initially grows slower than dysprosium (0.3 t/yr in 2030), but surpasses the dysprosium waste stream in 2050, reaching 39 t/yr by that date. Boron and terbium follow, with waste streams of 0.5 t/yr and 0.1 t/yr in 2030, respectively, and 9.5 t/yr and 8.2 t/yr in 2050.

Efforts should be made to significantly strengthen each of the steps along the end-of-life timeline, including collection, disassembly and recycling, as highlighted in the CRMA regulation. However, the secondary material streams of REEs and boron might still grow short of the EU's growing demand for these materials, highlighting the need for other strategies to complement for the remaining gaps in both REE and boron demand. These include, for instance, expanding the EU's network of strategic partnerships, and promoting domestic production and processing of REEs and boron.

Figure 13. Material streams coming from decommissioned onshore and offshore wind capacity installed by 2023, for dysprosium, praseodymium, boron and terbium.



Source: JRC, 2024.

Given the projected growth in REE and boron demand, the development of effective recycling technologies and strategies is thus crucial – if not sufficient - to reduce the wind energy sector's reliance on primary materials, mitigate supply chain risks, and minimise environmental impacts, ultimately supporting the EU's transition to a more circular and sustainable economy.

6 Blade materials – composites

6.1 Role of composites in wind turbines

Composites, specifically glass-carbon composites, play a crucial role in the manufacture of wind turbine blades. These materials combine glass fibers and carbon fibers embedded in a polymer matrix, providing a high strength-to-weight ratio, stiffness, and durability. Although composites are not considered CRMs or SRMs, they pose a critical challenge in terms of waste management for the wind energy industry, due to the low Technology Readiness Level (TRL) or high cost of the currently available recycling options.

6.2 Intensity and recyclability of composite materials in the blades

The amount of glass or carbon composites used in wind turbines is approximately 7 500 ± 1 500 kg/MW (see **Table 1**). Currently, most wind turbine blades are disposed of or recovered, while only a small percentage is recycled. This is due in part to the difficulty of disassembling the various materials from the blade: indeed, sorting the diverse types of materials, glass-carbon composites, polymers and metals, remains a critical challenge at end-of-life (EC-JRC, 2025). Even after sorting, the strong adhesion between the fibers and polymers makes these materials particularly challenging to recycle at the end of their life.

Several recycling strategies have been identified, including mechanical recycling, chemical recycling through solvolysis or high voltage pulse fragmentation, and thermal recycling through fluidised bed, microwave pyrolysis, or pyrolysis (Chen, 2019; Suschem, 2018). Of these, microwave pyrolysis and solvolysis rank highest in terms of waste management scores, but their Technology Readiness Level (TRL) is lower than for the other methods (TRL 4 for microwave pyrolysis and 5/6 for solvolysis; compared to TRL 4/5 for thermal recycling through fluidised bed, TRL 7 for thermal recycling with pyrolysis and TRL 9 for mechanical recycling) (Khalid, 2023). Pyrolysis, in particular, has a low/medium waste management score, due to the high temperature damaging the fibre surface and decreasing the fibres' mechanical properties (Khalid, 2023). Alternatively, the composite materials can also be repurposed for example in new structural applications, such as footbridges or playgrounds (EC-JRC, 2025). Overall, the recycling processes for composite materials are not yet fully established, and reuse of recycled materials is not widespread. Further research and development are therefore needed to industrialise the blade recycling industry and make it more cost-effective. To support this, the EoLO-HUBS project, which is funded by the EU's Horizon Europe programme, aims to develop innovative solutions for the recycling of wind turbine blades.

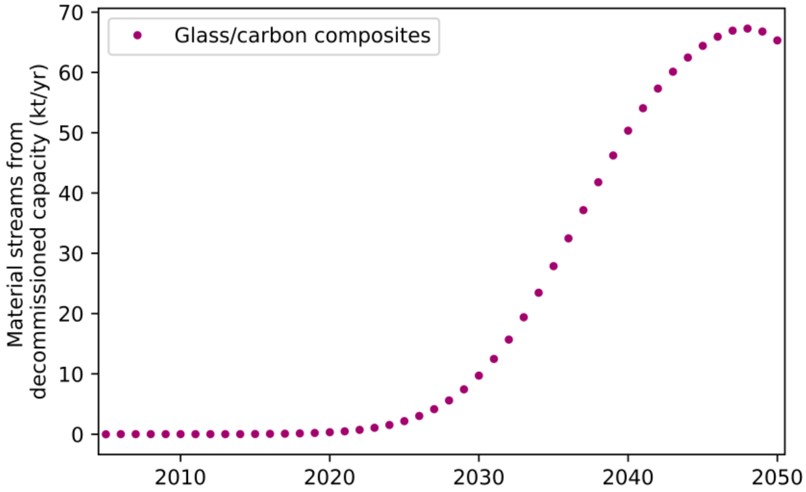
Given the challenges and opportunities related to blade recycling, the wind industry has committed to a Europe-wide landfill ban on decommissioned wind turbine blades by 2025 (WindEurope, 2024). This ban is part of a broader effort to increase the recycling and recovery of decommissioned blades, and it highlights the need for continued innovation and investment in blade recycling technologies.

Another possibility to enhance the recyclability of the wind turbine blades lies in the development of new types of blades, designed with recyclability in mind. Europe's leading wind turbine manufacturers, including Vestas, Siemens Gamesa, and Nordex, have all announced plans to develop recyclable blades (Vestas, 2024; Siemens Gamesa, 2024; Nordex, 2024). For example, Vestas has stated its goal to develop a 100% recyclable rotor by 2030, while Siemens Gamesa has committed to producing 100% recyclable turbines by 2040.

6.3 Decommissioned composite material stream

The decommissioned composite material stream from wind turbine blades is expected to grow significantly in the coming years. By 2030, the material stream is projected to reach 9.8 kt/yr, increasing to 65.3 kt/yr by 2050 (**Figure 14**).

Figure 14. Glass-carbon composites material stream coming from wind capacity installed by 2023.



Source: JRC, 2024.

To address the challenges related to blade recycling, policy support will be crucial. As highlighted by Foster et al., several policy gaps need to be addressed, including the creation of waste codes for wind turbine blades and the proposition to develop a Europe-wide registry of decommissioning (EC-JRC, 2025). These measures would provide the necessary information for the recycling of blades and help to track the progress of the wind industry towards a more circular economy. By addressing these policy gaps and continuing to invest in blade recycling technologies, the wind industry can reduce waste, increase recycling rates, and contribute to a more sustainable future.

7 Conclusions

In conclusion, this report provides a comprehensive assessment of the decommissioned material waste streams from the wind energy sector in the EU until 2050. Our analysis shows that the wind energy sector will generate significant waste streams, with concrete and steel being the largest contributors. However, these waste streams are expected to remain manageable within the existing recycling infrastructure, with the steel waste stream likely to be readily absorbed by the existing steel scrap ecosystem.

The report also highlights the importance of recycling and waste management for critical raw materials such as rare earth elements (REEs) and boron, which are used to manufacture the permanent magnets in wind turbines. Strengthening collection, disassembly, and recycling rates for REEs will be crucial to reducing waste and minimising environmental impacts, and to increasing the availability of secondary REE materials to meet the EU's growing demand.

Furthermore, the report emphasises the need for the wind industry to develop new recyclable blades, parallel to the effort of increasing recycling practices for blades currently being decommissioned. Several recycling strategies are identified, including mechanical recycling, chemical recycling, and thermal recycling. The development of innovative solutions for the recycling of wind turbine blades is crucial to reduce waste and minimise environmental impacts.

Overall, our findings suggest that the wind energy sector has the potential to contribute to a more circular and sustainable economy, but this will require a concerted effort from policymakers, industry stakeholders and researchers to develop effective strategies for managing the growing volume of wind energy waste streams. The EU's Critical Raw Materials Act and the Waste Framework Directive provide a framework for promoting recycling and waste management, but concerted efforts need to be made to support the development of closed-loop recycling and to reduce the sector's reliance on primary materials.

Our key recommendations are:

- to establish a comprehensive and standardised system for tracking and monitoring wind energy waste streams, including the collection and reporting of data on waste generation, recycling rates, and material recovery, to inform policy and industrial decision-making and ensure the effective management of waste streams;
- to develop and implement effective recycling technologies and strategies for critical raw materials such as REEs and boron: efforts should be made to strengthen each step of the end-of-life timeline, including collection, disassembly, and recycling, and to establish economic incentives to encourage the adoption of secondary raw materials;
- to foster the development of innovative recycling solutions for existing wind turbine blades, and to design a new generation of recyclable blades.

By implementing these recommendations, the wind energy sector can reduce its reliance on primary materials and minimise its environmental impacts, contributing both to the sector’s sustainability and to its circularity.

References

Antrekowitsch, J., Steinlechner, S., Unger, A., Rösler, G., Pichler, C., and Rumpold, R., 'Zinc and Residue Recycling', Handbook of Recycling, 2014, pp. 113-124, doi:<10.1016/B978-0-12-396459-5.00009-X>.

Bech Abrahamsen, A., Beauson, J., Wilhelm Lund, K., Skov Madsen, E., Philipp Rudolph, D., and Pagh Jensen, J., 'Method for estimating the future annual mass of decommissioned wind turbine blade material in Denmark', Wind Energy, 27(2):165-178, doi:<10.1002/we.2882178>, 2024.

Caro, D., Lodato, C., Damgaard, A., Cristóbal, J., Foster, G., Flachenecker, F., and Tonini, D., 'Environmental and socio-economic effects of construction and demolition waste recycling in the European Union', Science of The Total Environment, 908, 168295, doi:<10.1016/j.scitotenv.2023.168295>, 2024.

Carrara, S., Alves Dias, P., Plazzotta, B., and Pavel, C., 'Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised system', Publication Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-16225-4, doi:<10.2760/160859>, JRC119941.

Carrara, S., Baldassarre, B., Jakimów, M., Ierides, M., Kuzov, T., Mc Govern, L., Nohl, L., Christou, M., Deep dive on critical raw materials for wind turbines in the EU, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-27273-1, doi:<10.2760/742137>, JRC141759, 2025.

CEMBUREAU, 2016, Cement, concrete & the circular economy, Brussels, https://circulareconomy.europa.eu/platform/sites/default/files/cement_concrete_the_circular_economy.pdf.

Changming, D., Chao, S., Gong, X., Ting, W., Xiange, W., Plasma methods for metals recovery from metal–containing waste, Waste Management, 2018, Vol. 77, pp. 373-387, doi:<10.1016/j.wasman.2018.04.026>.

Chen, J., Wang, J., Ni, A., Recycling and reuse of composite materials for wind turbine blades: An overview, Journal of Reinforced Plastics and Composites, 2019, 38(12):567-577, https://journals.sagepub.com/doi/full/10.1177/0731684419833470.

Chen, Y., Cai, G., Zheng, L., Zhang, Y., Qi, X., Ke, S., Gao, L., Bai, R., Liu, G., 'Modeling waste generation and end-of-life management of wind power development in Guangdong, China until 2050', Resources, Conservation and Recycling, volume 169, 105533, doi:<10.1016/j.resconrec.2021.105533>, 2021.

Chen, W.-S., Chen, Y.-C., and Lee, C.-H., 'Hydrometallurgical Recovery of Iron, Nickel, and Chromium from Stainless Steel Sludge with Emphasis on Solvent Extraction and Chemical Precipitation', Processes, 10(4), 748, doi:<10.3390/pr10040748>, 2022, https://www.mdpi.com/2227-9717/10/4/748.

Chen, W.-Q., Eckelman, M. J., Sprecher, B., Chen, W., Wang, P., Interdependence in rare earth element supply between China and the United States helps stabilize global supply chains, One Earth, Volume 7, 2024, pp. 242-252, doi:<10.1016/j.oneear.2024.01.011>.

Cristobal Garcia, J., Caro, D., Foster, G., Pristera, G., Gallo, F., and Tonini, D., 'Techno-economic and environmental assessment of construction and demolition waste management in the European Union', Publications Office of the European Union, Luxembourg, 2024, doi: <10.2760/721895>, JRC135470.

Cusano, G., Gonzalo, M.R., Farrell, F., Remus, R., Roudier, S., Sancho, L.D., Best Available Techniques (BAT) Reference Document for the main Non-Ferrous Metals Industries, Publication Office of the European Union, Luxembourg, 2017, EUR 28648 EN, doi:<10.2760/8224>.

Eggert, R., Wadia, C., Anderson, C., Bauer, D., Fields, F., Meinert, L., and Taylor, P., 'Rare Earths: Market Disruption, Innovation, and Global Supply Chains', Annual Review of Environment and Resources, 41:199-222, 2016, doi:<10.1146/annurev-environ-110615-085700>.

European Commission: Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (EC-GROW, 2023), Grohol, M. and Veeh, C., Study on the critical raw materials for the EU 2023 – Final report, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2873/725585.

European Commission: Joint Research Centre (EC-JRC, 2023), Carrara, S., Bobba, S., Blagoeva, D., Alves Dias, P., Cavalli, A., Georgitzikis, K., Grohol, M., Itul, A., Kuzov, T., Latunussa, C., Lyons, L., Malano, G., Maury, T., Prior Arce, Á., Somers, J., Telsnig, T., Veeh, C., Wittmer, D., Black, C., Pennington, D., Christou, M., Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU : a foresight study, Publications Office of the European Union, Luxembourg, 2023, https://data.europa.eu/doi/10.2760/386650, JRC132889.

European Commission, Joint Research Centre (EC-JRC, 2024), Mc Govern, L., Tapoglou, E., Georgakaki, A., Mountraki, A., Letout, S., Ince, E., Gea Bermudez, J., Schmitz, A., Grabowska, M., Clean Energy Technology Observatory: Wind Energy in the European Union - 2024 Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2024, https://data.europa.eu/doi/10.2760/088270, JRC139320.

European Commission, Joint Research Centre (EC-JRC, 2025), Foster, G., Kastanaki, E., Beausion, J., Neuwahl, F., Marschinski, R., Circular Economy Strategies for the EU's Renewable Electricity Supply, Publications Office of the European Union, Luxembourg, 2025, https://data.europa.eu/doi/10.2760/559833, JRC138570.

European Environment Agency (EEA), Zinc production. Manufacture of basic precious and non-ferrous metals, EMEP/EEA air pollutant emission inventory guidebook, 2019.

European Parliament and Council (EPC, 2008), 'Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance) ', Official Journal of the European Union, 2008.

European Parliament and Council (EPC, 2023), 'Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652', Official Journal of the European Union, 2023.

European Parliament and Council (EPC, 2024), 'Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020 (Text with EEA relevance)', Official Journal of the European Union, 2024.

EuRIC (2022): Metal Recycling Factsheet, European Circular Economy Stakeholder Platform, https://circulareconomy.europa.eu/platform/sites/default/files/euric_metal_recycling_factsheet.pdf.

EUROFER AISBL (2024) European Steel in Figures 2024, covering 2023, Brussels, https://www.eurofer.eu.

Gast, L., Meng, F., and Morgan, D., 'Assessing the circularity of onshore wind turbines: Using material flow analysis for improving end-of-life resource management', Resources, Conservation and Recycling, Volume 204, 2024, 107468, doi: <10.1016/j.resconrec.2024.107468>.

Gu, F., Zhang, Y., Su, Z., Tu, Y., Liu, S., Jiang, T., Recovery of chromium from chromium-bearing slags produced in the stainless-steel smelting: A review, Journal of Cleaner Production, 2021, Vol. 296, 126467, doi:<10.1016/j.jclepro.2021.126467>.

IDTechEx, 'How Magnets Are Reshaping Rare Earth Supply, Demand, and Recovery', 2024, https://www.idtechex.com/en/research-article/how-magnets-are-reshaping-rare-earth-supply-demand-and-recovery, accessed March 2025.

Jardine, A.K.S., Anderson, P.M., Mann, D.S., 1987. Application of the Weibull proportional hazards model to aircraft and marine engine failure data. Quality and Reliability Engineering International 3(2), 77-93. doi:<10.1002/qre.4680030204>.

Jowitt, S. M., Werner, T. T., Weng, Z., Mudd, G. M., Recycling of the rare earth elements, Current Opinion in Green and Sustainable Chemistry, 2018, Vol. 13, pp. 1-7, doi:<10.1016/j.cogsc.2018.02.008>.

Judge, F., McAuliffe, F.D., Sperstad, I.B., Chester, R., Flannery, B., Lynch, K., Murphy, J., A lifecycle financial analysis model for offshore wind farms, Renewable and Sustainable Energy Reviews, Volume 103, 2019, pp. 370-383.

Khalid, M. Y., Arif, Z. U., Hossain, M., and Umer, R. "Recycling of wind turbine blades through modern recycling technologies: A road to zero waste", Renewable Energy Focus, Volume 44, 2023.

Krour, H., Tazi, N., Trauchessec, R., Ben Fraj, A., Lecomte, A., Idir, R., Barnes-Davin, L., Bolze, B., and Delhay, A., 'Industrial-scale valorization of fine recycled aggregates in cement raw meal: Towards sustainable mixtures', Journal of Cleaner Production, Volume 362, 2022, 132231, doi: <10.1016/j.jclepro.2022.132231>.

Marmier, A., Decarbonisation options for the cement industry, Publications Office of the European Union, Luxembourg, 2023, doi:<10.2760/174037>, JRC131246.

Mc Govern, L, Tapoglou, E., and Georgakaki, A. "Material requirements for wind turbines", European Commission, Petten, 2024, JRC139701.

Nordex, 'Nordex group aims to prove fully recyclable wind turbines by 2032', https://www.nordex-online.com/en/2023/03/nordex-group-aims-to-provide-fully-recyclable-wind-turbine-blades-by-2032/, consulted on 17/10/2024.

Ohno, H., Matsubae, K., Nakajima, K., Kondo, Y., Nakamura, S., Nagasaka, T., Toward the efficient recycling of alloying elements from end of life vehicle steel scrap, Resources, Conservation and Recycling, 2015, Vol. 100, pp. 11-20, doi:<10.1016/j.resconrec.2015.04.001>.

Pascovici, D.S., Kyprianidis, K.G., Colmenares, F., Ogaji, S.O.T., Pilidis, P., 2009. Weibull Distributions Applied to Cost and Risk Analysis for Aero Engines. Proceedings of the ASME Turbo Expo 2008, GT2008-51060, 681-690. doi:<10.1115/GT2008-51060>.

Peaslee, K.D., Webber, D.S., Lekakh, S.N., and Randall, B., 'Alloy Recovery and Control in Steel Melting', Proceedings of the SFSA Technical and Operating Conference, Steel Founders' Society of America (SFSA), 2005.

Reuter, M.A., van Schaik, A., Gutzmer, J., Bartie, N., and Abadías-Llamas, A., 'Challenges of the Circular Economy: A Material, Metallurgical, and Product Design Perspective', Annual Review of Materials Research, 49:253-274, doi:<10.1146/annurev-matsci-070218-010057>, 2019.

Schulze, R., and Buchert, M., 'Estimates of global REE recycling potentials from NdFeB magnet material', Resources, Conservation and Recycling, 113 (2016) 12–27, 2016, https://www.sciencedirect.com/science/article/pii/S0921344916301148.

Siemens Gamesa, 'Sustainability Vision 2040 - Delivering sustainability through actions', https://www.siemensgamesa.com/global/en/home/sustainability.html, consulted on 17/10/2024.

Suschem, European Technology Platform for Sustainable Chemistry, "Polymer Composites Circularity – White paper", 2018.

Topham, E., Gonzalez, E., McMillan, D., João, E., Challenges of decommissioning offshore wind farms: Overview of the European experience, Journal of Physics: Conference Series, Volume 1222, 2019, DOI: <10.1088/1742-6596/1222/1/012035>.

Telsnig, T., 'Wind Energy Technology Development Report 2020', Publications Office of the European Union, Luxembourg, ISBN 978-92-76-27273-1, doi:<10.2760/742137>, JRC123138, 2020.

Vestas website content on sustainability, environment and zero waste, 2024, URL: https://www.vestas.com/en/sustainability/environment/zero-waste, accessed 30/12/2024.

Wood Mackenzie, 'Global onshore wind power project installation database', updated with Q4 2024, 2024, accessed 30/12/2024.

Zimmermann, T., Rehberger, M., Gößling-Reisemann, S., 2013. Material Flows Resulting from Large Scale Deployment of Wind Energy in Germany. Resources, volume 2, 303-334. doi:<10.3390/resources2030303>.

List of abbreviations

Abbreviations	**Definitions**
AE	Alloying Element
C&DW	Construction and Demolition Waste
CRM	Critical Raw Material
DD	Direct Drive
DFIG	Doubly-Fed Induction Generator
EE	Electrically Excited
HREE	Heavy Rare Earth Element
HSLA	High-Strength Low-Alloy
LREE	Light Rare Earth Element
PM	Permanent Magnet
R&D	Research and Development
RCA	Recycled Concrete Aggregate
REE	Rare Earth Element
SCIG	Squirrel Cage Induction Generator
SRM	Strategic Raw Material
TRL	Technology Readiness Level
WRIG	Wound Rotor Induction Generator

List of figures

List of tables

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