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DEEP DIVE ON CRITICAL RAW MATERIALS FOR **WIND TURBINES** IN THE EU

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Contents

Abstract

The transition to clean energy is both a climate imperative and a materials challenge. This report provides a comprehensive analysis of the supply chain for wind turbines, a cornerstone of the EU's energy transition strategy.

Significant dependencies are found for rare earth elements including neodymium, dysprosium, praseodymium, and terbium, critical for high-performance wind turbine magnets, and balsa wood for turbine blades, with the People's Republic of China and Ecuador dominating these respective supply chains. Supply chain vulnerabilities are identified, including geopolitical risks and environmental concerns, alongside opportunities for enhancing circularity and advancing the use of substitute materials.

In line with EU measures such as the Critical Raw Materials Act and the Net-Zero Industry Act, this study underscores the urgency of diversifying supply sources, scaling recycling efforts, and fostering innovation to bolster the resilience of the EU's wind energy sector.

Foreword

The clean energy transition is our only path towards a sustainable future.

To tackle the dual challenge of reducing dependency on fossil fuels – particularly those imported from Russia following its war of aggression against Ukraine – and addressing the climate crisis, the EU has set ambitious targets to accelerate economic decarbonisation and achieve net-zero emissions by 2050. However, **the clean energy transition is essentially a materials transition**. The focus is shifting from fossil fuels to the critical materials needed to manufacture clean energy technologies.

Meeting the EU's energy and climate targets means deploying the right technologies, in the right quantities, at the right speed. Falling short on any of these fronts risks undermining the clean energy transition, delaying decarbonisation, and derailing the EU's climate ambitions. To mitigate these risks, the EU has adopted the **Critical Raw Materials Act**, which aims to ensure a secure and sustainable supply of critical raw materials.

This marks a **paradigm shift in energy security**: ensuring not only the availability of energy itself but also **the materials critical to building the technologies** that will power the future. In this context, the Joint Research Centre, in partnership with the Directorate General for Energy, have analysed the materials supply chains of three technologies, which are the **cornerstones of the clean energy transition: wind power, solar photovoltaic, and batteries for energy storage and electro-mobility**.

These analyses build on the structure and results of the **2023 JRC Foresight study** (*Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU*), but they go deeper, to provide further insights for policy and a better understanding of the potential bottlenecks of the relevant supply chains, of our exposure to disruption risks and of the potential risk mitigation measures that can be adopted.

In particular, the three deep dives shed light on:

- the profiles of the materials needed for the relevant technologies, including their use in other sectors, their sourcing and supply risk, and the material intensities used for these technologies;
- the detailed supply chains, including examples of the main companies that could ramp up production to strengthen EU domestic supply, and any dependencies related to that supply;
- the EU materials demand projections for 2030, 2040 and 2050, updated according to recent EU and global policy developments;
- the impact on materials consumption of an "accelerated innovation" scenario;
- the challenges and benefits of circularity in these technologies and the opportunities for substitution with advanced materials and innovative designs;
- insights on the way some other economies – such as the People's Republic of China – are addressing similar challenges and the resilience of the relevant supply chains;
- the measures available for mitigating supply disruption risks.

It is hoped that these deep dives, which are the fruit of a valued collaboration between two directorates-general, and the scientific evidence and knowledge that they provide, can support policies to secure resilient supply chains and climate neutrality for the benefit of all.

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Section 4.3 is based on work carried out in collaboration between the JRC and the following academic institutions: the Maastricht Sustainability Institute of Maastricht University, the University of Manchester, and University College London. The research objectives and overall framing of the analysis were defined by the JRC. The overall methodology was designed collaboratively. The research protocol was created by the academic institutions, who also executed the analysis. The research results were iteratively discussed, leading to the main insights and conclusions of the analysis. The authors of the report would like to thank Dr. Sampriti Mahanty, Dr. Riza Batista-Navarro, and Prof. Frank Boons for this valuable collaboration.

Section 4.4 builds on the work carried out in collaboration with Xiaoran Li, Vrije Universiteit Amsterdam. The overall methodology and research objectives were designed by the JRC. An initial data analysis of Chinese policies was carried out by Xiaoran Li. This analysis was later extended, refined and supplemented with additional data and analysis by the JRC.

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Executive summary

Policy context

The European Union has set ambitious targets to expand renewable energy, with **wind power playing a pivotal role** in achieving climate neutrality by 2050. The European Green Deal, the Fit-for-55 package, and the REPowerEU plan drive this transition by accelerating renewable energy deployment and reducing dependence on fossil fuels.

To ensure the secure and sustainable supply of critical materials needed for wind power, the EU has adopted the Critical Raw Materials Act (CRMA), setting targets for domestic extraction, refining, and recycling of key materials, including those used in wind turbines. Additionally, the Net-Zero Industry Act (NZIA) mandates that by 2030, the EU should manufacture at least 40% of its annual deployment needs for strategic net-zero technologies, including wind power.

This report, conducted by the Joint Research Centre (JRC) in partnership with and supported by an Administrative Arrangement from DG Energy, provides a **detailed analysis of wind turbine supply chains, with emphasis on raw materials**. It assesses material dependencies, supply chain risks, and the role of circular economy strategies in ensuring long-term sustainability.

The findings aim to support ongoing and future policy actions, particularly within the EU Wind Power Package, contributing to a more resilient European wind energy industry and a more secure and resilient EU supply of energy transition materials in general.

Main findings and key conclusions

The wind turbine supply chain consists of five key stages: raw materials, processed materials, components, assemblies, and super-assemblies. Critical materials include **rare earth elements (REEs)** – notably neodymium, praseodymium, dysprosium, and terbium – which are essential for the NdFeB permanent magnets used in generators. They also include **balsa wood**, a key component in turbine blades.

The REE supply chain is highly concentrated, with the **People's Republic of China** controlling over 90% of processing and magnet production, making the EU reliant on a single dominant supplier. Similarly, the global production of balsa wood is almost entirely concentrated in **Ecuador**. These dependences raise concerns over **trade restrictions and potential supply disruptions as well as environmental and economic risks**.

Material demand for wind turbines is expected to increase significantly in the coming decades. However, advances in material efficiency, recycling, and substitution could mitigate supply risks. **Circular economy** strategies – such as remanufacturing, repair, and end-of-life (EoL) magnet recycling – are key solutions but remain hindered by regulatory gaps, a lack of infrastructure, and financial barriers

Among other policy measures, this report recommends the following actions to strengthen the EU supply chain's resilience:

- **diversifying supply sources** through partnerships with alternative, geopolitically stable regions;

- **investing in domestic processing and refining** to reduce dependency on external suppliers;
- **expanding recycling capabilities** for REE magnets and turbine components;
- **exploring technological alternatives** to reduce reliance on critical materials, including advanced magnet designs, novel composite materials, and innovative turbine architectures.

These findings underscore the urgent need for stronger EU policy measures, particularly under the CRMA and NZIA frameworks, to secure Europe's wind energy future and enhance strategic autonomy.

Related and future JRC work

This report is one of three which launch a series of "deep dives" into the supply chains of the critical raw materials necessary for the main energy transition technologies; the other two address solar photovoltaics and batteries. It also intersects with the JRC's ongoing work on the wind turbine industry and its supply chain in the framework of the annual Clean Energy Technology Observatory[1] reports and with the series of foresight studies on "Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU", whose next edition is due in 2026.

Quick guide

The wind power supply chain is essential to the success of the EU's clean energy transition, and depends on critical raw materials (CRMs) including rare earth elements (REEs) and balsa wood. The report analyses the supply chain's vulnerabilities, material demand projections, and circular economy potential. It assesses geopolitical risks, recycling feasibility, and alternative materials using data-driven methodologies. Key uncertainties include future material availability, regulatory developments, and technological advancement. The findings support EU policies such as the Critical Raw Materials Act (CRMA) and the Net-Zero Industry Act (NZIA), providing insights for supply security and resilience.

[1] https://setis.ec.europa.eu/publications-and-documents/clean-energy-technology-observatory_en

1 Introduction

The European Climate Law, adopted in 2021, set binding targets to make Europe climate neutral by 2050. A year later, faced with the challenge of reducing EU dependence on fossil fuels imported from Russia, the EU accelerated its decarbonisation ambitions. This rapid energy transition brings a shift in focus: away from **fuels** and towards the **materials** necessary for manufacturing clean energy technologies, such as wind turbines, photovoltaic panels, batteries and hydrogen electrolysers. For that reason, the clean energy transition cannot be accomplished without secure access to the necessary quantities of these materials, many of which are classed as critical. This is a new dimension in the security of energy supply: the **security of supply of the critical raw materials** necessary for the clean energy transition.

In that context, and as part of an Administrative Arrangement on securing the supply of energy to the EU, the JRC is providing DG Energy with scientific evidence and knowledge in understanding the EU's needs for critical raw materials in clean energy technologies; the exposure to risks; and the availability and efficiency of measures to increase preparedness against disruptions and mitigate risks.

The work presented in this report takes a deep dive into the case of **supply chains of critical raw materials for wind turbines**, as wind power is one of the pivotal technologies on which the energy transition is based. The study builds on the results of the 2023 JRC Foresight report (Carrara et al., 2023), and provides more detailed analysis on:

- **Mapping of the supply chain of the critical raw materials for wind turbines**, with information on the sourcing of raw and processed materials, components and equipment; secondary sources (recycling); examples of the main economic operators along the complete value chain; other (competitive) users and applications of the relevant critical raw materials; assessment of bottlenecks along the supply chain; and the availability of alternative supply sources and substitute materials.
- **Material demand forecasts**, for the EU and globally, according to the most up-to-date EU Climate Targets of 2030, 2040 and 2050 and the Net Zero Emissions scenario for global demand. An additional scenario of accelerated innovation is also examined, as is the supply-demand balance.

The data and intelligence collected in this deep dive are expected to contribute to the future development of detailed models of the wind energy supply chain, and to be used for assessment of the impact of potential disruptions and in determining measures to increase resilience. This detailed analysis contributes to a better understanding of the EU's supply and demand of the critical raw materials necessary for wind turbine manufacturing, along with supply chain bottlenecks and the exposure of the wind power manufacturing industry to disruption risks. This understanding is essential for the implementation of the Critical Raw Materials Act and contributes significantly to the implementation of EU wind energy policy and the Net-Zero Industry Act.

1.1 Geopolitical context and the role of wind energy

As the world transitions towards a low-carbon economy, **wind turbines have emerged as a vital component of the renewable energy landscape**. At the end of 2023, the global installed capacity of wind power exceeded one terawatt (1 021 GW) – 220 GW of which was in the EU – accounting for 26% of the total renewable power capacity (GWEC, 2024; IRENA, 2024). In the same year, the global wind industry installed a record 117 GW of new capacity (16 GW in the EU), representing a 50% year-on-year increase from 2022 (GWEC, 2024). Moreover, wind power and solar photovoltaic are the predominant sources of power generation in the IEA "Net Zero Emissions by 2050" scenario, accounting for almost 90% of global energy demand (IEA, 2024).

Wind energy has proven to be a clean and abundant energy source, employing a mature technology to generate electricity. Wind turbine technology, on land (onshore) and at sea (offshore), has evolved significantly, reducing costs and unlocking more sites with lower wind speeds. **Offshore wind** in particular is expected to increase rapidly in the coming years, taking advantage of the stronger winds at sea.

The global wind turbine market is characterised by intense competition, with leading manufacturers such as Vestas, Siemens Gamesa, and Goldwind dominating the market (BNEF, 2023). Trade tensions and tariffs are common, with governments trying to support the competitiveness of their domestic industry, for example through the US Inflation Reduction Act (IRA) (CRS, 2024).

The need for rapid deployment and improved performance of wind turbines, especially offshore, has resulted in **increasing demand for rare earth minerals** (neodymium, praseodymium, dysprosium, and terbium) used for the permanent magnets. This, combined with the fact that the People's Republic of China[2] is a major supplier of these raw materials and the (almost) unique supplier of the processed materials, has raised concerns about supply chain security and the environmental impact of mining (see e.g. Carrara et al., 2023). The scale of increase in offshore wind deployment and the global materials demand, combined with the dominant role of China in the rare earth minerals supply chain, pose **significant challenges for material supply**, both in relation to the physical availability of the materials and to the geographic concentration of reserves and of processing facilities. Furthermore, the use of these materials in other emerging technologies, such as electric vehicle traction motors, electronics and robotics, creates **global competition** for access to the same resources between countries and between sectors. Last but not least, the strong global dependence on imports of rare earth minerals and permanent magnets from China raises concerns about **geopolitical risks and the strategic autonomy** of the EU and other economies, including through the weaponisation of these dependencies.

1.2 EU Policy context: Ambitious wind energy targets, with secure access to the necessary critical raw materials

The European Union has set ambitious targets to increase the share of renewable energy in its energy mix, with wind energy playing a crucial role in achieving these goals. The EU's wind energy policy is guided by the **European Green Deal** (EC, 2019), which aims to make Europe the first climate-neutral continent by 2050. The Fit-for-55 package (EC, 2021) puts in place the measures needed to reduce greenhouse gas (GHG) emissions by 55% by 2030, compared to 1990 levels. The REPowerEU Plan (EC, 2021), adopted in the wake of Russia's full-scale invasion of Ukraine, aims to accelerate these policies and rapidly increase the deployment of renewable energy to reduce EU dependence on Russian fossil fuels.

Relevant legislation such as the **Renewables Energy Directive (RED)** (EP&C, 2009 and EP&C, 2018) has been updated accordingly, with the revised RED-III (EP&C, 2023) requiring the EU to raise

[2] Henceforth, the People's Republic of China will be referred to simply as "China".

its share of renewable energy sources in its final energy consumption to at least 42.5% by 2030. In February 2024, the Commission also presented its assessment for an intermediate 2040 climate target (EC, 2024) of reducing net emissions to 90% relative to 1990.

Wind energy plays a pivotal role in the energy mix of all these policies. In 2022, wind already accounted for over one-third (37.5%) of the total electricity generated from renewable sources in the EU (Eurostat, 2024). The EU is committed to remaining the global leader in renewables in general, and in wind power in particular. Wind energy manufacturing supports the EU's transition to climate neutrality, while also creating growth and jobs.

To accelerate wind energy manufacturing across Europe, the Commission presented the EU Wind Power Package (EC, 2023a) in October 2023. It consists of two initiatives: the European Wind Power Action Plan and a communication on achieving the EU's offshore wind ambitions. The **European Wind Power Action Plan** (EC, 2023b) details measures for accelerating deployment through faster permitting and increased predictability, improved auction design, access to finance, a fair and competitive international environment, skills development, industry engagement and Member State commitments. The Ocean energy communication (EC, 2023c) also specifies measures to accelerate the deployment of offshore wind and achieve the necessary tenfold increase of annual new installation capacity (to 12 GW per year on average, from the 1.2 GW installed in 2022). Measures to help accelerate the roll out of offshore capacity include strengthening grid infrastructure, accelerating permitting, maritime spatial planning, strengthening the resilience of infrastructure, sustaining research and innovation, and developing supply chains and skills.

In order to meet the EU's energy and climate targets, we need to build the right technologies, in the right quantities, at the right speed. To secure the undisrupted supply of critical raw materials necessary for the energy and digital transitions and the space and defence agenda, the European Union adopted in 2024 the **Critical Raw Materials Act (CRMA)** (EP&C, 2024). The CRMA specifies prioritisation actions and measures to strengthen the supply of target materials: Strategic Raw Materials (SRM) and Critical Raw Materials (CRM), defined following a robust criticality assessment. It sets benchmarks for 2030 for EU domestic extraction (10% of consumption requirements), EU domestic manufacturing (40% of consumption needs) and recycling (25% of consumption needs), as well as for EU reliance on a single third country (no more than 65% of consumption needs). Wind technologies are one of the strategic technologies of the CRMA and particular attention is given to improving the recycling of materials in the permanent magnets of wind turbines generators (Art. 28 and 29).

In support of the development of the CRMA, the JRC carried out an extensive study of the materials supply chains of the key strategic technologies, analysing dependencies, bottlenecks and demand projections, summarising the findings in Carrara et al. (2023). That study presents a systematic and detailed analysis of the complete supply chains, from raw and processed materials to components, assemblies, super-assemblies and systems, for 15 key technologies across the five strategic sectors of renewables, electromobility, decarbonisation of energy-intensive industries, information and communications technology (ICT), and space and defence.

Last but not least, the **Net-Zero Industry Act (NZIA)** aims to strengthen Europe's net-zero technology manufacturing ecosystem, with wind energy among the strategic technologies identified. NZIA requires that by 2030, manufacturing capacity in the Union of the strategic net-zero technologies, including wind, reaches a benchmark of at least 40% of the Union's annual deployment needs in order to achieve the Union's 2030 climate and energy targets.

The implementation of the CRMA legislation and the EU wind energy policies requires a good understanding of the structure of the supply chains, their bottlenecks and EU dependency on third countries; the estimated materials needs over time – both for a baseline scenario and under assumptions of accelerated innovation; the supply-demand balance; the role of circularity and substitution; and the possibilities for diversification of supply and strengthening of domestic supply chains. Providing this understanding is the objective of this deep dive.

1.3 Description of wind turbines

1.3.1 Wind turbine functioning

Wind turbines are among the most widely deployed technologies for renewable energy generation, converting kinetic energy from the wind into mechanical energy, which is subsequently transformed into electricity through a generator.

The key components of a wind turbine include the **rotor blades**, **nacelle**, **tower**, and **foundation**. The rotor blades are designed to efficiently capture wind energy and typically span lengths of 40 to over 100 metres, depending on the turbine's capacity, which typically ranges from 1 MW to more than 15 MW (GWEC, 2024). The nacelle, mounted atop the tower, houses the drivetrain and generator, along with various systems for cooling, lubrication, and monitoring. The tower provides height to capture stronger winds at higher altitudes, while the foundation anchors the turbine to the ground or seabed, ensuring stability against wind forces and vibrations.

Modern wind turbines are highly efficient, operating even at low wind speeds through sophisticated blade design and advanced control systems. Turbines are equipped with **yaw mechanisms** that allow the nacelle to rotate, optimising the alignment of the blades with the wind direction. Additionally, **pitch control systems** adjust the angle of the blades to regulate rotational speed, ensuring that the turbine operates safely and efficiently under varying wind conditions.

Wind turbines are broadly classified into two categories: **onshore** and **offshore**. Onshore turbines are deployed on land and are typically smaller and less costly to install than their offshore counterparts. Offshore turbines, however, are significantly larger and designed to withstand harsh marine environments. They benefit from stronger and more consistent wind speeds over open water, making them an essential component of large-scale renewable energy projects.

Over the years, wind turbine technology has evolved significantly. Early designs were small and inefficient compared to today's sophisticated systems. Advances in materials, aerodynamics, and digital technologies have not only increased their efficiency but also reduced costs, making wind energy one of the most competitive renewable energy sources available.

1.3.2 Generators

Generators are the central component of wind turbines, converting the mechanical energy generated by the rotor blades into electrical energy. The choice of generator technology has significant implications for a turbine's efficiency, cost, maintenance, and compatibility with grid requirements, in addition to the security of supply related to the CRMs needed.

There are two primary types of generator: **gearbox-based systems (GB) and direct-drive systems (DD)**. Gearbox-based systems use a gearbox to increase rotational speed, enabling smaller generators to operate efficiently. These systems are further subdivided into high-speed and medium-speed drives, each with distinct characteristics. For example, high-speed drives often use induction generators, while medium-speed systems can combine gearboxes with permanent magnets, reducing reliance on rare earths. Direct-drive systems, by contrast, eliminate the gearbox altogether, which allows for enhanced reliability, reduced maintenance needs, and simplified design.

Within the GB and DD families, there are several types of drive train configurations, summarised in Table 1 and described in detail below.

Table 1. Types of drive train configurations in wind turbines.

Type	Gearbox/Gearless	Configuration	Main application
A	Gearbox	High-speed - Squirrel Cage Induction Generator (SCIG_NC) – Without full power converter	Onshore
B	Gearbox	High-speed Wounded Rotor Induction Generator (WRIG)	Onshore
C	Gearbox	High-speed Doubly-Fed Induction Generator (DFIG)	Onshore and offshore
D-EE	Gearless (Direct Drive)	Low-speed Electrically excited synchronous generator (EESG) with full power converter	Onshore
D-PM	Gearless (Direct Drive)	Low-speed Permanent magnet synchronous generator (PMSG) with full power converter	Onshore and offshore
E-EE	Gearbox	Medium/High-speed Electrically excited synchronous generator (EESG) with full power converter	Onshore
E-PM	Gearbox	Medium/High-speed Permanent magnet synchronous generator (PMSG) with full power converter	Onshore and offshore
F	Gearbox	High-speed - Squirrel Cage Induction Generator (SCIG) with full power converter	Offshore
-	Gearless (Direct Drive)	High-Temperature Superconductors (HTS)	Offshore

Note: Grey rows indicate technologies that were widely adopted in the past, but that no longer have a significant role in the current market. The blue row indicates a future technology, not yet on the market.

Source: adapted from Carrara et al. (2020) and Telsnig (2020).

- **Types A and F – Squirrel Cage Induction Generators (SCIG)** are a traditional type of wind turbine generator, characterised by their simple and robust design. They operate at a fixed speed and require an external power source for magnetisation. SCIGs are typically coupled with a gearbox to match the rotational speed of the turbine to the generator's requirements. While they are cost-effective and easy to maintain, their fixed-speed operation limits their efficiency under variable wind conditions. As a result, SCIGs are increasingly being replaced by more advanced variable-speed technologies, particularly in large-scale and offshore applications. However, they are still used in smaller-scale installations or in regions where cost and simplicity are prioritised over efficiency.

- **Type B – Wound Rotor Induction Generators (WRIG)** are an evolution of traditional induction generators, offering variable speed operation through the use of a wound rotor connected to external resistors or power electronics. This configuration provides better efficiency and grid integration compared to SCIGs, as it allows the rotor to adapt to varying wind speeds. WRIGs are commonly coupled with gearboxes, which help optimise the rotational speed of the generator. While they are more flexible and efficient than fixed-speed generators, WRIGs require additional components, such as slip rings and brushes, which can increase maintenance needs. As with SCIGs, they are being replaced by newer technologies in large-scale applications.

- **Type C – Doubly-Fed Induction Generators (DFIG)** are among the most widely used generator types in wind turbines, particularly for onshore installations. They use a partial-capacity converter to control the rotor circuit, allowing variable speed operation and efficient grid integration. This technology enables the generator to operate at a fixed frequency while accommodating changes in wind speed. DFIGs are cost-effective and well-suited for moderate wind environments but are less robust in harsh conditions compared to other generator types.

- **Types D and E – Synchronous Generators (SG)** are widely used in wind turbines and are divided into two main subtypes:

    - **Electrically Excited Synchronous Generators (EESG)** use an external electrical source to magnetise the rotor, allowing precise control of the magnetic field. They can be configured with a gearbox to increase the rotational speed of the generator or as direct-drive systems that eliminate the gearbox entirely. Gearbox-based EESGs are more cost-effective and lighter, while direct-drive EESGs are more reliable and require less maintenance, making them suitable for offshore applications. However, both configurations involve complex control systems and higher maintenance needs compared to permanent magnet systems.

    - **Permanent Magnet Synchronous Generators (PMSG)** rely on permanent magnets to generate the rotor's magnetic field, eliminating the need for external excitation. Like EESGs, PMSGs can be deployed in gearbox-based configurations, where the gearbox optimises the rotational speed, or as direct-drive systems, which remove the gearbox entirely for improved reliability and lower maintenance requirements. Direct-drive PMSGs are particularly well-suited for offshore installations due to their simplified design and high reliability. However, both configurations heavily depend on rare earth materials, such as neodymium and dysprosium, raising concerns about supply chain vulnerabilities.

- **High-Temperature Superconductors (HTS)** represent a cutting-edge development in wind turbine technology. By using superconducting materials to reduce electrical resistance, these generators can achieve greater efficiency and reduce the need for rare earth materials. However, they are still in the experimental phase and are not yet widely deployed.

The selection of generator type depends on several factors, including the turbine's location (onshore vs. offshore), expected wind conditions, and economic considerations. Each generator technology has strengths and limitations, making it critical to match the generator design to the specific requirements of the wind farm.

Throughout the report, the turbine types will be indicated with their acronym integrated with a specification about the relevant gearbox or direct-drive configuration, e.g., GB-DFIG or DD-EESG. Both SCIG turbines use a gearbox generator, which can make the acronym GB-SCIG somewhat ambiguous. However, since only the version with a full converter is still in use in the market, we will refer to it as

GB-SCIG. The earlier version, which lacks a full converter, will be identified with the suffix 'NC' (for 'no converter'), resulting in GB-SCIG_NC.

1.4 Rare-earth permanent magnets and their role in technology

1.4.1 How magnets work and the role of rare earths

Magnets are materials capable of producing a magnetic field, a force that attracts or repels certain objects, particularly ferromagnetic materials like iron, nickel, and cobalt. This magnetic behaviour arises from the alignment of magnetic domains within the material where the magnetic moments of atoms are naturally aligned. In magnets, these domains remain aligned even after an external magnetic field is removed, which is the defining property of permanent magnets.

Permanent magnets are invaluable in modern technology because they provide consistent magnetic fields without requiring continuous electrical input. This characteristic makes them essential in numerous applications, including electric motors, generators, and consumer electronics. Among permanent magnets, those incorporating Rare-Earth Elements (REEs) are particularly significant due to their exceptional strength and efficiency (Croat and Ormerod, 2022).

REEs such as neodymium (Nd), dysprosium (Dy), praseodymium (Pr), and terbium (Tb) enhance the magnetic properties of materials by contributing to a high intrinsic coercivity (resistance to demagnetisation) and magnetic energy density. These properties allow for the creation of compact and lightweight magnets with strong magnetic fields, making them indispensable in applications where size and weight constraints are critical. For example, the ability to generate powerful magnetic fields with small, lightweight magnets is a key enabler of efficient motors in wind turbines and electric vehicles.

Rare earth magnets are primarily alloys of neodymium, iron, and boron (NdFeB) or samarium and cobalt (SmCo). Among these, NdFeB magnets dominate due to their unparalleled performance-to-weight ratio and cost-efficiency compared to SmCo magnets.

In 2023, 29% of global rare earth demand by weight was used in magnet applications (Howley, 2024).

1.4.2 Types of magnet and the dominance of NdFeB

Magnets are categorised into different types based on their material composition and magnetic properties. Among these, **ferrite, samarium-cobalt (SmCo), and neodymium-iron-boron (NdFeB)** magnets stand out for their unique applications and characteristics. Each type has advantages and limitations, but **NdFeB magnets dominate modern technological applications** due to their unmatched strength and efficiency.

- **Ferrite magnets**, also known as ceramic magnets, are composed primarily of iron oxide and barium or strontium carbonate. They are **cost-effective, corrosion-resistant**, and widely used in low-performance applications such as refrigerator magnets, loudspeakers, and small motors. However, ferrite magnets are **relatively weak** compared to other types, making them unsuitable for high-performance applications where compactness and efficiency are critical.

- **Samarium-Cobalt (SmCo) magnets** were among the first widely used rare earth magnets. They offer **exceptional thermal stability**, with the ability to function in temperatures exceeding 300 °C, making them ideal for **aerospace and defence applications**. Also, SmCo magnets are highly resistant to corrosion and demagnetisation. Despite these benefits, they are significantly **more expensive than NdFeB magnets**, due to the high cost of samarium and cobalt. This limits their usage primarily to specialised applications where performance outweighs cost considerations.

- **Neodymium-Iron-Boron (NdFeB) magnets are the strongest permanent magnets available today**, offering a high energy density and excellent performance-to-weight ratio. They are the preferred choice for industries that require compact and powerful magnets, such as **wind turbines, electric vehicles, consumer electronics, robotics and medical technologies**. The incorporation of **rare earth elements** enhances their intrinsic coercivity, making them resistant to demagnetisation under high temperatures. NdFeB magnets can be configured as either **gearbox-based systems** or **direct-drive systems** in applications such as wind turbines. **Direct-drive turbines** benefit greatly from NdFeB magnets because they eliminate the need for a gearbox, reducing mechanical complexity and improving reliability. While SmCo magnets excel in thermal stability and ferrites offer cost advantages, NdFeB magnets strike a balance between cost, strength, and scalability, making them the backbone of modern magnetic technologies.
- In addition to ferrite, SmCo, and NdFeB magnets, other types such as **AlNiCo magnets and hybrid materials** are used in niche applications. AlNiCo magnets, made from aluminium, nickel, and cobalt, offer good thermal stability but are weaker than NdFeB and SmCo magnets. Emerging materials and designs, such as **composite or bonded magnets**, are being developed to address supply chain vulnerabilities by reducing dependence on rare earths while maintaining performance.

2 Supply chain mapping and risk analysis

The supply chain for wind turbines is a multifaceted network involving numerous stakeholders, complex logistics, and an extensive array of raw materials. In this analysis, we consider five steps in the wind turbine supply chain:[3]

- Raw materials
- Processed materials
- Components
- Assemblies
- Super-assembly

Within each step, the elements listed in Table 2, identified in Carrara et al. (2023), are used as a basis for this analysis.[4]

Table 2. Elements considered in the wind turbine supply chain.

Stage of the supply chain	Elements
Raw materials	Aggregates, aluminium, boron, chromium, copper, dysprosium, iron ore, lead, manganese, molybdenum, neodymium, nickel, niobium, praseodymium, silica, silicon metal, terbium, zinc
Processed materials	Balsa wood, carbon fibres, cement, copper semis, epoxide resins, glass fibres, NdFeB permanent magnet alloys, Polyurehtane, PE (polyethylene), PET, (Polyethylene terephthalate), PS (Polystyrene), steel (crude) *Not assessed: cast iron, steel (high-alloyed)*
Components	Bearings, blades, gearbox, nacelle casing, NdFeB permanent magnets, shafts, tower (concrete), tower (steel) *Not assessed: brushes, cables, foundation, monopiles (offshore wind), spinner (wind turbine), transformer (wind plant), transformer (wind turbine)*
Assemblies	Power generator
Super-assembly	Wind turbine

Source: Carrara et al. (2023). "Not assessed" indicates that the element was tracked, but the relevant Supply Risk (see Section 2.1) could not be assessed, usually due to the lack of data.

This chapter examines the intricacies of the wind turbine supply chain. Section 2.1 provides a **summary of the supply risk analysis** as carried out in Carrara et al. (2023), identifying vulnerabilities across the supply chain and highlighting the potential impacts of disruptions. Section 2.2 focuses on the **raw materials** essential for wind turbine production, providing an overview on all materials adopted and then offering quantitative details on the main strategic raw

[3] The detailed definintions of these steps are reported in Carrara et al. (2023).

[4] In line with Carrara et al. (2023), the word "element" identifies a generic entry in one of the supply chain steps, e.g. a raw material or a component depending on the step under consideration.

materials. Section 2.3 takes a detailed look at **NdFeB magnet supply chains**, a cornerstone of modern wind turbine efficiency, dissecting the stages from raw materials to final integration. Finally, Section 2.4 examines the **companies operating along the wind turbine supply chain**, with a focus on the REE/permanent magnet supply chain, showcasing the key players shaping this critical industry.

2.1 Supply risk analysis

On a three-year basis since 2011, the European Commission has carried out an exercise to produce a list of **critical raw materials (CRMs)**. These raw materials are characterised by high risk of supply disruption and high importance for the EU economy, assessed through two quantitative parameters, Supply Risk and Economic Importance, calculated as described in EC (2017). The last edition of the Criticality Assessment (EC, 2023) identified 34 CRMs. Further to that, the Critical Raw Materials Act (EP&C, 2024) introduced the concept of the **strategic raw material (SRM)**. SRMs are a subset of CRMs that are fundamental for technologies relevant for the dual (green and digital) transition as well as for aerospace and defence technologies, coupled with a projected future demand growth possibly outstripping supply. The Critical Raw Materials Act identified 17 SRMs.

Stemming from the criticality exercise, Carrara et al. (2023) developed a **supply risk analysis** for all the elements of the wind turbine supply chain listed in Table 2 (as well as for 14 other technologies strategic to the EU economy). For the raw materials, the Supply Risk values were directly sourced from the 2023 Criticality Assessment (EC, 2023). For the elements downstream of the raw materials, Supply Risk values were calculated ex-novo in Carrara et al. (2023). The Supply Risk is a composite index that takes into account various factors, including the level of concentration of supply, the political stability of the countries involved, and the potential for substitutability. Annex 1, largely based on Carrara et al. (2023), reports the methodological details for its calculation.

The **Supply Risk** can theoretically range from 0 to 20, although the highest value found in Carrara et al. (2023) is around 6. A raw material, as well as any generic element along the supply chain, is considered to be critical if its Supply Risk is higher than 1. An exception holds for copper and nickel, which have been included in the list of SRMs although their Supply Risk is lower than 1, given their fundamental importance to the EU economy. Figure 1 summarises the results of this supply risk analysis. Critical elements are indicated in red. In the raw material stage, the SRMs are further highlighted in dark red to distinguish them from the non-strategic CRMs.

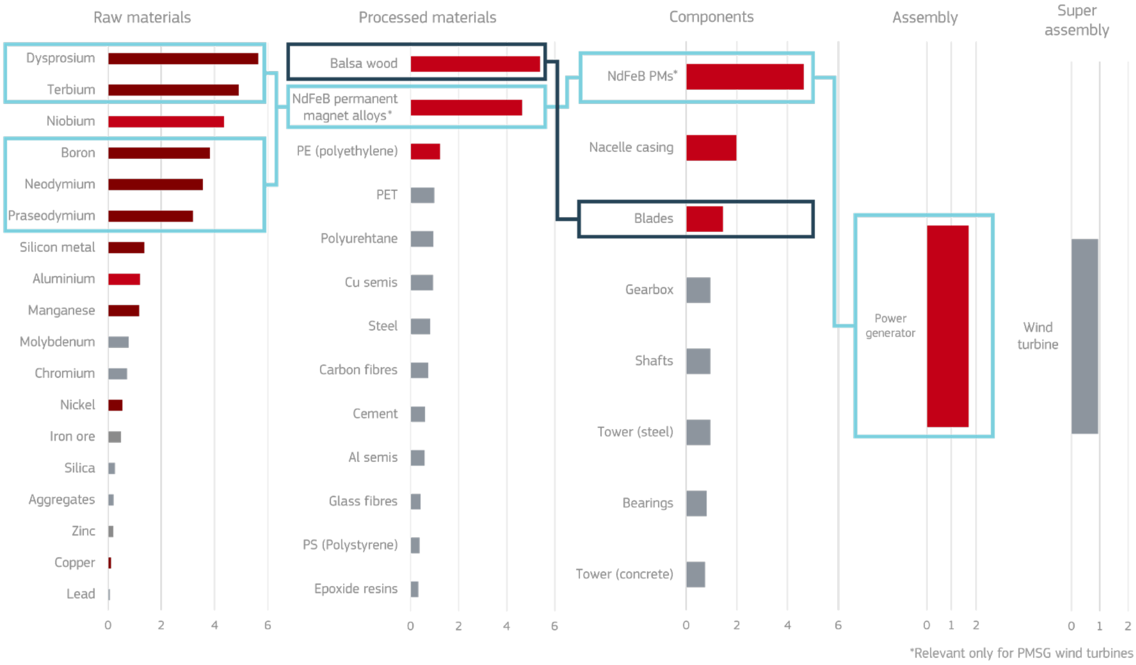
Figure 1 clearly highlights two critical supply chains characterised by high supply risk. The first critical supply chain, highlighted in light blue in Figure 1, comprises the elements needed for the **power generation in wind turbines featuring rare earth-based permanent magnets.** The raw materials are rare earths (dysprosium, terbium, neodymium, and praseodymium) and boron;[5] the processed materials are NdFeB permanent magnet alloys; the components are NdFeB permanent magnets; and the assemblies are power generators.[6] The second critical supply chain, highlighted in

[5] Iron ore is also needed for magnets, but it is not a critical raw material, so it is not included in this list.

[6] The analysis for power generators comprises all types of generators, so it is not restricted to machines equipped with rare-earth permanent magnets.

dark blue in Figure 1, involves **balsa wood among processed materials**[7] **and blades among components**.

Figure 1. Detailed Supply Risk of all elements in the wind turbine supply chain, with a focus on the REE/magnet (light blue) and balsa wood/blade (dark blue) supply chains



Source: adapted from Carrara et al. (2023).

The **REE market** is dominated by China across the whole permanent magnet value chain, from raw materials to magnet production, as shown in Table 3.[8]

Table 3. Country share in the global market along the REE PM supply chain.

Region	Mining	Oxides	Metals and Alloys	NdFeB Alloys and Powders	NdFeB Magnets
China	64%	92%	92%	91%	89%
US	6%	<1%	0%	<1%	<1%
Europe	0%	<1%	<1%	<1%	<1%
Australia	7%	0%	0%	0%	0%
Japan	0%	0%	8%	7%	7%
Other	23%	8%	1%	<1%	1%

Source: Adamas Intelligence (2024).

[7] Balsa wood does not feature in the list of raw materials analysied in the 2023 Criticality Assessment. Therefore, it has been considered a processed material in Carrara et al. (2023).

[8] These data are more recent than those used to calculate the Supply Risk in Carrara et al. (2023) and reported in Figure 1, but the difference is minimal. In some columns, figures do not sum up to 100% due to rounding.

However, a closer look at the numbers highlights that whereas China's share in the global market is close to, or higher than, 90% in all steps from oxides to magnets, it is significantly lower in the mining stage (64%). This picture reflects a conscious process that **China** has pursued in the past 15 years, gradually easing its monopolistic control over the early stages of the REE supply chain while strengthening its dominance in the later stages. In 2010, China accounted for 97% of global REE mining and concentration and 75% of magnet manufacturing (Eggert et al., 2016). This shift can be justified with several considerations: the high environmental impact of mining, suggesting outsourcing if possible (China has outsourced some of its REE production to Myanmar); the higher economic value added ensured by the downstream stages of the supply chain; and the willingness to strengthen its competitive and geopolitical positioning in a strategic value chain (Carrara et al., 2023).

Table 3 does not show the global shares for power generators. Although to a lesser extent, China controls the majority of this market (52%), which results in a Supply Risk value higher than 1 for this step as well, according to the methodology adopted in Carrara et al. (2023).

Balsa wood plays a key role in **wind turbine blades** due to its lightweight and strength. However, its production is almost exclusively located in **Ecuador**, which accounts for more than 90% of global supply, thus resulting in very high supply risk. Also, the surge in global wind energy deployment has led to a significant strain on the balsa wood supply chain, with Ecuador facing challenges of over-logging, environmental degradation, and soaring prices driven by demand. These issues have raised concerns about the sustainability of balsa wood as a resource for wind turbine manufacturing. Countries are exploring countermeasures to reduce their near-total reliance on external balsa wood supplies. For instance, China is working on establishing domestic balsa production, with the goal of meeting 10% of its demand by 2024 (BNEF, 2022). This would be key to sustaining the country's blade production that currently accounts for more than 50% of the global supply (while the EU share is 13%), thus explaining the high supply risk found for this component as well (Carrara et al., 2023).

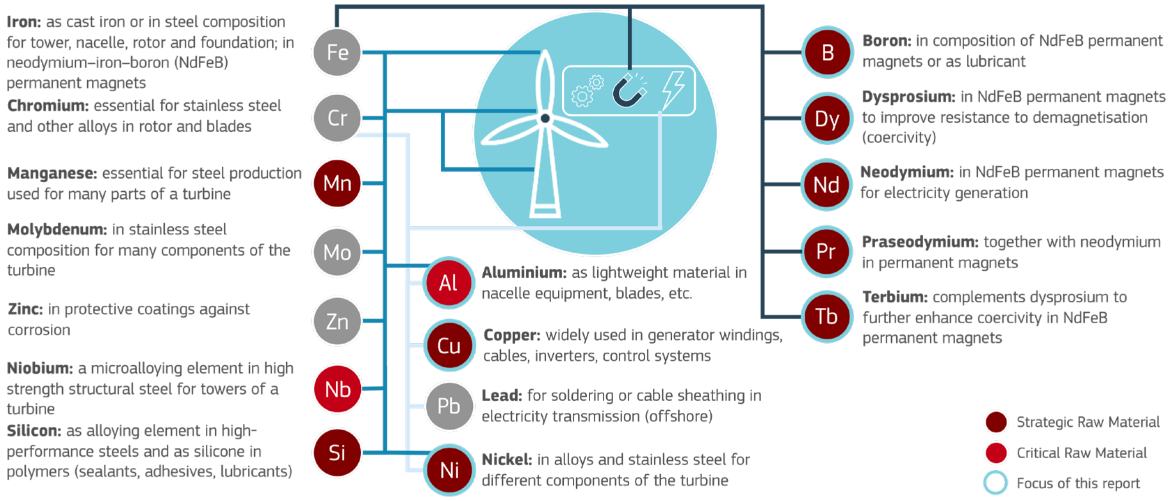
2.2 Raw materials in wind turbines

Figure 2 provides an overview of the main raw materials used in wind turbines, along with a short description of their usage, highlighting the critical raw materials (light red) and the strategic raw materials (dark red).

In addition to the raw materials listed in Figure 2, other processed materials are fundamental for wind turbine manufacturing, and thus will be considered in the material demand scenarios described in Section 3. These materials are concrete, steel, glass/carbon composites, plastics, in addition to the abovementioned balsa wood.

Concrete is predominantly used in the turbine's foundation, providing the structural stability needed to anchor the turbine securely, particularly in varying geological conditions. **Steel** plays a critical role in the towers, nacelles, and other components, offering the strength and resilience necessary to withstand environmental stresses. **Glass and carbon composites** are integral to the blades, enabling lightweight designs that enhance aerodynamics and turbine efficiency. **Plastics** are utilised in various parts, including the nacelle covers and cable insulations, due to their versatility, weather resistance, and lightweight properties.

Figure 2. Selection of raw materials used in wind turbines and their function



Source: adapted from Carrara et al. (2023).

The following sub-sections provide a detailed description of the main strategic raw materials adopted in wind turbines: rare-earth elements – distinguishing between **light rare-earth elements** (**LREE**, i.e., **neodymium** and **praseodymium**) and **heavy rare-earth elements** (**HREE**, i.e., **dysprosium** and **terbium**) – **boron, aluminium, copper,** and **nickel**. A set of infographics (from Figure 3 to Figure 10) summarise the main parameters relevant for supply risk assessment of the raw material based on data sourced from the European Commission's Raw Materials Information System (RMIS, 2024), which in turn builds on the Study on the Critical Raw Materials for the EU (EC, 2023).

These parameters are:[9]

- Country shares of the global reserves
- Share of the main uses
- Country production share in the global market (global supply)
- Country share for the EU supply (EU sourcing)
- EU reliance on imports for its supply (import reliance)
- Demand coverage with secondary sources (end-of-life recycling input rate)
- Material substitutability (substitution index; if it is equal to 1, no substitution is viable)
- Supply Risk

The Criticality Assessment identifies two stages in the raw material analysis: **extraction** and **processing**. The extraction stage involves obtaining raw materials from the environment, while the processing stage encompasses the operations required to refine these materials into purified

[9] Annex 1 reports a more detailed description of the listed parameters. The data presented in the infographics pertain to raw materials in general and are not limited to their use in wind turbine manufacturing. Due to data availability, some of this information may be missing for some raw materials.

substances for the production of semi-finished and finished products. If available, the parameters described above are provided for both stages. In the Criticality Assessment, the official values for the single raw material are those associated to the more critical stage between the two.

2.2.1 Light rare-earth elements: neodymium and praseodymium

Neodymium (Figure 3) and praseodymium (Figure 4) are essential LREEs mainly used to produce **permanent magnets**, among which those used in PMSG wind turbines. **Neodymium provides the primary magnetic strength**, making it indispensable in NdFeB magnets. **Praseodymium**, often used in combination with neodymium, **enhances the magnets' performance and thermal stability**, ensuring they can operate efficiently under varying environmental conditions.

However, the EU completely relies on third countries for the supply of these raw materials, especially China, Japan, and the US. In particular, **China** dominates their global production and is the main EU supplier, determining **vulnerability in the relevant supply chains**. Also, recycling and recovery efforts for these materials are still in their infancy, further exacerbating supply risks. As demand for wind energy grows, securing sustainable sourcing and developing recycling technologies for these elements will be crucial. These challenges will be discussed further in the next chapters of this report.

2.2.2 Heavy rare-earth elements: dysprosium and terbium

Dysprosium (Figure 5) and terbium (Figure 6) are HREEs primarily used to enhance the performance of NdFeB magnets. **Dysprosium increases the magnets' resistance to demagnetisation at high temperatures**, a vital property for ensuring the longevity and efficiency of turbines operating under variable and extreme weather conditions (which is the case especially for offshore turbines). **Terbium**, though used in smaller quantities, provides similar enhancements, thus it **complements dysprosium** in enabling further improvements in magnetic performance.

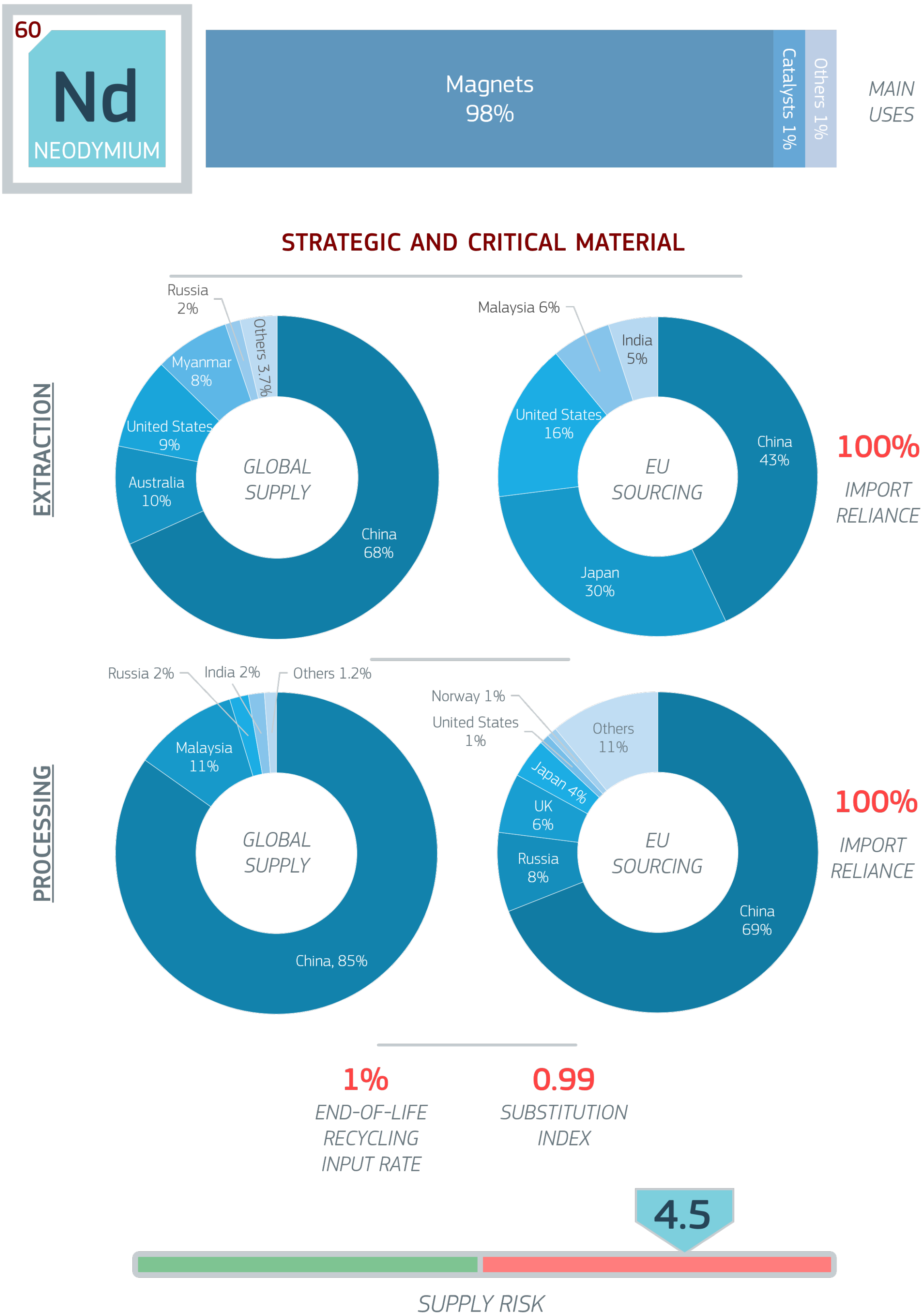
Despite their advantages, dysprosium and terbium encounter major supply constraints. Their production, even more so than LREEs, is highly concentrated in **China**, with minimal diversification in extraction and virtually no alternative processing capacity globally. Furthermore, HREE extraction and processing involve environmentally intensive processes, leading to **sustainability concerns**. Efforts to minimise reliance on these materials, such as research into alternative magnet technologies and enhanced recycling methods, are ongoing (see Chapter 4 and Chapter 5).

2.2.3 Boron

Boron (Figure 7) plays a less visible, yet important role in the **manufacturing of NdFeB permanent magnets**. Acting as an alloying element, boron improves the **structural integrity and magnetic properties** of these magnets. Also, by enhancing the magnets' strength and resistance to corrosion, boron contributes significantly to the long-term performance and reliability of turbines. It is also used as a lubricant. Beyond magnets, boron is used in various other applications, mainly glass and ceramics, improving **thermal and chemical stability**, as well as in metallurgy, agriculture (fertilisers), and nuclear shielding due to its unique chemical properties.

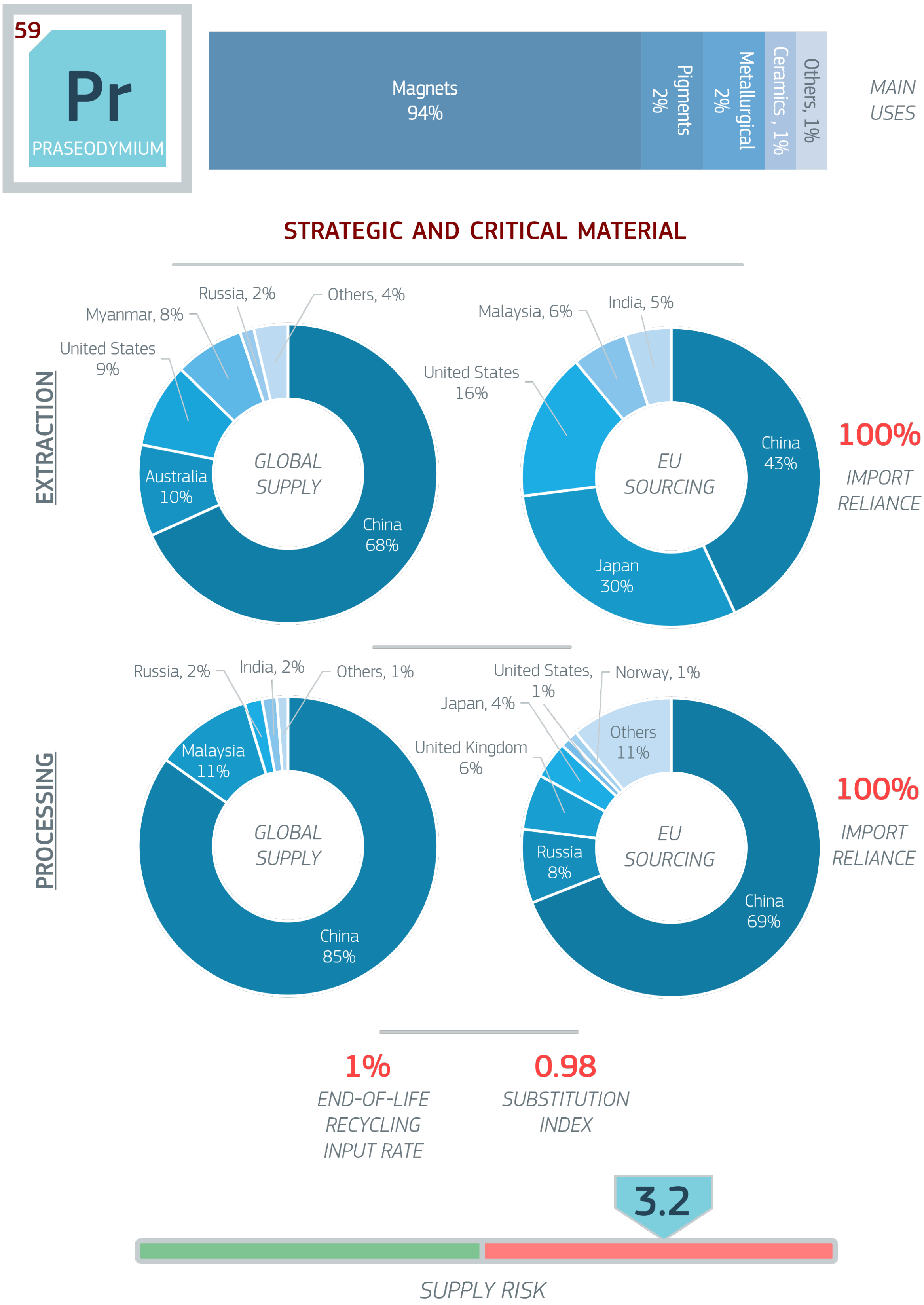
Boron's availability is relatively less constrained compared to rare earths, with major deposits located in countries like Türkiye and the US. While the EU relies entirely on Türkiye for its supply of borates – the primary source of boron oxides – it has some domestic processing capacity, notably in Germany. This reduces import reliance for the processing stage to 70%, partially mitigating supply risks.

Figure 3. Raw material factsheet: neodymium



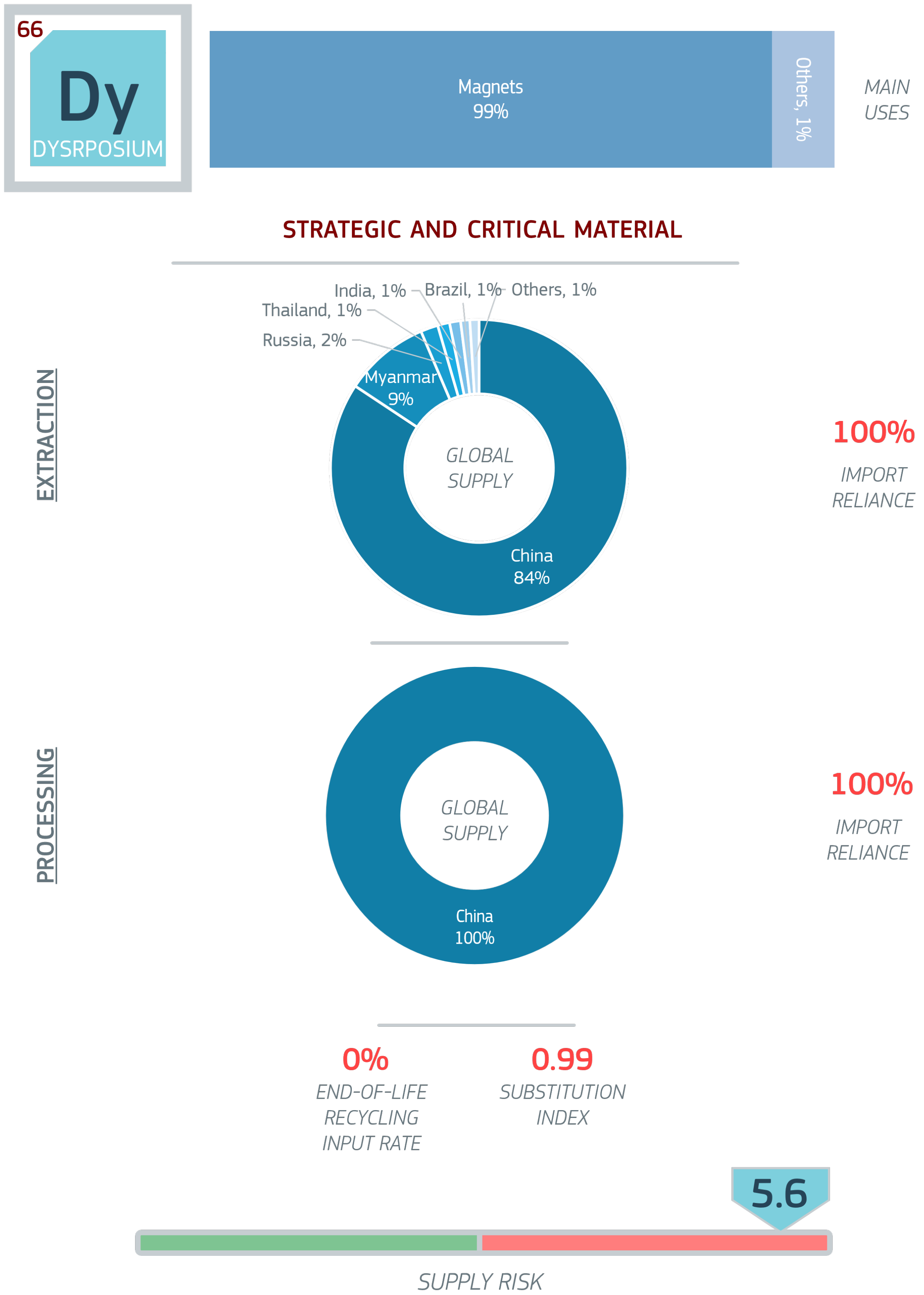
Source: own elaboration based on EC (2023) and RMIS (2024).

Figure 4. Raw material factsheet: praseodymium



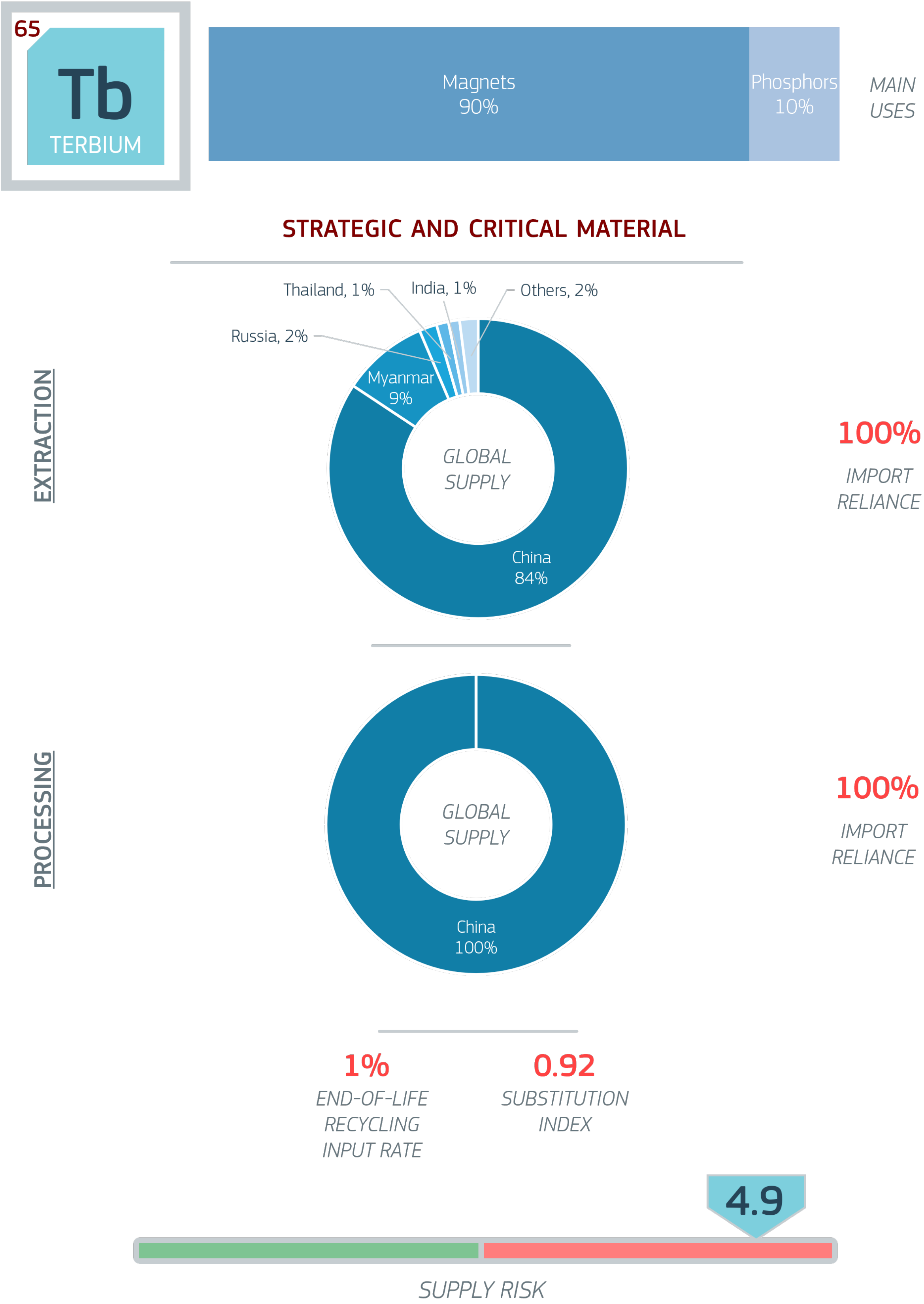
Source: own elaboration based on EC (2023) and RMIS (2024).

Figure 5. Raw material factsheet: dysprosium



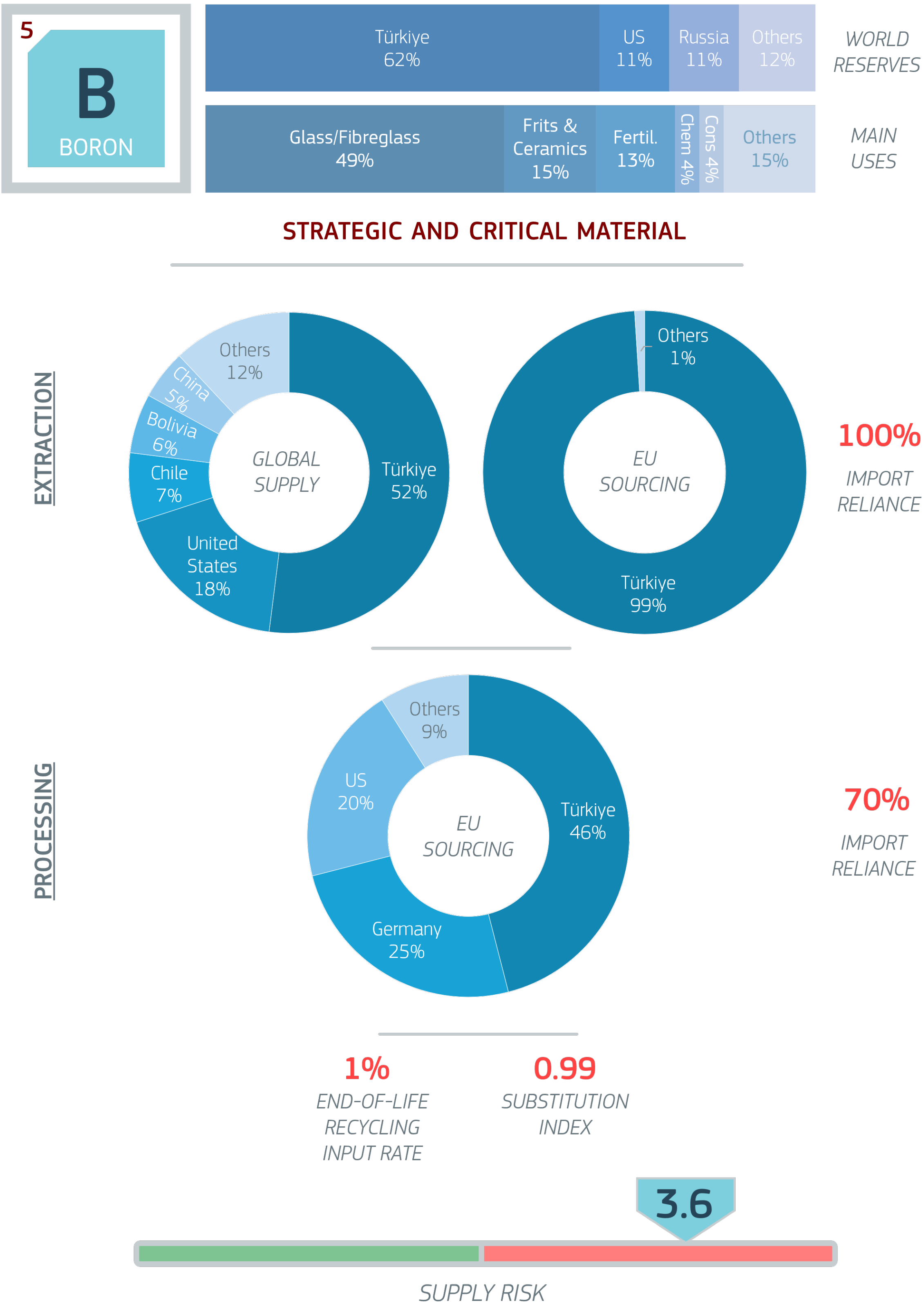
Source: own elaboration based on EC (2023) and RMIS (2024).

Figure 6. Raw material factsheet: terbium



Source: own elaboration based on EC (2023) and RMIS (2024).

Figure 7. Raw material factsheet: boron



Source: Own elaboration based on EC (2023) and RMIS (2024).

2.2.4 Aluminium

Aluminium (Figure 8) is a key material in **wind turbine construction**, valued for its lightweight and corrosion-resistant properties. It is commonly used in the **nacelle housing, blades, and electrical components**, including cables and connectors. Its low density allows for lighter turbine components, reducing transportation and installation costs, particularly for offshore turbines. Beyond wind energy, it is widely used in **transport, construction, and packaging**, thanks to its versatility and durability.

Although aluminium is **recyclable**, primary production remains **energy-intensive** and dependent on **bauxite** mining. The EU heavily relies on third countries – especially **Guinea** – for its supply of bauxite, the key raw material for aluminium production. However, it has some **domestic processing capacity**, spread across multiple countries, which reduces its import reliance for this stage of the supply chain. Ensuring a stable and sustainable supply, alongside enhanced recycling and resource efficiency, is crucial for securing aluminium availability in the wind energy sector.

2.2.5 Copper

Copper (Figure 9) is indispensable in wind turbines due to its exceptional **electrical conductivity and durability**. It is primarily used in the **wiring, generators, transformers, and grounding systems**, ensuring efficient energy transmission and minimal losses. Its role is particularly critical in offshore wind farms, where long-distance energy transmission demands high-performance materials. Beyond wind energy, copper is widely used in **electronics, construction, and transportation**, further driving global demand.

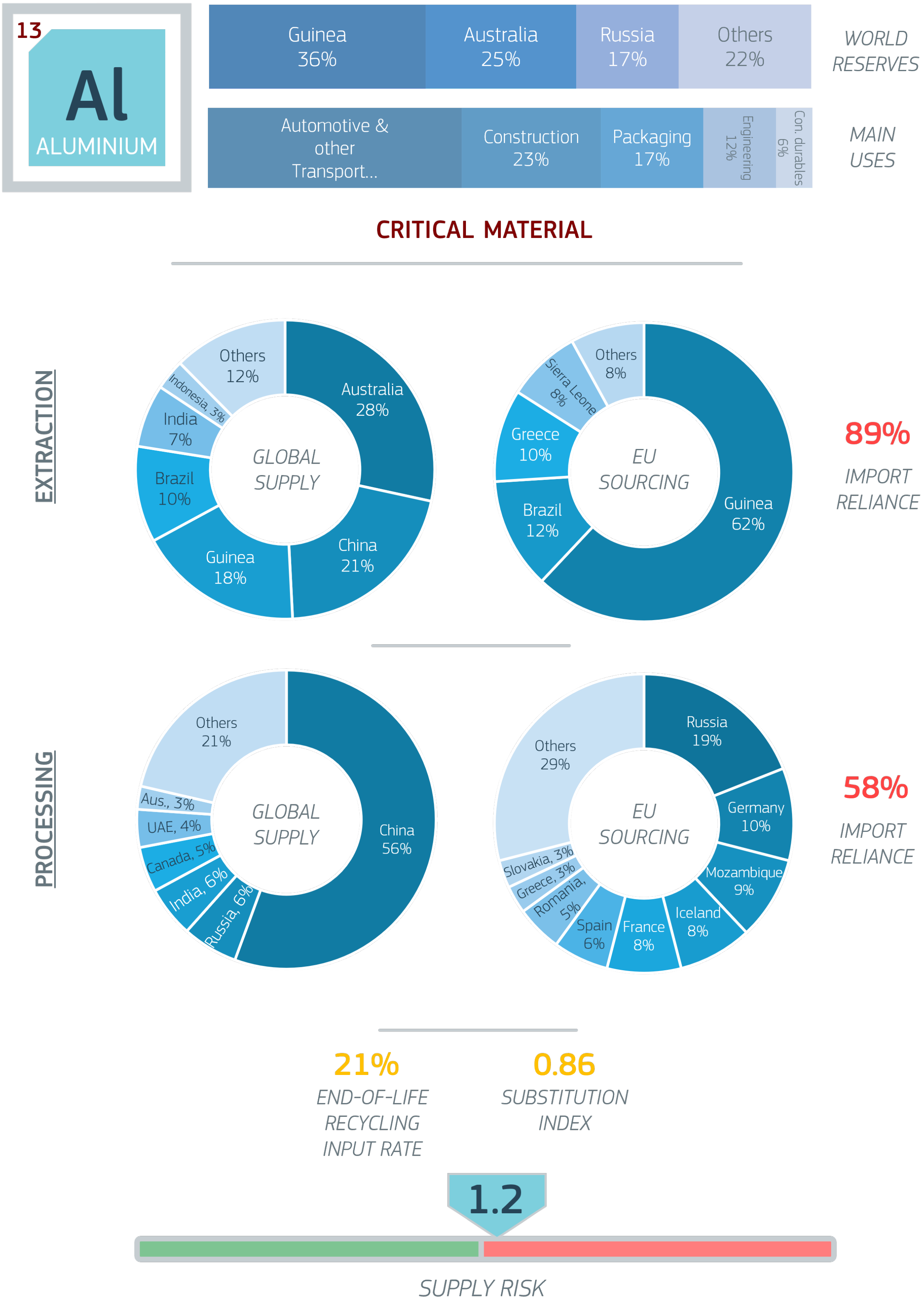
A key advantage of copper is its indefinite **recyclability** without any loss of properties, making it a cornerstone of the **circular economy**. Although not among the main players in global supply, the EU does have some **extraction and processing capacity**, particularly in **Poland**, reducing its reliance on imports. However, the EU still partly depends on **South American countries for copper ore**, requiring **stable trade relations** to secure long-term supply. While the Supply Risk for copper is very low, its capital importance for the EU industry makes it a **strategic material**, which makes it crucial to ensure efficient recycling, sustainable sourcing, and continued investment in processing capacity.

2.2.6 Nickel

Nickel (Figure 10) is a crucial material in wind turbines, primarily used as an **alloying element in the production of stainless steel and other corrosion-resistant materials**. These nickel-based alloys are essential **shafts, fasteners, and certain electrical systems**, where strength and resistance to wear and corrosion are critical. Offshore turbines particularly benefit from nickel's corrosion resistance, ensuring long-term performance in harsh marine environments. Apart from wind energy, nickel is widely used in **batteries, aerospace, and electronic systems**.

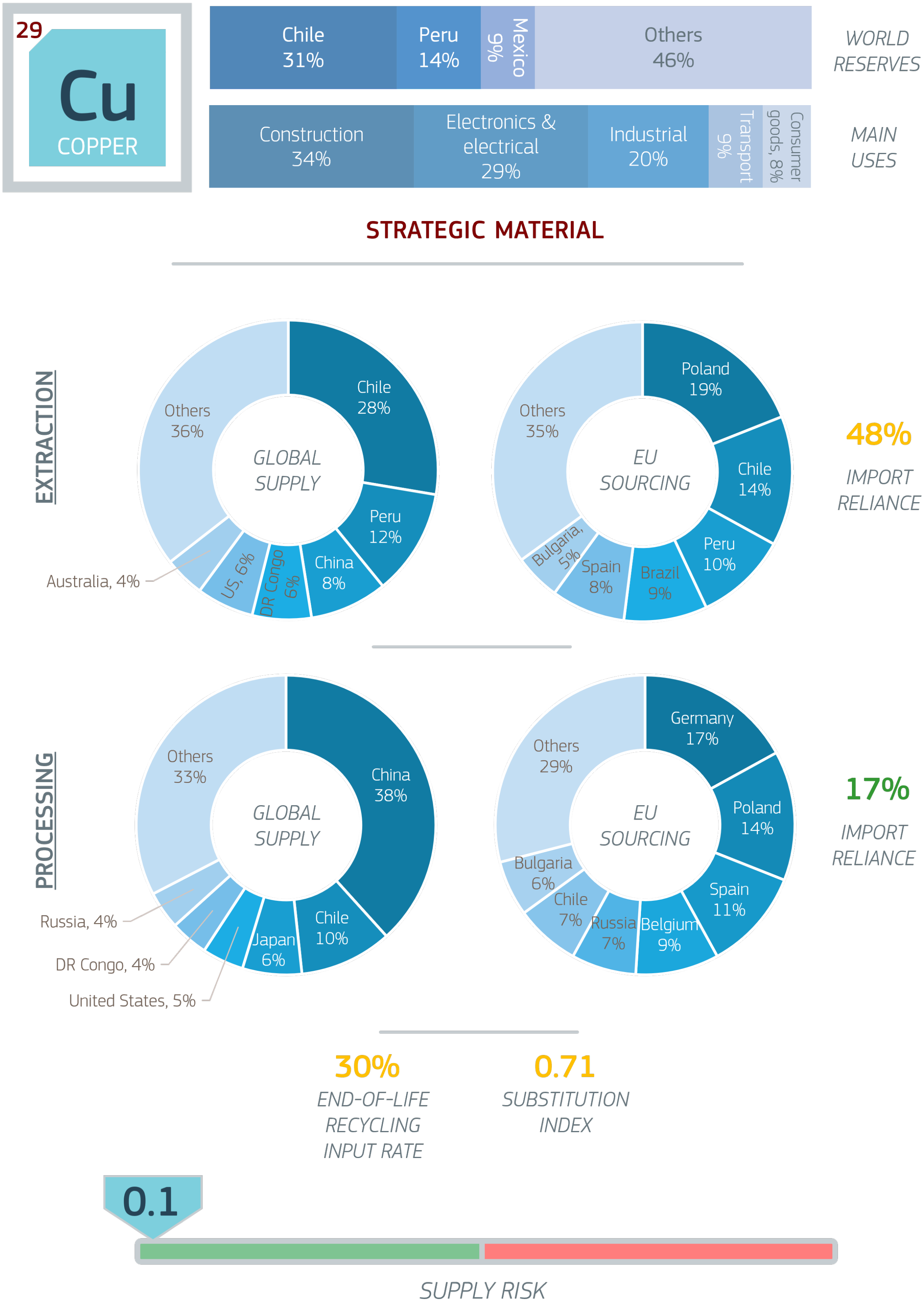
While nickel is widely available globally, with major reserves in Indonesia, the Philippines, and Russia, its extraction and refining are **energy-intensive** and pose **environmental challenges**. The EU has some **domestic capacity** both for extraction and processing, notably in **Finland** and **Greece**, which partially reduces its import reliance. However, this parameter remains high in the processing stage, although Russia's share has been decreasing since 2022 (Eurostat, 2025), which was not yet captured in EC (2023) and RMIS (2024). Similar to copper, nickel's key role in the EU economy makes it a **strategic material** despite its low Supply Risk. Therefore, it is crucial for demand and risk mitigation to enhance domestic processing capacity, secure sustainable sourcing, and strengthen recycling.

Figure 8. Raw material factsheet: aluminium



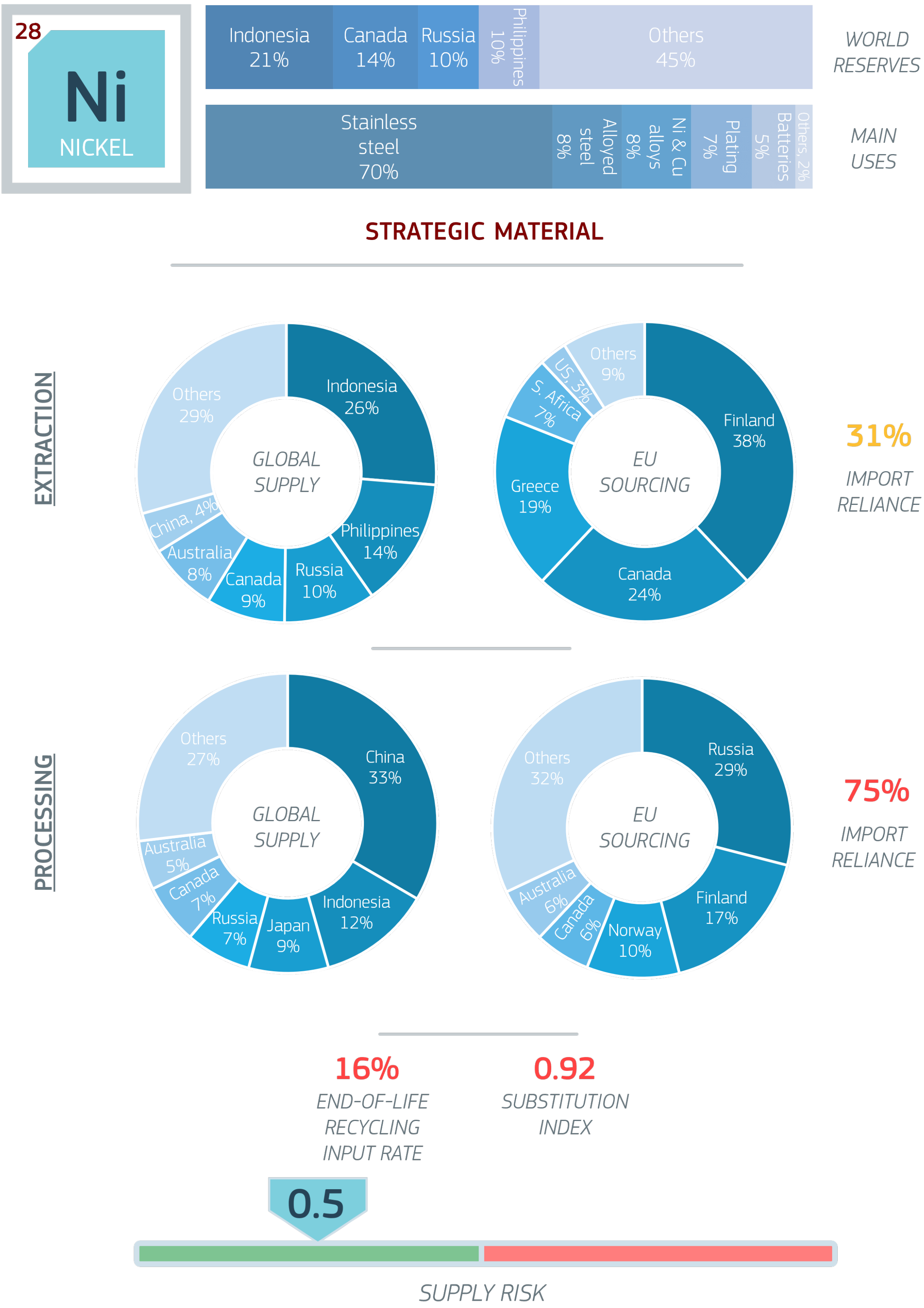
Source: own elaboration based on EC (2023) and RMIS (2024).

Figure 9. Raw material factsheet: copper



Source: own elaboration based on EC (2023) and RMIS (2024).

Figure 10. Raw material factsheet: nickel

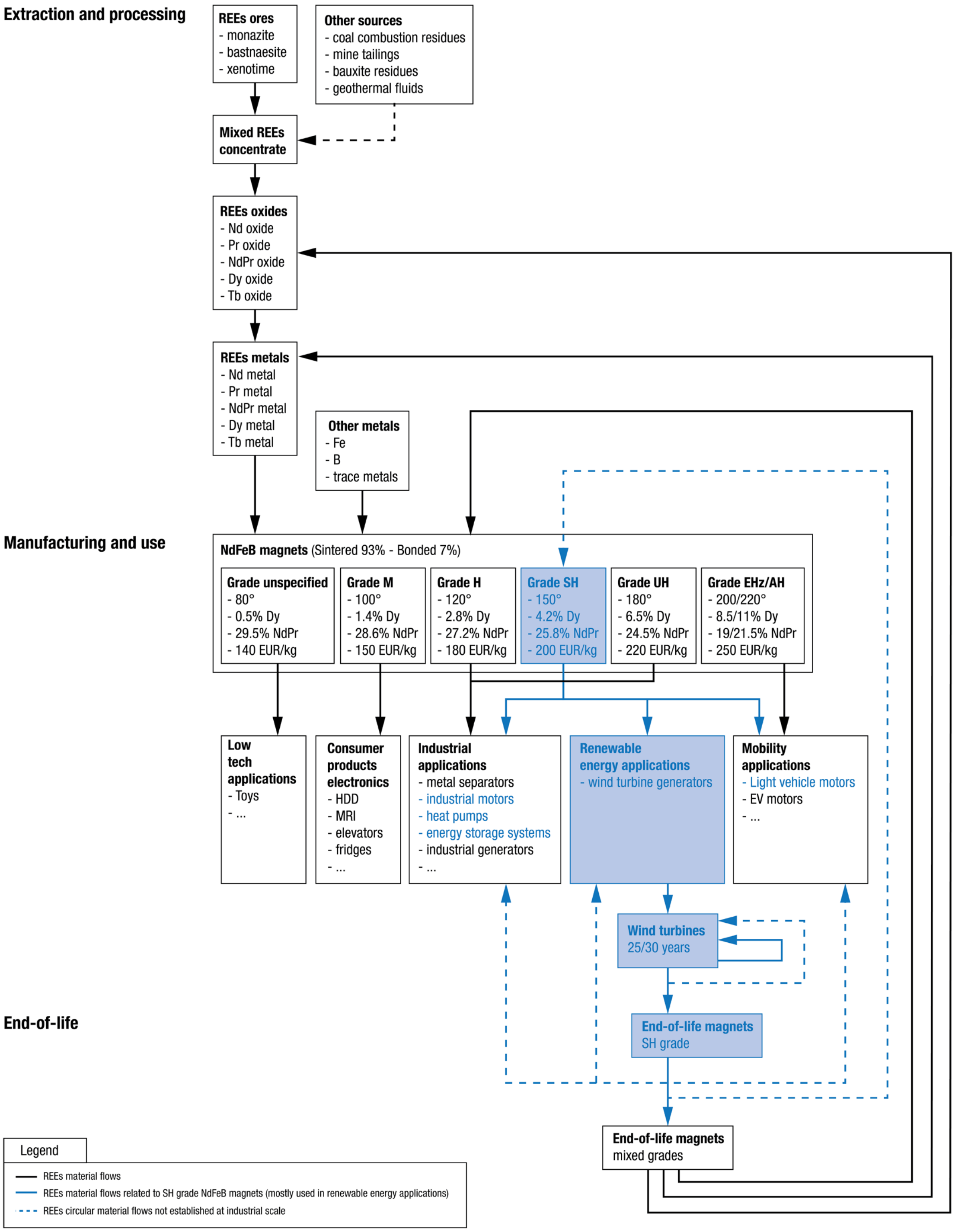


Source: own elaboration based on EC (2023) and RMIS (2024).

2.3 NdFeB magnet supply chain structure

This section focuses on the structure of the NdFeB magnet supply chain. The supply chain is schematised in Figure 11.

Figure 11. Diagram of the supply chain of NdFeB permanent magnets with a focus on wind energy applications



Source: JRC analysis.

2.3.1 Extraction and processing

Rare earth elements are essential for producing NdFeB magnets for various applications, including wind energy. They mainly include neodymium (Nd), but also dysprosium (Dy), praseodymium (Pr), and terbium (Tb), all of which are primarily extracted from rare earth ores, including bastnaesite, monazite, and xenotime.

The **mining** of rare earth elements is concentrated in countries with significant reserves, mainly China, followed by the USA and a limited number of other countries (European Raw Materials Alliance, 2021; United States Department of Energy, 2022). The extraction of ores takes place in open-pit or underground mines. Once extracted, the ores undergo crushing and grinding, followed by chemical processing to separate the different valuable rare earth oxides from other materials and from each other. The **separation** of rare earth oxides involves a series of solvent extraction steps, which is **highly energy-intensive and generates significant amounts of waste**, including radioactive thorium and uranium, as well as water treatment challenges (United States Department of Energy, 2022). The result is individual rare earth oxides, which must then be further processed into metals or alloys. Metal refining typically involves electrolysis and strip casting at 1400 °C, which are costly and energy intensive processes (Jensen, 2018; Sprecher et al., 2014). Globally, over 90% of all these processes take place in China (European Raw Materials Alliance, 2021).

2.3.2 Manufacturing and use

NdFeB magnets are produced primarily through a **high-temperature sintering process** involving rare earth metal powders alloyed with iron (Fe) and boron (B). This process, conducted at approximately 1000 °C, is highly energy-intensive (United States Department of Energy, 2022). While permanent magnets can also be manufactured via bonding, this method constitutes only 7% of the total market share (United States Department of Energy, 2022). **Various grades of NdFeB magnets** are available, differentiated by the mix of rare earth elements. In certain applications, Dy, Pr, or Tb are added to Nd for improving resistance to demagnetisation at elevated temperatures. Coating with nickel (Ni) and copper (Cu) is applied to prevent corrosion.

The specific magnet grades, with their applications and prices, are described below. Prices are largely driven by composition (particularly influenced by the levels of Dy and Pr), by global demand shifts (e.g., in the renewable energy and electric vehicle sectors), and by geopolitical factors affecting the rare earth supply chain (Alves Dias et al., 2020; United States Department of Energy, 2022). This overview is based on United States Department of Energy, 2022, which considers a reference REE content in NdFeB magnets of 30%. However, in general the REE content can range between 28% and 35%, with more frequent values in the range 30-33% (Alb Materials; Alves Dias et al., 2020; Howley, 2024; Kumari et al., 2018; Lacal-Arántegui, 2015; Smith and Eggert, 2016).

- **Unspecified Grade** – Operating up to 80 °C, with 0.5% Dy and 29.5% Nd+Pr, this grade is primarily used in low-tech applications, such as **toys**. It typically falls at the lower end of the price spectrum due to its limited high-temperature resistance and straightforward applications, often around EUR 140 per kilogram.
- **Grade M** – With an operating threshold up to 100 °C, containing 1.4% Dy and 28.6% Nd+Pr, this grade is widely applied in **consumer electronics, hard disk drives, MRI machines, elevators, and refrigerators**. Grade M constituted 29.4% of global rare earth demand in 2020, with forecasts indicating a drop to 10.6% by 2030 and 8.7% by 2050. Its typical price

is relatively moderate in the NdFeB magnet range, given its mid-level temperature tolerance and common use cases.

- **Grade H** – This grade operates up to 120 °C and includes 2.8% Dy and 27.2% Nd+Pr, making it suitable for more intensive industrial applications, such as **metal separators and industrial generators.** Grade H magnets are also generally priced on the lower to middle end, around EUR 150 to EUR 180 per kilogram, depending on market dynamics.

- **Grade SH** – Capable of withstanding temperatures up to 150 °C with 4.2% Dy and 25.8% Nd+Pr, Grade SH magnets are integral to industrial and renewable energy applications, including **heat pumps, energy storage systems, offshore wind turbines, and light vehicle electric motors**. Considering the focus of this report on wind turbines, the material flows related to SH grade permanent magnets are highlighted in blue in the supply chain diagram in Figure 11. This grade accounted for 14.2% of global rare earth demand in 2020, with projections increasing to 36.0% by 2030 and 36.3% by 2050. Prices for Grade SH are typically higher, reflecting its performance in high-demand sectors, often ranging from EUR 180 to EUR 220 per kilogram.

- **Grade UH** – This grade, with a high operational limit of 180 °C, contains 6.5% Dy and 24.5% Nd+Pr[10]. It employed in advanced industrial applications, particularly for **industrial motors**. Representing 30.2% of global rare earth demand in 2020, it is expected to decrease to 13.9% by 2030 and 11.4% by 2050. The price for Grade UH often exceeds EUR 220 per kilogram due to its suitability for high-temperature industrial use.

- **Grade AH** – Designed for extreme high-temperature performance up to 220 °C, Grade AH includes 8.5-11% Dy and 19-21.5% Nd+Pr and is extensively used in **electric vehicles**. This grade represented 6.1% of global demand in 2020, with demand expected to rise to 29.5% by 2030 and 35.3% by 2050. Grade AH magnets are the most expensive, reflecting the cost of high Dy content and advanced applications, often priced upwards of EUR 250 per kilogram due to their critical role in electric vehicles and other high-stress environments.

2.4 Companies along the wind turbine supply chain

This section provides an overview of manufacturing companies in the wind turbine supply chain in the EU, with a particular focus on rare earths and permanent magnets. At the end of this section, Figure 12 shows the main European countries with projects at various development stage along the different steps of the rare earth supply chain, including the final wind turbine manufacturers.

2.4.1 Raw materials

While **Europe has various rare earth deposits, none are currently mined** (Adamas Intelligence, 2024a). As discussed above, the highest global share of REE mining pertains to China. Since 2011, when the share was nearly 100%, it decreased to about 60% in the early 2020s while mining increased in the United States, Australia and Myanmar (Adamas Intelligence, 2024b; Alves Dias et al., 2020; Rizos et al., 2022). In recent years, China has also gained access to sources abroad, for example

[10] Although the sum should be 30%, United States Department of Energy (2022) reports these values adding up to 31%.

in California, Madagascar and Greenland (Gauß et al., 2021). The mining companies in China are state-owned, as are production and export (Alves Dias et al., 2020). In 2021, three of the six biggest mining companies in China merged into another state-owned company: China Minmetals Rare Earth Co, Chinalco Rare Earth & Metals Co and China Southern Rare Earth Group Co (Daly, 2021). The largest mines outside of China are **Mountain Pass in the US**, owned by MP Materials, and **Mount Weld in Australia**, owned by Lynas Rare Earths (Alves Dias et al., 2020).

Rare earth deposits with advanced exploration or mining development **in the EU** are located in **Sweden, Finland and Spain**. **Advanced exploration and mining development projects** include Norra Kärr and Kiruna in Sweden, Sokli in Finland, and Matamulas in Spain (Adamas Intelligence, 2024a; S&P Global, 2025). The discovery of the Pier Geijer deposit was announced in 2023. It is the largest rare earths deposit in Europe, located in the Kiruna iron ore mine in Sweden (LKAB, 2023). Other projects currently in the **early stages** include Olserum in Sweden as well as Korsnäs and Jokikangas in Finland (S&P Global, 2025). **Companies involved in the development of these mining projects** are LKAB (Per Geijer deposit) (LKAB, 2023), Leading Edge Materials (Norra Kärr deposit) (Leading Edge Materials, 2024), European Green Transition (Olserum deposit) (European Green Transition, 2023), the Finnish Materials Group (Sokli deposit) (Finnish Minerals Group, 2023), Prospech/Bambra (Korsnas and Jokikangas deposits) (Prospech, 2024) and Quantum Minería (Matamulas deposit) (Hendrich, 2022).

Additionally, there are projects developed in **countries associated with the EU** (in the European Economic Area or overseas territories): Kvanefjeld, Ivigtût, Tanbreez and Sarfartoq in **Greenland** are developed by Energy Transition Minerals (Energy Transition Minerals, 2023), Eclipse Metals (Eclipse Metals, 2024), Critical Metals Corp (Tanbreez, 2024) and Neo Performance Materials (Neo Performance Materials, 2023a), respectively. The Kvanefjeld project is the most advanced project and already in preproduction stage. However, the project is currently under litigation (S&P Global, 2025). In **Norway**, there is the Fen field, where Rare Earths Norway (Rare Earth Norway, 2022) and REE Minerals (REE Minerals, 2023) are developing projects (S&P Global, 2025).

The challenges associated with mining are thus not a lack of resources. They are rather related to the **lengthy, cost-intensive and complex process required to establish and operate a mine**. Before and during building the actual mine and infrastructure, lengthy permitting timelines and social opposition contribute to delays in project development. Additionally, there is still little permanent magnet production in Europe and thus demand for raw and processed materials in Europe is low.

2.4.2 Processed materials

When it comes to REE processing, the picture is much more polarised than the mining stage. **China** provides more than 90% of the global demand of processed REEs (see Table 3). There is to date **only one processing facility operated in Europe**, located in Estonia. It is owned by the Canadian company Neo Materials and run by NPM Silmet OÜ. Neo materials is also building a mine in Sarfartoq, Greenland and a REE magnet factory (Neo Performance Materials, 2023a and 2023b). When finished, **this could become Europe's first integrated mine-to-magnet supply chain** (EC, 2023). LKAB started to build a demonstration plant for processing phosphorous and rare earth elements (LKAB, 2025). Another new REE separation plant is also to be built in Pulawy, Poland and operated by Mkango Polska, a subsidiary of Mkango (a Canadian company) (Mkango Resources, 2021). In addition, there are two planned processing plants for REEs in the UK (Pensana) and Norway (REEtec) (Adamas Intelligence, 2024a).

Magnet recycling provides large potential in REE processing (see also Section 3.2 on the decommissioned material streams of rare-earth elements). The increased focus on recycling by the CRMA has sparked activity both from established companies and start-ups to invest in REE magnet recycling. For example, Heraeus REMLOY GmbH is a start-up of the Heraeus group focusing on producing recycled NdFeB powder. The production capacity of the first factory starts with 600 t/y, which can be extended to 1 200 t/y (Heraeus Remloy, 2024; Schönfeld et al., 2024). Other start-ups include HyProMag GmbH (Germany), owned by Maginito, a subsidiary of Canadian company Mkango, then Carester and MagREEsource (both French) (Carester, 2024; Mkango Resources, 2024; Schönfeld et al., 2024). Outside of Europe, there are start-ups such as Noveon Magnetics (USA), which already sells a recycled magnet, REEcycle (Canada), Cyclic Materials and Geomega Resource Inc. (Canada) (Cyclic Materials, 2024; Geomega, 2024; Noveon Magnetics, 2022; REEcycle, 2024; Schönfeld et al., 2024).

2.4.3 Components

REE magnets are also mainly produced in China (Gauß et al., 2021). One reason for this might be the price pressure, since there is no tax refund for Chinese companies when they export processed ores, but there is for exporting the rare earth magnet. Thus, magnets produced, for example, in Europe would be 20-30% more expensive (Gauß et al., 2021). Even European companies, such as Bakker Magnetics (the Netherlands), produce in a joint venture in China (Bakker Magnetics, 2024). Some Chinese companies have European subsidiaries, such as Newland Magnetics Europe, which is a subsidiary of Ningbo Newland Magnetics Group; however, the production remains in China (Newland Magnetics, 2023). **Only some limited production capacity is provided in Europe** by companies such as Vacuumschmelze, Neorem or Magneti Ljubljana (Adamas Intelligence, 2024b).

One project to build a REE magnet manufacturing site is planned by Neo Magnequench, a subsidiary of Neo Performance Materials. Together with GKN Powder Metallurgy they are planning a factory in Estonia, which would be part of the mine-to-magnet supply chain of Neo Materials mentioned above (GKN Powder Metallurgy, 2022; Neo Performance Materials, 2023b).

On the other hand, **European manufacturing facilities are still covering the domestic demand** for the other turbine components, such as **blades, nacelles and towers** (Mc Govern et al., 2024; RystadEnergy et al., 2023). However, forecasts by RystadEnergy project shortcomings from 2026 (RystadEnergy et al., 2023).

The biggest independent **blade** manufacturer on a global scale is estimated to be TPI Composites, an American company (RystadEnergy et al., 2023). In Europe, about two thirds of the blade manufacturing capacity is situated in Spain, France, Denmark and Germany (RystadEnergy et al., 2023). Companies manufacturing blades in Europe include the main European turbine OEMs such as Vestas (with blade facilities in Denmark, Italy, Spain, Poland and the UK), Siemens Gamesa (with offshore blade facilities in France and Denmark), Nordex (with a blade facility in Spain), LM Wind Power/GE Vernova (Spain and Denmark) and Enercon (Portugal, Türkiye) (Enercon, 2024; Nordex, 2024; RystadEnergy et al., 2023; Vestas, 2024a).

Nacelle manufacturing in Europe is also mainly situated in Spain, France, Denmark, Germany, Portugal, Poland, and the Netherlands with Germany taking the lead (Kuzov et al., 2024). Companies manufacturing nacelles in Europe include Vestas (Denmark, Germany), GE Vernova, Siemens Gamesa (Germany), Nordex (Germany, Spain) and Enercon (Germany) (Enercon, 2024; Nordex, 2024; RystadEnergy et al., 2023; Vestas, 2024a).

Some European companies are also active across the world. Vestas, for example, has factories in China (blades, nacelles and generators), India (blades and nacelles), the US (blades and nacelles) and Mexico (blades) (Vestas, 2024a).

Some companies struggle to keep up with global competition, with many government auctions focusing mainly on price. The **demand for lower prices** pushes some companies to **close their European factories**. For example, Nordex closed its blade factory in Germany in 2022 (Ferris, 2022). On the other hand, new manufacturing capacity for offshore blades and nacelles in Poland has been announced by Vestas (Vestas, 2024b; Vestas, 2024c), and Siemens Gamesa has extended its factory in the UK (BW magazine, 2024).

2.4.4 Assemblies: power generators

Generators for wind turbines are also produced in Europe. For example, Vestas produces generators in Germany and Enercon has production sites in Germany, Poland and Portugal (Enercon, 2024; Vestas, 2024a). GE also produces its own generators (Tapoglou et al., 2023). A company specifically focusing on permanent magnet generators is The Switch, a Finland-based company, now owned by Japanese BEMAC Group (The Switch, 2024). Still, China controls more than 50% of the global market, which makes this supply chain step critical in Carrara et al., 2023.

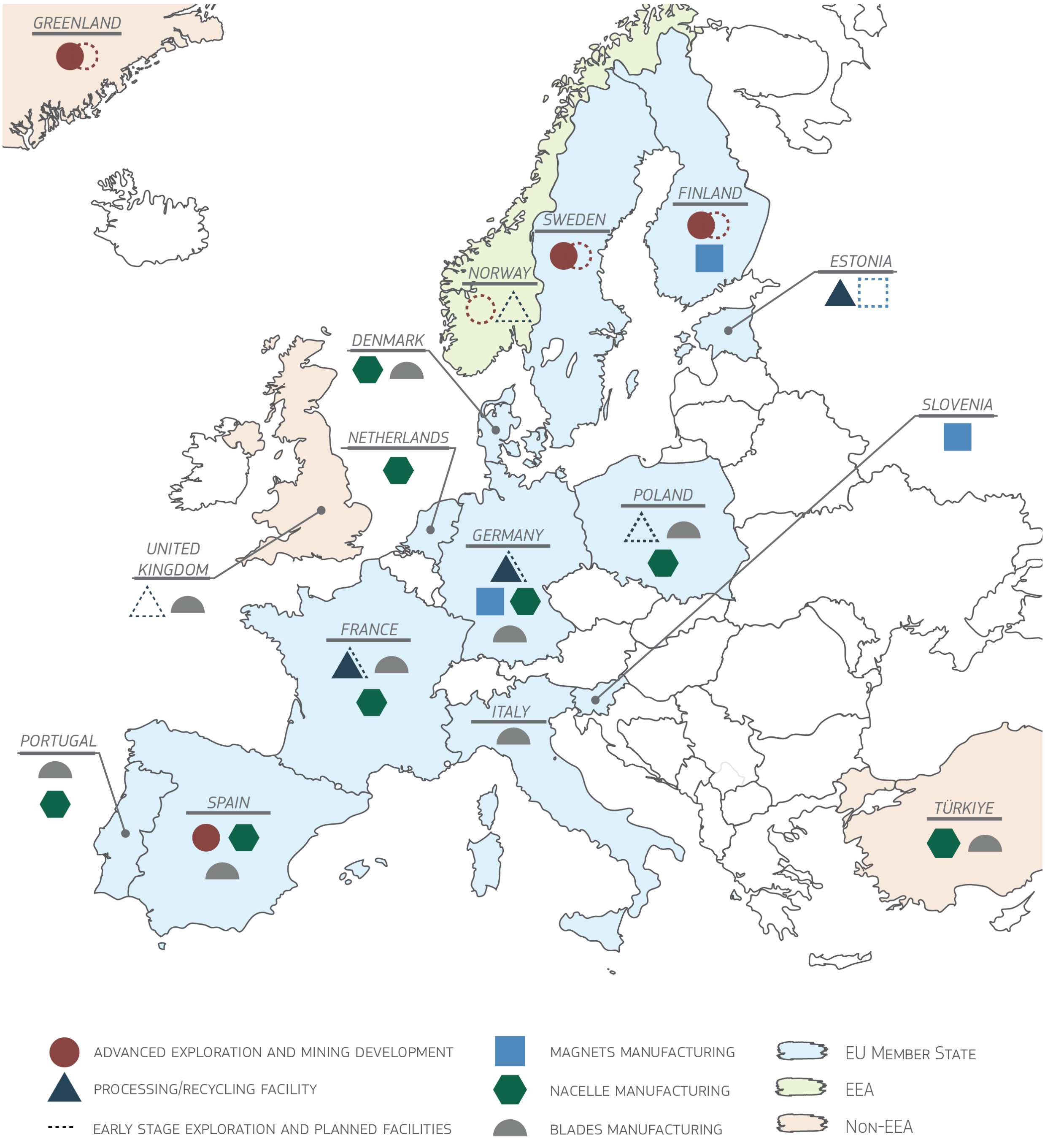
2.4.5 Super-assemblies: wind turbines

When it comes to wind turbines, **Chinese companies dominate the global market**. Among the ten largest suppliers of wind turbines in 2023, six were Chinese (Goldwind, Envision, Windey, Mingyang, Sany and Dongfang Electric), one was American (GE Vernova) and three were European (Vestas, Siemens Gamesa, Nordex) (BNEF, 2024; GWEC, 2024; Wood Mackenzie, 2024). Nonetheless, focusing specifically on the **offshore wind** segment, **European companies** like Vestas and Siemens Gamesa **take the global lead** (Mc Govern et al., 2024).

There is still a **separation between the Chinese market and the rest of the world**. On the one hand, in 2023, **the global market excluding China was dominated by western companies** (Wood Mackenzie, 2024a). Goldwind and Envision, the top two Chinese companies in 2023 (BNEF, 2024; GWEC, 2024; Wood Mackenzie, 2024), have shares of installed capacity outside of China of less than 2% each (Wood Mackenzie, 2024). The **EU market in particular is still dominated by European companies** (Mc Govern et al., 2024). Vestas, Nordex and Siemens Gamesa accounted for 84% of onshore installations. On the other hand, **western companies have little presence in China** (GWEC, 2024).

However, a strong decrease in price and an increase in innovation of Chinese turbines could **change the situation on the global ex-China market** (Hayley, 2024). Chinese companies are already securing an increasing number of orders in the global market outside of China (Lewandowski, 2024) and projects in Europe are also starting to invest in Chinese turbines (Luxcara, 2024; Renexia, 2024).

Figure 12. Countries hosting the main European companies and/or projects along the wind turbine supply chain with a focus on examples for rare earths, permanent magnets, and manufacturing of blades and nacelles



Source: JRC analysis and EC (2024).[11]

[11] Disclaimer: This map is for visualisation purposes only and is not intended to be exhaustive or definitive. The information presented is based on selected available data presented in this chapter and should not be considered an official EU position on all resources, capacities or any other potential issues. The boundaries and designations used on this map do not imply official endorsement or acceptance by the European Commission and the Joint Research Centre. This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory or area.

3 Material streams in wind turbines

This chapter provides a quantitative assessment of material streams related to wind turbines until 2050, focusing on two key dimensions. First, it develops **future material demand scenarios**, exploring the main materials required for wind turbine deployment under varying assumptions (Section 3.1). Second, it evaluates the **future quantities of decommissioned materials in the EU**, focusing specifically on **rare earths** (Section 3.2).

By framing the first section as an exploration of potential material inputs required for future wind turbine deployments, we establish a pattern of need based on projected capacity growth and technological developments (irrespective of where the materials are practically utilised for manufacturing purposes). The second section complements this by presenting an analysis of the outputs, specifically the decommissioned materials that will become available for recycling or disposal. This juxtaposition allows for a comparison of material flows – both inputs and outputs – thereby facilitating a comprehensive understanding of the entire life cycle of wind turbine materials.

3.1 Material demand scenarios and supply/demand balance

This section develops future demand scenarios for the main materials relevant to the wind turbine supply chain, including non-raw materials such as concrete, steel, plastic, glass/carbon composites, and balsa wood. Scenarios are developed for the EU, USA, China, and the world, and show results in 2022 (base calibration year), 2030, 2040, and 2050.

The material demand scenarios are developed based on the following three parameters:

- **Technology deployment**: this parameter indicates the wind power capacity installed over the years; specifically, the annual capacity deployment is needed to calculate the material demand; if only the overall installed capacity is available, information on the turbine lifetime is necessary to derive the annual installations from the cumulative amounts.
- **Sub-technology deployment shares**: as discussed in Chapter 1, there exist several configurations of wind turbines, essentially based on the types of electric generators, which are characterised by specific material requirements.
- **Material intensity and efficiency**: material intensity quantifies the mass of material needed per unit of installed capacity (e.g., tonnes per gigawatt); scenarios consider future possible change of material intensities (material efficiency).

In line with the two twin deep-dive reports on solar PV (Taylor et al., 2025) and batteries (Latunussa et al., 2025), two material demand scenarios are considered in this work:

- **Baseline scenario (BASE)**: this scenario assumes that the technological trends broadly follow the patterns of the latest years.
- **Innovation scenario (INNO)**: this scenario assumes increased levels of R&D investment and spending, resulting in an introduction of innovative solutions in the market.

The modelling details related to the two scenarios are described in the next three sections, which provide details for each of the three parameters: Section 3.1.1 for the technology deployment, Section 3.1.2 for the sub-technology deployment shares, Section 3.1.3 for the material intensity and efficiency. Finally, Section 3.1.4 presents and discusses the results.

3.1.1 Technology deployment

In 2022, global **wind power capacity** reached 905 GW, comprising 841 GW from onshore wind (93%) and 64 GW from offshore wind (7%) (GWEC, 2024). Among the analysed regions, China led in both onshore and offshore capacity, with 334 GW and 31 GW, respectively. The EU accounted for 188 GW of onshore wind capacity and 16 GW of offshore wind capacity. In the US, almost the totality of wind capacity was onshore (144 GW), as offshore capacity was minimal, amounting to some 40 MW (constant since 2020). That year, China was the region with the highest levels of yearly capacity deployments at global level, adding 33 GW out of 69 GW for onshore wind (compared to 15 GW in the EU and 9 GW in the US) and 5 GW out of 9 GW for offshore wind (compared to 1 GW in the EU).

This work considers **one single capacity pattern for both BASE and INNO scenarios**. For the EU, the capacity scenario considers targets from REPowerEU for 2030 (EC, 2022) and the Climate Target Plan for 2050 – MIX scenario (EC, 2020a). These align with the specific goals outlined in the EU Offshore Strategy (EC, 2020b). The Net Zero Emissions Scenario in 2050 (NZE) by the International Energy Agency (IEA) was considered in the other regions and globally (IEA, 2023).[12,13]

We consider only one technology deployment scenario for both scenarios for two reasons. First, we wished to focus on the impact that technology changes have on demand, discarding capacity which is normally the overarching driver. Second, we assumed that all regions in the world, at least in the long run, would stick to fulfilling the climate targets upon which they agreed in recent years.

In the considered **scenario**, global wind capacity reaches some 2 800 GW in 2030 (2 450 GW of onshore wind and 350 GW of offshore wind) and about 8 150 GW in 2050 (7 100 GW of onshore wind and 1 150 GW of offshore wind). The EU, USA, and China show a similar pattern for onshore wind capacity, which grows up to around 1 000 - 1 200 GW in 2050, although China's capacity plateaus towards the end of the period. The EU and China also share a similar pattern for offshore wind capacity, reaching some 250 - 300 GW in 2050, while the growth is less marked in the US (about 30 GW in 2050). Figure 13 shows the wind capacity evolution in the areas in focus.

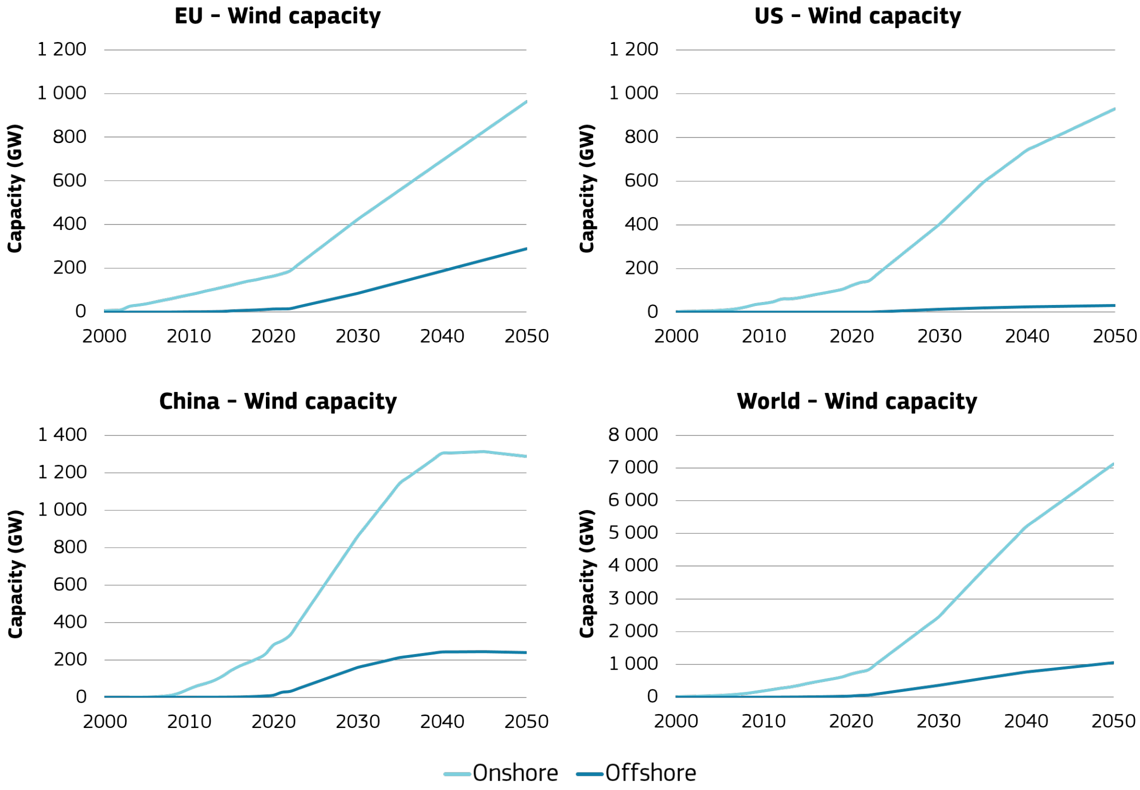
Manufacturers normally set a wind turbine lifetime of 20-25 years by design. However, evidence from actual operations seems to show that the lifetime of wind turbines before decommissioning them is longer. Section 3.2 reports a detailed analysis showing that the average actual lifetime is 33 years for onshore turbines and 38 years for offshore turbines. Conservatively, in our scenarios we have assumed **30 years for onshore turbines and 35 years for offshore turbines**. Indeed, it is often the case that wind turbines are not decommissioned because they reach the end of their operational lifetime, but rather for economical reasons, and specifically to be replaced with larger turbines (repowering).

Figure 14 shows the **capacity that should be deployed annually** to achieve the capacity levels indicated in Figure 13 assuming these lifetime levels. The graphs focus on the current values (2022) as well as on significant future milestones, i.e., 2030, 2040, and 2050.

[12] Only data at global level and for the "advanced economies" were available for the IEA-NZE scenario, while no explicit data were directly available for the specific regions. Therefore, regional data have been derived from the two values above by keeping the same regional proportionality as in the APS (Announced Policy Scenario) (IEA, 2023). Also, IEA (2023) does not sort between onshore and offshore wind capacity. Thus, we kept the same proportion between onshore and offshore wind that is found in IEA (2024) for the the year 2028 (the last year explored in that publication).

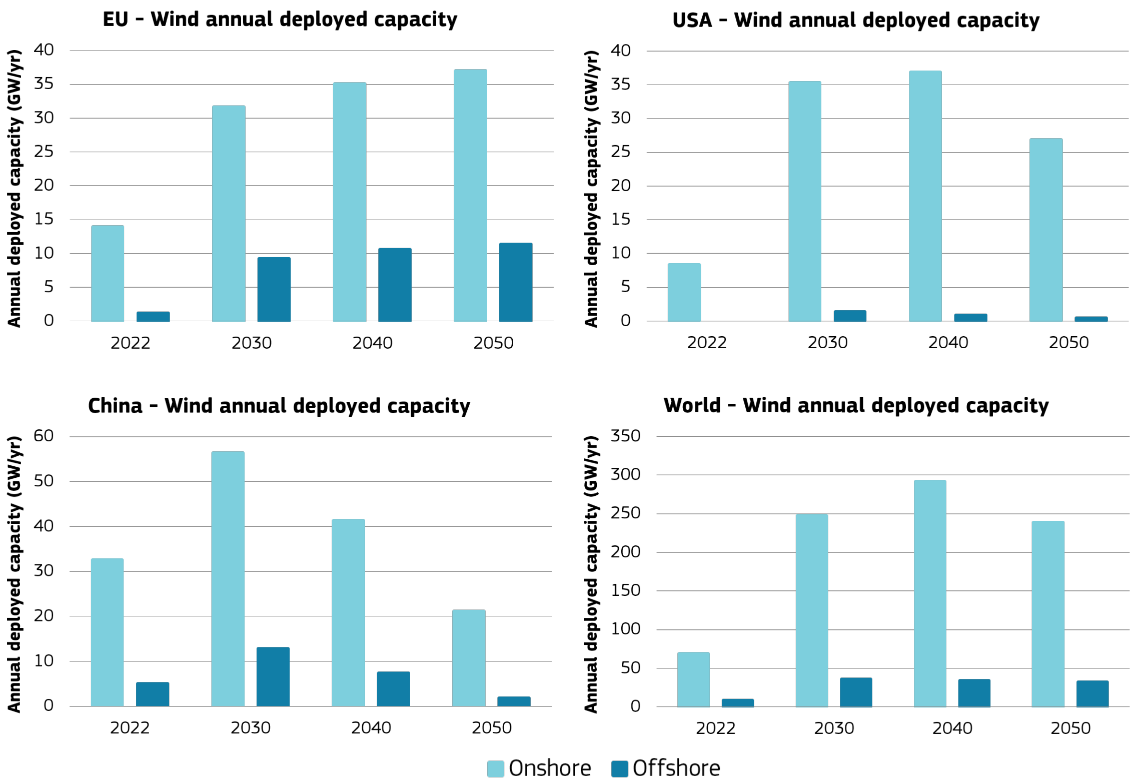
[13] The IEA-NZE global capacity has been adjusted by replacing their EU capacity with the scenario considered in this work.

Figure 13. Onshore and offshore wind capacity in the EU, US, China, and globally



Source: JRC analysis based on EC (2020a), EC (2022), IEA (2023).

Figure 14. Onshore and offshore wind annual deployed capacity in the EU, US, China, and globally



Source: JRC analysis.

The **2022 deployment levels** for onshore and offshore wind are as follows: in the EU, 14 GW/yr and 1 GW/yr; in China, 33 GW/yr and 5 GW/yr; globally, 69 GW/yr and 9 GW/yr, respectively. As noted above, wind capacity deployment in the USA was limited to onshore wind (8 GW/yr), while no capacity was installed in 2022 for offshore wind.

In the **short term** (up to 2030), a significant acceleration in annual capacity deployment is required across all regions to achieve the capacity levels outlined in Figure 13. For onshore wind, annual installations must increase by two to four times their current levels across all regions. For offshore wind, a similar acceleration is needed in China and globally, while the EU requires an even steeper increase, with annual installations growing nearly eightfold. In the US, the offshore wind sector would need to be developed almost entirely from scratch.

After 2030, the rate of capacity deployment begins to slow in the EU, while a decline in the deployed capacity is observed in the US, China, and globally. This trend corresponds to a gradual reduction in the overall capacity growth rate, which eventually even plateaus for China toward the end of the period leading up to 2050.

This deceleration is influenced not only by the choice of the reference scenarios outlined earlier in this section, but also by the assumptions regarding **turbine lifetimes**. With lifetimes of 30 years for onshore turbines and 35 years for offshore turbines exceeding the scenario timeframe (2022-2050, i.e. a span of 28 years), the capacity deployed before 2050 is not impacted by the retirement of capacity installed from 2022 onwards. Notably, the deployed capacity does not exhibit a spike towards 2050, which would otherwise occur if the turbine lifetimes were shorter (for instance, 25 years). This would happen because the deployed capacity towards 2050 would be affected not only by the capacity target, but also by the near-term deployments, which are considerably higher than the historical values, given the need for acceleration until 2030 discussed above. For example, this dynamic is evident in Carrara et al. (2023), where shorter lifetimes contribute to different deployment patterns compared to those observed in this analysis (aside from the different scenarios, which clearly also contribute to the differences).

3.1.2 Sub-technology deployment shares

In 2022[14], **wind turbines equipped with permanent magnets** (DD-PMSG and GB-PMSG) represented 42% of the onshore wind market in China, 25% in the world, 21% in the EU, and only 2% in the USA. In all regions, the highest share of the market was owned by the GB-DFIG wind turbines. On the other hand, PM wind turbines dominated the offshore wind market, with 100% of the installations in the EU, 92% at global level, and 88% in China. As seen previously, no installations have recently taken place in the US. However, all the installed capacity is equipped with permanent magnets, so we assume that this technology would still represent 100% of the annual installations.

Looking to the future, the **BASE** scenario considers a continuation of the latest trends, which in practical terms means shares remaining constant until 2050 for onshore wind. For offshore wind, the same is valid for the EU and the US, where PM turbines already fully dominate the market. In China and globally, first the residual share of non-PM wind turbines is phased out linearly until 2030, and only then can the market shares remain constant until 2050. This trend is perfectly in line with the

[14] In order to compensate for excessive sensitivity on annual fluctuations, the technology rates for the calibration year 2022 were calculated as the average of the 2021, 2022, and 2023 values.

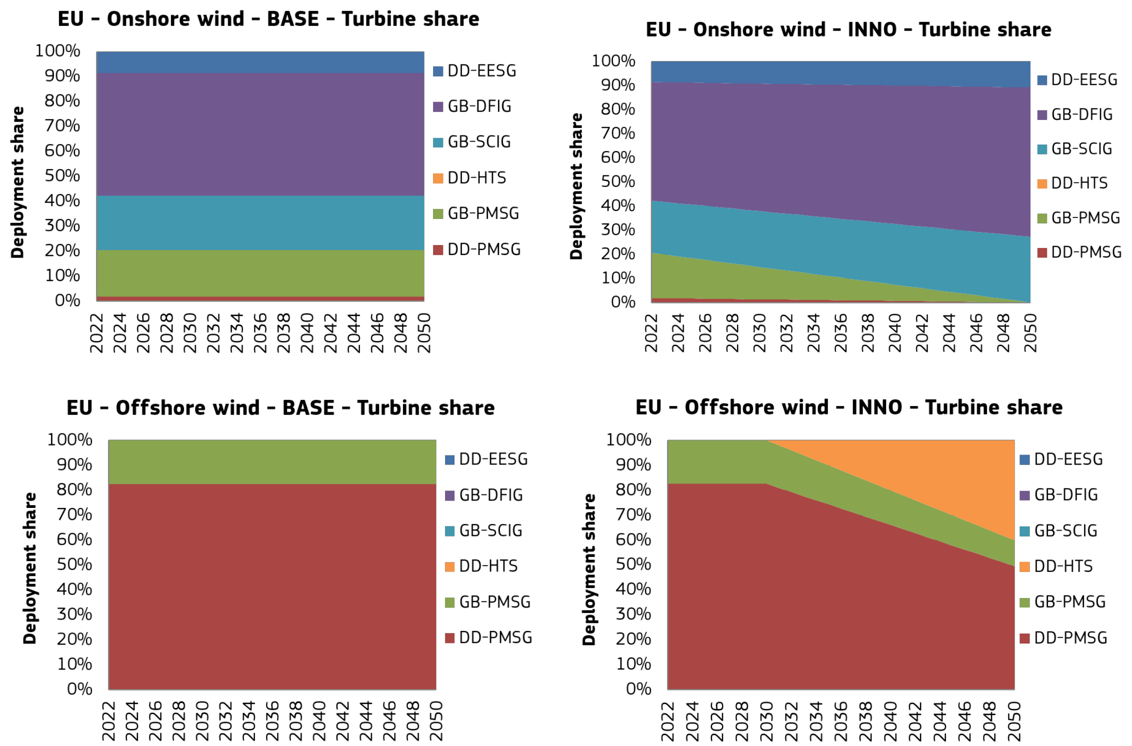
pattern observed in recent years, where PM turbines have rapidly been gaining market dominance, although in China and at global level this would still require some years to fully materialise (see Figure 28 in Annex 2 for more details on the historical trends).

In the **INNO** scenario, the share of PM wind turbines in the onshore market decreases linearly to zero in 2050, thus mimicking a scenario where rare-earth consumption decreases, while the other technologies grow keeping the same proportion as today. The reason for this latter assumption is that the focus of this exercise is on the generators with rare-earth permanent magnets, while we do not wish to allow for an additional degree of freedom in the competition e.g. between DD-EESG and GB-DFIG turbines. For offshore wind, the pattern is the same as the BASE scenario until 2030, i.e. a constant 100% share of PM wind turbines in the EU and the US, and a linear phase out of non-PM wind turbines until full dominance is reached in China and globally. After 2030, we assume a linear growth of DD-HTS wind turbines up to 40% in 2050 (i.e. 2% per year), while PMs decrease proportionally.

These scenarios represent a what-if exercise and should not be considered predictions of actual future deployment.

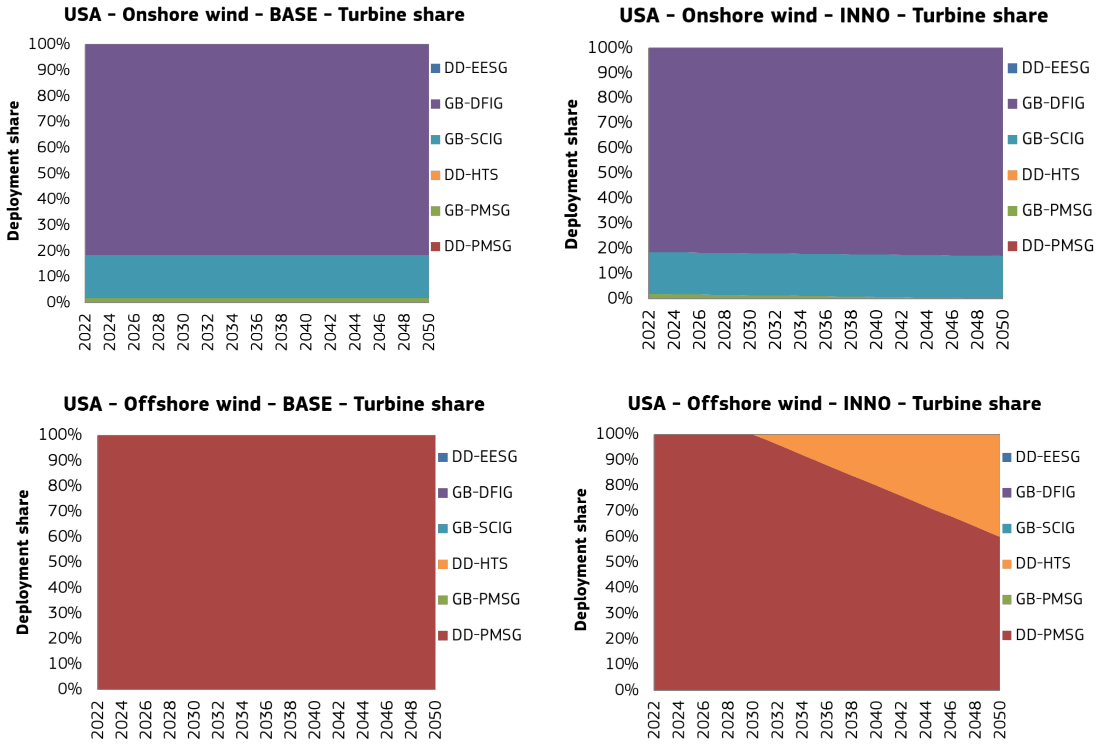
The detailed evolution of the wind turbine deployment shares for onshore and offshore wind in the BASE and INNO scenarios is reported in Figure 15 for the EU, Figure 16 for the US, Figure 17 for China, and Figure 18 for the world.

Figure 15. Deployment shares of onshore (top) and offshore (bottom) wind turbine sub-technologies in the BASE (left) and INNO (right) scenarios in the EU market



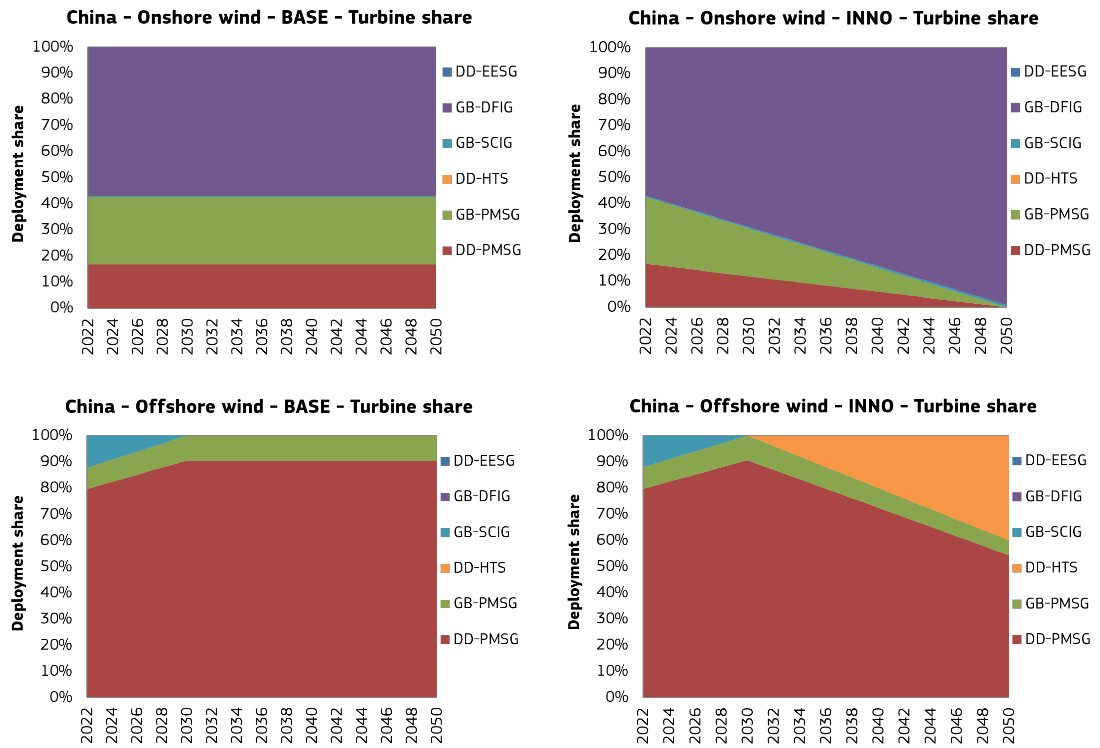
Source: JRC analysis.

Figure 16. Deployment shares of onshore (top) and offshore (bottom) wind turbine sub-technologies in the BASE (left) and INNO (right) scenarios in the US market



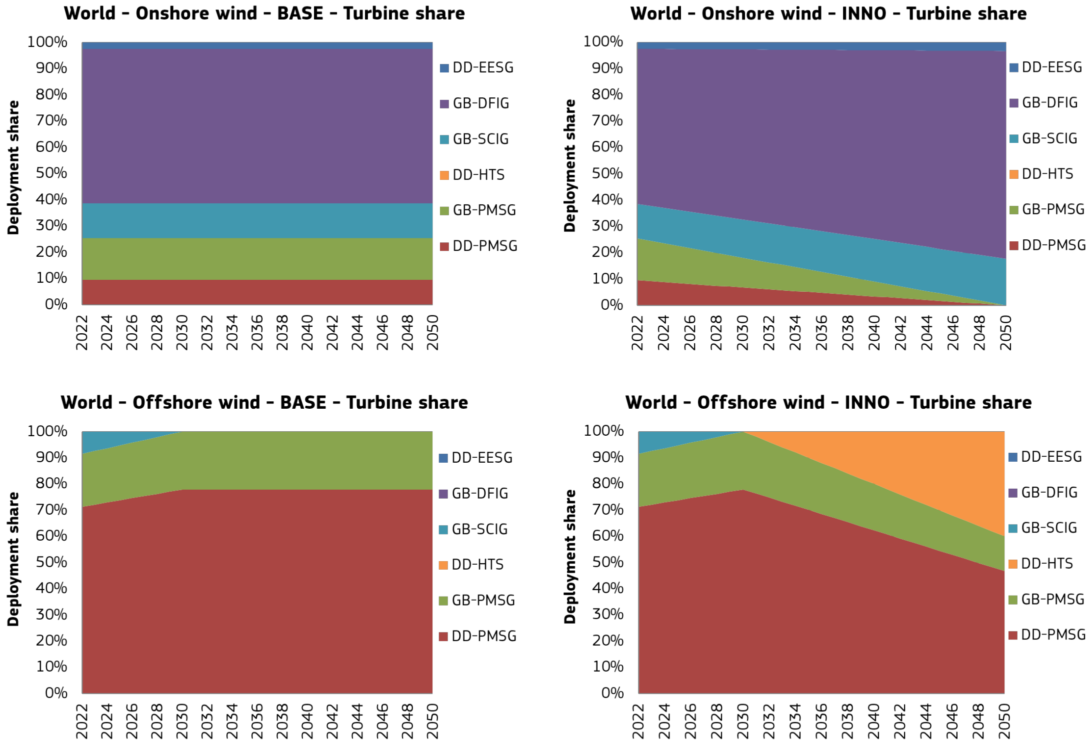
Source: JRC analysis.

Figure 17. Deployment shares of onshore (top) and offshore (bottom) wind turbine sub-technologies in the BASE (left) and INNO (right) scenarios in the Chinese market



Source: JRC analysis.

Figure 18. Deployment shares of onshore (top) and offshore (bottom) wind turbine sub-technologies in the BASE (left) and INNO (right) scenarios in the global market



Source: JRC analysis.

3.1.3 Material intensity and efficiency

Table 4 reports the material intensity values adopted in this work, sorting among the **different types of generators**. Values are based on Mc Govern (2024), which builds on a previous JRC analysis developed in Carrara et al. (2020).

For many materials, the table provides a range, resulting from the different technical configurations developed by manufacturing companies. As a rule, the average value of the range was adopted to develop the scenarios discussed in this report.

Table 4 does not report material intensities for REEs for DD-EESG turbines, as it was not possible to retrieve data in the literature or in the manufacturers' publications. Given that these turbines do not feature permanent magnets, the REE material intensities valid for GB-DFIG turbines were used for this technology as well.

No detailed material intensities are shown for DD-HTS turbines either. This technology is still at an early stage, so no consolidated industry data are available. However, since these kinds of generators are direct drive and do not rely on rare earths, it is reasonable to consider the same assumptions as for the DD-EESG turbines (hence, the assumptions for GB-DFIG for rare earths). However, DD-HTS will require 0.3 t/GW of another REE, yttrium (Viebahn et al., 2015; Månberger and Stenqvist, 2018).

Finally, Table 4 does not report the material intensity for balsa wood. Sources vary significantly between 270 kg/MW (Telsing et al., 2022) and some 2 000 kg/MW (Liu and Barlow, 2016; Fraunhofer Materials). In this work we have set the figure at 725 kg/MW (Rainforest Rescue).

Considering an average weight for permanent magnets of 650 kg/MW in DD-PMSG turbines and 160 kg/MW in GB-PMSG turbines (Pavel et al., 2017), the reported values for rare earths in these two types of configurations would correspond to an overall share of REEs in the magnets of around 37%. This is above the upper limit of the normal content range reported in Section 2.3 (28-35%). However, for this analysis our aim is not to model a "real" magnet, but rather to consider conservative values found in the literature for all the single rare-earths (dysprosium, neodymium, praseodymium, and terbium), although in practice relatively high values for one would imply relatively low values for the others.

Table 4. 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 - 4600	900 ± 250	850 ± 150
Iron (cast) (Fe)	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).

Regarding the future evolution of material intensity, two distinct trends have been identified: one for structural materials and another for technology-specific materials. **Structural materials**, including concrete, steel, plastic, glass/carbon composites, aluminium, chromium, copper, iron, manganese, molybdenum, nickel, and zinc, are expected to see a moderate decline in material intensity. By 2050, their intensity is projected to reach 90%, and 80% of current levels under the BASE and INNO scenarios, respectively, with a linear decrease from the current levels.

Technology-specific materials, including, boron, neodymium, praseodymium, dysprosium, terbium, and balsa wood follow a different pattern. Their material intensities are characterised by a 1.5% and 3% annual reduction under the BASE and INNO scenarios, respectively. As a result, material intensity by 2050 is estimated to be approximately 65% and 40% of the current levels in the BASE and INNO scenarios, respectively. A slightly stronger reduction is considered for dysprosium (2% and 3.5%

annual reduction in the BASE and INNO scenarios, respectively), considering the higher margin of development for this material, which has seen strong reductions in its material intensity in recent years (up to 6% annually, a level which does not seem sustainable for future decrease, however) (Adamas Intelligence, 2024).

According to Viebhan (2015), yttrium's material intensity would remain constant until 2050. However, in case of marked penetration, such as that considered in the INNO scenario (see previous section), it is reasonable to consider some reduction. Therefore, we assumed a 1% yearly reduction starting from 2030, the year when this technology begins penetrating the market in the INNO scenario.

3.1.4 Material demand and demand/supply balance

Figure 19 and Figure 20 show the future demand of the main materials relevant for manufacturing wind turbines. The former focuses on the EU, while the latter shows the global results, disaggreged to the EU, USA, China, and rest-of-world.

In line with the focus of the report, the graphs show results for the materials needed for manufacturing permanent magnets, i.e., **boron** and the four REEs – **neodymium, praseodymium, dysprosium, and terbium** – as well as for **balsa wood**, which is a fundamental material for blades (please refer to Annex 3 for more detailed results of the material demand scenarios).

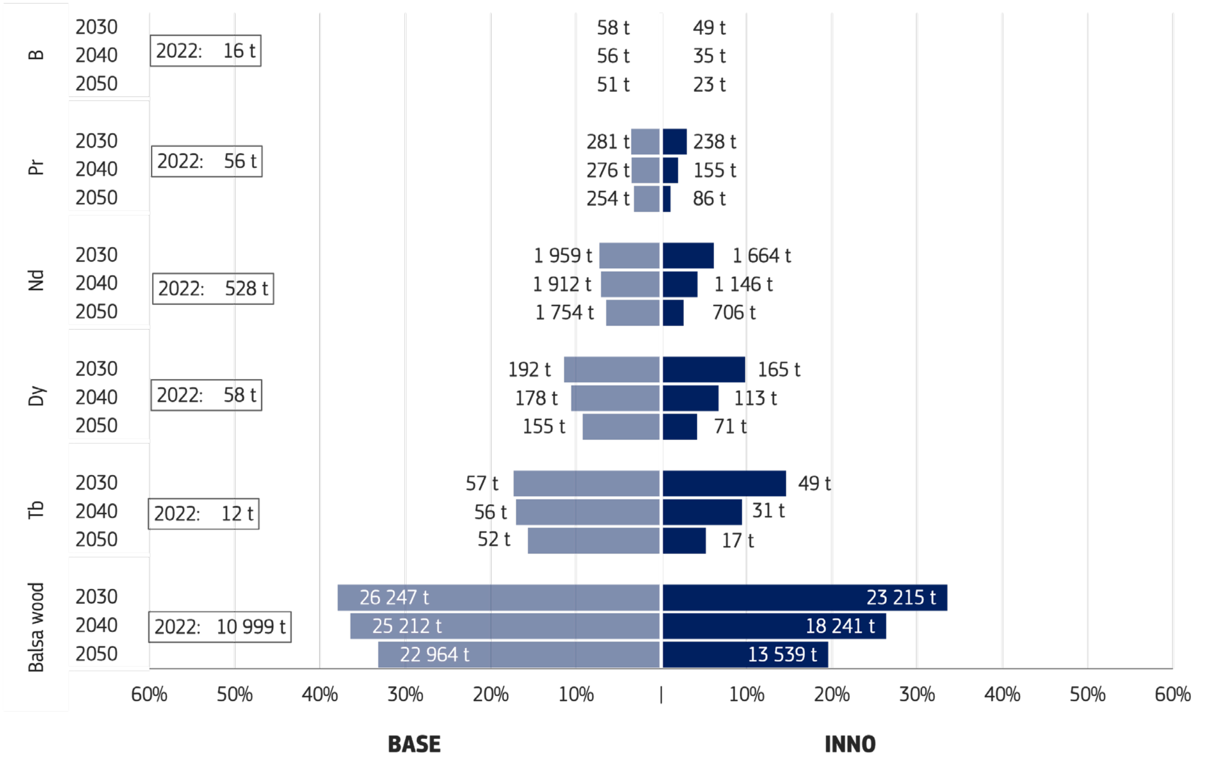
The graphs show both the **absolute material demand** in tonnes per year and the demand in **relative terms with respect to the current global consumption** of that material in all applications, in order to set the demand values in the context of their potential impact on the whole market. Results are shown for the BASE (left part of the graphs) and INNO scenarios (right part of the graphs) for the years 2030, 2040, and 2050, in addition to the base calibration year, 2022.

The yearly material demand shows a rapid increase until 2030 (by 2-3 times for balsa wood and 3-5 times for REEs in the BASE scenario, depending on the region), followed by a decreasing trend from 2030 to 2050 (even below the current demand at global level for REEs). This decreasing trend is In line with the **capacity evolution** shown in Figure 14 coupled with the **material efficiency**, which produces a progressive reduction of the material intensity over time.

As one can argue from the scenario definition, the material demand is lower in the INNO scenario than in the BASE scenario due to the faster reduction in the material intensity, which is more and more marked with time: depending on the geographic focus, in 2030 the INNO demand is 90% (balsa wood) and 75-85% (REEs and boron) of the BASE demand, while in 2050 this ratio goes down to 60% (balsa wood) and 20-45% (REE and boron). This difference is more marked for REEs specifically than for balsa wood (as well as the other materials) due to the different market configuration, as the INNO scenario considers a partial phase-out of wind turbines based on rare-earth permanent magnets.

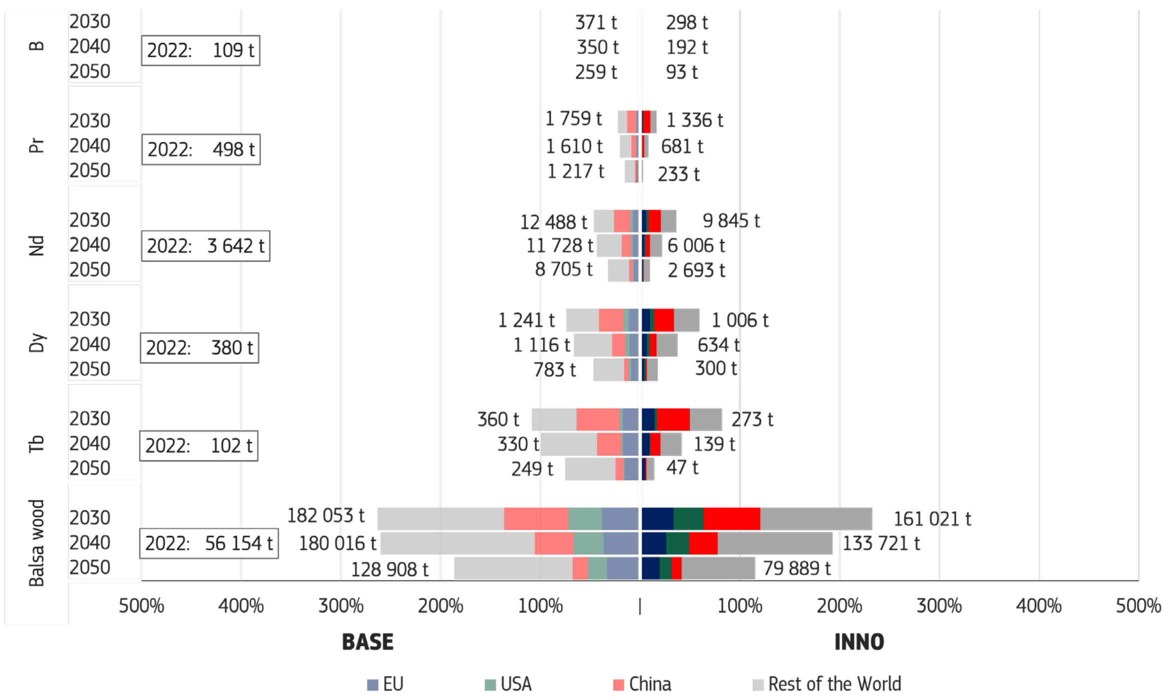
Focusing on material specifically, **balsa wood** shows the highest demand compared to the current overall supply, even considering the material efficiency gains over time. In all scenarios and all focused years, the global demand would outstrip the current global supply of this material. Among rare earth elements, the **HREEs (terbium and dysprosium)** show higher relative demand compared to the current global supply than **LREEs (neodymium and praseodymium)**. Specifically, terbium demand in the BASE scenario in 2030 may exceed the current consumption in all sectors today. Lower, yet non-negligible, levels are found for LREEs (neodymium and praseodymium). Boron holds a negligible share, as its diverse applications minimise the impact of wind turbine demand.

Figure 19. Future material EU demand for wind turbines according to the BASE (left) and INNO (right) scenarios.



Source: JRC analysis (B = boron, Pr = praseodymium, Nd = neodymium, Dy = dysprosium, Tb = terbium).

Figure 20. Future global material demand for wind turbines according to the BASE (left) and INNO (right) scenarios.



Source: JRC analysis (B = boron, Pr = praseodymium, Nd = neodymium, Dy = dysprosium, Tb = terbium).

3.2 Decommissioned material streams of rare-earth elements

3.2.1 Method

Our aim is to estimate the **material streams of REEs** (from dysprosium, neodymium, praseodymium and terbium) that will be decommissioned in the EU between 2023 and 2050. To do this, we first establish a model for the decommissioning of wind capacity, using a Weibull distribution function. We then consider the commissioned wind capacity, both onshore and offshore, and propagate this capacity towards decommissioned capacity in the future, until 2050. This exercise is done per wind turbine type, which is necessary for the final step of our methodology: the multiplication by the material intensity factor (in kg/MW), which is dependent on this wind turbine type. Finally, we obtain the estimated decommissioned material streams, from 2023 to 2050, of all REEs present in the wind turbines (Mc Govern, 2025).

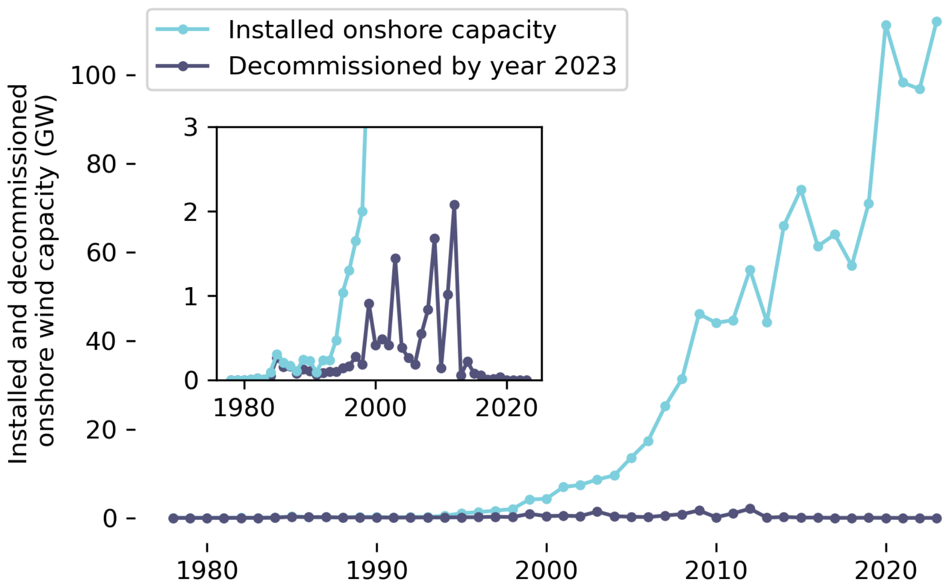
We note that **these material streams, once decommissioned, are not entirely recyclable**, and thus represent an upper boundary to the total potential secondary raw material streams of REEs. Theoretically, permanent magnets from wind turbines could be extracted with 75% efficiency (combining a collection efficiency of 90%, a disassembly efficiency of 90%, and a recycling efficiency rate of 92%) (Schulze, 2016).

3.2.2 Decommissioning model

To build our decommissioning model, we utilise a comprehensive **dataset** encompassing worldwide wind turbine installations and decommissions (Mc Govern, 2025).

In Figure 21, we display the global annual onshore wind capacity additions from 1978 to 2023. The installations remain below 1 GW until 1995, followed by an exponential increase, peaking at 46 GW in 2009, and then continuing to grow in a non-linear pattern, resulting in 112 GW by 2023.

Figure 21. Global annual capacity additions of onshore wind between 1978 and 2023, and associated decommissioned capacity by 2023



Source: JRC analysis based on Wood Mackenzie (2024).

Between 1978 and 1993, the decommissioned capacity aligns with the installed capacity for each year, suggesting that the majority of wind capacity installed during this period has since been decommissioned. From 1994 onwards, the decommissioned and installed capacity curves separate, with the average decommissioned capacity for wind energy installed after 1998 stabilising at a baseline of 200-400 MW per year. This trend is punctuated by peaks of high decommissioning, such as 900 MW being decommissioned from wind capacity installed in 1999, 1.5 GW from the capacity installed in 2003, 1.7 GW from the capacity installed in 2009, and 2.1 GW from the capacity installed in 2012.

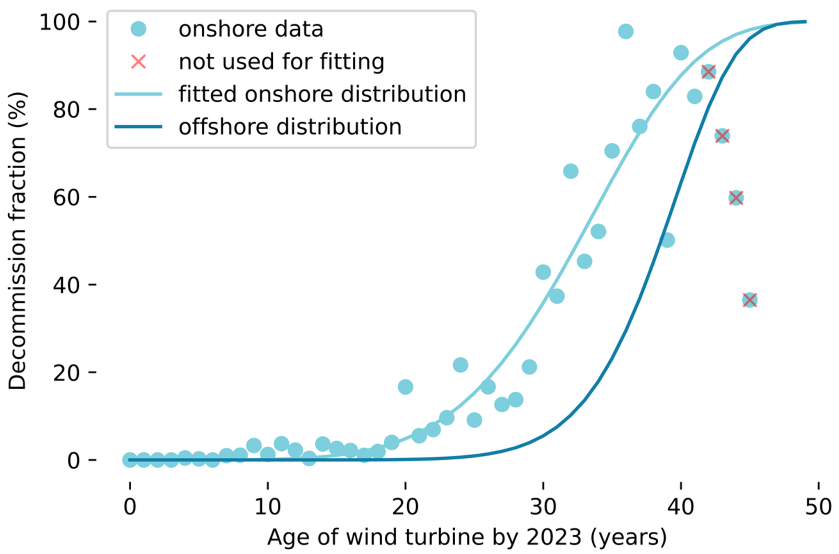
The data shown above is employed to build a decommission fraction curve, as detailed in references (Mc Govern, 2025) and (Bech Abrahamsen, 2024). We fit a Weibull distribution function to this data, resulting in a global onshore decommissioning model with a scale parameter (λ) of 35 years and a shape parameter (k) of 5.5. This equates to 50% ($t_{50\%}$) of onshore wind energy capacity being decommissioned after 32.6 years.

Due to limited **offshore** wind decommissioning data, we cannot develop an independent offshore decommissioning model. Instead, we **adapt the onshore model** with approximations to create the offshore decommissioning model.

Onshore wind turbines have a design lifetime of 20 years, while offshore wind turbines have a lifespan of 25 years (Bech Abrahamsen, 2024). We thus adjust the onshore Weibull distribution function by setting an offset of 5 years, and find a scale parameter λ of 40 years for offshore wind. Furthermore, we assume a faster decommissioning rate for offshore installations compared to onshore installations, as multiple turbines in a single offshore wind farm can be decommissioned simultaneously, whereas onshore turbines are more readily accessible for individual decommissioning (Bech Abrahamsen, 2024). Here, we set a shape parameter (k) of 10 for offshore wind. This is equivalent to 50% ($t_{50\%}$) of offshore wind energy capacity being decommissioned after 38.6 years.

The onshore and offshore distribution functions are shown, respectively, in blue and in yellow in Figure 22.

Figure 22. Decommissioning ratio for onshore wind as a function of wind turbine age and fitted Weibull distribution



Source: JRC analysis.

3.2.3 Existing wind capacity to be decommissioned by 2050

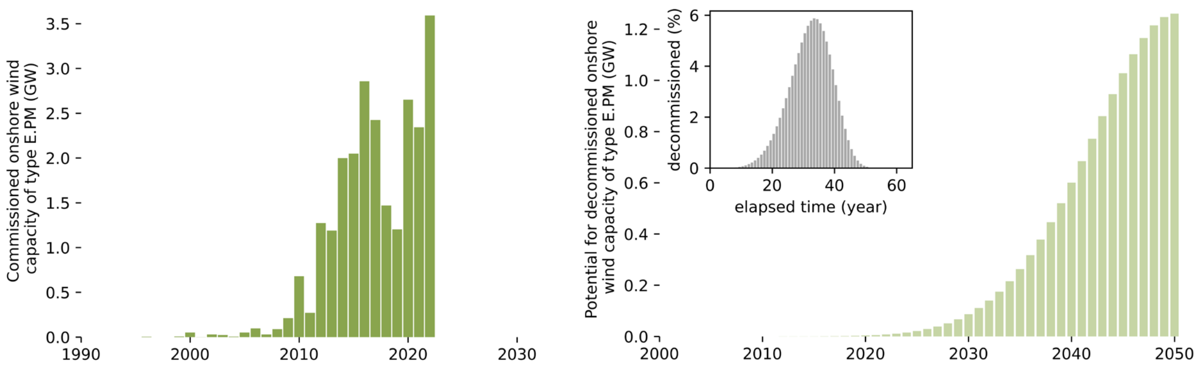
The models presented in the previous section allow us to calculate the total potential for decommissioned wind capacity until 2050.

However, wind turbines come in **various configurations** that affect the REE content they contain. For instance, wind turbines of type C (DFIG), contain 12 ± 6 kg/MW of neodymium (Nd), while those of type D-PM (DD-PMSG) contain 180 ± 30 kg/MW of Nd, those of type E-PM (GB-PMSG) have 50 ± 20 kg/MW, and those of type F (SCIG), 7-34 kg/MW (see Table 4). We therefore project the decommissioned wind capacity, for both onshore and offshore wind installations, as a function of wind turbine type, considering wind turbines of type C, D-PM, E-PM, and F.

Figure 23 presents the onshore wind installations of type E-PM in the EU between 1985 and 2023; and the **corresponding estimated decommissioned wind capacity** of type E-PM in the EU, between 2020 and 2050 (Mc Govern, 2025). The probability density function for decommissioning, as a function of the time since installation of the wind capacity, is presented in the inset. We find that the decommissioned onshore wind capacity of type E-PM remains low between 2020 and 2030 (below 0.1 GW/yr), then steadily increases to reach 0.6 GW/yr in 2040, continues to rise to 1 GW/yr in 2045, and reaches 1.2 GW/yr by 2050.

Similar distributions of potential decommissioned wind capacity are developed for types C, D-PM, and F (Mc Govern, 2025).

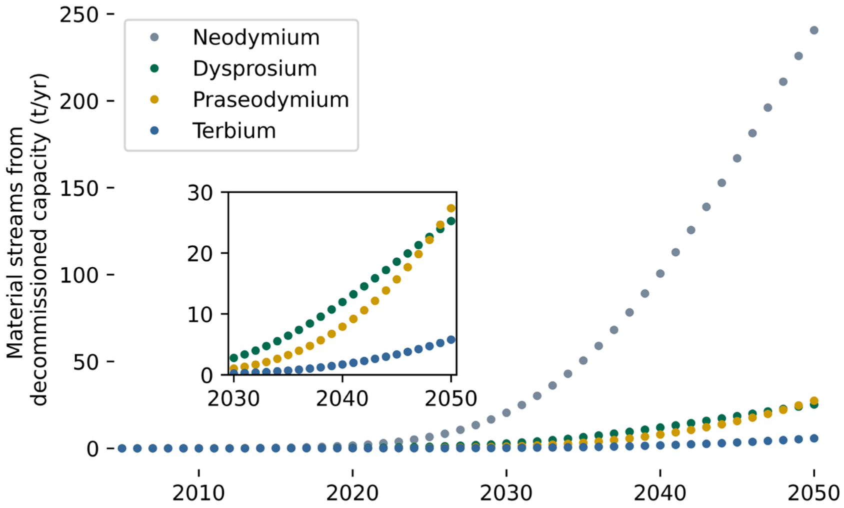
Figure 23. EU onshore wind annual installations of type E-PM (GB-PMSG) (top) and the corresponding decommissioning annual capacity curve (bottom)



Source: JRC analysis.

3.2.4 Decommissioned REE material streams by 2050

Using the projected decommissioned wind capacity in the EU for each wind turbine type, we multiply these figures with the corresponding REE material intensity (in kg/MW), per wind turbine type, to installed by 2023, for neodymium, dysprosium, praseodymium and terbium.



Source: JRC analysis.

The largest decommissioned material stream corresponds to **neodymium**, starting from a negligible amount in 2020 and reaching 21 t/yr in 2030, and 241 t/yr in 2050. **Dysprosium** is the second material waste stream to grow, reaching 3 t/yr in 2030 and 25 t/yr in 2050. It is followed by **praseodymium**, which initially grows slower than dysprosium (1 t/yr in 2030), but surpasses the dysprosium waste stream in 2050, reaching 27 t/yr by that date. **Terbium** is the smallest REE material waste stream originating from wind turbines, corresponding to 0.2 t/yr in 2030 and 6 t/yr in 2050.

Compared to the BASE and INNO demand scenarios (see Section 3.1), **this corresponds to a very small fraction of the demand in 2030**: below or close to 1% for Nd, Pr and Tb; and 2-4% of the demand for Dy. However, **this proportion increases substantially by 2050**, with decommissioned REE streams from wind capacity installed in 2023 meeting 34% of Nd demand, 35% of Dy demand, 31% of Pr demand, and 35% of Tb demand in the INNO scenario; or 14% of Nd demand, 16% of Dy demand, 11% of Pr demand, and 12% of Tb demand in the BASE scenario.

We note that the material streams presented here are the reflection of the decommissioned wind energy capacity that was installed until 2023, i.e. that any further addition in wind energy installations in the EU (as is expected from the ambitious REPowerEU targets) will result in a larger decommissioned wind capacity in the future, and thus larger material waste streams.

4 Circularity in wind turbines

Wind turbines play a pivotal role in the transition to renewable energy, but they also pose significant challenges to circularity due to their complex material composition and the scale of their deployment. Addressing these challenges is essential to achieving sustainable growth in the wind energy sector while reducing its environmental impact. This chapter examines the circularity of wind turbines, with a particular focus on **rare earths and NdFeB permanent magnets**, and explores opportunities to enhance sustainability across the value chain.

Section 4.1 introduces the **general circularity challenges** in wind energy, highlighting the issues associated with recycling and material recovery. Section 4.2 focuses on **NdFeB magnet circularity**, analysing the barriers and opportunities for improving recycling and reuse. Section 4.3 provides an extensive **analysis of the scientific literature** on the circularity of NdFeB magnets in wind energy applications, identifying key trends and gaps. Finally, Section 4.4 explores **circularity and sustainability in Chinese industry and policies,** discussing China's evolving approach to circular economy practices in the wind energy sector.

4.1 Wind energy circularity challenges

4.1.1 Recyclability and circularity of wind turbine materials and components

Wind turbine systems (comprising the turbine and its foundations) can currently be recycled to a percentage of approximatively 90-95% of their mass, according to data provided by the main European OEMs (Vestas, 2024; Siemens Gamesa, 2024; Nordex, 2024).

Concrete and **steel**, making up the largest material intensities by weight (see Section 3.1.3), can be recycled (or reused in the case of concrete), contributing to the large recyclability mentioned above and to the circularity of wind turbine systems overall. Specifically, concrete foundations can be reused, enlarged for a new wind turbine, or demolished to produce aggregate, while steel scrap can be recycled as secondary steel. **Cast iron**, representing the third largest material intensity of the wind turbine system, is also completely recyclable.

Glass/carbon composites, which make up the blades, currently pose the greatest circularity challenge in the sector. Specifically, they are more challenging to recycle due to the heterogeneity of the material and the strong adhesion between the fibres and polymers. Recycling processes for these materials are not yet fully established, and reuse of recycled materials is not widespread. The EU supports research and innovation in this area, notably through the Blades2Build (EUR 12.4 million), REFRESH (EUR 11.5 million) and EoLO-HUBs (EUR 10 million) projects, which were all funded by Horizon Europe (Europe's largest research and innovation programme) in 2023 (Mc Govern et al., 2024).

While **balsa wood** offers significant advantages in blade construction, its circularity poses challenges. Unlike metals or other recyclable materials, balsa wood is difficult to recover and reuse from decommissioned turbine blades. Its incorporation into composite materials, combined with strong adhesives, makes separation and recycling highly complex. Current practices often involve downcycling or energy recovery in cement kilns, which do not preserve the material's original properties. Furthermore, the reliance on virgin balsa wood exacerbates environmental pressures, highlighting the need for improved recycling technologies and design strategies that facilitate blade material recovery, as well as alternative solutions to reduce reliance on this resource (Tapoglou and Tazi, 2023).

Other metals appearing in considerable quantities in wind turbines, such as **copper**, **aluminium**, and **zinc**, as well as the alloying elements such as **manganese**, **chromium**, **nickel**, and **molybdenum** are recyclable to a high extent.

Though they are the least material-intensive, **rare-earth elements** in wind turbines represent an essential point of focus, due to their classification as critical and strategic raw materials. The 2024 Critical Raw Materials Act (CRMA) sets three benchmarks for the EU's consumption of raw materials by 2030 for strategic raw materials: 10% from local extraction; 40% to be processed in the EU, and 25% to come from recycled materials (EP&C, 2024). This last threshold emphasises the need for improved collection and recycling of CRM-rich waste into secondary critical raw materials.

4.1.2 Challenges in End-of-Life management

With an increasing number of turbines reaching the end of their lifecycle, the volume of decommissioned materials is rising. By 2030, waste from decommissioned turbines in the EU alone is projected to exceed 4.7 million tonnes. The complexity of managing this waste stems from several factors (Tapoglou and Tazi, 2023):

- **Logistical challenges**: Turbines are often located in remote or offshore areas, complicating collection, transportation, and recycling efforts.
- **Blade recycling limitations**: Blades, accounting for 60,000 tonnes of waste by 2023 and potentially 400,000 tonnes by 2040, are particularly challenging due to their composite construction (Tapoglou and Tazi, 2023). Emerging technologies like solvolysis and high-voltage fragmentation are promising but are not yet widely implemented.
- **Rare-earth magnet recovery**: Although permanent magnets in generators represent a valuable source of secondary REEs, their recycling is impeded by a lack of dedicated infrastructure and efficient recovery technologies (see Section 4.2).
- **Diverse End-of-Life scenarios**: Turbines may undergo lifetime extensions, retrofitting, partial repowering, or complete decommissioning. Each scenario presents unique challenges for waste management and circularity.

4.1.3 Opportunities for enhancing circularity

Addressing the challenges discussed in the previous section requires a multi-pronged approach involving policy interventions, technological innovation, and collaboration across the value chain. Key opportunities include (Tapoglou and Tazi, 2023):

- **Design for recycling**: Implementing eco-design principles, such as modular components and materials that facilitate dismantling and recycling, can significantly enhance circularity.
- **Legislative support**: Binding requirements, such as extended producer responsibility (EPR), can ensure traceability of materials, higher collection rates, and improved recycling efficiency.
- **Investment in recycling technologies**: Scaling up emerging technologies for blade and magnet recycling is critical. Public and private investments can accelerate the development and deployment of these technologies.

- **Non-price criteria in procurement**: Public procurement policies can include circularity criteria, incentivising eco-design and sustainable waste management practices.
- **Enhanced collaboration**: Coordination among manufacturers, policymakers, and researchers is essential to develop harmonised standards and best practices for circularity in wind energy.

4.2 NdFeB magnet circularity patterns

Based on the description of the NdFeB magnet supply chain structure reported in Section 2.3, this section explores the main circularity patterns involved. The investigation is based on the **review of scientific and grey literature**, leveraging a methodological blueprint from former circularity research using the supply chain as unit of analysis (Axt et al., 2023; Baldassarre, 2025; Baldassarre et al., 2022; Baldassarre et al., 2023a; Maury et al., 2023). An overview of supporting literature is reported in Table 6 in Annex 4.

The main **circularity patterns** are visualised in the supply chain diagram in Figure 24 below, replicating the supply chain structure of NdFeB magnets for wind energy applications reported in Figure 11. The discussion below also replicates the structure of Section 2.3, encompassing the stages of extraction and processing as well as manufacturing and use, which are now complemented by end-of-life.

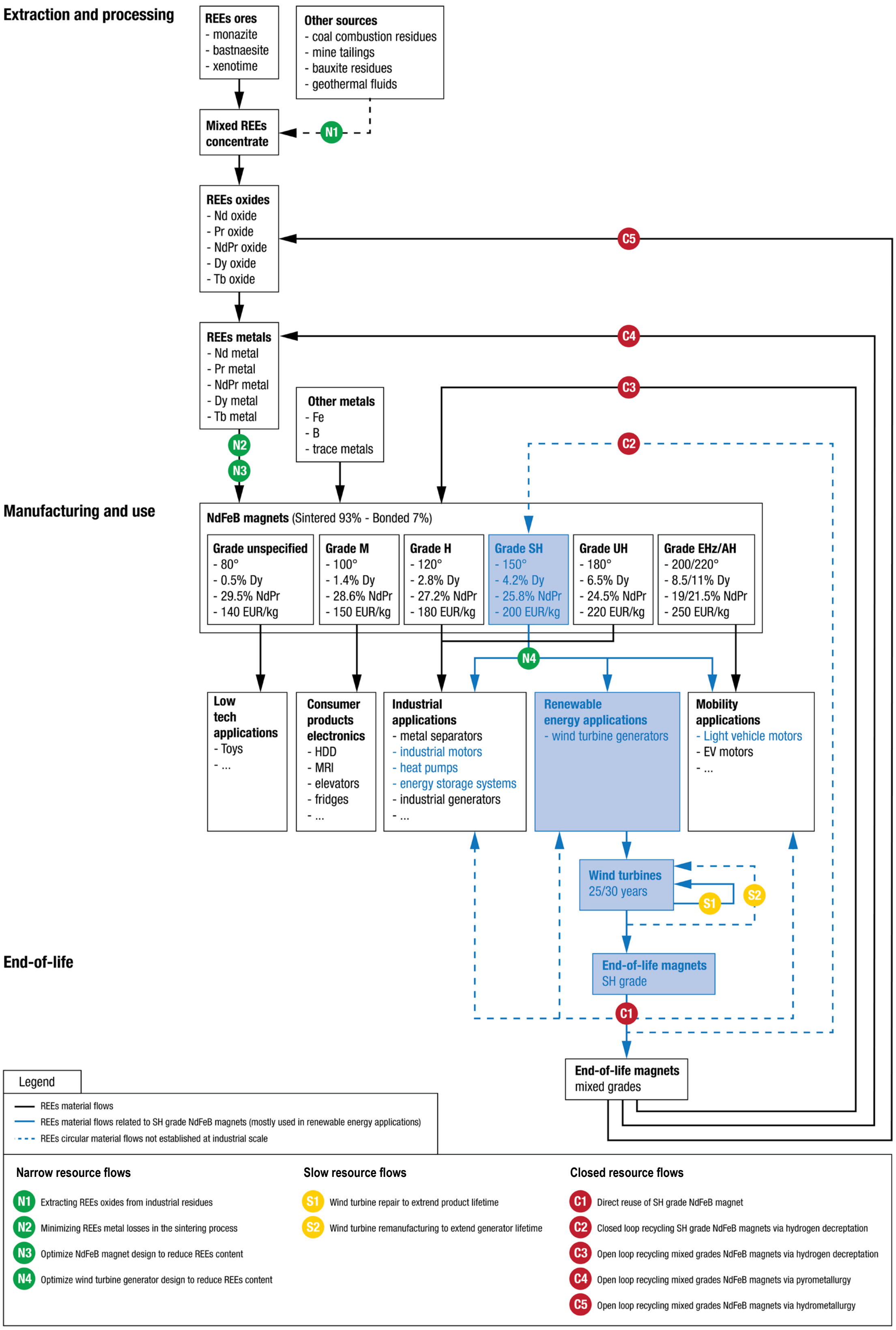
4.2.1 Extraction and processing

Circularity plays an important role in reducing raw material supply concentration and resource extraction against rapidly increasing demand (Baldassarre et al., 2023b; Carrara et al., 2023; Hartley et al., 2023). Importantly, in the extraction and processing stage, it is possible to **narrow resource flows** – minimising the input of resources in production process (Konietzko et al., 2020; Konietzko et al., 2024) – by sourcing rare earth oxides from **coal combustion residues, bauxite residues, and from the tailings of different mining operations**. Research on the technical and economic viability of these methods is ongoing. While the volume of these inputs may be small compared to overall demand, when the rare earth oxide concentration in the tailing is high (especially from uranium mining), recovery might be viable through in-situ leaching (Levett et al., 2024).

4.2.2 Manufacturing and use

Narrowing resource flows is also possible in the magnet manufacturing stage. Research and innovation (R&I) efforts are focusing on **minimising material losses during the sintering process**, where material losses can range from 15% to 40% (Jensen, 2018; United States Department of Energy, 2022). Typically, magnets are sintered in block form, and achieving the final shape requires additional machining, which generates scrap material. One key R&I area involves direct sintering of magnets into their final shapes, significantly reducing waste from machining, with the potential to reduce demand for rare earth oxides by up to 30% (Jensen, 2018). Another approach focuses on **decreasing the total amount of critical materials**, notably neodymium and dysprosium, needed for magnet production. This often involves design optimisation algorithms in laboratory experiments, enabling the creation of efficient magnets with reduced material use while maintaining essential performance characteristics (Chen et al., 2015; Lilla et al., 2014; Riddle et al., 2015).

Figure 24. Diagram of the supply chain of NdFeB permanent magnets with a focus on circularity patterns relevant for wind energy applications



Source: JRC analysis.

In renewable energy applications, NdFeB permanent magnets are essential for manufacturing direct-drive generators used in offshore wind turbines. Several R&I projects showcase **innovative generator designs** aimed at narrowing resource flows and decreasing the demand for rare earths through resource-efficient technologies (Telsnig, 2022).

- The EcoSwing project, for instance, tested a superconducting, lightweight drivetrain in a 3.6 MW wind turbine. This design narrows resource flows by reducing generator weight by 40% and nacelle weight by 25% compared to conventional magnet-based generators, while cutting rare earth element use by two orders of magnitude. Although the system demonstrated over 650 hours of successful operation, further refinement – particularly in quench protection – is needed before it is ready for industrial scaling.

- Greenspur has developed a different solution to narrow resource flows, creating a direct-drive generator that uses ferrite-based magnets with an axial flux design. This configuration arranges the rotor and stator as discs along the machine's axis, allowing for a broader interaction area between magnets and coils. By replacing rare earth elements with ferrite, the design reduces resource demand and has been successfully tested in a 250 kW prototype, with scalability options up to 12 MW by stacking multiple modules.

- In the United States, the Department of Energy is supporting the development of new designs to narrow resource flows in generator manufacturing. For example, General Electric has been working on a 15 MW superconducting generator that could reduce mass by 40%, increase torque density by 218%, and completely eliminate rare earth elements.

Next to circular economy strategies based on narrowing resource flows in the manufacturing and use stage, there are also important efforts to **slow resource flows** – extending the lifetime of products and components through **reuse, repair, refurbish, remanufacture, and repurpose** (Bocken et al., 2021; Nyffenegger et al., 2024). As discussed in Chapter 3, modern wind turbines have a design lifetime of 20 to 25 years, although their actual lifespan may vary depending on usage and environmental conditions, such as the wind conditions specific to the site. For instance, extreme weather can affect wind turbine components (De Laurentis and Windemer, 2024). While magnets may experience corrosion in marine environments and minor flux losses due to high temperatures or currents, testing indicates that these losses are minimal and can be managed through careful design of the generator and overall system, which is crucial for extending turbine life (Jensen, 2018). Research and development efforts will be essential to explore innovative solutions for more durable generators, thereby helping to reduce dependence on rare earth imports (Carrara et al., 2023). In most cases, **life extension** is the preferred option, as it is the easiest way to maximise return on investment (Grijelmo et al., 2022). However, this approach requires owners to assess the condition of their assets concerning their potential lifespan.

Remanufacturing is also an important strategy to enhance the resilience of the wind sector. Some generators of wind turbines can continue to function after a turbine is decommissioned and can thus be **upgraded for reuse** (Graulich et al., 2021). In principle, disassembling, inspecting, and reconditioning generators is feasible, which reduces reliance on new rare earth materials and extends turbine lifespan without sacrificing efficiency (Ortegon et al., 2013). It is estimated that 65% of components salvaged from decommissioned turbines can be reused as spare parts in operational turbines still in service. Furthermore, a reliable supply of spare parts is necessary. This may prove challenging, as original equipment manufacturers may not have information readily available about the original design of certain wind turbines (Grijelmo et al., 2022). This potential for reuse is particularly significant, as many older models lack manufacturer support for replacement parts, making it difficult to find high-quality components on the market (Grijelmo et al., 2022). For first-tier suppliers, this demand for durable parts presents an opportunity to diversify their business models by offering services or spare part supplies to extend the lifespan of existing turbines. Their specialised knowledge in manufacturing key components positions these suppliers well to contribute to the circular economy by supporting sustainable practices in turbine maintenance. Challenges to remanufacturing include critical activities in the wind turbine reverse supply chain, such as recovery methods, transportation logistics, quality of returns, and the quality of reprocessed wind turbines, as well as the economic and business issues associated with end-of-service life wind turbines (Ortegon et al., 2013).

When remanufacturing is unfeasible, a **repowering** approach is necessary, involving the dismantling of wind turbines and their replacement with modern models, along with potential minor upgrades to grid connection infrastructure (Grijelmo et al., 2022). Repowering wind farms – by replacing older turbines with more efficient models – enables operators to **enhance output while often retaining existing generators that still contain functional rare earth magnets**. This method supports the EU's circular economy policies by facilitating the reuse of existing generators where feasible, thereby reducing the need for new resources. When assessing dismantled assets against life-extended assets, there may be considerable opportunities for reuse and refurbishment of major components, including gears, inverters, generators, blades, actuators, powertrains, and controls (Grijelmo et al., 2022). However, the feasibility of repowering is contingent on regulatory support, including incentives and streamlined permitting processes, which can make this approach economically viable (De Laurentis and Windemer, 2024). There is currently no single European directive that harmonises this process. EU policy is needed, particularly to meet the targets of the Critical Raw Materials Act aimed at increasing the supply resilience of rare earth elements (EP&C, 2024). Under the EU Waste Framework Directive (2008/98/EC), rare earth elements are classified as non-hazardous. The second-hand market for decommissioned turbines in the EU is limited, often leading to their export abroad (De Laurentis and Windemer, 2024). Another consequence of decommissioning is the export of used turbines from the EU to countries in Eastern Europe or Latin America, where they continue to be utilised. While this allows for further use, it might also result in the export of waste management burdens to countries with less stringent environmental regulations, as well as in a significant loss of resources for the EU, as the rare earth magnets within exported turbines are effectively removed from Europe's resource loop (Graulich et al., 2021).

4.2.3 End-of-life

At the end of their life, products containing NdFeB magnets can be collected to **close the loop in rare earth resource flows**, minimising material and energy waste through efficient **recycling**. Increasing demand for rare earths, coupled with concerns over supply risks, is spurring efforts to develop recycling technologies for NdFeB magnets (Baldassarre et al., 2023b; Carrara et al., 2023). Recycling is crucial not only for conserving rare earth resources but also for reducing **environmental impacts** associated with mining and processing. However, recycling is complex due to the difficulty in recovering rare earth elements from used products and the need for high-purity materials to maintain magnet performance.

As demand increases, the potential for circularity especially in the **wind sector** becomes significant, especially given the high volumes of rare earths involved, the relatively streamlined supply chain (compared to other sectors using NdFeB magnets) and the significant volumes of wind turbine waste projected for the coming decades (see Section 3, and also Alves Dias et al., 2020; European Environment Agency, 2021; Grijelmo et al., 2022; van Nielen et al., 2023). For example, circularity in the electronics sector is complicated by the small and scattered volumes of rare earths, as well as data protection concerns related to end-of-life hard disk drives (Jin et al., 2020; Sprecher et al., 2014; Walzberg et al., 2022). Regarding electric vehicles, the situation is more favourable, with traction motors containing about 1.25 kg of NdFeB (Binnemans et al., 2013; Yang et al., 2017). In contrast, offshore wind turbines typically utilise around 400 kg of magnets per megawatt, with modern models like the GE Haliade-X incorporating approximately 600 to 1 000 kg per megawatt, resulting in a total of 7 200 to 18 000 kg of magnets per turbine (Binnemans et al., 2013; Yang et al., 2017). This large quantity simplifies sourcing and recycling efforts, especially considering that about 108 000 turbines in the EU are owned by roughly ten OEMs as of 2022 (Grijelmo et al., 2022; van Nielen et al., 2023)

In contrast with other markets such as steel (see Section 4.1), the **market for recycled rare earth elements remains underdeveloped**, highlighting the need for further research into efficient recycling methods (Ortegon et al., 2013). However, as more turbines reach decommissioning in the next 10 to 20 years, opportunities for recycling are expected to increase (Carrara et al., 2023; Graulich et al., 2021). Although various technologies exist for recycling NdFeB magnets, their economic and environmental viability must be validated at full scale. Efficient recycling depends on the ability to dismantle products to access the magnets, and small quantities can limit economic incentives (Jensen, 2018). Demagnetisation is essential, as handling magnetised materials poses challenges. Various methods have been tested, but their impacts require further scientific assessment. Research indicates that the outer rotor containing the magnets can be separated from the generator (Jensen, 2018). The back plate is removed to reduce heating energy and facilitate access, while perforating the steel encapsulation prevents cracking. Sandblasting is employed to eliminate coatings before the rotor is heated above the Curie point, reaching nearly 400 °C over four hours for demagnetisation. After cooling, the encapsulation is cut open, allowing for the removal and cleaning of the magnets, which incur a recovery loss of 5-8% due to brittleness. Although **direct reuse** is the most economically and environmentally friendly option, it is **often impractical** (Binnemans et al., 2013; Jin et al., 2020). In the case of hard disk drives, reuse may be viable, but issues related to shape and business models persist, while for wind turbine generators changing grades, compositions, and shapes render reuse more complex (Frost et al., 2021; Jensen, 2018; Jin et al., 2020). Consequently, recycling remains the most feasible option.

Several recycling methods are available for NdFeB magnets (United States Department of Energy, 2022). After demagnetisation, **hydrogen decrepitation** involves exposing magnets to hydrogen gas, causing them to break down into a fine powder that retains much of the original magnetic properties. This powder can be re-sintered into new magnets with performance comparable to virgin materials (Binnemans et al., 2013; Yang et al., 2017). This method is particularly beneficial for recycling large magnets from electric vehicles due to its energy efficiency and minimal waste. However, it is not suitable for mixed scrap with varied compositions or oxidised magnets, and large-scale testing on wind turbine magnets remains limited (Jensen, 2018). The **pyrometallurgical approach** employs high temperatures to selectively separate and concentrate rare earth elements from magnet scrap, resulting in metal alloys that can be further refined into new magnets (Binnemans et al., 2013; United States Department of Energy, 2022). Techniques such as roasting, melt processing, and liquid metal extraction facilitate separation, making pyrometallurgy widely applicable to different compositions while avoiding wastewater generation. Nevertheless, it requires significant energy input and can produce solid waste from certain refining methods, such as electroslag and glass slag processes. **Gas phase extraction** complements pyrometallurgy by utilising controlled high temperatures to volatilise specific elements from neodymium iron boron scrap, enabling efficient recovery of high-purity rare earth elements with minimal chemical waste. However, this process is energy-intensive and necessitates precise temperature control, making it best suited for high-value recovery scenarios (Binnemans et al., 2013; United States Department of Energy, 2022). **Hydrometallurgy** involves dissolving NdFeB magnets in acid to create an aqueous solution of rare earths, which are then separated through precipitation or solvent-based methods to yield rare earth oxides suitable for conversion into alloys or metals (Binnemans et al., 2013; United States Department of Energy, 2022). While effective for various compositions, including oxidised materials, hydrometallurgy entails multiple processing steps, substantial chemical input, and significant wastewater generation, prompting research into bio-leaching techniques to reduce environmental impacts. Additionally, **electrorefining** can be integrated with hydrometallurgical processes to selectively extract rare earth elements from dissolved magnet materials through an electrochemical method, producing high-purity rare earth oxides or metals. However, this technique requires complex setups and can generate chemical waste (Binnemans et al., 2013; United States Department of Energy, 2022).

Recent experiments indicate that the **salvage value** of NdFeB permanent magnets, depending on the dysprosium content, range from EUR 10 to EUR 15 per kilogram (Jensen, 2018). The value of demagnetised magnets was found to be twice the cost of the demagnetisation process, suggesting potential for optimisation. However, interest in scrapped magnets was limited, with only two European companies expressing interest in contrast with many in China, likely due to uncertainties around recycling and the lack of commercial-scale recycling facilities in the EU. In Europe, the **dysprosium** content significantly influenced the salvage price, rather than neodymium content. Various research networks, including ERECON, REMANENCE, REProMAG, EREAN, DEMETER, and SCRREEN, have focused on different aspects of recycling rare earth materials to enhance material retention within the EU and mitigate sourcing risks, which is also advantageous for companies seeking stable supplies (Jensen, 2018). R&I in this space is ongoing (Telsnig, 2022). For example, the VALOMAG project developed techniques for disassembling and recycling permanent magnets from end-of-life products such as hard disks, electric vehicles, and wind turbines, evaluating methods like hydrogen decrepitation and strip casting for high-quality magnets and hydrometallurgical processes for lower-quality magnets (Coelho et al., 2021). This project achieved a technology readiness level of 6 to 7 and demonstrated that its recycling methods could reduce environmental impact by 31% to 55% compared to virgin magnet production. Similarly, the SUSMAGPRO project created a pilot supply chain for recycled neodymium magnets, applying hydrogen-based technologies to separate and purify neodymium iron boron powders from robotically sorted materials, which were then remanufactured into various magnets and alloys. Pilot reprocessing routes were tested in Germany, Slovenia, and the United Kingdom, ensuring the final products met Siemens Gamesa specifications for wind turbines.

4.2.4 Discussion

The three resource loop strategies for NdFeB magnets in the wind sector – narrow, slow, and closed – offer different paths toward sustainability. The **narrow resource loop** focuses on optimising manufacturing processes to minimise material inputs and losses, an ongoing effort essential for enhancing efficiency. The **slow resource loop** emphasises repair and remanufacturing, representing a more cost-effective and environmentally friendly approach. This strategy benefits from supply chain alignment, particularly among smaller players who leverage spare parts business models. Additionally, the co-design of wind turbine generators is critical to facilitate better repair and remanufacturing options. Nevertheless, this approach requires strong policy support to establish effective systems for collection and refurbishment. The **closed resource loop**, which focuses on recycling EoL NdFeB magnets, presents a viable option but also necessitates regulatory backing and economies of scale. Although recycling may be easier compared to the development of new technologies, it tends to be less environmentally friendly. Therefore, while all three strategies have their merits, the **slow resource loop** appears particularly promising for the wind sector, combining economic viability with environmental benefits, provided that supportive policies are implemented to facilitate these practices.

Despite the potential of the narrow, slow, and closed resource loop strategies for NdFeB magnets in the wind sector, **several barriers hinder their effective implementation** (Rizos et al., 2024). Limited financial incentives for secondary markets and a lack of R&I funding restrict innovation and investment in sustainable practices. Additionally, the absence of ecodesign requirements and clear recycling targets complicates the alignment of industry practices with environmental goals. The complex legal framework governing the intra-EU movement of end-of-life products and insufficient policies for their collection further exacerbate these challenges. There is also a lack of certification systems and a comprehensive EU industrial policy framework, which undermines confidence in the recycling market. Moreover, costly extraction of end-of-life magnets, competition with primary magnets and non-EU suppliers, and volatile rare earth prices contribute to uncertainty about the profitability of recycling. These barriers must be addressed to unlock the full potential of sustainable resource loops in the wind sector, especially with a focus on new responsible innovation prototyping practices and underlying business models to ensure economic viability (Baldassarre et al., 2024; Baldassarre and Calabretta, 2023).

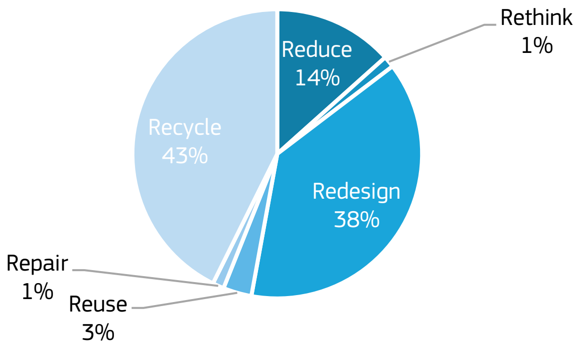
An important path in overcoming these barriers is represented by a **deeper understanding of existing R&I** in this space, based on the systematic study of scientific literature on the subject. A first step in this direction is presented in the next section.

4.3 Systematic analysis of scientific literature on the circularity of NdFeB permanent magnets in wind energy applications

This section presents the results of a **systematic analysis of scientific literature** focusing the circularity of permanent magnets in wind energy applications, building on previous JRC work on research and innovation (R&I) intensity for critical products in the supply chain of strategic technologies (Baldassarre et al., 2023a). This work advances recent analyses on R&I in the supply chain of strategic technologies (Arcipowska et al., 2024; Axt et al., 2023; Baldassarre et al., 2023b; Buesa et al., 2023; Buesa et al., 2024; Nyffenegger et al., 2023). A selection of key findings is reported in Figure 25 and Figure 26. A complete account of the methodology and results of the analysis is provided in Annex 5.

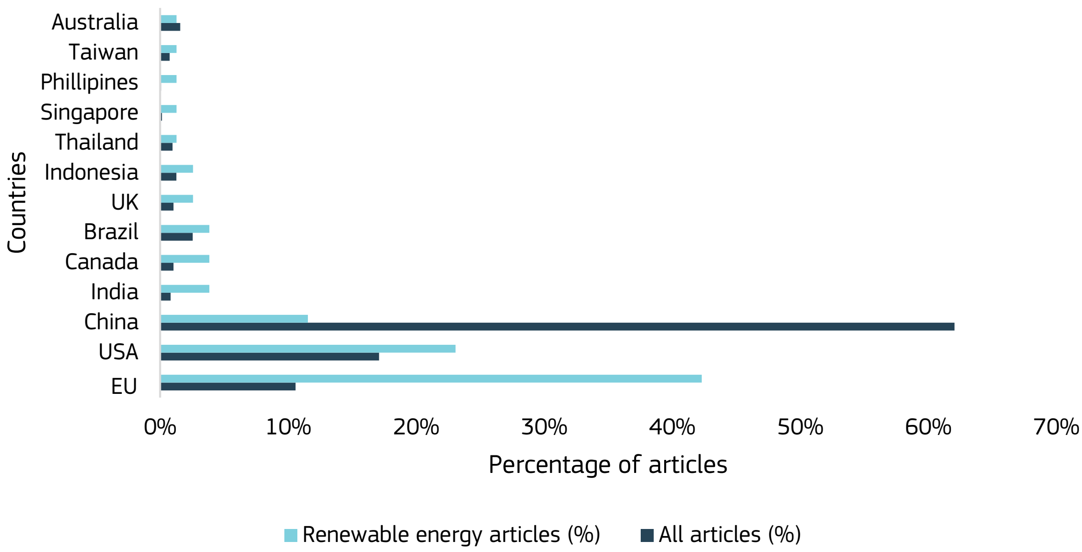
While **considerable progress** has been made in understanding and promoting the circularity of permanent magnets, particularly through **recycling and redesign**, there remain **gaps** in exploring other strategies like **reuse and repair**. Future research should aim to balance short-term, technologically feasible solutions with longer-term approaches that extend product lifetimes and enhance material sustainability. Additionally, the role of the EU in driving both scientific output and funding highlights the region’s pivotal position in advancing circular economy principles in the renewable energy sector, offering a strong foundation for future innovations in this field.

Figure 25. Distribution of articles across different circularity strategies



Source: JRC analysis.

Figure 26. Top funding countries for research on permanent magnet circularity



Source: JRC analysis.

4.4 Circularity and sustainability in Chinese industry and policies

Wind power has been a relatively slow-burn industry in China, compared to the rapid upscaling in the solar PV and electric vehicle (EVs) sectors. However, the preparation for industry dominance can be traced back as early as the 1980s, when China designated rare earths 'protected and strategic materials', and began investing in their mining and refining (Kalantzakos, 2016). In recent years, the wind industry in China has experienced particularly intensive growth, with Chinese companies not only pushing the previously leading EU companies out of the Chinese market, but also initiating rapid global expansion.

This section first outlines a brief history of the sector in China, and explains why the circular economy (CE) is increasingly important for the industry. It then examines the policies and state interventions introduced to boost and monitor CE solutions in the industry. Finally, it touches upon some voluntary industry initiatives to identify good practices and provide a brief overview of up-to-date CE actions in China.

4.4.1 A brief history of wind sector development in China

The development of industrial policies for the wind sector started comparatively early in China, in 1986, with the establishment of its first demonstration wind farm in the province of Shandong (Greenpeace Power Lab, 2022). The first policy to support wind power development titled ''Provisions for Grid-Connected Wind Farm Management'' was issued in 1994. This was followed by the 1997 "double increase programme" aiming to increase the wind power capacity to 160MW, which ended up with success mainly due to foreign governments' involvement supporting sales of their own wind energy technologies to China. However, even at this early stage, the 9th Five-year plan (FYP) (1996-2000) had already set local content requirements at 40%. In years 2003-2007 five rounds of wind concessions were granted by the government on the basis of a competitive bid, and resulted in 18 wind farms with a total of 3350MW capacity, which was a major milestone in wind energy market development in China. Since few local companies existed at the time in China, European industry leaders were encouraged to invest. However, **their entry into the Chinese market was conditional upon partnerships (joint ventures) with local companies and local content requirements** (increased to 70% in 2003), which forced foreign companies to establish production facilities in China, and resulted in **technology transfers to domestic Chinese companies** (Lewis, 2016).

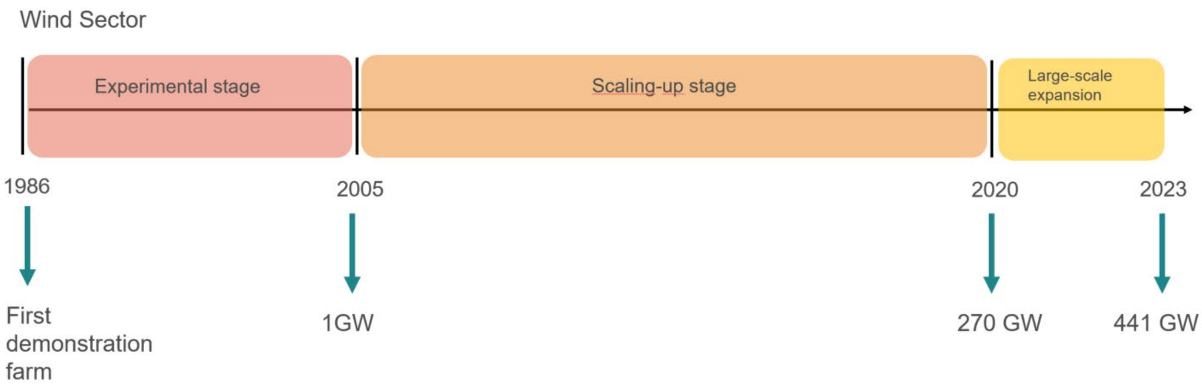
The industry scaled up slowly, with a prominent turning point in 2006 when the **Renewable Energy Law** was introduced, which explicitly prioritised the development of renewable energy among all energy sources (State Council, 2009). Although this law was not exclusive to wind power, it regulated the renewable energy market by introducing targets and establishing preferable feed-in-tariffs, among other things, which was essential for attracting investments and bringing stability to the sector (Lewis, 2016). This policy was later supplemented with various pricing policies, including one on wind power pricing announced in 2009 by the National Development and Reform Commission (NDRC), which established a stable and standardised wind power energy price (NDRC, 2009).

Wind energy remained dominated by state-owned enterprises (SOEs) for much longer than other green energy sectors. Indeed, the first policy to address privatisation was the 2016 **Development plan for wind power,** released as a part of the 13th FYP (2016-2020) (see next section). This policy was designed to partially release the sector from state control and ownership. For the first time, wind turbine companies would be subject to market forces, and the level of subsidies and state support (such as price fixing or subsidies for technological development and upgrading) would be moderated by market mechanisms. However, this was done only partially, in order to stimulate greater competition in the sector and to speed up the outgoing foreign direct investments (OFDI), in alignment with the Belt and Road Initiative. These aims were best served by private or semi-privatised companies, which would be more efficient and create a more market-driven impression overseas. However, state control over wind companies remained strong, resulting in many cases in partial co-ownership, or even majority ownership in the 'privatised' companies.

Since 2021, the Chinese wind sector has witnessed a rapid **displacement of non-Chinese companies with Chinese ones**. Since the onset of the 'going global' strategy of Chinese wind companies, they have also been increasing their stakes in global markets outside China, and pose a threat to the current dominance of EU companies. Chinese companies have a competitive edge in that they offer lower prices and high-quality technology. The combination of generous state subsidies, paired with state control over the price of land and energy, have underpinned this competitive edge, now additionally strengthened by growing overcapacity in the Chinese wind industry. Security of supply, thanks to Chinese control over the entire value chain for wind turbines, ensures the long-term longevity of the Chinese wind industry's global competitiveness.

Figure 27 summarises the development of the wind industry in China from its origin in 1986 to the present day.

Figure 27. Schematic development of the wind industry in China



Source: Own elaboration on the basis of Greenpeace Power Lab (2022) (figures refer to cumulative installed capacity).

4.4.2 Chinese policies concerning wind sector circularity

The speed and scale of wind farm deployment in China, with a cumulative capacity of 441 GW in 2023, of a total 1 020 GW globally (GWEC, 2024), means that in the future, China will face the largest regional volumes of decommissioned wind turbine waste in the world.

In response to this looming challenge, the Chinese central government has made substantial progress on the development of policies for the introduction and strengthening of CE and waste management solutions in the sector. Table 5 below presents a selection of these policies.

Table 5. Key selected policies concerning the circular economy in the wind sector (all policies target the wind and solar sectors).

Year	Policy title and number	Type of policy and aim
2009	Regulations on the Recycling and Management of Discarded Electrical and Electronic Products (State Council [2009] No. 551)[15]	All electronic and electric (EE) waste, Regulatory. **No solar or wind listed as a category**.
2016	13th FYP development plan for wind power (NEA[2016]No. 314)[16]	*Wind, non-CE related* **Partial privatisation** of companies, pushing for OFDI**,** and **moderating subsidies** (partial releasing of pricing control by establishing pricing mechanism based on market bidding with fixed subsidies to drive technological progress and cost reduction)

[15] https://www.gov.cn/gongbao/content/2006/content_240244.htm

[16] http://zfxxgk.nea.gov.cn/auto87/201611/t20161130_2323.htm

2021	14th Five-Year Plan for the Development of Renewable Energy (NDRC [2021] No.1445)[17]	*Wind, Solar among others* **Recycling and processing technologies promotion**
	Guiding Opinions on the Comprehensive Recycling of Bulk Solid Waste (14th FYP) (MEE[2021]No.381)[18]	*Wind, Solar, among others* **Exploring standardised recycling methods for circular, high-value recovery.**
2022	Matters relating to the promotion of the healthy development of the photovoltaic industry chain (NDRC [2022] No.788)[19]	*Wind, solar* **Decarbonisation:** encourage green energy use, **large-scale wind** and PV farms construction**,** among other
	Guiding Opinions on Accelerating the Advancement of Urban Environmental Infrastructure Construction (State Council [2022] No.7)[20]	*Wind, solar, among others;* **100 demonstration projects for utilisation of waste, including wind turbine components.**
2023	Guiding Opinions on Promoting the Recycling of Retired Wind and Photovoltaic Equipment (NDRC [2023] No.1030)[21]	*Wind, Solar,* **Green design**, **standardised recovery**, **high-value utilisation**, **harmless disposal, integration of value chain**
2024	Guiding Opinions on Accelerating the Green Development of the Manufacturing Industry (MIIT [2024] No. 26)[22]	*Wind, Solar,* **Decarbonisation** of manufacturing Accelerate **research, development, and industrial application of CE technologies**

Source: JRC analysis.

Wind turbine circular economy-related policies have been rolled out comparatively recently. This reflects the overall time lag in policy developments concerning the wind turbine sector, especially compared with the much earlier introduction of electric vehicle and solar photovoltaics-related policies (Taylor et al., 2025). Indeed, wind CE policies were introduced around ten years after the first solar PV CE policy was rolled out with ''the 863 Programme'' in 2011. In addition, unlike in solar PV sector, **there is no single policy which only targets wind turbines**: all CE policies for the sector are bundled up with solar PV and often other renewables.

The CE policies concerning wind started with the 14th FYP (2021) and, in particular, with the policies attached to it, such as the 14th FYP for the Development of Renewable Energy, where both solar PV and wind turbine sectors were mentioned, among others, as targets for the development of full lifecycle closed-loop production. The policy also pushed for further development of recycling

[17] https://www.ndrc.gov.cn/xwdt/tzgg/202206/t20220601_1326720.html

[18] https://www.mee.gov.cn/xxgk2018/xxgk/xxgk10/202103/t20210326_826255.html

[19] https://www.ndrc.gov.cn/xxgk/zcfb/tz/202210/t20221028_1339677.html?code=&state=123

[20] https://www.gov.cn/zhengce/zhengceku/2022-02/09/content_5672710.htm

[21] https://www.ndrc.gov.cn/xxgk/zcfb/tz/202308/t20230817_1359879.html

[22] https://www.miit.gov.cn/zwgk/zcwj/wjfb/yj/art/2024/art_f1be5a86074d46c99c20be36713f6838.html

technologies in both sectors. The 2021 14th FYP for Circular Economy Development recognised the importance of the Circular Economy for resource security, targeting both sectors. Other policies were also issued in 2021, including fiscal packages supporting CE-minded companies and activities, and further policies encouraging recycling technology experimentation in both sectors.

Waste management-related policies were issued in 2022-2024, including the building of collection, recycling, remanufacturing, and other relevant infrastructure and establishing demonstration projects. In 2023, NDRC's 'Guiding Opinions on Promoting the Recycling of Returned Wind and Photovoltaic Equipment' added green design to the previously listed fostering of standardised recovery, high-value utilisation and integration of circularity within the value chain. The 2024 Ministry of Industry and Information Technology (MIIT)'s 'Guiding Opinions on Accelerating the Green Development of the Manufacturing Industry' further amplified these priorities, also pushing for the decarbonisation of manufacturing.

4.4.3 Chinese wind turbine companies' CE initiatives

According to their self-declared environmental, social and governance (ESG) reports, Chinese wind companies have undertaken robust measures to integrate sustainability and circularity measures within their value chains. Some examples are listed below.

- **Remanufacturing and repurposing of core components** (Goldwind, Envision). Goldwind established a development and service centre for remanufacturing, which boasts a complete process flow, including component transportation, cleaning, dismantling, process standard setting, testing and recycling. The reuse activities include remanufacturing of gearboxes and generators as spares for replacement in post-service maintenance in operating wind turbines (Goldwind, 2023). Envision also prioritises the reuse of gearbox components: the company's procedure mandates the disassembly of the gearbox and assessment of components for repair before scrapping (Envision Energy, 2022).
- **Reuse/refurbishment of obsolete equipment** (Goldwind). Goldwind has established closed-loop recycling and refurbishment chains, within which it refurbishes old wind turbines for second life applications (selling to businesses as reused products) (Goldwind, 2023).
- **Dismantling, recycling and remanufacturing of obsolete magnetic steel** (Goldwind). In 2015-2022 Goldwind recycled 1 800 tonnes of magnetic steel and recovered 640 tonnes of rare earth ore concentrate. It also remanufactured 1 360 tons of magnetic steel (Goldwind, 2023).
- **Recycling of decommissioned blades** (Goldwind). Some companies have developed programmes to recycle decommissioned blades. For instance, Goldwind is developing an industrial chain to create local recycling centres which crush, screen and mix powder and then 3D-print new products (e.g., garden/flower beds). In order to reduce the costs of transportation, the company also deploys mobile 3D printing robots in the decommissioned wind farms. It also recycles the obsolete blades to produce packaging (pallets) for new blades. The pilot programme has succeeded in recycling 229 blades in 2022 (Goldwind, 2023).
- **R&D projects on developing recyclable blades** (Envision, Mingyang, Sinoma). Three companies have developed technologies which can achieve high levels of recyclability in wind turbine blades. Since 2021, Envision has been using recyclable thermoplastic polyethylene terephthalate (PET) cores. It has also developed a new material, the thermosetting epoxy resin, which is 66% recyclable, and is planning to deploy a new recyclable material,

thermoplastic resins, by 2025 (Envision Energy, 2022). Mingyang developed 95% recyclable thermosetting resin blades in 2023 and is the industry leader in that respect (Norwegian Energy and Environment Consortium, 2023). Sinoma has also integrated thermoplastic composite into their production process, but the recyclability rate for these blades is still unknown (CBMInfo, 2023).

- **Committing to GHG emissions monitoring and targets** (Envision, Mingyang, Titan Wind, Goldwind). Several companies have committed to monitoring their greenhouse gas (GHG) emissions and have made various climate neutrality production pledges. Envision has joined the Science Based Targets Initiatives (SBTIs) and committed to achieving carbon neutrality across its entire value chain by 2028 (with 100% green energy reliance already by 2025) (Envision Energy, 2022). Mingyang has committed to the monitoring of GHG emissions across the value chain (Mingyang, 2023). Titan Wind has set targets for energy efficiency in its production process to increase by 20% in 2025 as compared to 2020 figures (Titan Wind, 2022). Goldwind was the first wind turbine producer to release Environmental Product Declaration (EPD) (Xinjiang Goldwind Science and Technology, 2020).
- **Waste sorting and recycling** (Titan Wind). Some companies have committed to various third-party schemes aiming at sorting waste and directing it to recycling points. This is particularly visible for steel, with companies such as Titan Wind now sourcing 99% recyclable steel from their suppliers, promoting decarbonisation and circularity across the value chain (Titan Wind, 2022).

As is clear from this short overview, **circular economy policies and initiatives in the wind turbine sector in China have been rapidly scaled up in recent years**. Moreover, considering that most policies which encourage recycling (along with associated funding for developing relevant recycling technologies) are initiated by the NDRC, it is likely that funding dedicated to CE policies will continue. It can also be expected that, having being identified as strategic for China's self-sufficiency in the 14th FYP, CE will continue to figure as a key policy area. Finally, there is also a clear push towards standardisation in circular economy technologies in the renewable energy sector. This trend is in line with the China Standards 2035 Strategy which aims to make China the global leader in technology standardisation by 2035 (Central Government of the People's Republic of China, 2018).

4.4.4 EU-China competitiveness

There are several factors posing a major challenge to the EU's competitiveness and economic security vis-à-vis China in the wind turbine sector. Already in 2019, China's investments in wind energy assets were three times those of EU investors (Alves Dias et al., 2022). Despite the EU wind turbine companies' long-standing dominance in the international markets, Chinese companies' lower production costs and their control over the relevant value chains puts **Chinese companies in a privileged position, likely to upend** EU companies in international markets (and possibly also in the EU market). In addition, China's wind turbine industry has been running over capacity for several years now, which puts pressure on domestic EU companies and the EU wind market (Yu et al., 2021). Finally, China's dominance in wind turbine value chains, especially the EU's dependence on China for NdFeB permanent magnets, **directly impacts the EU's economic security**.

The circular economy is both a new frontier in this **competition** and an area of possible **cooperation** and alignment between China and the EU in relation to climate goals. Thus, any potential cooperation in this area needs to be carefully weighed against the possible risks linked to diverging objectives.

This necessitates a better understanding of the actual objectives of Chinese circular economy policies and initiatives, and their possible impact on the EU market.

For the wind sector, as compared to other renewable sectors, especially solar, Chinese CE policies have been less concerned with boosting domestic technological development and competitiveness, and more with the **environmental goals of effective waste utilisation**. They do not focus, for instance, on the development of recycling technology as they do in the solar sector, and they refer to "technological upgrading" in rather vague terms. As to the waste policies, while clear progress has been initiated towards creating full lifecycle waste treatment and a comprehensive recycling system for wind turbines, this area remains relatively underdeveloped. Indeed, wind turbine-related CE policies focusing on circularity were deployed relatively late (around 2021) and these policies bundle wind with solar, revealing a lack of clear focus on the wind sector. In addition, as previously noted in the context of Chinese CE policies in general, clear indicators and targets for recycling rates are lacking (Wang et al. 2020, Alves Dias et al., 2022), which is also the case for wind turbine-specific CE policies.

However, for the wind sector overall, beyond circularity, **Chinese** policies have placed a **clear focus on technological upgrading**. In comparison, **EU** policies for the wind industry have been much **more climate mitigation-focused**. Only very recently, with the addition of the EU Wind Power Action Plan, Net-Zero Industry Act and Critical Raw Materials Act, has the EU started to integrate more **industrial competitiveness considerations**. Conversely, Chinese policies have long been oriented towards industrial targets: they have prioritised the maintenance of subsidies and fixed prices for wind energy (though most subsidies have recently been phased out), technological development and the creation of industrial standards. This focus is also apparent in CE policies, judging from the fact that the leading ministries for these policies are mostly NDRC or MIIT: the same two ministries who are responsible for industrial policy and R&D development.

For the EU, the challenge lies in how to respond to such a **combination of climate mitigation and industrial policies**, as this situation currently exacerbates an already uneven playing field for EU companies. This is because there are few constraints for products manufactured using more carbon-intensive sources of energy (and produced with lower ESG standards overall) to enter the EU market and outcompete EU products (which meet higher ESG standards) on the basis of price. While Chinese CE policies might aid a shared climate mitigation objective, they might also limit the EU's policy toolkit to protect an increasingly fragile domestic market. There are currently no policies constraining access to the EU market on the basis of non-price criteria such as ecodesign. Even if these were to be further developed, due to increasing momentum in recent years for decarbonisation and circularity in Chinese value chains, the capacity of such policies to support home industries is time-limited. In addition, the EU recycling industry is still nascent. In other words, **the crucial time window** during which such policies could still aid the domestic wind industry, which is increasingly under pressure to compete with Chinese companies even in the domestic market, **is rapidly shrinking**.

5 Substitution, advanced materials and technological developments

5.1 Rare earths, permanent magnets and generators

The EU's reliance on imported raw materials from a limited number of third-country suppliers poses significant risks to the security of supply, potentially undermining the EU's ability to achieve its energy and climate objectives. This is particularly true for REEs, and the products containing them.

To mitigate these risks, several strategies can be explored. These can be broadly clustered in two categories: **substitution and reduction**.

The **substitution** category includes:

- approaches that substitute a **CRM** with a non- or less critical raw material within a component;
- substitution of **entire components** or technologies with others that require less or no CRM;
- substitution of **processing technologies** that enable the elimination of certain materials.

The **reduction** category includes:

- optimisation of **component design**;
- **processing improvements** that improve efficiency and enable reductions of material usage.

Advanced materials play a key role in most approaches, as they provide enhanced and targeted properties within the components in which they are used.

5.1.1 Substitution

5.1.1.1 CRM substitution

Replacing dysprosium and neodymium with **cerium and lanthanum** in permanent magnets (PMs) is an example of one-for-one material substitution. Cerium (Ce) and lanthanum (La) are mined together with other rare earth elements (REEs), and coextracted mainly from bastnaesite and monazite, along with neodymium (Nd), dysprosium (Dy), and other REEs. They represent some 70% of the weight of REEs in said minerals, but less than 10% of their commercial value and are in many cases stored as the demand is lower than the supply. The properties of PMs with Ce and La remain similar to those of conventional NdFeB magnets for up to 20% substitution (albeit with a lower Curie temperature, decreasing their operating temperature range), but drop significantly for higher substitution rates. The maturity of Ce-La PMs is estimated to be at TRL 4-6. While Ce and La cannot entirely substitute more critical raw materials, decreasing their use has the potential to decrease negative environmental and social impacts linked to extraction of Nd and Dy.

5.1.1.2 Component or technology substitution

Substituting PMs with high temperature superconductors is an example of a technology substitution. **High temperature superconductors (HTS)** use superconducting windings, which can generate magnetic fields which are a hundred times stronger than copper windings of the same dimension (Pavel et al., 2017). Consequently, HTS turbines are significantly smaller and lighter. HTS operate at temperatures of 30-50 K (i.e., between -243 °C and -223 °C) and therefore require an advanced cooling system utilising mainly liquid nitrogen. An HTS-based 3.6 MW wind turbine has been demonstrated and operated for 650 hours, providing power to the grid (Bergen et al., 2019). Hence, the maturity of this approach is estimated to be at TRL 6-7. While the performance of the turbine is similar, the main advantage of HTS turbines is the significantly lower weight, which allows the use of floating foundations which can be installed in deeper waters (up to 220 m compared to 50-60 m for monopiles and jackets often used with PM generators) (Horwath et al., 2020), as well as lighter towers which utilise less material. The elimination of CRMs significantly reduces the adverse impacts linked to CRM sourcing. Nevertheless, challenges that still need to be addressed are the **complex cooling system** required to reach temperatures below 50 K (-223 °C) and the **high cost of superconductive wire**.

Rotary electrical contacts are a technology that could replace Permanent Magnet Synchronous Generators (PMSG), under development by Sandia National Laboratories in the USA and currently at TRL 5 (Staats, Jr. et al., 2018). The approach utilises an electrically conductive belt or chain interacting with an epicyclic two-degree-of-freedom structure to transfer charge to a wire-wound generator, similar to an open differential gear set. It eliminates PMs and therefore REE use, although it relies on windings, which require higher amounts of copper compared to PMSG. Due to the continuous contact of the belt/chain, the efficiency penalties are minimal, and generator efficiency is similar to PMSG. Service life is estimate at 30 years, while 50 million rotation cycles have been demonstrated (although it is not clear whether this is in the absence of current). Environmental and social impacts are lower due to the absence of REEs. The LCOE of the technology is similar to PMSG, estimated at 122.5 USD/MWh (Staats, Jr. et al., 2018). One of the challenges that need to be addressed is the growth of **oxide film formation on copper surfaces** and its influence on grain growth.

Iron nitride magnets are an example of a component/technology that could replace PMs. They are already commercial for low value applications such as speakers, while efforts are being made to scale them up for use in wind turbines. Niron Magnetics (USA) and GreenSpur (UK) are working on a 15 MW demonstrator, announced in 2022. Iron nitrite has the potential to arrange iron into a structure so that the free electrons in the iron atoms spin in the same direction. This generates a strong magnetic field due to the high number of free electrons in iron atoms, similar to the properties provided by REEs (Crownhart, 2024). The energy product of commercially available magnets (by Niron Magnetics) is around 10 MGOe, which is significantly lower than the ~50 MGOe required for wind turbines, but the theoretical energy product maximum is above 130 MGOe, higher than NdFeB-based PMs. Due to the elimination of REEs, the negative environmental and social impacts are significantly reduced. **Costs** are currently higher than PMSG due to the lack of economies of scale, although they are expected to be significantly lower in the long term, due to the elimination of REEs. The primary focus for commercialisation will be to **enhance the energy product**.

Electrically Excited Synchronous Generators (EESGs) were commercially available before Permanent Magnet Synchronous Generators (PMSGs) gained prominence. With certain improvements, EESGs could serve as a viable alternative, particularly for onshore applications. As described in Chapter 1, gearless EESGs make use of a wound rotor excited by a direct current source using slip-rings and brushes. Some manufacturers have also made brushless variants that require less maintenance, e.g., Enercon. They have the potential to eliminate REEs since they do not use PMs, but would increase the use of copper used for the windings. Due to the absence of REEs they avoid the negative environmental and social impacts linked with REE sourcing. Nevertheless, they **have lower performance due to resistive heat losses, copper losses, and brush friction**, among other factors. Efficiency is 6% lower than most efficient plants with PMSGs (Habib and Wenzel, 2016; Månberger and Stenqvist, 2018; Shahni et al., 2019).

5.1.1.3 Process substitution

An example of process substitution is the use of **additive manufacturing (AM)** technologies to produce PMs, which is an alternative to the established powder metallurgy process route. The desired shape is acquired by the successive addition of layers. The main strength of the process is its potential to reduce scrap rates, and therefore the use of initial material to manufacture the permanent magnet, as well as the production of complex shapes. Such complex shapes could introduce cooling channels which could further reduce the operating temperature and therefore the need for certain CRMs. At the moment, AM for PM production is still in its infancy. AM printed magnets are porous and exhibit relatively **low density and poor thermal stability**, which limits application at elevated temperatures. In addition, they require various post-processing steps (e.g. machining, polishing, and sintering).

5.1.2 Reduction

5.1.2.1 Design optimisation

Optimisation of PMSG design entails improvements in design and the use of a cooling system to **decrease the operating temperature** of the turbine. Decreasing operating temperature allows for the use of lower grade and/or regular grade magnets instead of high temperature, which have lower REE content, mainly dysprosium. In addition, reducing operating temperature increases the performance of the magnet, since typically, NdFeB magnets operate best at lower temperatures (Bhuiyan and McDonald, 2019). Optimised designs can have a similar performance to conventional designs while using lower amounts of REE, or higher performance for the same REE content. If an active cooling system is used, some of the energy harvested will be used for the cooling of the turbine. Based on modelling, it is shown that using a regular magnet at 80 °C (with cooling) instead of an H grade magnet at 80 °C can reduce the turbine cost of energy by about 0.1%. This is partly explained by reduced copper losses and additional remanent flux density. It is worth mentioning that the additional cooling system cost and energy consumption accounts for about 0.3% of the cost of energy (Bhuiyan and McDonald, 2019). Environmental and social impacts could be reduced as well, due to the lower amounts of REE used. The main challenges of this approach include optimisation of magnet design without sacrificing robustness, as well as the design of an **efficient cooling system** that does not add significant weight to the tower (which would increase material use).

5.1.2.2 Process improvement

The use of the **Grain Boundary Diffusion (GBD)** process is an example of a process improvement. It involves diffusing dysprosium, terbium, or other heavy rare earth elements (HREE) into the grain boundaries of NdFeB magnets by coating the surface of the sintered magnets with HREE compounds and performing a thermal treatment, allowing the HREE element to penetrate the magnet, rather than incorporating these elements uniformly throughout the magnet. This method allows for the **more efficient use of dysprosium** by concentrating it where it is most needed – at the grain boundaries – where it can effectively enhance coercivity and thermal stability. The process can result in achieving the same performance with lower amounts of dysprosium. Using current production technology, the amount of dysprosium can be reduced by half, being brought down to 2% in content without reducing coercivity (Gielen and Lyons, 2022). While this is a promising technology, considered to have reached market maturity, the main challenge is to increase the throughput of the process, since the magnet needs to be at temperatures of 800-1 000 °C for several hours. In addition, improvement of Dy diffusion would allow for more uniform properties.

5.1.3 Discussion

While substitution and reduction strategies enable the reduction of adverse social and environmental impacts linked with the extraction of CRMs, there is currently **no silver bullet**. The uptake of these strategies means overcoming challenges such as **improving the performance of alternatives, reducing costs, and increasing process throughput**. Still, reducing the EU's reliance on CRMs will ultimately require a combination of measures including at least some of the strategies outlined above.

5.2 Balsa wood and blades

Balsa wood is a critical component for wind turbine blades, being primarily used as a core material within composite structures. However, as highlighted in earlier chapters, the growing demand for wind energy and the inherent limitations in balsa wood availability have prompted a shift toward exploring alternative materials and innovative solutions. These advances are not only aimed at addressing **supply challenges** but also at enhancing the **sustainability and efficiency** of blade manufacturing as a whole.

5.2.1 Emerging alternatives

A key substitution material gaining prominence is **recycled polyethylene terephthalate (rPET)**, which offers comparable structural benefits to balsa wood while leveraging circular economy principles (Telsnig et al., 2022). rPET is derived from post-consumer waste, making it a more sustainable choice that reduces dependency on natural resources. Additionally, **polyurethane foams and resins** and other synthetic core materials have emerged as strong contenders, offering lightweight and structurally sound alternatives with high scalability (Ahmad and Haq, 2011; Covestro/bewind, 2022). **Hybrid designs** are also gaining traction, combining materials like glass fibre composites, rPET, and bio-based substances. These approaches not only reduce reliance on any single material, such as balsa wood, but also optimise blade performance, making them better suited to future turbine designs that demand greater efficiency and recyclability (Telsnig et al., 2022).

5.2.2 Challenges to scaling substitutes

Despite the promise of alternatives, there are several challenges to widespread adoption. For instance, transitioning to rPET depends on the establishment of efficient **collection and processing systems for recycled plastics**. Similarly, the production of synthetic materials, such as polyurethane foams, can involve **energy-intensive processes**, raising concerns about their life-cycle carbon footprint.

From a manufacturing perspective, integrating new materials into turbine blade designs requires significant **re-engineering of production methods**. Blade manufacturers must validate these materials to ensure they meet stringent safety and performance standards, which can involve extensive testing and regulatory approval. Investments in R&D, as well as close collaboration between material suppliers and turbine manufacturers, will be crucial in overcoming these barriers.

Substituting balsa wood with advanced materials and hybrid solutions is not just about addressing material availability. It represents a broader shift in how blades are **designed and manufactured**. New materials offer opportunities to improve the recyclability of blades, addressing the circularity challenges highlighted earlier in this report. Additionally, they open avenues for innovations in blade **aerodynamics and durability**, allowing for longer, more efficient blades that can operate under diverse environmental conditions.

6 Conclusions and policy recommendations

6.1 Conclusions

The wind turbine supply chain is a complex global network which plays a critical role in the transition to renewable energy. The following conclusions are based on comprehensive analysis, including the sourcing of critical elements, the manufacturing and assembly of components, the companies operating along the supply chain, future materials streams, circularity challenges and opportunities, and the routes for material substitution.

The wind turbine supply chain is exposed to geopolitical, environmental and economic risks. It is highly dependent on the sourcing of critical raw materials such as rare-earth elements, which are subject to supply risks. Raw material processing and the manufacturing and assembly of components are also concentrated in a limited number of countries and vulnerable to disruption.

Our supply risk analysis has identified two critical supply chains characterised by high risk: the first involves the **rare earth-based permanent magnets** needed for power generation in wind turbines, while the second is **balsa wood**, the key material in wind turbine blades.

The REE market is dominated by China across the whole permanent magnet value chain, from raw materials to magnet production. This concentration of production in one country poses significant risks to the supply chain, particularly in terms of geopolitical risks and the strategic autonomy of the EU and other economies.

No mining of REEs is currently taking place in Europe and only one processing plant is active, owned by the Canadian company Neo Materials. REE deposits do exist in the EU, and European mining companies have started the processes of building mines. However, the permitting process is long and cost-intensive. The **permanent magnets** needed for wind turbine generators are mainly produced in **China** by Chinese companies. Only a few European companies operate in this area; Vacuumschmelze, Neorem and Magneti Ljubljana among them. The manufacturing of other components (blades, nacelles, and towers), power generators and the final assembled wind turbines **is carried out domestically**, mostly by European companies (Vestas, Siemens Gamesa, Nordex and Enercon).

This work has developed two **material demand scenarios**, defined as BASE and INNO, covering the EU, the US, China, and the world, over a time horizon from 2022 to 2050. The BASE scenario broadly follows recent market and technological trends, while the INNO scenario assumes higher R&D investment, driving market innovation. Our scenarios indicate that **both EU and global demand for wind turbine materials will rise considerably in the coming decades**, requiring significant shares of the current global supply for all applications, especially in the case of rare earths and balsa wood. For instance, **global demand for terbium and dysprosium is expected to more than triple** from 2022 to 2030 for wind turbine production alone, reaching similar levels to the elements' current consumption rate across all sectors. For balsa wood, global demand **may be more than double the current total supply** of this material by 2030. However, a **slowdown in turbine deployment, combined with technological advancements** that reduce material intensity, could lead to a decline in demand over the long term, at least within the considered scenarios. Significant technological progress (such as that considered in the INNO scenario) could even lead to an **overall reduction in demand** by 2050 compared to current rates, despite increased wind turbine deployment.

Our analysis of decommissioned materials shows that **significant quantities of REEs will become available for recycling or disposal** by 2050: 241 t/yr of neodymium, 27 t/yr of praseodymium, 25 t/yr of dysprosium, and 6 t/yr of terbium (based on the wind energy power installed in the EU by 2023). This corresponds to 31-35% of REE demand in 2050 in the INNO scenario or to 11-16% of REE demand in the BASE scenario. The recycling of these materials will thus be critical in reducing the demand for primary materials and mitigating supply risks.

The circularity of NdFeB magnets in the wind energy supply chain is a complex issue that requires a multifaceted approach. The three resource loop strategies for NdFeB magnets in the wind sector – narrow, slow and close – each contribute to sustainability in different ways. The narrow loop aims to optimise manufacturing by reducing material inputs and losses, a key factor in improving efficiency. The slowed loop prioritises repair and remanufacturing, offering a cost-effective and environmentally friendly alternative. The closed loop focuses on recycling end-of-life (EoL) NdFeB magnets, a promising approach that requires regulatory support and economies of scale to become widely viable.

Despite the potential of these strategies, **several barriers hinder their effective implementation**. The absence of adequate recycling infrastructure prevents the full-scale development of these processes, limiting their impact. Limited financial incentives for secondary markets and insufficient R&I funding restrict innovation and investment in sustainable practices. Additionally, the absence of ecodesign requirements and clear recycling targets complicates the alignment of industry practices with environmental goals. The complex legal framework governing the intra-EU movement of end-of-life products and insufficient policies for their collection further exacerbate these challenges.

Our analysis highlights the **need for a deeper understanding of existing R&I** in this area, based on the systematic study of scientific literature on the subject. This understanding is crucial for overcoming the barriers to the implementation of sustainable resource loops in the wind sector. Furthermore, our analysis emphasises the importance of **policy support** in establishing effective systems for collection and refurbishment, as well as the need for certification systems and a comprehensive EU industrial policy framework.

The **substitution of rare earth elements** in wind turbine generators, along with the development of advanced materials and other technological advancements, are crucial for reducing the sector's reliance on critical raw materials. The potential for substitution is significant, particularly in the development of new, magnet-free technologies and the use of alternative materials. Advanced technologies, such as high-temperature superconductors, also offer promising opportunities for increasing efficiency and reducing material usage. Substitution routes are also available for **balsa wood in blades**, though these are not without challenges.

Continued innovation and investment in research and development are needed to drive these advancements forward. The development of new technologies and materials will be critical in reducing the wind energy sector's environmental impact and improving its sustainability. Additionally, our analysis emphasises the importance of considering the **entire value chain** when assessing the sustainability of wind energy technologies. By taking a holistic approach, the sector can identify opportunities for improvement and work towards a more sustainable, resilient future.

6.2 Policy recommendations

Based on the findings of this report, and building on the spirit of the Critical Raw Materials Act (CRMA) and the Net-Zero Industry Act (NZIA), we propose the following **policy recommendations for strengthening the wind energy supply chain in the EU**.

- **Strengthening rare earth supply chains for wind energy**
  - **Increase EU production capacity**: Invest in domestic mining and refining of rare earth elements, such as neodymium and dysprosium, which are critical for permanent magnets in wind turbine generators; incentivise exploration and sustainable extraction projects to meet the CRMA benchmarks.
  - **Diversify imports and partnerships**: Establish strategic partnerships with like-minded third countries for rare earth sourcing, focusing on countries with strong environmental and ethical governance; negotiate long-term supply agreements to reduce reliance on China, which dominates rare earth processing globally.
  - **Improve processing capabilities**: Invest in EU-based rare earth processing facilities to reduce dependency on external processors, notably to take full advantage of the recycled material streams (see next point); and support public-private partnerships to develop state-of-the-art processing technologies.
- **Advancing circular economy in wind energy materials**
  - **Enhance rare earth recycling**: Support programmes to recover rare earths from decommissioned wind turbines and other sources, and invest in advanced recycling technologies to maximise material recovery and create a closed-loop system.
  - **Standardise and regulate recycling practices**: Develop EU-wide standards for dismantling and recycling wind turbines to ensure consistent material recovery rates; and require manufacturers to design turbines with recyclability in mind, focusing on easier extraction of magnets and other critical components, while at the same time ensuring the safe operation and functionality of the turbines.
- **Supporting innovation in wind turbine design**
  - **Develop magnet alternatives**: Fund research into alternatives to NdFeB magnets for turbine generators, such as ferrite-based or advanced ceramic magnets, which can reduce reliance on rare earth elements.
  - **Explore superconducting technologies**: Invest in the development of superconducting generators for wind turbines, which promise higher efficiency and reduced dependence on rare earths.
  - **Promote modular designs**: Encourage modular designs for wind turbines that allow for easier maintenance and replacement of components, extending their lifecycle and reducing material waste.
- **Enhancing EU manufacturing and upstream capacity**
  - **Leverage existing strengths in manufacturing**: Building on the fact that the EU already hosts global leading wind turbine manufacturers (unlike the solar and battery

sectors), reinforce and expand domestic manufacturing capabilities, ensuring sustained competitiveness and technological leadership.

  - **Develop upstream capacity**: Focus on developing domestic capacity for raw material extraction, processing, and component manufacturing, ensuring that every step of the value chain is robust and sustainable.
  - **Accelerate offshore deployment**: Streamline permitting and planning for offshore wind projects; prioritise grid integration and port infrastructure development to accommodate larger and more advanced turbines.

- **Improving supply chain transparency and resilience**
  - **Digital supply chain mapping**: Create a real-time digital platform to track rare earths and wind turbine components across the supply chain; use this platform to assess risks and plan mitigation strategies for disruptions.
  - **Strategic stockpiling**: Establish EU stockpiles of strategic and critical raw materials, notably rare earths, to buffer against supply chain shocks.
  - **Joint purchasing**: Establish an EU joint purchasing mechanism to cover (a significant share of) the collective needs of the EU wind turbine industry, with the purpose of increasing resilience, negotiating better prices, and reducing the impact of price volatility.
- **Aligning policies with sustainability and strategic autonomy**
  - **Ethical sourcing standards**: Collaborate with international organisations to ensure rare earths and other materials are sourced responsibly; require suppliers to adhere to strict environmental and social standards; trace the origin of materials and ensure the conformity of the sourced materials to the established standards.
  - **Leverage EU trade agreements**: Incorporate strategic raw material and critical raw material access and sustainability clauses into trade agreements with exporting nations to secure reliable and ethical supply chains.
- **Addressing workforce and skills gaps**
  - **Training for wind energy specialists**: Develop EU-wide training and certification programmes to prepare workers for roles in wind turbine manufacturing, installation, maintenance, and recycling.
  - **Promote STEM education**: Focus on science, technology, engineering, and mathematics (STEM) education to ensure a steady pipeline of talent for the wind energy sector.
- **Research and monitoring for adaptive policymaking**
  - **Invest in long-term research**: Support ongoing research into material substitution, recycling technologies, and supply chain optimisation for wind turbines.

Concerning competitiveness in relation to China, and specifically the landscape depicted in Section 4.4, we propose two sets of policy recommendations: one concerning **legislative** measures and the second concerning **diplomatic** tools.

The **legislative measures** should reflect the above-mentioned challenges emerging from the current approach to the wind sector and the prioritisation of carbon-neutrality. We recommend the following.

- Explore the possibility of **ecodesign measures** for key components in wind turbines to ensure their recyclability, durability, energy yield, and other ESG measures in the production process.
- Develop a separate **waste from electrical and electronic equipment (WEEE) category for permanent magnets**, which boosts the re-use of permanent magnets and retrieval of the REEs contained therein.
- Make the **circular economy** (CE) approach more central in legislation concerning the development, production and deployment of renewable technologies.
- Ensure that **key components**, such as permanent magnets, **stay in the EU** after decommissioning.

While the legislative recommendations above address competitiveness, the **diplomatic tools** recognise the win-win potential for both the EU and China of a circular approach. These include the following.

- **Registering patents and setting standards for CE technologies** may soon play a part in global competition, as Chinese companies develop novel CE solutions for EoL treatment. A possible area of cooperation and dialogue would be that concerning the **harmonisation of international rules and standards** and a **common taxonomy**. Comparing CE indicators and current data sets could also aid both actors' progress towards greater circularity.

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Chapter 2 Supply chain mapping and risk analysis

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Chapter 5 Substitution, advanced materials, and technological developments

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List of abbreviations and definitions

Abbreviations	Definitions
AM	Additive Manufacturing
BASE	Baseline scenario
CE	Circular Economy
CRM	Critical Raw Material
CRMA	Critical Raw Materials Act
DD	Direct-drive
DFIG	Double-Fed Induction Generator
EESG	Electrically Excited Synchronous Generator
EoL	End-of-Life
EoL_{RIR}	End-of-life Recycling Input Rate
EPD	Environmental Product Declaration
EPR	Extended Producer Responsibility
ESG	Environmental, Social, and Governance
EV	Electric Vehicle
FYP	Five-Year Plan
GB	Gearbox
GBD	Grain Boundary Diffusion
GHG	Greenhouse gas
HEV	Hybrid Electric Vehicle
HHI	Herfindahl-Hirschman Index
HREE	Heavy Rare-Earth Element
HTS	High-Temperature Superconductor
ICT	Information and Communications Technology
INNO	Innovation scenario
IR	Import Reliance
IRA	Inflation Reduction Act
LLM	Large Language Model
LREE	Light Rare-Earth Element
MIIT	Ministry of Industry and Information Technology

Abbreviations	Definitions
NDRC	National Development and Reform Commission
NZIA	Net-Zero Industry Act
OFDI	Outgoing Foreign Direct Investment
PET	Polyethylene terephthalate
PM	Permanent Magnet
PMSG	Permanent Magnet Synchronous Generator
RED	Renewables Energy Directive
REE	Rare-Earth Element
R&D	Research and Development
R&I	Research and Innovation
rPET	Recycled polyethylene terephthalate
SBTI	Science Based Targets Initiative
SCIG	Squirrel Cage Induction Generator
SG	Synchronous Generator
SI	Substitution Index
SOE	State-Owned Enterprise
SR	Supply Risk
SRM	Strategic Raw Material
STEM	Science, Technology, Engineering, and Mathematics
TRL	Technology Readiness Level
US(A)	United States (of America)
WGI	World Governance Index
WRIG	Wound Rotor Induction Generator

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Annex 1. Methodology for the supply chain analysis

In the Criticality Assessment exercise, the Supply Risk for raw materials is calculated according to the following formula (EC, 2017):

$$SR = \left[(HHI_{WGI,t})_{GS} \cdot \frac{IR}{2} + (HHI_{WGI,t})_{EUsourcing} \left(1 - \frac{IR}{2}\right) \right] \cdot (1 - EoL_{RIR}) \cdot SI_{SR} \quad (1)$$

Where:

- *SR = supply risk;*
- *GS = global supply, i.e. global suppliers countries mix;*
- *$EU_{sourcing}$ = actual sourcing of the supply to the EU, i.e. EU domestic production plus other countries importing to the EU;*
- *HHI = Herfindahl-Hirschman Index (used as a proxy for country concentration);*
- *WGI = scaled World Governance Index (used as a proxy for country governance);*
- *t = trade parameter adjusting WGI;*
- *IR = import reliance;*
- *EOL_{RIR} = end-of-life recycling input rate;*
- *SI_{SR} = substitution index related to supply risk.*

Source: EC (2017).

The $HHI_{WGI,t}$ parameter describes the concentration of supply and is defined as follows (EC, 2017):

$$(HHI_{WGI,t})_{GS\ or\ EUsourcing} = \sum_c (S_c)^2 WGI_c * t_c \quad (2)$$

where:

- *S_c = the share of country c in the global supply mix or in the EU sourcing mix of the raw material considered;*
- *WGI_c = the scaled World Governance Indicators of country c;*
- *t_c = the trade-related variable of country c for a candidate raw material (RM).*

Source: EC (2017).

The WGI is an indicator produced by the World Bank aggregating the following six dimensions of governance: voice and accountability, political stability and absence of violence/terrorism, government effectiveness, regulatory quality, rule of law, and control of corruption (World Bank, 2022). WGI is used to assess quantitatively a country's governance. Carrara et al. (2023) considered the average between the six parameters from 2016 to 2020. The original parameter is comprised between -2.5 and 2.5, but then it was scaled up to between 0 and 10 in the Criticality Assessment (EC, 2023), and so was in Carrara et al. (2023).

The t_c trade parameter quantifies the impact that trade conditions (e.g., export restrictions and trade agreements between countries) have on the Supply Risk related to a specific country for a candidate raw material. EC (2017) reports detailed instruction to calculate this parameter, which can amount to 0.8 (EU countries) or between 1 and 2 (non-EU countries, depending on the actual trade conditions).

The import reliance is calculated as follows (EC, 2017):

$$Import\ Reliance\ (IR) = \frac{Net\ Import}{Apparent\ Consumption} = \frac{Import - Export}{Domestic\ production + Import - Export} \quad (3)$$

Source: EC (2017).

EoL_{RIR} indicates the end-of-life recycling input rate, i.e., the material demand share covered with secondary sources, while the substitution index (SI_{SR}) is a measure of the possible substitution options which may reduce the supply risk. This parameter is calculated according to detailed instructions reported in EC (2017) and can range between 0.8 and 1.

As specified in Section 2.1, Carrara et al. (2023) directly sourced the Supply Risk values for raw materials from the 2023 Criticality Assessment (EC, 2023), while calculated them for the elements in the supply chains steps following raw materials. In principle, the same Supply Risk formula has been used in those steps. Practically, data that are needed to calculate the parameters appearing in the Supply Risk formula according to Equation 1 are often difficult to find for most of the elements beyond raw materials, especially for the EU sourcing and the import reliance. Also, it is very difficult to assess the substitution options for these elements. Therefore, the following simplified formula based on global supply and derived from Equation 1 was often applied in Carrara et al. (2023) for the elements after raw materials:

$$\boldsymbol{SR = \left(HHI_{WGI,t}\right)_{GS} \cdot (1 - EoL_{RIR})} \qquad (4)$$

Source: Carrara et al. (2023).

Also, the t_c trade parameter for non-EU countries is always set to 1, which implies no specific trade restrictions or regulations.

The reader is referred to Carrara et al. (2023) for further details on the practical calculation of the Supply Risk.

Annex 2. Historical wind turbine deployment shares

Figure 28 shows the historical annual deployment shares for onshore and offshore wind turbines in the EU, US, China, and the world. Data are available back to 1991 for the EU and the world and to 2010 for the US and China.[23][24] For details on the different technologies and acronyms, please refer to
Section 1.3.2.

Technology adoption in the **onshore wind** sector has progressed gradually, leading to a relatively balanced mix of technologies today. While dominating the market in the early 1990s, GB-SCIG_NC and GB-WRIG turbines were phased out over time as GB-DFIG turbines steadily gained market share, now accounting for around 50% of the yearly installations in the EU, China, and globally, and more than 80% in the US. This dominance is now being increasingly challenged by the rise of permanent magnet turbines (DD-PMSG and GB-PMSG) as well as SCIG turbines. On the other hand, DD-EESG turbines have maintained a relatively consistent deployment share throughout the considered period.

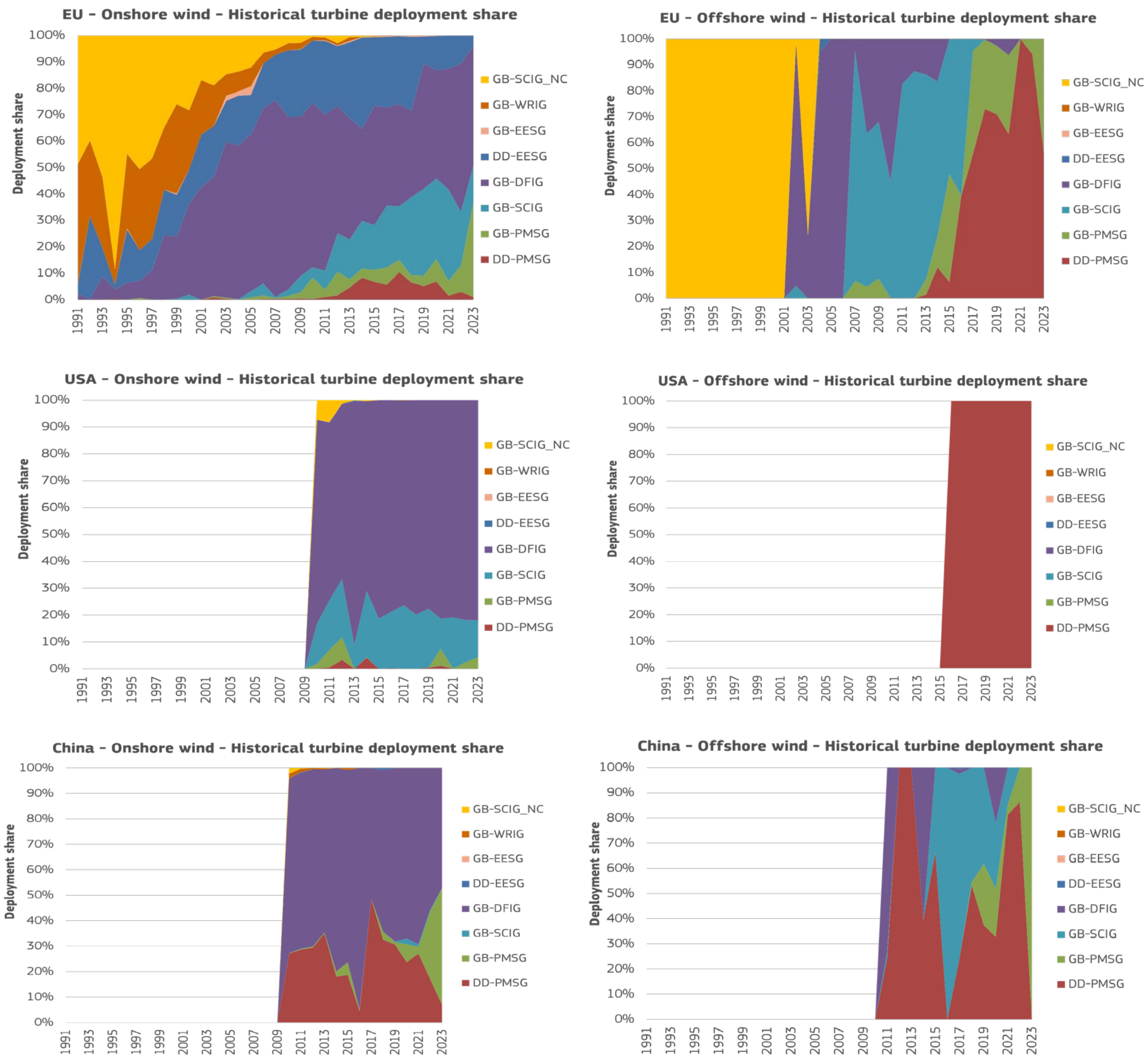
Differently from the onshore sector, the **offshore wind** market has been characterised by very distinct phases, common to both the EU and global levels (after all, until some ten years ago the EU featured most offshore installations in the global market). From the early 1990s to the early 2000s,

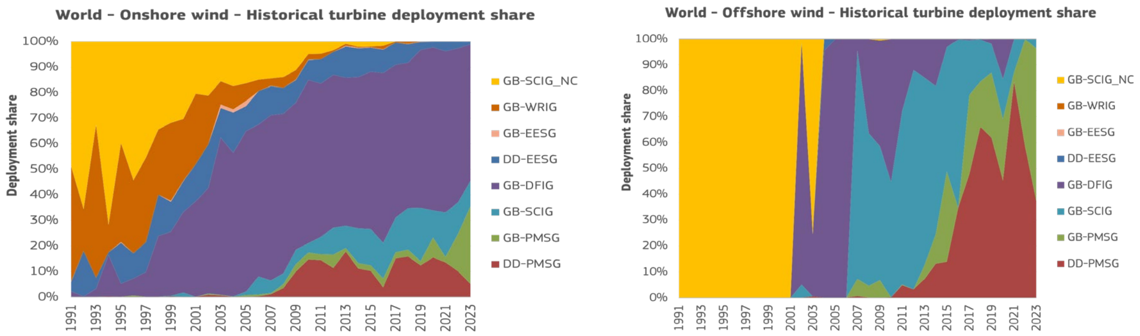
[23] The “Brussels effect” is the process of European Union (EU) regulations spreading well beyond the EU’s borders.

[24] For offshore wind in the US, Figure 28 presents data starting from 2016, as installations were negligible before.

the market was dominated by GB-SCIG_NC turbines. These were supplanted by GB-DFIG turbines, which, in turn, were replaced by the widespread adoption of GB-SCIG turbines around 2007. Starting from the beginning of the past decade, these turbines have been gradually replaced by permanent magnet turbines which by now dominate the offshore wind market in all regions, as already discussed in Section 3.1.2. Between the two PM turbine types, over the years there has been a clear prevalence of the DD-PMSG turbines, although 2022 and 2023 saw a significant rise in the adoption of GB-PMSG turbines (the next years will determine whether this marks the start of a consolidated trend or if it was a temporary phenomenon).

Figure 28. Historical deployment shares of onshore (left) and offshore (right) wind turbine sub-technologies in the EU (top), US (mid-top), Chinese (mid-bottom), and global (bottom) markets





Source: JRC analysis based on GWEC (2024) and 4C Offshore (2024).

Annex 3. Global material supply and material demand scenarios

Data can be retrieved online at the following link:

https://zenodo.org/records/14961594

Annex 4. Sources from the scientific literature analysis

Table 6. Selected literature sources on NdFeB magnets and wind sector circularity patterns.

Author	Year	Title	Type	NdFeB circularity	Wind sector circularity
Alves Dias et al.	2020	The role of rare earth elements in wind energy and electric mobility: An analysis of future supply/demand balances	Policy report	x	x
Baldassarre et al.	2023	Analysis of Circular Economy Research and Innovation (R&I) intensity for critical products in the supply chains of strategic technologies	Policy report	x	
Binnemans et al.	2013	Recycling of rare earths: a critical review	Scientific article	x	x
Carrara et al.	2023	Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study	Policy report	x	x
Carrara et al.	2020	Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system	Policy report	x	x
Chen et al.	2015	Reduced Dysprosium Permanent Magnets and Their Applications in Electric Vehicle Tracti...	Scientific article	x	
Coelho et al.	2021	Upscaling of Permanent Magnet Dismantling and Recycling through VALOMAG Project	Scientific article	x	
Laurentis and Windemer	2024	When the turbines stop: Unveiling the factors shaping end-of-life decisions of ageing wind infrastructure in Italy	Scientific article		x
European Environment Agency	2021	Emerging waste streams: Opportunities and challenges of the clean- energy transition from a circular economy perspective	Policy report	x	x
European Raw Materials Alliance	2021	Rare Earth Magnets and Motors: A European Call for Action	Industry report	x	
Grijelmo et al.	2022	Wind, PV and batteries recycling in Europe: an opportunity for the recovery of critical raw materials	Industry report	x	x

Jensen	2018	Narrowing, slowing and closing the resource loops: circular economy in the wind industry	Doctoral thesis	x	x
Jin et al.	2020	Life cycle assessment of emerging technologies on value recovery from hard disk drives	Scientific article	x	
Levett et al.	2024	Water-soluble rare earth elements (REEs) recovered from uranium tailings	Scientific article	x	
Lilla et al.	2014	Optimization of High Voltage Geared Permanent-Magnet Synchronous Generator Systems	Scientific article	x	x
Mancheri et al.	2019	Effect of Chinese policies on rare earth supply chain resilience	Scientific article	x	
Mendoza et al.	2022	Circular economy business models and technology management strategies in the wind in...	Scientific article	x	x
Ortegon et al.	2013	Preparing for end of service life of wind turbines	Scientific article	x	x
Raspini et al.	2022	Drivers and barriers to a circular economy adoption: a sector perspective on rare earth magnets	Scientific article	x	x
Rizos et al.	2024	Understanding the barriers to recycling critical raw materials for the energy transition: The case of rare earth permanent magnets	Scientific article	x	
Sprecher et al.	2014	Recycling Potential of Neodymium: The Case of Computer Hard Disk Drives	Scientific article	x	
Telsnig	2022	Mapping and analysis of current circular economy approaches in the wind energy sector	Policy report	x	x
United States Department of Energy	2022	Rare Earth Permanent Magnets Supply Chain Deep Dive Assessment	Policy report	x	x
Van Nielen et al.	2023	Towards neodymium recycling: Analysis of the availability and recyclability of European waste flows	Scientific article	x	x
Waltzberg et al.	2022	An investigation of hard-disk drive circularity accounting for socio-technical dynamics and data uncertainty	Scientific article	x	
Yang et al.	2017	REE Recovery from End-of-Life NdFeB Permanent Magnet Scrap: A Critical Review	Scientific article	x	x

Source: JRC analysis.

Annex 5. Systematic analysis of scientific literature on the circularity of NdFeB permanent magnets in wind energy applications – Complementary information

Objective and method

Following established systematic review protocols in the circular economy field (Mahanty et al., 2021), the literature was sourced from the Scopus database. A search string was created in consultation with subject matter experts and refined through multiple iterations. The output of the search, spanning the period from 1959 to April 2024, consisted of a final dataset of 3395 publications. These 3395 articles were initially classified according to the following permanent magnet application areas (United States Department of Energy, 2022):

- **Low-tech applications** (magnets in toys/games, etc.)
- **Consumer products and electronics** (mobile phones, hard disk drives, etc.)
- **Industrial applications** (magnets for industrial equipment, etc.)
- **Renewable energy applications** (wind turbine power generators)
- **Mobility applications** (electric traction motors)

To categorise the articles into the five application areas, a two-step approach was implemented, combining **manual screening** done by a researcher with the application of a **large language model (LLM)**. The automated categorisation by **application areas** allowed us to identify a subset of literature specifically addressing permanent magnet circularity in relation to renewable energy applications, particularly wind turbine power generators. This subset comprised 126 articles, which were further analysed to gain deeper insights into circularity. The abstracts of these articles were examined to categorise them based on circularity literature as follows (Baldassarre and Saveyn, 2023; Kirchherr et al., 2017):

- **reduce**: Decrease demand of resources and materials in product manufacturing and use by consumers;
- **rethink**: Make product use more intensive (e.g., by product sharing);
- **redesign**: Increase resource efficiency through innovative product (eco) design;
- **reuse**: Extend product lifetime by reusing the discarded product (reuse can be in the form of direct reuse where the original function of the product is maintained);
- **repair**: Repair and maintenance of defective product so it can be used with its original function;
- **refurbish**: Restore an old product and bring it up to date;
- **remanufacture**: Use parts of discarded product in a new product with the same function;
- **repurpose**: Use discarded product or its part in a new product with a different function;
- **recycle**: Collect materials at the end-of-life of a product and process them to obtain the same (high grade) or lower (low grade) quality;
- **recover**: Incineration of material with energy recovery.

The categorisation by circularity strategy followed a similar process to that used for the application areas. The categorisation results offered valuable insights into which **circularity strategies** for permanent magnet have received the most attention in scientific research. A **geographical analysis**, which is a key aspect to consider (Baldassarre, 2025; Baldassarre et al., 2023; Jakimow et al., 2024), was also conducted as part of the literature review. This final layer of analysis offered insights into which countries produce most research outputs on permanent magnet circularity, both globally and within the EU. Additionally, it identified leading research institutions and top funding countries.

Results – Application areas

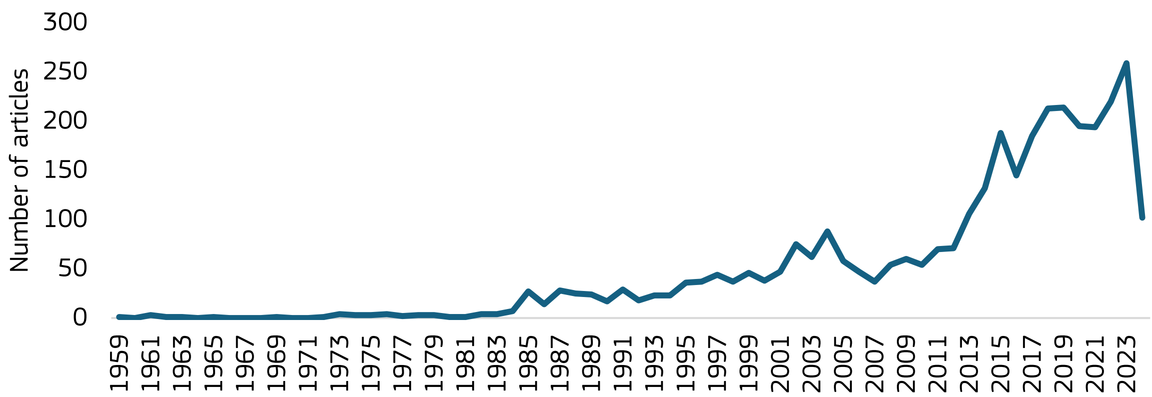
An overview of the results from the literature review on permanent magnet circularity is provided here. The search yielded 3395 articles published between 1959 and April 2024. Figure 29 illustrates the trend in annual publication numbers over time, showing a consistent increase. Articles were categorised according to their different application areas. The results of the categorisation are shown in Figure 30.

Results – Circularity strategies

This section examines the various circularity strategies explored in scientific literature related to the use of permanent magnets in renewable wind energy applications. Figure 25 in Section 4.3 has already illustrated the prominence of different circularity strategies in these studies, i.e., reduce, rethink, redesign, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover.

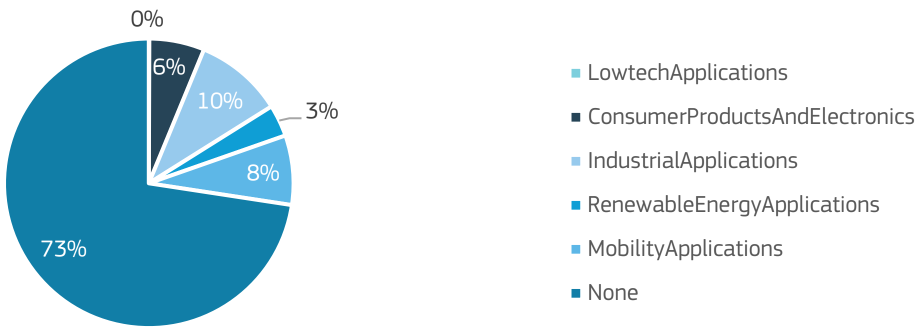
To provide an additional level of analysis and discussion, the different circularity strategies identified earlier are hereby further clustered according to their **objective**, namely narrowing resource flows, slowing resource flows, and closing resource flows (Bocken et al., 2016). Figure 31 reports the categorisation of scientific articles according to the objectives of narrowing, slowing, and closing resource flow, as well as by considering their focus on horizontal measures.

Figure 29. Distribution of articles on permanent magnets over the years



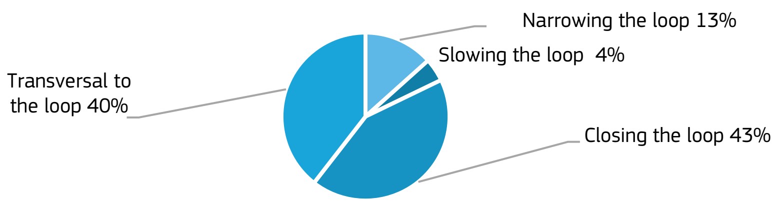
Source: JRC analysis.

Figure 30. Distribution of articles across different application areas



Source: JRC analysis.

Figure 31. Distribution of circularity strategies by narrowing, slowing, closing resource flows, and horizontal measures

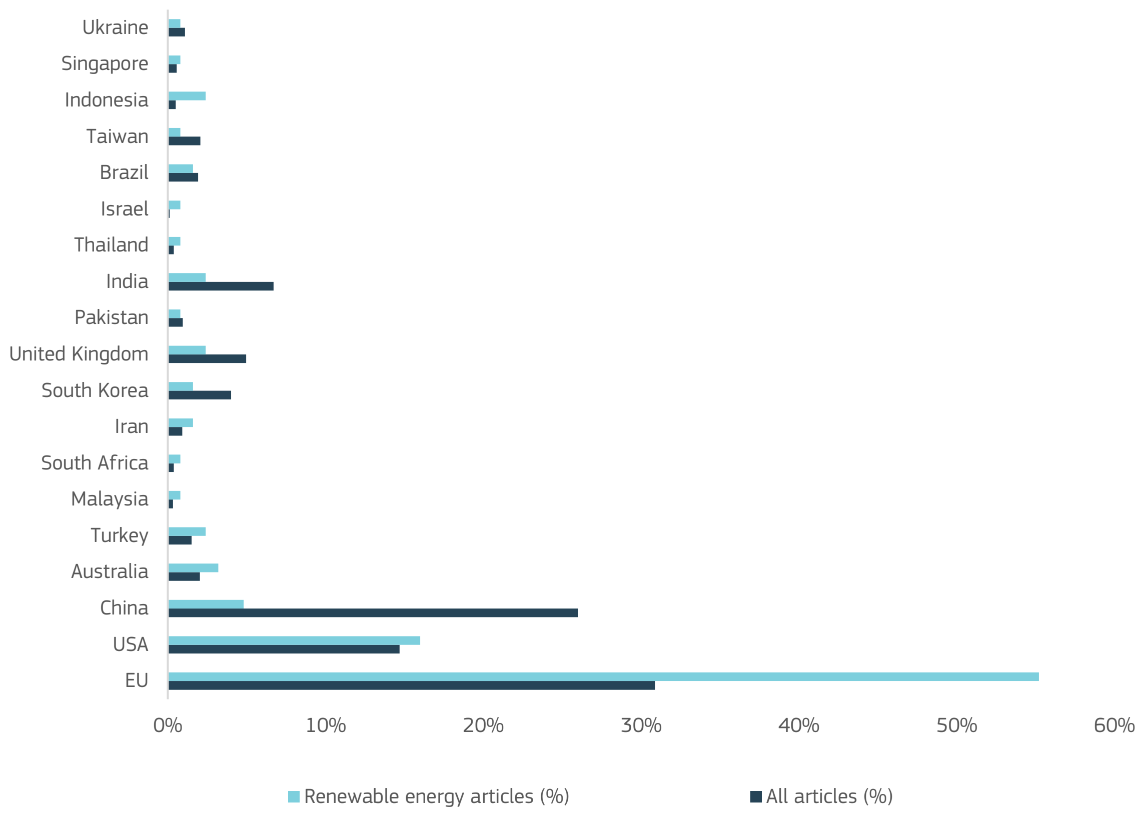


Source: JRC analysis.

Results – Geographical analysis

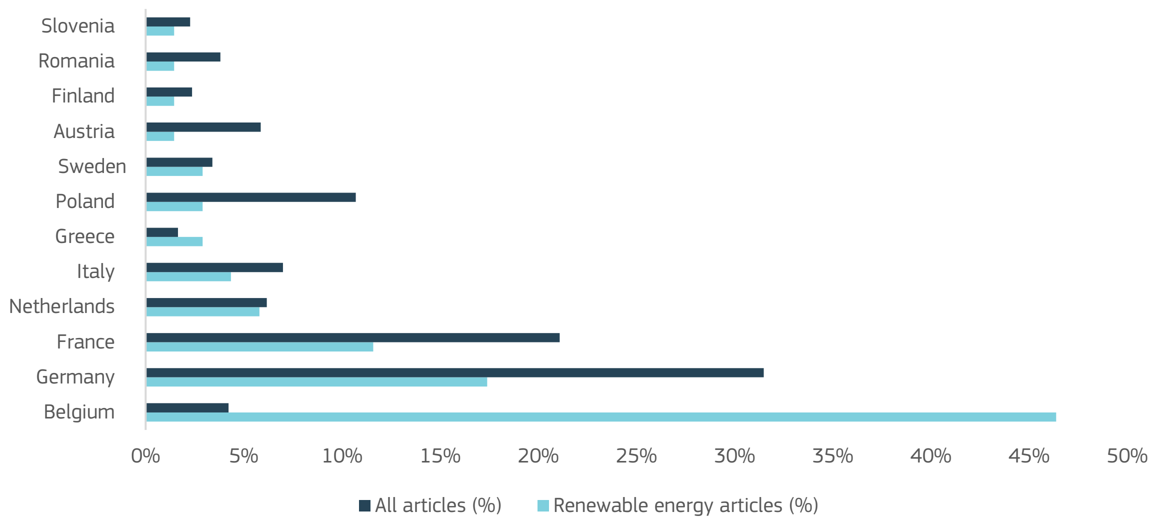
This section focuses on publications about permanent magnet circularity from a geographical perspective. It examines the distribution of scientific articles across countries globally and across EU Member States. Furthermore, it identifies leading research institutions and top funding countries. Figure 32 illustrates the distribution of publications by country, based on the authors' affiliations. Figure 33 and Figure 34 show the distribution of publications across all EU Member States, comparing them both by percentage share and by the absolute number of articles produced. Figure 35 highlights the primary research affiliations by country for the analysed articles. Figure 26 in the main text has already compared the funding sources for all articles on permanent magnet circularity with those focused on renewable wind energy.

Figure 32. Distribution (% shares) of publications on permanent magnet circularity across countries globally



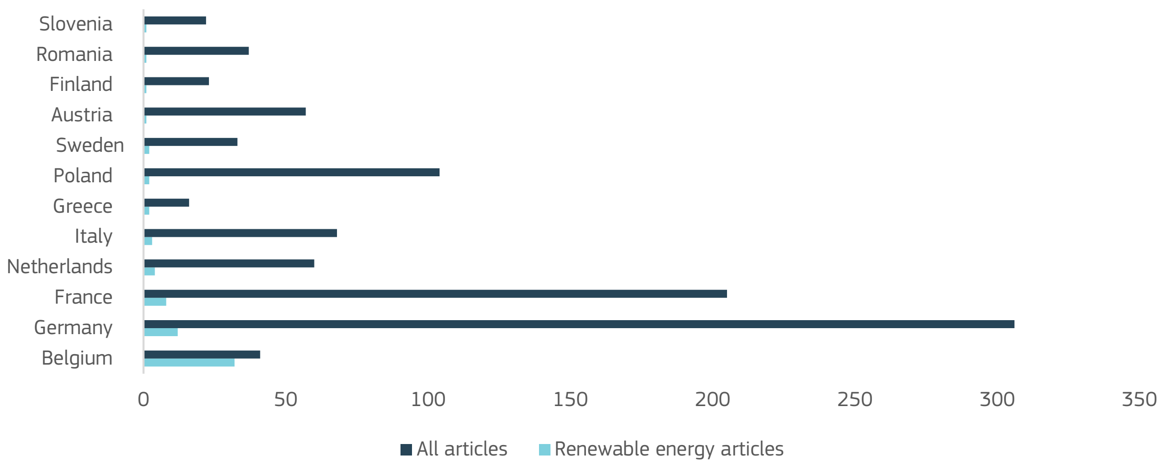
Source: JRC analysis.

Figure 33. Distribution (% shares) of publications on permanent magnet circularity across EU Member States



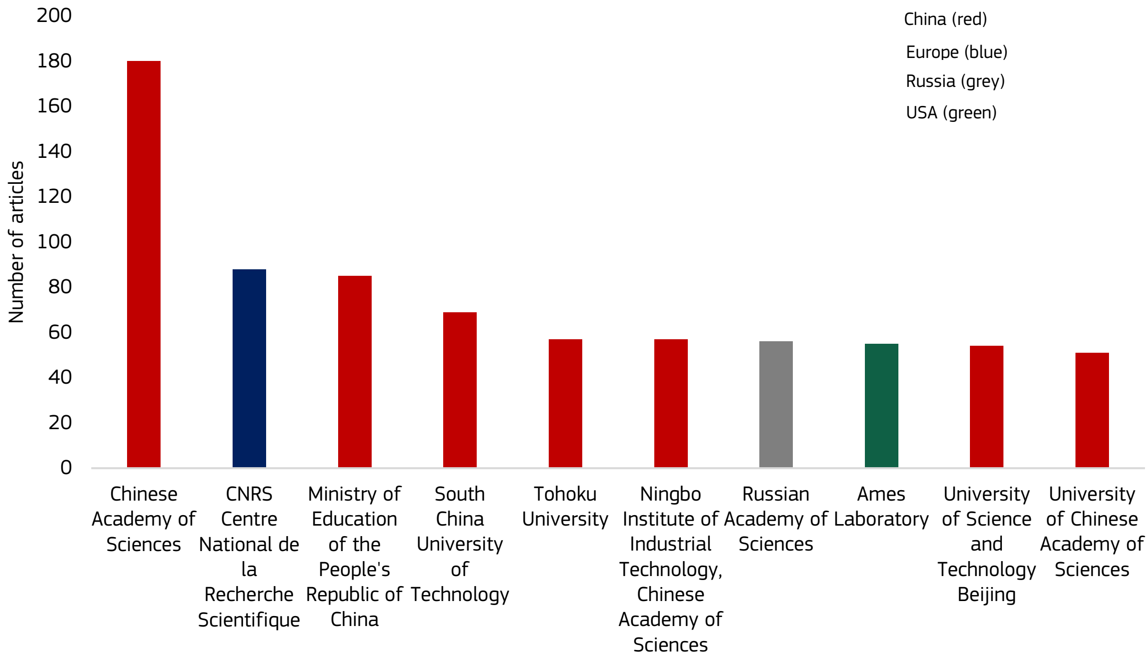
Source: JRC analysis.

Figure 34. Distribution (absolute numbers) of publications on permanent magnet circularity across EU Member States



Source: JRC analysis.

Figure 35. Leading research institutions for publications on permanent magnet circularity



Source: JRC analysis.

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