UK Critical Minerals
Intelligence Centre

A UK foresight study of materials in decarbonisation technologies: the case of wind turbines

Decarbonisation and Resource Management Programme

Open report CR/24/009N

Department for Business & Trade

British Geological Survey

BRITISH GEOLOGICAL SURVEY

Decarbonisation and Resource Management Programme

Open REPORT CR/24/009N

Keywords: foresight, critical minerals, decarbonisation, wind turbines, magnets

Front cover: EdWhiteImages. 2022. wind-energy-7342177_1280. pixabay.

Bibliographical reference: Petavratzi, E, Josso, P, Shaw, R, Horn, S, Hsu, W, and Singh, N. 2024. A UK foresight study of materials in decarbonisation technologies: the case of wind turbines. British Geological Survey Open report, CR/24/009N. 48pp.

A UK foresight study of materials in decarbonisation technologies: the case of wind turbines

E Petavratzi, P Josso, R Shaw, S Horn, W Hsu, N Singh

Editors

A G Gunn, J M Hannaford

Contributors

G Mudd, A Luce

Keyworth, Nottingham British Geological Survey 2024

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham and Cardiff (Welsh publications only). Shop online at shop.bgs.ac.uk

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation. We publish an annual catalogue of our maps and other publications; this catalogue is available online or from BGS shops.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of UK Research and Innovation.

British Geological Survey offices

Nicker Hill, Keyworth,
Nottingham NG12 5GG

Tel 0115 936 3100

BGS Central Enquiries Desk

Tel 0115 936 3143
email enquiries@bgs.ac.uk

BGS Sales

Tel 0115 936 3241
email sales@bgs.ac.uk

The Lyell Centre, Research Avenue South,
Edinburgh EH14 4AP

Tel 0131 667 1000
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road,
London SW7 5BD

Tel 020 7589 4090
Tel 020 7942 5344/45
email bgslondonstaff@bgs.ac.uk

Cardiff University, Main Building, Park Place,
Cardiff CF10 3AT

Tel 029 2167 4280

Maclean Building, Crowmarsh Gifford,
Wallingford OX10 8BB

Tel 01491 838800

Geological Survey of Northern Ireland, Department for the Economy, Dundonald House, Upper Newtownards Road, Ballymiscaw, Belfast, BT4 3SB

Tel 0289 038 8462

www2.bgs.ac.uk/gsni/

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU

Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

UK Research and Innovation, Polaris House,
Swindon SN2 1FL

Tel 01793 444000
www.ukri.org

Website www.bgs.ac.uk
Shop online at shop.bgs.ac.uk

Disclaimer

Where International Energy Agency (IEA) data have been used to generate figures in this report the following IEA disclaimer applies:

'This is a work derived by the British Geological Survey (BGS) from IEA material and the British Geological Survey is solely liable and responsible for this derived work. The derived work is not endorsed by the IEA in any manner.'

Contents

FIGURES

TABLES

1 Introduction to wind turbine technology

Wind turbines are a well-established and widely used renewable technology capable of harnessing energy from wind. The kinetic energy imparted to the blades of a wind turbine by the wind is converted into electricity by the rotation of a rotor within a generator (IRENA, 2024). In 2023, wind power accounted for the largest share of renewable energy generation in the UK, contributing 29 per cent of total electricity generation, followed by biomass and solar energy, each contributing 5 per cent (National Grid ESO, 2024).

The UK possesses significant potential to further expand wind energy production, particularly offshore due to its long coastlines and shallow waters (Frangoul, 2023). As a result, the UK has set an ambitious target to deploy up to 50 GW by 2030 (DESNZ, 2023). This will require about 2600 additional wind turbines to be built (Ukpanah, 2024). The Climate Change Committee further suggests that the UK may require up to 125 GW by 2050 (Committee on Climate Change, 2020). The scaling up of wind turbine deployment in the UK will therefore be very rapid up to 2050 and the materials required to build these installations will need to follow a similar growth trajectory.

1.1 PRINCIPLES OF OPERATION

The primary components of a wind turbine include the foundation, tower, nacelle and rotor blades (Figure 1).

Positioned at the top of the tower, the nacelle contains the generator, together with a gearbox in some turbine types, and several other functional components. To optimise operational efficiency, the nacelle's facing direction can be adjusted to align with the prevailing wind using a yaw drive mechanism. When wind flows perpendicular to the rotor blades, their complex three-dimensional geometry, also known as an airfoil design, imparts a rotational movement onto the rotor (EERE, 2024). As the rotor spins, it generates a rotating magnetic field within the generator, inducing an electric current in the windings of the generator stator (Marscheider-Weidemann et al., 2021). Subsequently, electrical energy is transmitted down the tower to the base, where a transformer increases the voltage to meet the energy grid's requirements (National Grid, 2024).

In some wind turbines, the generator is directly linked to the rotor, a setup commonly known as a direct drive, which operates at a low rotational speed. Conversely, in other turbines the rotor links to the generator through the shaft and a gearbox, which amplifies the rotational speed. Commonly, wind turbines with gearboxes require physically smaller generators. While enhancing rotor spin, the gearbox configuration may lead to reduced energy efficiency and introduces complexity to the system, making it more susceptible to operational faults and necessitating increased maintenance (Marscheider-Weidemann et al., 2021).

Commonly reported key parameters for wind turbine include capacity, which is the amount of energy produced under optimal conditions (megawatts, MW) and the capacity factor, representing the ratio between the average generated output and the turbine's capacity (per cent) (Marscheider-Weidemann et al., 2021).

There are important differences between the operation of wind turbines situated on land (onshore) or off the coast (offshore), which influence the choice of turbine technology. Onshore wind power has been used in the UK since 1991, offering advantages such as lower investment costs, faster installation and lower maintenance costs. However, onshore wind turbines yield less power than their offshore counterparts due to a higher variation in wind speed and direction. This inconsistency renders turbines inoperable during intervals of intermittent wind speeds (National Grid, 2022). The standard size of onshore wind turbines has increased from 5 MW turbine capacity in 2010 to 10 MW in 2023 and they are projected to increase to 15 MW by 2030 (Lee and Zhao, 2024).

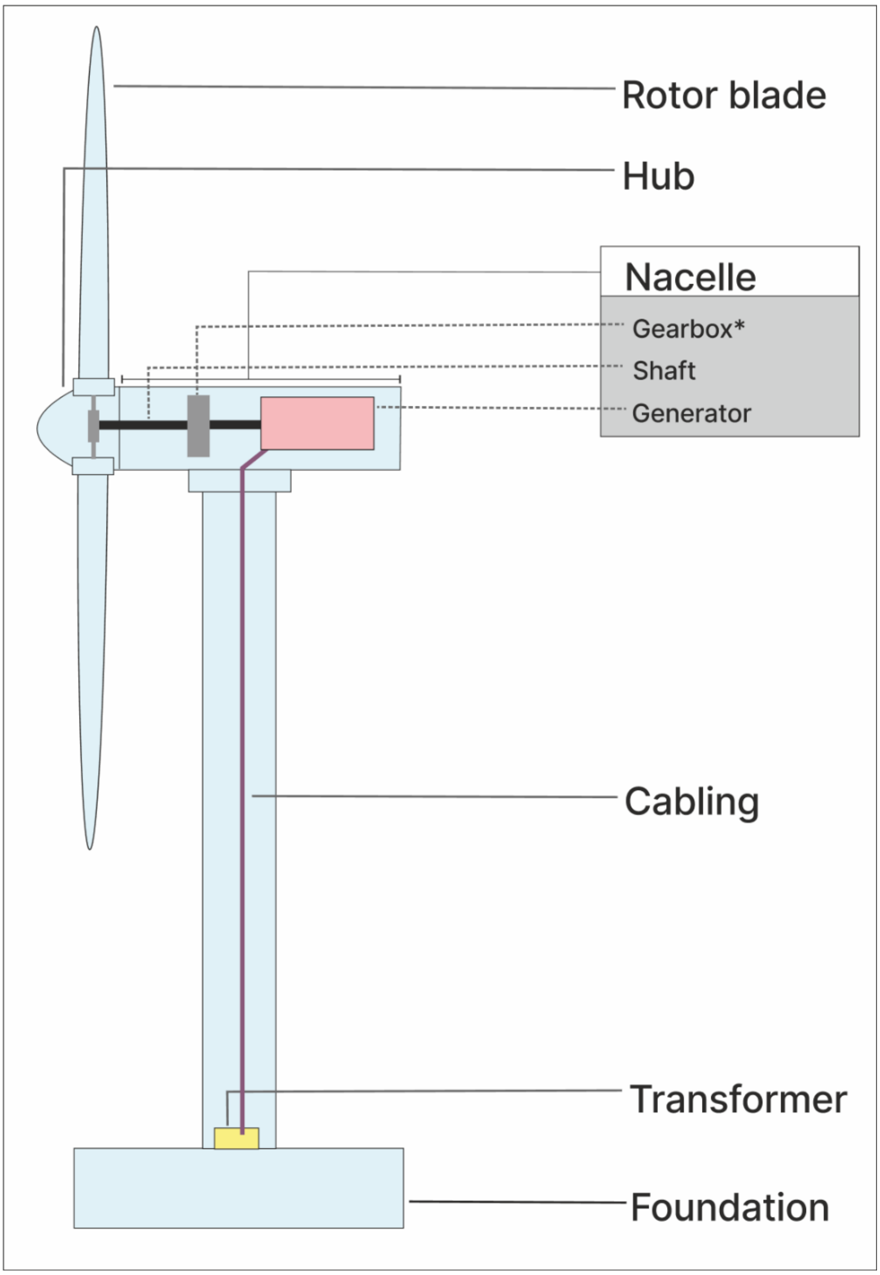


Figure 1 Schematic illustration of a wind turbine and its key components. Modified after European Commission et al. (2020b), EERE (2024). * A gearbox is not used in direct-drive wind turbines. BGS © UKRI.

Offshore wind power provides greater efficiency due to more consistent unidirectional wind speeds and the opportunity to deploy larger wind turbines capable of generating more energy (National Grid, 2022). However, offshore installation poses challenges due to the requirements for infrastructure to support the turbine, submarine cabling and a specialised shipping fleet. This makes them more expensive to build and maintain, given the rough conditions commonly encountered at sea (Marscheider-Weidemann et al., 2021, National Grid, 2022).

While most offshore technologies require shallow waters for their installation, new developments use floating foundations, which are more flexible in their location and can be used in deeper waters (Marscheider-Weidemann et al., 2021). Offshore turbines have grown rapidly in size from 5 MW in 2010 to 15 to 18 MW for wind turbines installed in 2023. They are expected to reach capacities of 25 MW by 2030 (Lee and Zhao, 2024).

The disparity in operating conditions between onshore and offshore wind turbines also leads to the use of different subtechnologies (Figure 2). In 2020, the predominant technology for onshore wind turbines in the UK was the gearbox double-fed induction generator (GB-DFIG), owing to its market maturity and ability to run at variable speeds (Pavel et al., 2017, Liang et al., 2023). However, in the offshore market, direct-drive permanent-magnet synchronous generator (DD-PMSG) wind turbines dominate, with a 76 per cent market share. DD-PMSGs offer high efficiency; the absence of a gearbox also reduces the requirement for complex offshore maintenance and repairs. Electrically excited induction generators are not used in offshore applications, but their use continues in onshore turbines (Pavel et al., 2017, Liang et al., 2023).

1.2 ESSENTIAL COMPONENTS AND MATERIALS

This study focuses on the four dominant turbine technologies used in onshore and offshore wind applications (Figure 2). These are:

- gearbox double-fed induction generator (GB-DFIG)
- gearbox permanent-magnet synchronous generators (GB-PMSG)
- direct-drive permanent-magnet synchronous generator (DD-PMSG)
- direct-drive electrically excited synchronous generators (DD-EESG)

(Table 1)

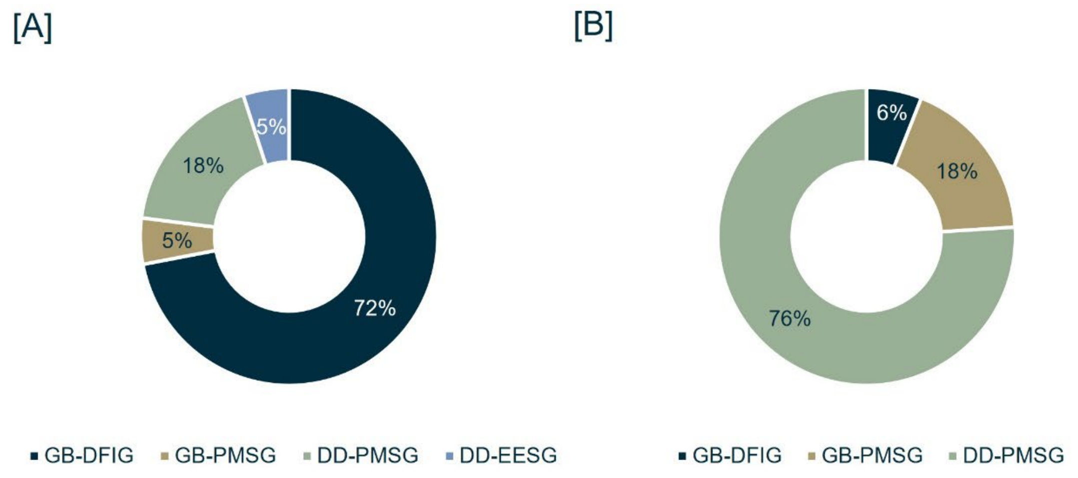


Figure 2 Global market share of wind turbines in 2020. [A] onshore; [B] offshore. GB-DFIG: gearbox double-fed induction generator; GB-PMSG: gearbox permanent-magnet synchronous generator; DD-PMSG: direct-drive permanent-magnet synchronous generator; DD-EESG: direct-drive external-excitation synchronous generator. (Liang et al., 2023).) BGS © UKRI.

Table 1 Materials used in wind turbine technologies.

Technology	UK critical elements	Other
GB-DFIG	Manganese (Mn), nickel (Ni), rare earth elements (REE): dysprosium (Dy), neodymium (Nd),	Aluminium (Al), boron (B), carbon fibre*, chromium (Cr), concrete*, copper (Cu), iron (Fe), molybdenum (Mo), zinc (Zn)
GB-PMSG	Cobalt (Co), manganese (Mn), nickel (Ni), rare earth elements (REE): dysprosium (Dy), neodymium (Nd), praseodymium (Pr), samarium (Sm), terbium (Tb)	Aluminium (Al), boron (B), carbon fibre*, chromium (Cr), concrete*, copper (Cu), iron (Fe), molybdenum (Mo), zinc (Zn)
DD-PMSG	Cobalt (Co), manganese (Mn), nickel (Ni), rare earth elements (REE): dysprosium (Dy), neodymium (Nd), praseodymium (Pr), samarium (Sm), terbium (Tb)	Aluminium (Al), boron (B), carbon fibre*, chromium (Cr), concrete*, copper (Cu), iron (Fe), molybdenum (Mo), zinc (Zn)
DD-EESG	Manganese (Mn), rare earth elements (REE): dysprosium (Dy), neodymium (Nd), praseodymium (Pr), terbium (Tb)	Aluminium (Al), boron (B), carbon fibre*, chromium (Cr), concrete*, copper (Cu), iron (Fe), molybdenum (Mo), zinc (Zn)

Elements in red are excluded from the analysis either because they are used in structural components, or they are not used in the most common configuration of the technology. See Appendix A for a list of excluded raw materials and components.

* Concrete and carbon fibre are not chemical elements, but processed materials.

1.2.1 Permanent-magnet synchronous generators

Permanent-magnet synchronous generators (PMSG) can be equipped with either a direct drive or a gearbox. Both have neodymium-iron-boron (NdFeB) permanent magnets in their rotor and copper windings in the stator.

Permanent-magnet generators can be designed with a reduced size and weight compared to other turbine technologies as a result of the high magnetic density derived from permanent magnets (Lacal-Arántegui, 2015). The use of a gearbox enables higher spin on the rotor shaft, allowing for the use of a smaller generator for the same power output. This reduces the material intensity of permanent-magnet raw materials as well as that of copper (Cu) in the stator windings (Farina and Anctil, 2022).

1.2.2 Gearbox double-fed induction generators

Double-fed (also called doubly fed) induction generators (DFIG) are the only induction generators still used on a large scale. They include stator and rotor windings, both made of Cu. The rotor is supplied with an alternating current signal via slip rings, which creates an electric magnetic field. As the rotor spins, the magnetic field interacts with the stator windings, thereby generating electricity. The energy required is significantly less than the energy generated (Marscheider-Weidemann et al., 2021).

Induction generators operate under high-speed rotation and thus require a gearbox to multiply the lower rotational speed of the rotor blades to the higher speed requirement of the generator (Farina and Anctil, 2022).

1.2.3 Direct-drive electrically excited synchronous generators

Electrically excited synchronous generators (EESG) were mostly used in the 2000s as they are able to operate under the variable wind conditions commonly experienced onshore (Pavel et al., 2017). They do not require a gearbox and can run at lower speeds, making them a direct-drive alternative to permanent-magnet generators (Pavel et al., 2017). However, they are significantly heavier than PMSG turbines and are therefore not used offshore.

EESGs have rotor windings and slip rings to induce power onto the rotor, similar to designs found in DFIGs. However, the rotor rotates at the same speed as the induced magnetic field (synchronous) (Marscheider-Weidemann et al., 2021).

1.3 SUPPLY CHAIN MAPPING OF WIND TURBINES

As the majority of wind turbines use permanent magnets, this study focuses on their embedded materials, which are the rare earth elements (REEs) (dysprosium (Dy), neodymium (Nd), praseodymium (Pr) and terbium (Tb)), and boron (B). Cu, which is a key constituent of the generator and transformer, has also been evaluated.

The supply chain stages for wind turbines and the associated material transformation steps are shown in Figure 3. It is important to note that, at the component stage, only those parts that use the selected raw materials are shown. Other essential parts such as the rotor blades and tower foundation were excluded, either due to lack of data (carbon fibre for rotor blades) or due to them representing structural materials (concrete in tower foundations) (see Appendix A).

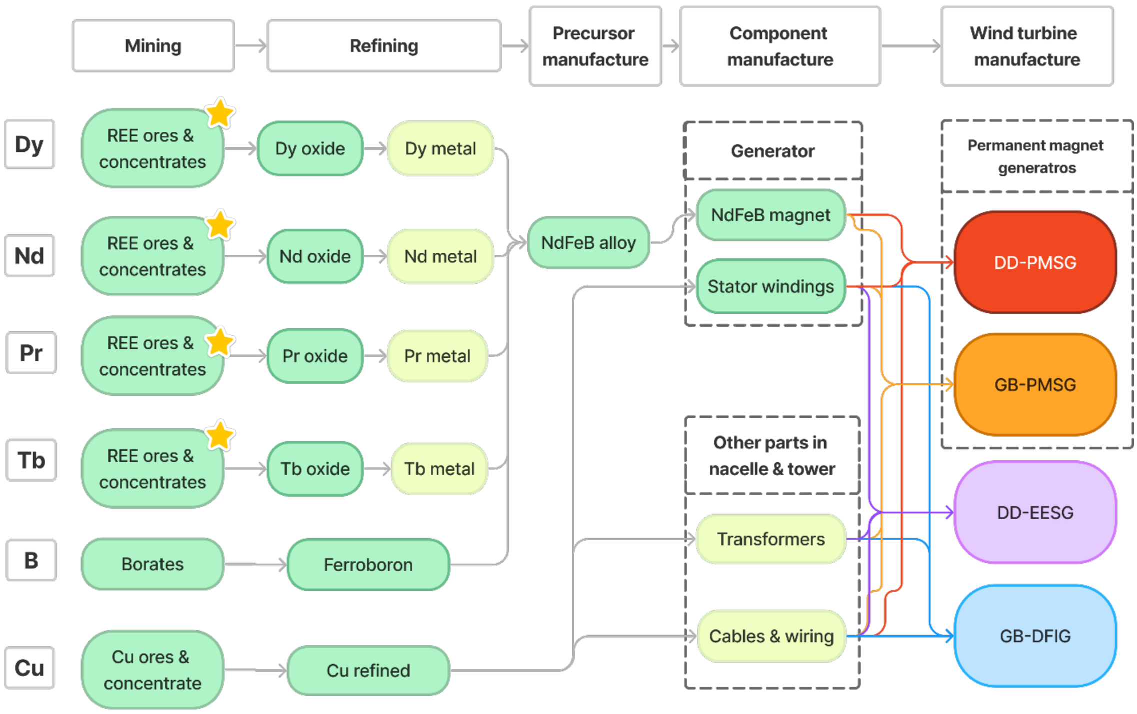


Figure 3 Supply chain mapping of wind turbines, key raw materials and components. The green shading indicates materials that have been included in the analysis. A star indicates a material produced as a co-product. REEs are dominantly a co-product of Fe ore and phosphate mining but are increasingly being produced as the main commodity of other types of deposits. The lime green shade indicates a material that was only partially analysed. REE: rare earth elements; DD: direct drive; GB: gearbox; PMSG: permanent-magnet synchronous generator; EESG: electrically excited synchronous generator; DFIG: double-fed induction generator. BGS © UKRI.

The REEs are a group of 17 elements, including the lanthanides as well as yttrium (Y) and scandium (Sc), that occur together in a variety of deposit types with individual elements present in varying concentrations. The REEs are mined and processed into rare earth oxides (REOs) from REE mineral concentrates (Wall, 2014).The majority of REEs are produced from carbonatites, ion-adsorption deposits and alkaline igneous rocks (for example, Bayan Obo, China and Mount Weld, Australia). They also have the potential to be produced as a co-product of Fe and phosphate mining. Commonly, a mixed REO is produced following mining and the use of various physical and chemical separation processes. Separation of individual REEs is challenging due to the minor differences in properties between members of this group. The separation of Nd and Pr is particularly difficult and they may be used unseparated in a Nd-Pr alloy called didymium, together with Nd metal, to achieve the optimal Nd-Pr ratio for use in magnets (Smith et al., 2022).

B is generally extracted as borates (boron oxides), which are refined to boric acid and subsequently into ferroboron (17 to 20 per cent boron) for permanent magnets. Refined REEs and ferroboron are combined with iron (Fe) to form NdFeB alloy, used to make sintered permanent magnets, or NdFeB powder to make bonded permanent magnets via a different process. Only NdFeB alloys and sintered permanent magnets are considered here as they are the preferred magnet types for traction motors and represent the majority of the NdFeB magnet market.

The permanent magnets are ultimately integrated into the rotor of permanent magnet wind turbines (GB-PMSGs and DD-PMSGs). Apart from their primary application in the generator of these turbine technologies, permanent magnets are also used in internal fixtures across all turbine technologies, albeit in smaller quantities compared to the generator (European Commission et al., 2020b). The demand calculations account for the total material intensities of REEs and B used in wind turbines.

Cu ore is processed by smelting or hydrometallurgical processing and further refined by electrowinning into Cu metal (Mudd and Jowitt, 2018). Cu is required in all wind turbine technologies but in varying quantities. The main application of Cu in all wind turbine types is in the stator windings of the generator, followed by use in the transformer. It is worth noting that Cu usage for cabling within the turbine and for connection to the transformer and the grid largely exceeds Cu usage within the turbine generator itself. However, as this requirement depends on factors such as location, the size of the turbine mast and the distance to the grid connector, this aspect is excluded from the study focusing on the operational parts of the wind turbine (Copper Development Association Inc., 2024).

Generator manufacturing and nacelle assembly are typically integrated processes managed by wind turbine manufacturers, who also undertake their installation. Nacelle assembly, being the final stage, is conducted at a manufacturing facility (Hutchinson and Zhao, 2023). However, the rest of the wind turbine assembly, including the foundation, tower and rotor blades, is carried out at the site of operation (for example, a wind energy park) and is not considered in this analysis.

2 Supply chain bottlenecks

The supply chain of wind turbines requires complex processing and manufacturing steps that are not widely available. Consequently, it is highly concentrated in a few countries. Production concentration is evident at various supply chain stages, which are therefore vulnerable to supply disruptions (Figure 4).

At the mining stage, REEs are produced predominantly in China, while borates are derived chiefly from central Asia and the USA. Mine production of Cu is more widespread, with important producers operating in many countries. At the refining stage, a significant portion of the production is derived from China and other central and south-east Asian countries. It is estimated that more than 90 per cent of magnet REOs are produced in China, with additional but minor refining activity also taking place in Malaysia and Estonia (Adamas Intelligence Inc., 2022). This Chinese dominance in the market also applies for REE metal refining, with several other minor producers, but their production share is uncertain and was therefore not included in the supply chain analysis.

Chile is the leading producer of refined Cu, followed by China and Japan.

The production of NdFeB alloys and permanent-magnet manufacturing is highly concentrated in China and south-east Asia. It should be noted that almost 30 per cent of the global magnetic REO supply comes from secondary REO production from the major alloy and magnet production centres in China and Japan (Adamas Intelligence Inc., 2022). This is largely from the recycling of NdFeB production waste (metal chips or filings, known as swarf). However, this was not considered in this analysis.

China also leads production and assembly of generators as well as nacelle assembly, but there is also a large presence of Eu ropean manufacturers at the end of the supply chain, some of which have manufacturing capability in China (Hutchinson and Zhao, 2023).

2.1 MINING AND REFINING

2.1.2 Production concentration

The global production share of materials used in the manufacture of permanent magnets used in generators in wind turbines was calculated for the top three producing countries at both the mining and refining stages of the supply chain. Some raw materials have been excluded from this study because of a lack of data of suitable quality and resolution. For example, production data for the individual REEs are not available; instead, the mixed REO content of REE ores was assessed at the mining stage.

At the mining stage, three materials were considered: Cu ores and concentrates, borates and REOs. However, it should be noted that the REOs are a proxy for individual REEs, including Dy, Nd, Pr and Tb. Of all the materials considered, REOs are the most concentrated, with the top three producing countries (China, Myanmar and Australia) accounting for 90 per cent of global supply and the single largest producer (China) producing 70 per cent.

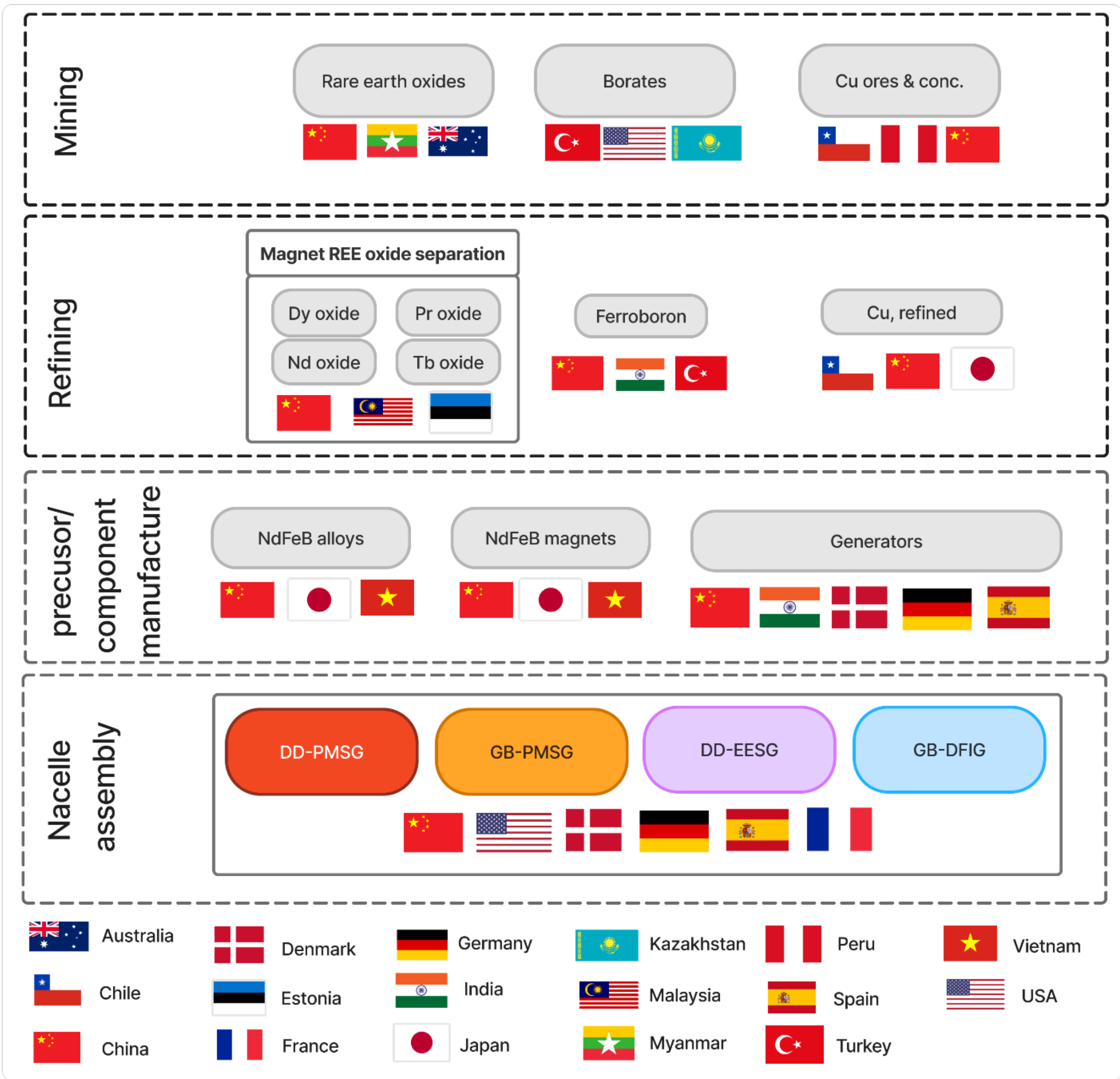


Figure 4 Geographical production concentration in the wind turbine supply chain. All steps show the top three producers, from left to right, except for ferroboron, and for the manufacture of generators and wind turbines where the flags highlight key producers, but their order does not reflect their respective market share. Materials at the mining stage and Cu at the refining stage are based on quantitative data for 2017 to 2021 from the BGS World Mineral Statistics Database (Idoine et al., 2023). The top three producing countries of REOs at the refining stage and the NdFeB alloy production are from Adamas Intelligence Inc. (2022); magnet manufacturing data are based on data from Smith et al. (2022). Production shares of generator and wind turbine manufacturing countries are based on data from Hutchinson and Zhao (2023). REE: rare earth elements; DD: direct drive; GB: gearbox; PMSG: permanent-magnet synchronous generator; EESG: electrically excited synchronous generator; DFIG: double-fed Induction generator. BGS © UKRI.

The mine production of borates exhibits a high level of concentration with the top three producers (Turkey, USA and Kazakhstan) collectively contributing more than 80 per cent of global supply. However, the share of production held by the single largest producer (Turkey) is lower than for REOs, at 59 per cent of the total.

Conversely, mine production of Cu is weakly concentrated, with the top three producing nations (Chile, Peru and China) accounting for less than 50 per cent of the global total. Among these, the single largest share is held by Chile, which produces about 27 per cent of the global total (Figure 5).

Although production data for the individual REEs are unavailable, work conducted by BGS focusing on the geochemical signature of REE deposits indicates that global mine production consists of (approximately, by mass):

- 15 per cent neodymium
- 5 per cent praseodymium
- 1 per cent dysprosium
- 0.1 per cent terbium

In contrast, the mass of contained cerium (Ce) and lanthanum (La) is about 25 to 43 per cent. This highlights an additional challenge in supply, as not all deposits contain viable economic concentrations of all the REEs. Many deposits are rich in Ce and La, but have lower concentrations of Dy, Nd, Pr, and Tb.

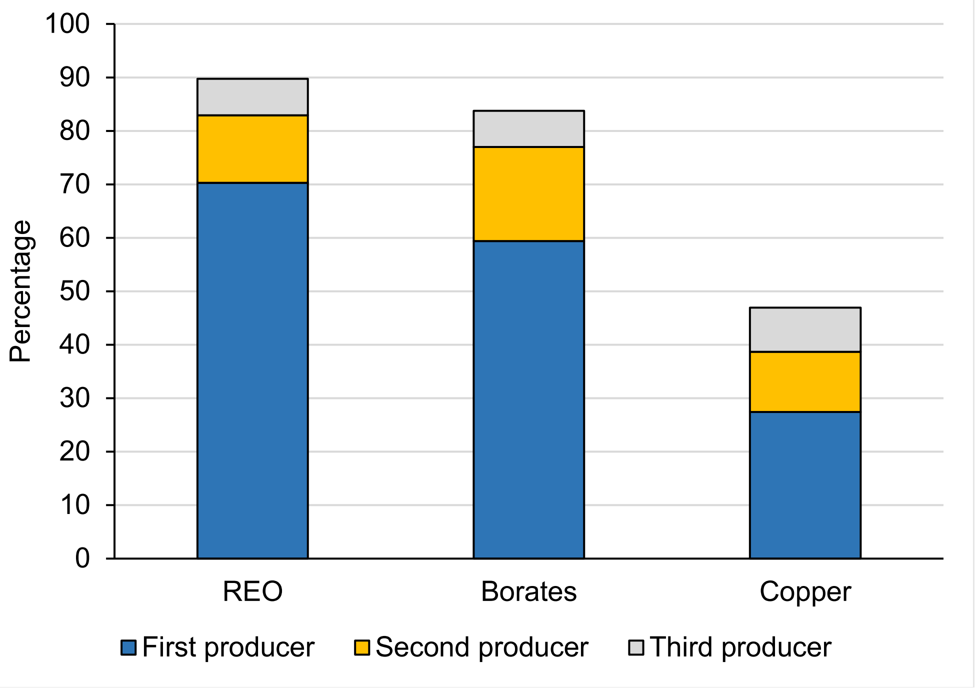


Figure 5 Global mine production of Cu ores and concentrates, borates and REOs, showing the production shares of the top three producing countries. Data from the British Geological Survey World Mineral Statistics Database (Idoine et al., 2023). BGS © UKRI.

At the refining stage, it was only feasible to assess the production concentration of refined Cu, as data pertaining to the production of ferroboron and the individual REE metals are not available. While it remains impracticable to quantify the production concentration of ferroboron, it is acknowledged that China, India and Türkiye are the foremost producers (Smith et al., 2022). The production of refined Cu is moderately concentrated with the top three producers (China, Chile and Japan) accounting for 56 per cent of the global total. The single largest producer (China) is responsible for 42 per cent of the global total.

The production concentration calculation relies on the methodology outlined in the revised guidelines for UK criticality assessment (Josso et al., 2023). This is derived from the production shares of the leading producers, modified by a factor that reflects the environmental, social and governance (ESG) performance of those countries. At both at the mining and refining stages of Cu, the production concentration scores are relatively low, mirroring the modest concentration of production and the ESG scores ranging from low to intermediate in the main producing countries. Conversely, the production concentration score for REOs at the mining stage is high, reflecting the significant share of production held by the top three countries and the poor ESG score of the top two producers (China and Myanmar) (Figure 6).

The absence of production data for refined REE metals and ferroboron precludes the calculation of a production concentration score. Nevertheless, given the geographically restricted location of the production and the ESG scores of production centres of these materials, it is anticipated that the scores for these materials would be high.

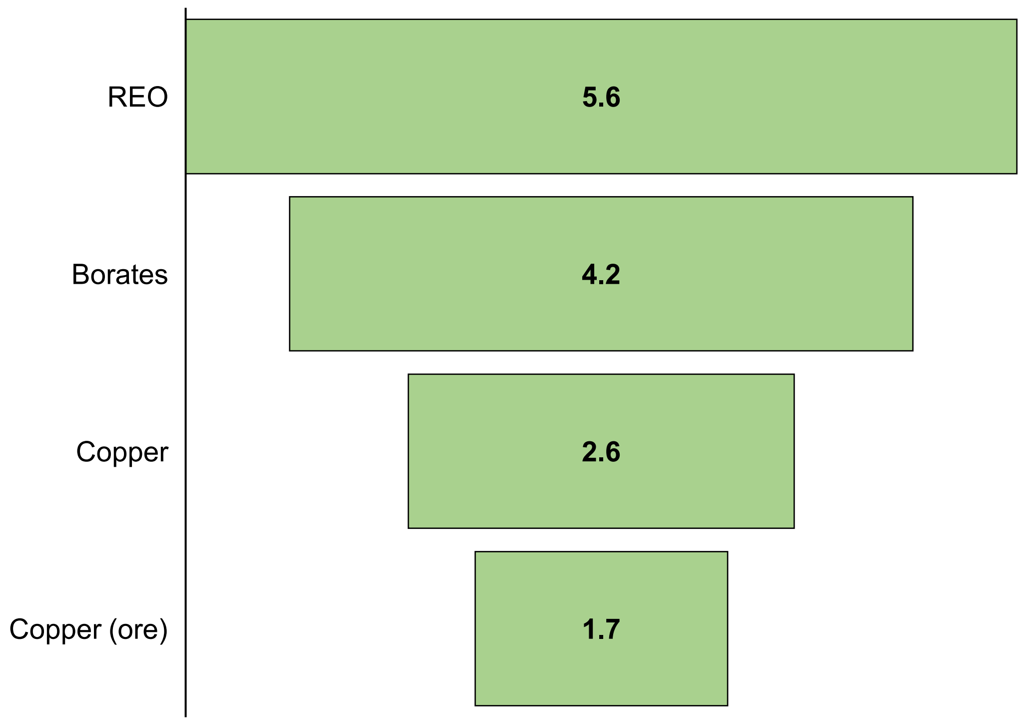


Figure 6 Ranked production concentration scores for key metals (mined and refined) used in wind turbines based on an ESG-weighted Herfindahl-Hirschman index for each of the top three producing countries. BGS © UKRI.

2.1.3 Global trade concentration and trade restrictions

As with the production of mined and refined materials used in the manufacture of permanent magnets, their trade is geographically concentrated and may be subject to restrictions imposed by trading nations. It is important to note that the trade data for some of the permanent magnet materials assessed (ores and refined metals) are not available or are reported at too low a resolution to be useful. For example, ferroboron is typically reported under a single trade code with ferrophosphorus and ferrosilico-magnesium.

The absence of suitable data for assessing the trade concentration of REE ores and concentrates is also notable. At the six-digit level, the trade code under which these materials are reported (Harmonized System (HS) 253090) is highly aggregated and includes numerous mineral substances such alunite, pozzolana and mineral pigments, making it very difficult to extract data that specifically relate to REE ores and concentrates. At the eight- and ten-digit level there are trade codes for REE ores and concentrates (for example, HS 25309050); however, not every country reports trade data, at this level of detail and such data are not typically publicly available. In effect, these trade flows are 'hidden'.

A summary of the HS trade codes used to assess trade concentration is listed in Table 2.

Table 2 Summary of the six-digit HS trade codes used to assess trade concentration of materials used in the manufacture of wind turbines.

HS code	Description	Stage
252800	Borates, natural, and concentrates thereof, whether or not calcined, and natural boric acids containing <= 85% of H3BO3 calculated on the dry weight (excl. borates separated from natural brine)	Mining
260300	Copper ores and concentrates	Mining
280530	Rare-earth metals, scandium and yttrium, whether or not intermixed or interalloyed	Refining
284690	Compounds, inorganic or organic (excluding cerium), of rare-earth metals, of yttrium, scandium or of mixtures of these metals	Mining
740200	Copper, unrefined; copper anodes for electrolytic refining	Refining

Trade of borates is moderately to highly concentrated, with 57 per cent of global imports being shared between China, Brazil and India. Türkiye is the largest exporter of borates, accounting for 63 per cent of global exports, with Bolivia and Argentina accounting for a combined 27 per cent (Figure 7). Exports of borates are subject to active trade restrictions: Argentina applies a 4.5 per cent tax to its exports and Bolivia mandates a license agreement and fiscal tax equivalent to 0.05 per cent of the total trade value to its exports.

The trade of Cu ores and concentrates demonstrates a moderate to high level of concentration, with 42 per cent of exports being shared among the top three countries: Peru, Chile and Australia. Furthermore, 75 per cent of imports are shared between China (57 per cent), Japan (14 per cent) and South Korea (4 per cent) (Figure 7). It is also important to highlight that Chile imposes a 10 per cent fiscal tax on its exports of Cu ores and concentrates.

The trade of refined (separated) REE compounds is moderately concentrated with the top three exporting nations (the USA, Malaysia and Russia) accounting for 54 per cent of the global total.

Of these, the USA is the single largest exporter, accounting for 30 per cent of the total. Imports of REE compounds are less concentrated with the top three importers (China, Germany and Japan) accounting for only 28 per cent of the global total.

Despite possessing substantial REE-refining capacity, China does not rank among the top exporters of REE compounds. This can be attributed to the high level of domestic consumption of these materials, primarily in the manufacture of magnets and the production of refined REE metals, of which China is a major global exporter.

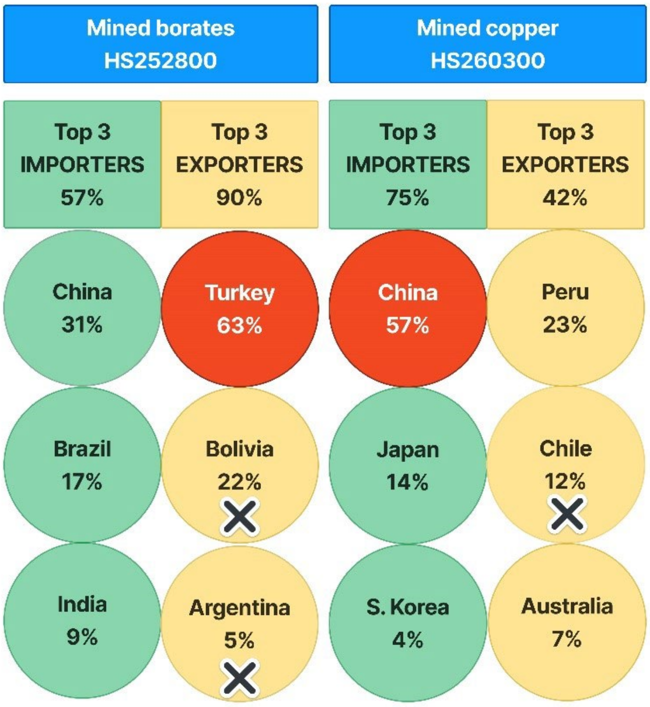


Figure 7 The top three importing and exporting countries for mined (ores and concentrates) REEs (compounds), borates and Cu with the share of global trade flows shown for each country. Countries highlighted in red are dominant exporters or importers (where global share exceeds 40 per cent), while countries with a cross have active trade restrictions. Compiled from data derived from United Nations (2023) and Organisation for Economic Co-operation and Development (2020). BGS © UKRI.

The trade of refined Cu and refined REEs (metals) are both highly concentrated (Figure 8). Specifically, 69 per cent of global imports of refined Cu are distributed among the top three traders, while 73 per cent of global imports of refined REEs (metals) are controlled by the top three traders. It should be noted that trade data for Malaysia for refined REE metals have been excluded from the analysis, as it appears the reported trade data actually represent imports of REE mineral concentrates from Australia and not refined metals.

A similar picture is observed for exports of refined Cu, where 70 per cent of global exports are controlled by the top three trading countries (Zambia, Chile and Bulgaria), with Zambia holding the largest share at 42 per cent. Refined REEs (metals) are controlled by China, Vietnam and the Philippines at 82 per cent of global exports, with China holding the largest share at 71 per cent of the total. Although there are presently no active restrictions on the trade of refined REEs (metals), Chile and Zambia have imposed restrictions on their exports of refined Cu, which take the form of export taxes, fiscal taxes and licensing agreements.

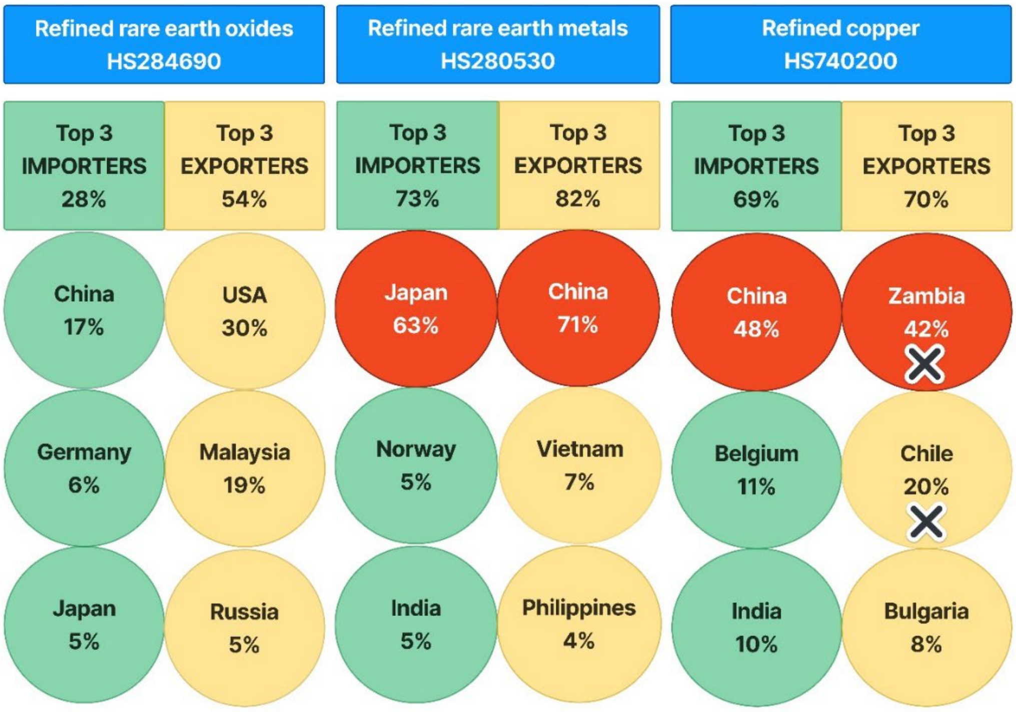


Figure 8 The top three importing and exporting countries for refined REEs (metals and compounds) and Cu, with the share of global trade flows shown for each country. Countries highlighted in red are dominant exporters or importers (where global share exceeds 40 per cent) while countries with a cross have active trade restrictions. Compiled from data derived from United Nations (2023) and Organisation for Economic Co-operation and Development (2020). BGS © UKRI.

The key points derived from analysis of the global trade in materials required for permanent magnets used in traction motors are:

- China is the largest importer of mined Cu, borates, refined REEs (metals and compounds) and refined Cu
- global trade of refined REE metals is highly concentrated, with China accounting for 71 per cent of exports and Japan accounting for 63 per cent of imports
    - the top three countries account for more than 70 per cent of the global total for both trade flows
- global imports of materials required for permanent magnets at both the mining and refining stages are dominated by countries in Asia, especially China
- global exports of materials required for permanent magnets at both the mining and refining stages are dominated by countries in South America; however, Zambia dominates exports of refined Cu and Turkey is the main exporter of mined borates
- where trade restrictions are imposed, they are almost always applied to exports, with the most common restrictions being licence agreements or export taxes
- the most significant risk to supply is where global trade is dominated by a few countries (for example, China accounts for 71 per cent of global exports of refined REE metals)

- risk may increase if restrictions are applied to trade: for example, China recently applied export licensing to refined gallium (Ga), which led to price increases and some international traders being cut out of the market (MMTA, 2023)

2.2 COMPONENT AND PRODUCT MANUFACTURE

At the precursor and component stage, China is the dominant actor with more than 90 per cent of NdFeB alloy production and magnet manufacturing. The remainder is divided among Japan and Vietnam, with minor production in Europe and the USA (Adamas Intelligence Inc., 2022, Smith et al., 2022). Additionally, many magnet-producing companies headquartered outside China actually operate production facilities in China and are thus dependent on the supply chain within China (Smith et al., 2022).

It is worth noting that China has quotas on REE production and refining, which have increased over the past years to reflect the increasing market demand (domestic and international). However, the quotas for medium and heavy REEs have shown a decline year-on- year, which highlights the supply issues associated with elements essential for permanent magnets (Tang, 2024).

In the past, European companies have dominated wind turbine manufacturing. However, China has recently emerged as the leading manufacturer, accounting for 65 per cent of generator manufacturing and 60 per cent of nacelle assembly capacity in 2023 (Hutchinson and Zhao, 2023). Nevertheless, Europe remains a significant player, retaining 22 per cent of generator manufacturing capacity and 19 per cent of nacelle assembly, mostly in Denmark, Spain, Germany and France. In contrast, the USA has no domestic generator manufacturing, but is the third-largest nacelle assembler with 9 per cent of the global total (Hutchinson and Zhao, 2023).

3 UK supply chain in wind turbine technology

Many UK companies provide services in the installation, operation and maintenance of wind turbines and wind energy parks, particularly those located offshore. However, there are few producers of raw materials and component manufacturers for industrial-scale wind turbines.

There is currently no mining of REEs, B or Cu in the UK. While Cu has been mined in the past at many locations across the country, there are currently no active mining operations; the South Crofty tin (Sn) mine in Cornwall, which also produced Cu, ceased production in 1998. Cornish Metals is currently investigating if the mine can be re-opened with Cu as a co-product. It recently published a positive preliminary economic assessment, although the available resources are minor compared to the top producing countries (Szebor and Chesher, 2023, Cornish Metals Inc., 2024). The company is also investigating Cu-Sn mineralisation at United Downs, 8 km east of South Crofty.

While there are REE mineral occurrences in the UK and potential for further investigations, notably in Scotland, there has not been any systematic exploration for REEs in the UK and no resources are known (Deady et al., 2023, Currie and Elliott, 2024). There are also no known resources of B.

Refining activity for wind turbine raw materials in the UK is currently very limited. There are, however, some notable ongoing developments. Pensana is constructing an REO separation facility at Humber Freeport, East Yorkshire (BEIS, 2022). This plant is projected to have an annual capacity to produce 12 000 t total REOs and 4400 t Nd-Pr oxides, positioning it as the largest REE refinery outside China (Pensana Plc, 2024). REE concentrate for this refinery will be supplied by Pensana's mining project in Angola, planned to start production in 2026 (Pensana Plc, 2024).

Less Common Metals is one of the most important producers of REE metals and alloys outside China. It produces the Nd, Nd-Pr metal and NdFeB alloy needed for magnet manufacturing. Its facility at Ellesmere Port in Cheshire has a capacity of 1400 t per annum of alloys (Innovation News Network, 2024). The company recently partnered with Rainbow Rare Earth to buy REOs from their Phalaborwa mine in South Africa, with the aim of building an ethical, integrated supply chain providing key material to the UK magnet sector (Less Common Metals, 2023).

While there are a few permanent-magnet assemblers and suppliers in the UK, none of these supply the wind turbine industry and they specialise in other sectors such as the automotive, aerospace and electronics sector (Arnold Magnetic Technologies, 2024, Bunting Europe, 2024, Cermag Ltd, 2024, Eclipse Magnetics, 2024, Greenwood Magnetics, 2024, SG Technologies, 2024). It is unclear if they could supply the wind turbine market in future.

Two major multinational companies manufacture wind turbine blades in the UK. Vestas Wind Systems A/S, headquartered in Denmark, manufactures wind turbine blades on the Isle of Wight for offshore application. Since 2002, Vestas has produced more than 10 000 blades (BBC News, 2023). In addition, Siemens Gamesa, located in Hull, has been manufacturing offshore wind turbines blades since 2016. They have produced more than 1500 blades and recently expanded the site to produce larger, 108 m-long blades for 15 MW wind turbines (Siemens Gamesa, 2021, Memija, 2023).

Other notable component manufacturers in the UK include JDR Cable Systems based in Edinburgh, which specialises in the manufacture of subsea cables required for offshore wind-farm grid connection (JDR Cable Systems Ltd., 2024). In addition, the aerospace company

Babcock International, with facilities at Rosyth near Edinburgh, supplied wind turbine transformer modules for the Beatrice wind farm (Energy Voice, 2016).

Although there are no industrial-scale wind turbine manufacturers in the UK, there are several companies specialising in wind turbines for domestic applications with up to 100 kW power output. These include Marlec, Britwind and Evoco (Richardson, 2023).

The UK is developing recycling capabilities for the REEs found in permanent magnets. HyProMag initiated the production of NdFeB magnets by using magnet scrap material. Founded at the University of Birmingham and owned by the mineral exploration company Mkango Resources, HyProMag is transitioning from pilot plant testing, during which it produced 3000 permanent magnets between 2022 and 2023, to full-scale commercial production in 2024 (University of Birmingham, 2023). The company has a target capacity of 20 t permanent magnets per year. In contrast, Ionic Technologies, based in Belfast, specialises in recycling magnet scrap into individual REOs. The company has recently switched from a small-scale pilot to a larger demonstration plant (Ionic Technologies, 2023). This aims to recover 30 t per annum of waste magnets and swarf scrap and produce over 10 t separated magnet REOs (Ionic Technologies, 2024).

4 UK future demand

4.1 MARKET SHARE SCENARIOS AND MODELLING CONDITIONS

The future demand for the raw materials needed for the manufacture of wind turbine generators requires an in-depth understanding of technological developments and market trends. The technological evolution of wind turbine generators has previously been modelled in a range of scenarios at the European Union and global level up to 2050 (European Commission et al., 2020a, European Commission et al., 2020b, Liang et al., 2023).

The future development of wind power technologies and their market shares are subject to considerable uncertainty. While existing literature may provide indicative overviews, the level of detail available does not provide a sound basis for the authoritative evaluation of raw material use (European Commission et al., 2020a, European Commission et al., 2020b, Liang et al., 2023). Nevertheless, the role of offshore wind turbines in achieving net zero is undeniable and technological improvements will play a major role in future material requirements, such as REE permanent magnets.

A significant, rapid technological transformation has been observed over the past five years; wind turbines, especially those offshore using permanent magnets, continue to grow in capacity, gradually displacing conventional generators that do not require these magnets. For example, technologies like DD-EESG and GB-DFIG turbines remain effective in onshore settings but cannot be considered for future offshore installations because of their considerable weight (Centre for Sustainable Energy, 2017, Rabe et al., 2017). The trend for larger-capacity turbines sited offshore is generally expected to persist.

In this analysis, the future material requirements for the UK wind power are estimated on the following bases:

- projected UK offshore and onshore wind power generation capacity (Figure 9) (National Grid, 2023)
- gradual transition of generator types (subtechnologies) in wind turbines from 2020 onwards, based on current trends and developments from literature (Figure 10) (European Commission et al., 2020a, European Commission et al., 2020b, Liang et al., 2023)
- materials intensity of each wind turbine generator (t/GW) (Ballinger et al., 2019, European Commission et al., 2020b) — it is assumed that, with technological optimisation in the future, the intensity of material usage will likely change; for example, even if the consumption of raw materials increases with the capacity of the installation, the effect could be offset by higher energy generation from resource-efficient design

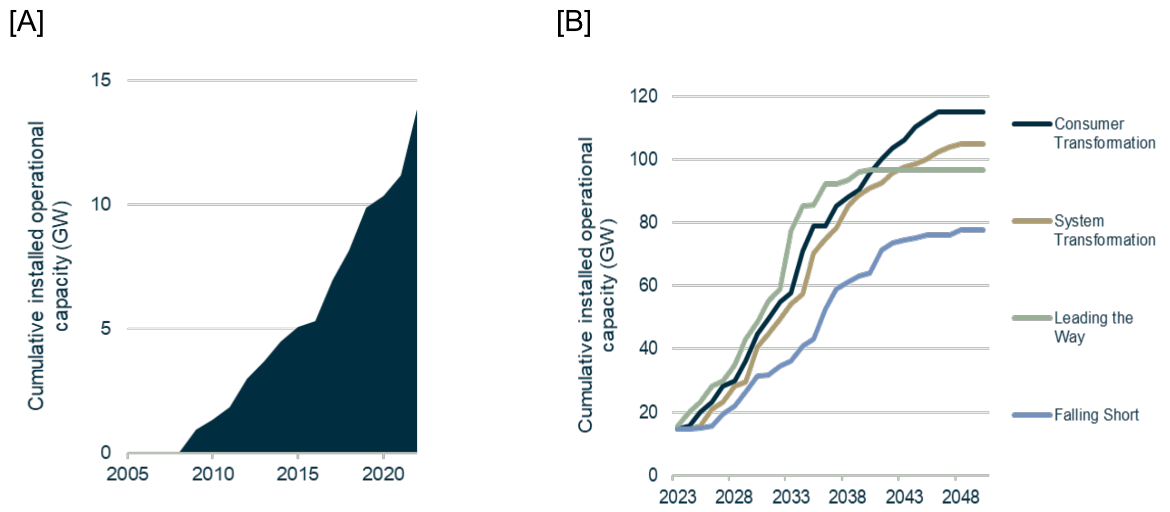


Figure 9 [A] Cumulative installed wind power operational capacity up to 2022 (DESNZ, 2024b); [B] Future cumulative operational installed wind power capacity based on four different future energy scenarios (National Grid, 2023, DESNZ, 2024b).

In the onshore sector, GB-DFIGs are the dominant type, with a market share of 72 per cent. The remainder is split among DD-PMSGs, DD-EESGs and GB-PMSGs, accounting for 18 per cent, 5 per cent, and 5 per cent of the market, respectively. Over time, the market share of permanent-magnet generators (DD-PMSG and GB-PMSG) in the onshore sector is expected to increase to a combined share of 70 per cent by 2050. At the same time, the GB-DFIG market share is projected to decline to 25 per cent by 2050, while the DD-EESG share is assumed to remain stable (Figure 10A).

In the UK offshore power-generation sector, permanent-magnet generators (DD-PMSG and GB-PMSG) dominated in 2020, with a combined market share of 94 per cent. The remaining 6 per cent was attributed to GB-DFIG. The share of permanent-magnet generators in the offshore sector is anticipated to reach 100 per cent in 2050 (Figure 10B).

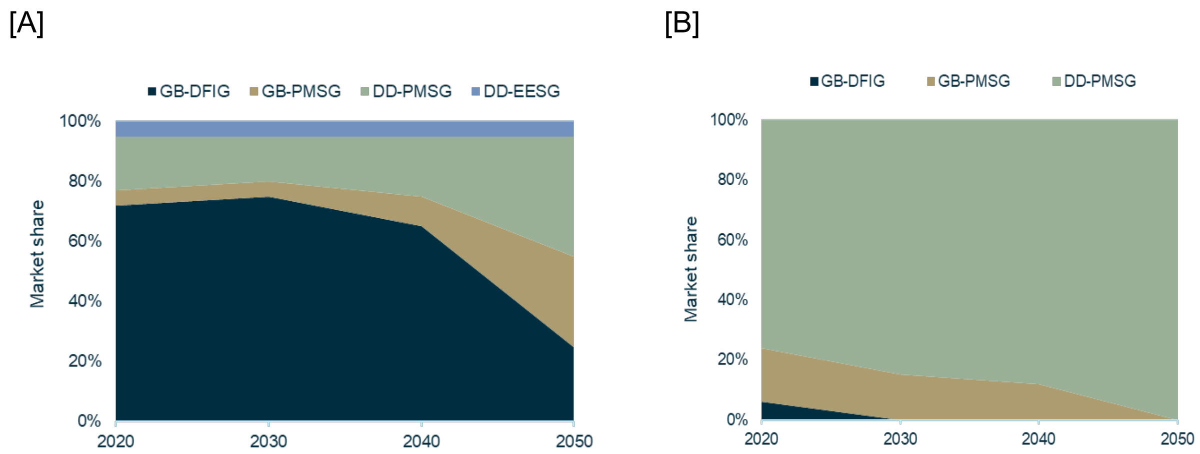


Figure 10 Evolution of the wind turbine market [A] onshore and [B] offshore between 2020 and 2050, showing the technology transformation that is likely to take place (European Commission et al., 2020b, Liang et al., 2023). The market shares shown were used in the material demand calculations. GB-DFIG: Gearbox double-fed induction generator; GB-PMSG: gearbox permanent magnet synchronous generator; DD-PMSG: direct drive permanent-magnet synchronous generator; DD-EESG: direct drive external excitation synchronous generator. BGS © UKRI.

4.2 FUTURE UK RAW MATERIAL NEEDS FOR WIND TURBINES

The installed capacity of wind generation, including both onshore and offshore turbines, in the UK from 2010 to 2022 is based on data reported by the Department for Energy Security and Net Zero (DESNZ) (DESNZ, 2024b). Data for the period 2023 to 2050 are derived from the National Grid's Future Energy Scenarios (FES) (National Grid, 2023). The forecast models are built upon the operational capacity of wind generation. The average lifespan of both onshore and offshore wind turbines is therefore assumed to be 25 years and the replacement of installed wind generation capacity reaching its end of life during the analysis period was accounted for in the calculations.

The future demand in the UK for the selected materials embedded in wind turbine generators is presented in two ways (Table 3):

- the quantity in tonnes required from 2020 to 2050 for each of the FES
- the percentage of current global metal production (based on average production between 2017 and 2021)

At present, precise figures for the global production of individual REEs such as Dy, Nd, Pr and Tb are not accessible. However, internal estimates by BGS yield production volumes for these metals proportional to their global average individual concentration in ore deposits (Table 3). The current global production volumes of B and Cu are very large and predominantly cater to other industries. Only a relatively small proportion of these is refined into materials for wind power generators.

Table 3 Global metal production (five-year average, 2017 to 2021) for the elements assessed in this analysis. REO data from BGS (2023) modified by in-house calculations for individual metals.

Element	Global production (5-year average) (tonnes)
Borate	7 370 822
Cu (smelter)	17 064 904
Dy	1249
Nd	26 286
Pr	8151
Tb	288

Between 2030 and 2040, the demand for all the materials evaluated is projected to increase by a factor of 1.5 to 1.6 compared to demand for the decade spanning 2020 to 2030. This is consistent with the expected deployment rate of wind energy across all FES. The strongest demand increase rate is anticipated for B and Tb. Between 2040 and 2050, the demand for all materials is expected to decrease by 20 per cent to 40 per cent compared to the previous decade, with the largest reduction in demand expected for Cu (Figure 11).

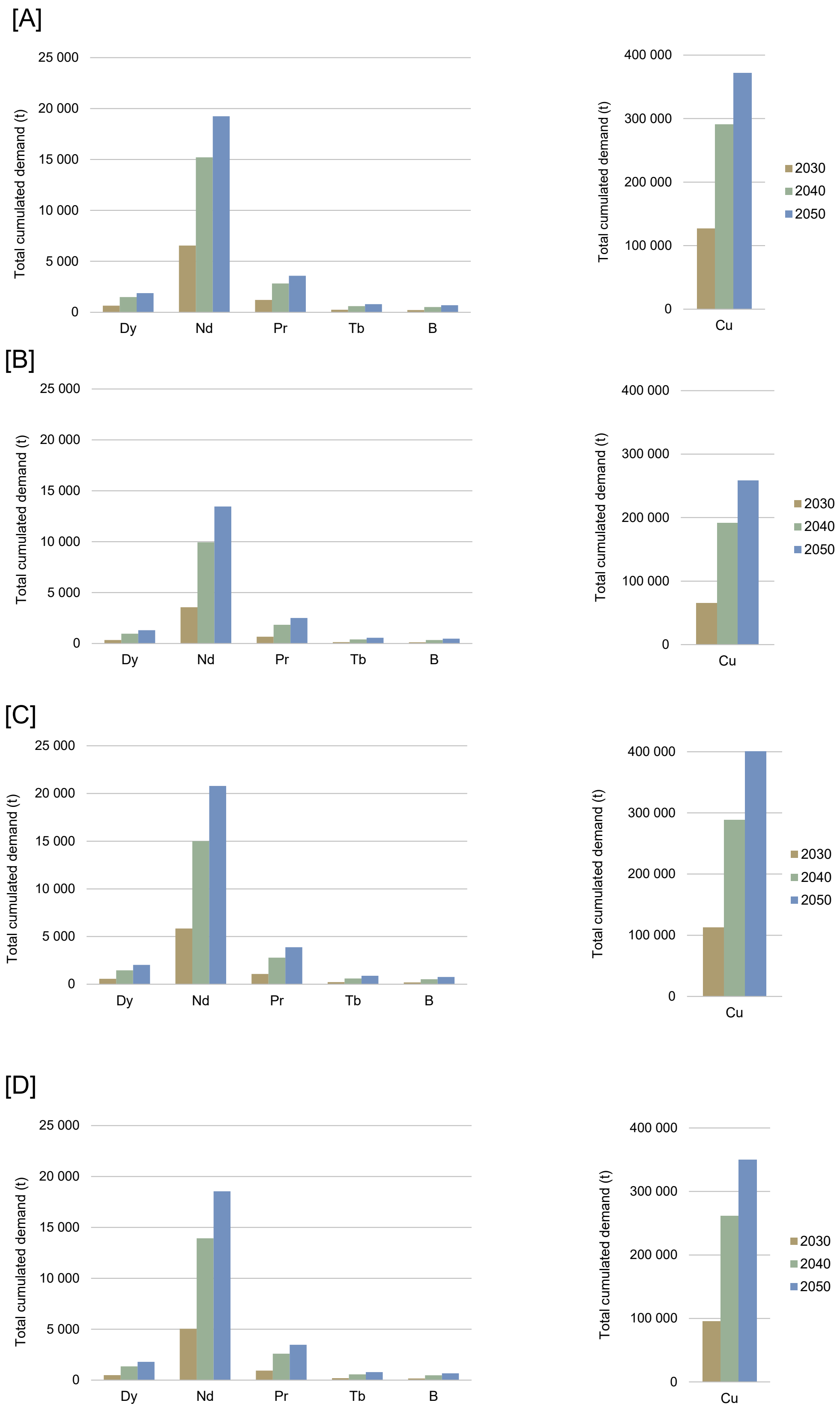


Figure 11 Cumulative forecast UK demand (tonnes) between 2020 and 2050 in wind turbines for the elements considered in this study under four different FES. [A] 'Leading the way'; [B] 'Falling short'; [C] 'Consumer transformation'; [D] 'System transformation'. BGS © UKRI.

For the REEs and Cu, annual demand peaks in 2030, reaches its lowest point in 2040 and then starts increasing again towards 2050 (Appendix B). This trend stems from the expected rapid deployment rate of offshore wind energy generation capacity throughout the 2020s in all the FES, with over 95 per cent of planned capacity deployment of the 'Leading the way' scenario to be achieved over the next 10 years. This is to achieve the Government's target of 50 GW offshore wind energy generation by 2030 (National Grid, 2023). Subsequently, as the wind farms age, the need for renewing decommissioned capacity towards the later years of the scenarios results in an increased material demand to maintain energy generation (Appendix B).

Comparison of these demand projections with current global production levels highlights the scale of the future demand increases required for wind-power materials (Figure 12). For example, the UK alone would require:

- between 11 and 24 per cent (minimum to maximum) of the current global production of Tb by 2030
- between 6 and 13 per cent of the current global Dy production by 2030
- between 3 and 14 per cent of current global Tb production by 2040
- between 2 and 7 per cent of current global Dy production by 2040

For other elements used in electric generators, potential supply concerns are likely to occur for Nd in 2030 and 2040 and Pr in 2030 and 2040.

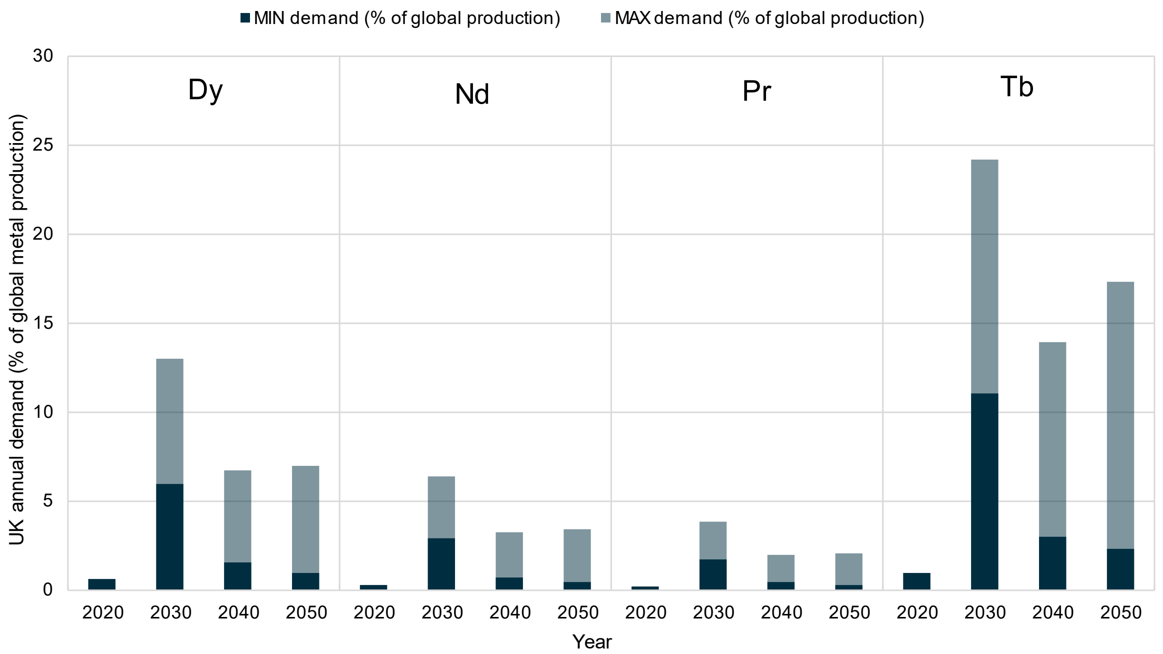


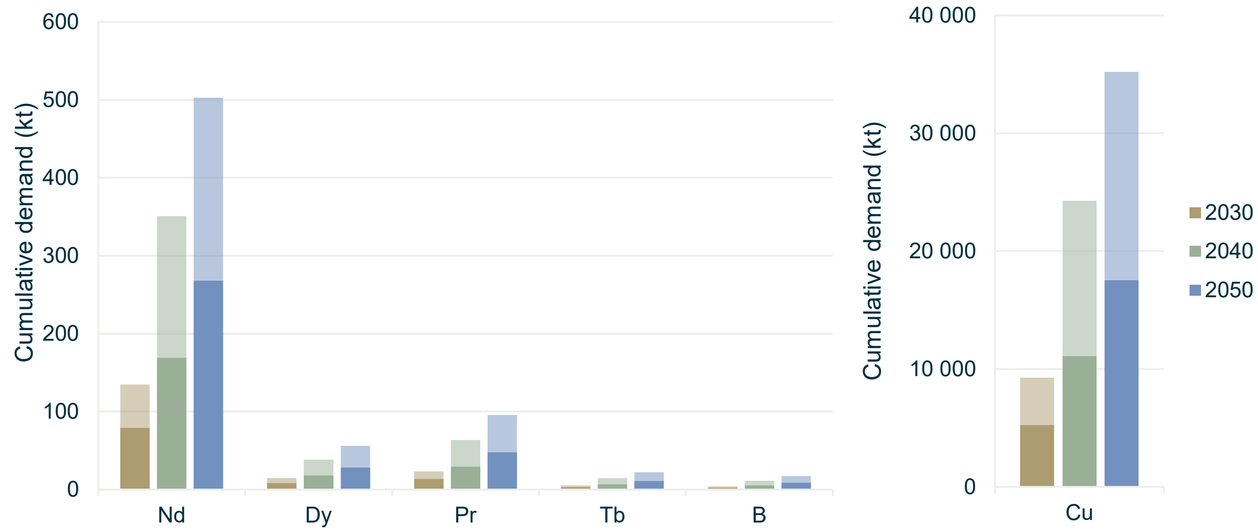
Figure 12 Annual UK demand for 2030, 2040 and 2050 as a percentage of current global metal production (five-year average, 2017 to 2021). Data from the BGS World Mineral statistics Database (BGS, 2023) with authors' own calculations on individual metals. The minimum and maximum values represent the outputs of the different scenarios. BGS © UKRI.

4.3 COMPARISON OF GLOBAL AND UK MATERIAL DEMAND PROJECTIONS

The global material demand projections used in this analysis are sourced from data published by the IEA (International Energy Agency, 2023). The demand projections are presented in a similar way to that of the modelling in this study, showing minimum and maximum values based on the different scenarios used by the IEA (Figure 13).

The results indicate that the global demand for all the materials assessed is higher by a factor of about 25 compared with UK demand. This is unsurprising given the relative size of the UK and world wind-energy markets. Comparing these projections shows that the UK demand for Dy, Nd, Pr and Tb is not insignificant, ranging from 4 to 6 per cent of the global demand between 2020 and 2050. For B, the UK wind-energy demand is between 4 and 7 per cent of global demand between 2030 and 2050, while UK demand for Cu in wind turbines amounts to 1 to 2 per cent of the global demand in the same period.

[A] Global



[B] UK

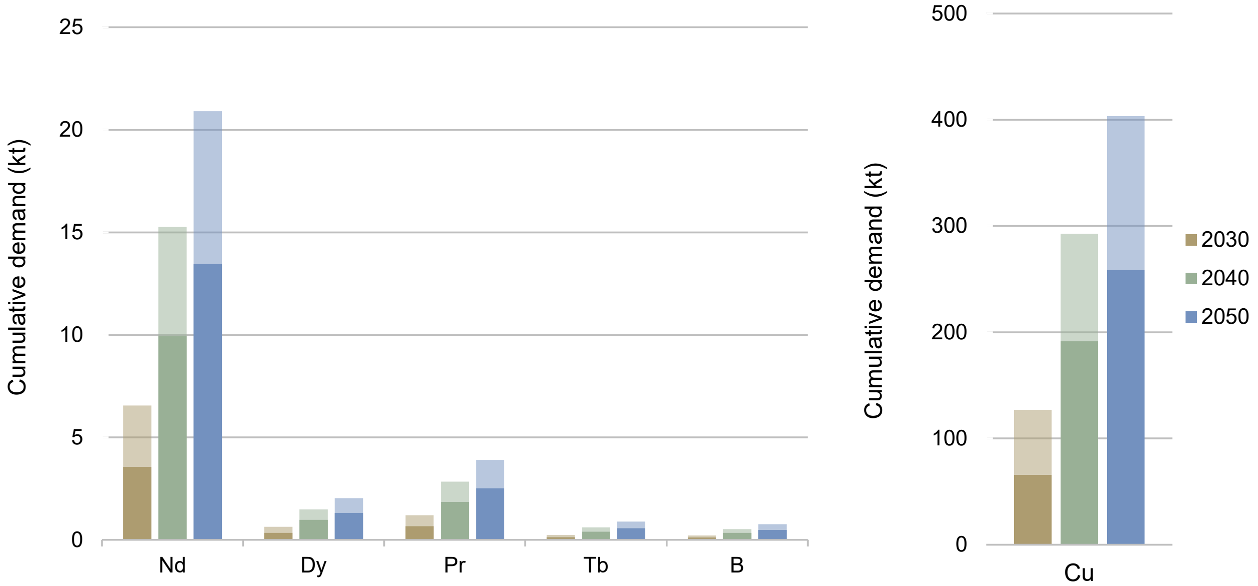


Figure 13 Material demand for selected elements (in kilotonnes) embedded in wind turbines in the UK compared with global demand between 2020 and 2050. The data for the non-UK demand projections are based on the IEA estimates for different scenarios (International Energy Agency, 2023). [A] Global material demand for wind turbines showing the maximum and minimum values derived from all scenarios: 'Stated policies'; 'Announced pledges'; 'Net zero emissions by 2050'. [B] UK material demand for wind turbines, showing the maximum and minimum values derived from all scenarios: 'Leading the way'; 'Falling short'; 'Consumer transformation' and 'System transformation'. BGS © UKRI.

5 Discussion and conclusions

The UK total installed capacity of wind power in 2023 comprises 15 GW onshore, 15 GW offshore and 80 MW of floating wind generators (DESNZ, 2024a). However, this capacity is going to increase rapidly in line with the UK Government's net zero commitment for up to 50 GW installed offshore wind power by 2030 (DESNZ, 2023). Subsequently, further expansion is likely, with up to 125 GW offshore wind capacity installed by 2050 (Committee on Climate Change, 2020).

At the same time, wind technology will undergo significant changes, with larger turbines that rely on permanent magnets becoming standard. Consequently, demand for the materials used in the manufacture of wind turbines will follow a similar pattern of rapid growth to 2050. To ensure these targets are met, the security of supply of the materials and component parts used in wind turbines will be pivotal. New supply chains for the design, manufacture, installation, maintenance and decommissioning, including reverse options such as remanufacturing and recycling, will have to be developed.

Currently, only a small part of the wind turbine supply chain is located in the UK. However, domestic expertise in certain parts of the system is well developed, including:

- manufacture of specific components such as turbine blades
- development of technologies for domestic and small-scale applications
- physical installation of plants, both offshore and onshore

The manufacture of generators and permanent magnets is largely absent from the UK, as are participants in the permanent-magnet supply chain. Reliance on overseas supply chains is therefore inevitable. Barriers to security of supply are many and varied, resulting from:

- limited available time to increase green technologies required to tackle climate change
- competing global demand
- geopolitics
- market conditions
- environmental, social and economic challenges

In this assessment, we estimated the UK demand for key elements embedded in wind generators of four different types:

- gearbox double-fed induction generators (GB-DFIG)
- gearbox permanent-magnet synchronous generators (GB-PMSG)
- direct-drive permanent-magnet synchronous generators (DD-PMSG)
- direct-drive electrically excited synchronous generators (DD-EESG)

An analysis of the global supply chains and UK demand requirements for six elements used in these generators was undertaken. These were:

- B
- Cu
- Dy
- Nd
- Pr
- Tb

The UK material demand forecasts were produced using the National Grid FES. These forecasts were compared with global demand estimates based on the projections and scenarios from the IEA.

Supply bottlenecks were assessed based on the following parameters:

- production concentration, derived from analysis of national production data and the ESG ranking of the main producers
- trade concentration, derived from analysis of national trade data and trade restrictions currently imposed by the main trading nations

Wherever possible, quantitative data from authoritative sources were used in this analysis. However, there are significant issues concerning the availability and quality of data for some parts of the supply chain, such as trade, material intensities and production levels. For example, data for assessing the production and trade of individual REEs are missing, while quantitative data on the production of REE alloys and permanent magnets are not well documented. Consequently, no systematic quantitative analysis of supply risk could be undertaken for some materials in the wind turbine supply chain.

Production concentration in the upstream supply chain of REOs is significant, with China predominant in mining. It is important to note that not all deposits contain viable economic concentrations of those REEs used in permanent magnets. Many deposits are relatively enriched in Ce and La, which are not used in magnets. Therefore, the geographical production concentration of the permanent magnet REEs (Dy, Nd, Pr and Tb) is significantly greater than for total REOs and represents a serious risk to supply security.

The mine production concentration of borates is also highly concentrated, with Turkey the leading producer (59 per cent of world total). Mine production of Cu is more diversified, with Chile accounting for the largest share (27 per cent). At the refining stage, it was only possible to assess the status of refined Cu: this is moderately concentrated, with China the largest producer accounting for 42 per cent of the global total.

In the midstream supply chain, REE alloy and permanent-magnet manufacture is highly concentrated in China (92 per cent of the global magnet manufacturing market). It is important to also note that most magnet producers operating outside China have facilities in China too, and their supply chains are therefore highly dependent on the Chinese market (Smith et al., 2022).

Wind turbine manufacture and assembly is led by China, but some capacity is also present outside China, especially in Europe (Hutchinson and Zhao, 2023). While the current leading producers are likely to continue to dominate the market in the future, there is an appetite for manufacturing and assembly close to the end-use location, thus minimising transportation costs. However, there will inevitably be bottlenecks in the rapid expansion of the wind industry supply chain in the UK. These include the demand for new factories, port capacity, connection to the grid, skilled personnel and ships (Wind Europe, 2023).

The assessment of trade concentration has revealed that China adds value to its REE resources prior to exporting them in the form of metal. The trade concentration at the REE metal stage from China is significant and a potential risk to the wind turbine supply chain, if the supply of REOs and REE metal from other jurisdictions does not grow rapidly enough to meet demand. The prominence of China in permanent-magnet manufacture is likely to increase in response to the current strong global demand. In conjunction with the potential imposition of trade restrictions, this could further escalate supply risks. As the UK is nearly 100 per cent reliant on imported REE compounds, metals and permanent magnets, any escalation in supply risk is likely to be detrimental to an industry dependent on these materials and will deter future investment.

The wind generator market is very dynamic and expected to undergo significant changes up to 2050. The PMSG technologies (DD-PMSG and GB-PMSG) are currently dominant in offshore wind turbines worldwide, with a combined market share of 94 per cent; this dominance is likely to increase to 100 per cent beyond 2030. While all technologies require REEs, the material intensity in PMSG technologies is the largest by a significant margin. For example, the Nd material intensity in DD-PMSGs is about 180 kg/MW; about 50 kg/MW in GB-PMSGs and 12 kg/MW and 28 kg/MW in GB-DFIGs and DD-EESGs, respectively (European Commission et al., 2020b).

In the onshore sector, GB-DFIGs predominate at present, with a market share of 72 per cent, but this is expected to decline in the future (25 per cent share by 2050). At the same time, permanent-magnet generators (DD-PMSG and GB-PMSG) will become increasingly dominant in global onshore and offshore installations, leading to rapid and large demand growth for REE permanent magnets.

The global demand for Cu will also accelerate in a similar manner. The increase in the market share of DD-PMSGs from 76 per cent in 2020 to 100 per cent by 2050 will be the key driver for the strong Cu demand. However, the resource base for Cu is large and geographically diversified, so attendant supply risks are likely to be less significant.

The demand trajectory for B is increasing in a similar pattern to that of the REEs. The resource base for borates (the primary raw material for B) is large. Nevertheless, supply issues associated with the production of ferroboron may become apparent as the demand for NdFeB magnets escalates.

Analysis of future UK demand for wind turbines and embedded materials was derived from the installed capacity of wind generation (onshore and offshore) based on data reported in (DESNZ, 2024b) and future projections based on the National Grid's FES (National Grid, 2023). Between 2030 and 2040, the UK demand for B, Cu, Dy, Nd, Pr and Tb is projected to increase by an average factor of 1.5 compared to the previous decade. Demand in this period will grow rapidly for B and Tb across all scenarios. Between 2040 and 2050, the UK demand for all commodities is expected to decrease (between 20 and 40 per cent) compared to the previous decade. For example, UK demand for Nd and Cu in wind turbines will amount to 7500 t and 146 000 t, respectively, between 2030 and 2040, and 4600 t and 89 000 t between 2040 and 2050.

A comparison of the annual UK demand projections for wind turbines with annual average global production levels for 2017 to 2021 reveals that the UK alone would require 17.5 per cent of current global Tb production and 9.5 per cent of the current global Dy produced by 2030. These fall to 7.5 per cent and 3 per cent, respectively, by 2040.

The comparison of future global and UK material demand for wind turbine applications (all technologies) highlights that the global demand is higher by a factor of 25, primarily due to the global market size. The UK alone would require between 4 and 6 per cent of the current global demand for the permanent magnet REEs between 2020 and 2050. For B and Cu, the UK demand will be about 5 per cent and 1 per cent, respectively, of the global demand between 2030 and 2050. Considering the very small quantities of these materials currently produced globally and the market size of the UK, these numbers are particularly significant for the REEs and B. Competing demand from industry participants overseas, in both wind turbines and other clean technologies which use REE magnets, will also pose a serious risk to the security of material supply to the UK.

In the case of Cu, the large resource availability and its broad geographical distribution mean that supply issues are likely to be less significant. However, Cu is used in many other renewable technologies and is also essential for the connection of green energy to the grid. Consequently, the overall UK demand for Cu is likely to represent a much larger share of global Cu demand in the future.

Finally, the UK has no wind turbine generator manufacturing capacity. Material supply risks do not therefor directly affect the UK, but they will be critical for those countries that manufacture components and wind turbines

6 Recommendations

This assessment leads to the following key recommendations for the wind industry in the UK.

6.1 STRENGTHEN RESEARCH AND SUPPORT INVESTMENT

The UK is a world leader in offshore wind technology with installed capacity accounting for 24 per cent, second only to China (The Crown Estate, 2023), accompanied by high levels of research and innovation and the availability of technical expertise and a skilled workforce. However, achieving the net zero targets will be critically dependent on the ability of the UK to access the materials in adequate quantities and the required forms, at competitive prices and following sustainable and responsible supply principles. Continued Government funding to strengthen innovation and research capabilities related to the wind industry and its supply chains will be essential. The provision of support for investment will also be crucial: for example, through the Contracts for Difference support scheme (DESNZ, 2024c) and, specifically on critical minerals, through the Circular Critical Minerals Supply Chains (CLIMATES) fund (DBT et al., 2023).

6.2 INTERNATIONAL COOPERATION

Increased international cooperation such as trade agreements and strategic partnerships with overseas governments and commercial entities will help to strengthen wind technology supply chains for the UK. For example, the strategic partnership between Less Common Metals and Rainbow Rare Earths will contribute towards increasing the security of REE supply to the UK for use in the alloys required for permanent magnets (Less Common Metals, 2023). It is important to stress that there is less than a decade available for the UK to develop a competitive domestic value chain underpinned by secure and sustainable material supplies.

6.3 DIVERSIFY THE RARE EARTH VALUE CHAIN

The UK demand for wind turbines and the elements assessed is large relative to current global production levels and is especially problematic for the REEs required to manufacture permanent magnets. Therefore, diversification of the REE value chain through investment in projects outside China would reduce UK and global supply risks.

6.4 TAKE ACTION IN THE NEAR FUTURE

The UK Government should support new mining and refining projects (such as REE refining) to bring new commercial activities on stream in the near term, preferably within five years. They should also assist through providing technical assistance for capacity building, training and knowledge sharing, particularly in developing countries. Support for overseas investment by UK companies in the supply of REEs, Cu and B should also be made available.

Similarly, global demand for Cu in clean energy applications will increase rapidly up to 2050. Therefore, there is an urgent need to increase the global capacity for mining and refining of Cu (International Energy Agency, 2024).

6.5 INVEST IN THE RARE EARTH ALLOY SECTOR

The midstream stage of the value chain, which produces REE alloys and permanent magnets, is dominated by China. Although the UK is already a producer of REE alloys, further investment and incentives are required to strengthen this sector.

6.6 DEVELOP A UK PERMANENT-MAGNET ECOSYSTEM

The absence of permanent-magnet manufacturing means that alloys produced in the UK are exported, chiefly to China, for the production of magnets. These are then re-imported for use in wind turbines, traction motors and other applications. It is therefore crucial that the Government supports the development of a permanent-magnet ecosystem in the UK. This would also facilitate the establishment of reverse supply chains from magnets that become available from decommissioned wind turbines and other applications (Hsu et al., 2024).

6.7 ENSURE A RESPONSIBLE WIND TURBINE SUPPLY CHAIN

The UK is not a manufacturer of wind turbines or key components that include critical minerals. Considering the aggressive wind energy targets set by the UK, a preventative approach to supply-chain monitoring and management is recommended to ensure that the right products are manufactured and supplied responsibly to serve the UK demand for wind turbines.

6.8 IMPROVE DATA AVAILABILITY, TRANSPARENCY AND QUALITY

This assessment provides many useful insights into potential material bottlenecks associated with the expansion of wind energy. However, the robust estimation of future material demand and the identification of potential supply issues depend on reliable supply chain analysis and data of many types. Improving data availability, transparency and quality is essential. At the same time developing infrastructure for harmonised data collection and new data generation, while ensuring key data providers are fully engaged, are also of fundamental importance.

6.9 MONITOR SUPPLY CHAIN CONDITIONS

Like other decarbonisation technologies, the wind turbine market is dynamic and market conditions, geopolitical challenges, techno-economic changes and other social and environmental factors can rapidly impact any part of the supply chain. Ongoing supply chain monitoring and the establishment of data observatories (UK Technology Metals Observatory, 2024), together with the development of stocks and flows models supported by scenario analysis, can provide critical insight into future material challenges. This would underpin the development of effective mitigation strategies and increased resilience of the supply chain.

Appendix A

Wind turbine raw materials and components that have been excluded from the analysis. PMSG = permanent magnet synchronous generator.

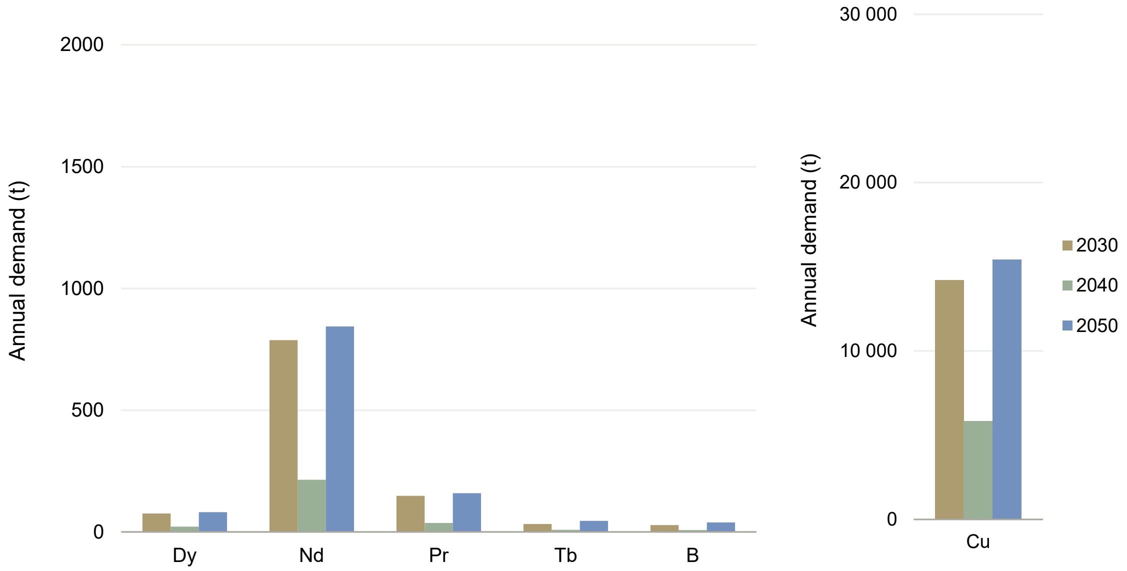
Component	Function	Reason for exclusion
Raw materials		
Al	Alternative to Cu in generators, transformers and structural material (for example, nacelle housing)	Currently not commonly used in wind turbine generators and structural material is excluded from the analysis
Carbon fibre	Used to make rotor blades	Lack of data
Co	Used in samarium-cobalt (SmCo) permanent magnets	SmCo magnets are not commonly used in current permanent-magnet generators
Concrete	Large quantities required for the foundation	Not part of the main technology
Cr	Used in steel in rotors and blades	Not part of the main technology
Mn	Used in steel in various components	Not part of the main technology
Ni	Used in steel in various components	Not part of the main technology
Fe	Used in NdFeB permanent magnets for PMSG and steel in various components	Demand in permanent magnets is negligible compared to iron use in structural components (steel), which are not considered
Mo	Used in steel in some generator components	Not part of the main technology
Sm	Used in SmCo permanent magnets	SmCo magnets are not commonly used in current permanent-magnet generators
Si	Used in electrical steel to make the stator and rotor core	Not part of the main technology
Zn	Used in protective coatings	Not part of the main technology

SmCo permanent magnet	Other type of permanent magnet used in PMSG	Currently not used in wind turbines
Electrical steel	Used to make rotor and stator core	Not part of the main technology
Wind turbine subtechnologies		
Squirrel-cage induction generator	Mature technology, commonly used from 1990s onwards	Use has phased out and replaced with other technology
Wound-rotor induction generator	Mature technology, commonly used from 1990s onwards	Use has phased out and replaced with other technology
Reluctance generators	Future technology, uses low-cost materials	Future uptake is uncertain
High-temperature superconductor generator	Future technology, with lower material requirement	Future uptake is uncertain

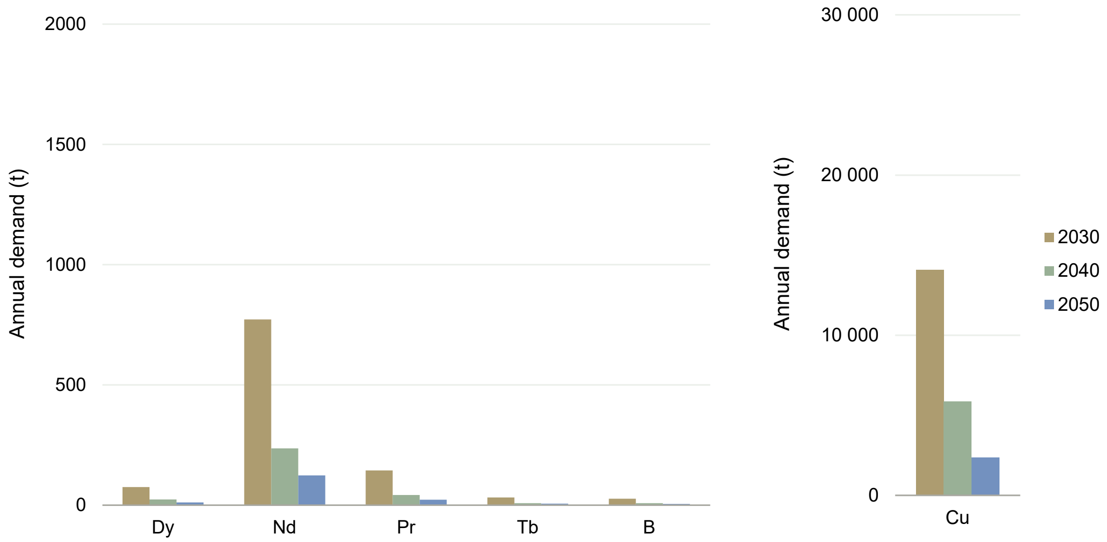
Appendix B

Annual forecast demand (tonnes) for the elements considered in this study up to 2050 and compared with 2020 under four FES. [A] 'Leading the way'; [B] 'Falling short'; [C] 'Consumer transformation'; [D] 'System transformation' scenarios. BGS © UKRI.

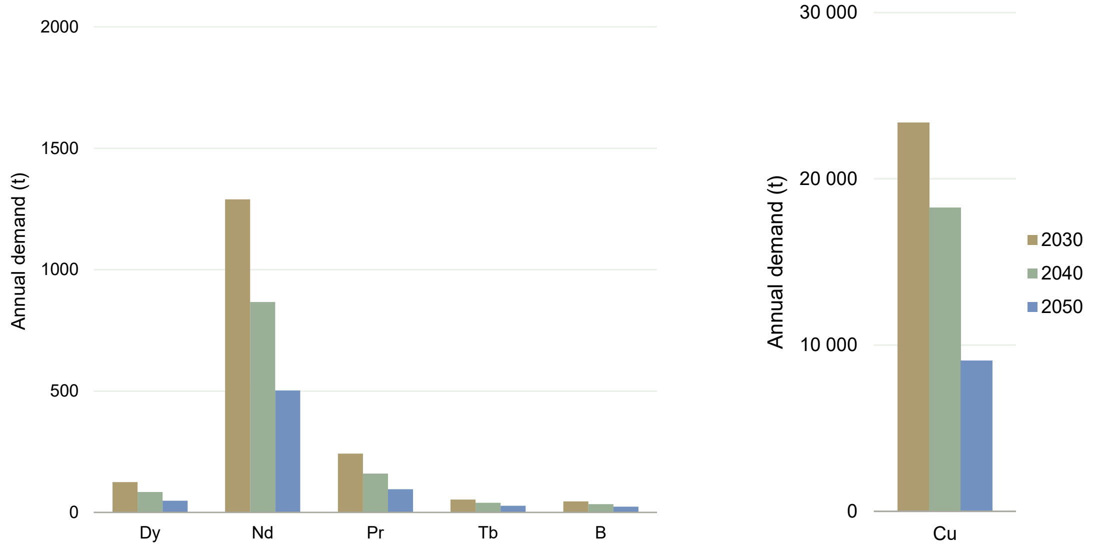
[A]



[B]

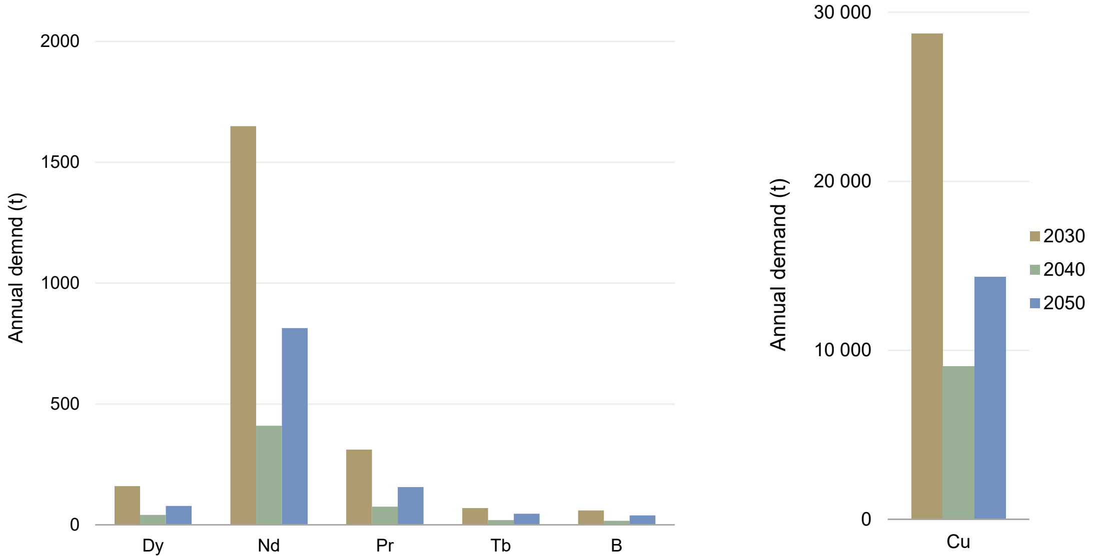


[C]



2000
1500
1000
500
0
Annual demand (t)
Dy
Nd
Pr
Tb
B
30 000
20 000
10 000
0
Annual demand (t)
Cu
2030
2040
2050

[D]



2000
1500
1000
500
0
Annual demnd (t)
Dy
Nd
Pr
Tb
B
30 000
20 000
10 000
0
Annual demand (t)
Cu
2030
2040
2050

Acronyms and abbreviations

BGS	British Geological Survey
DD	Direct drive
DD-PMSG	Direct-drive permanent-magnet synchronous generator
DESNZ	Department for Energy Security and Net Zero
DFIG	Double-fed (or doubly fed) induction generators
EESG	Electrically excited synchronous generators
ESG	Environmental, social and governance
FES	(National Grid) Future Energy Scenarios
GB	Gearbox
GB-DFIG	Gearbox double-fed induction generator
HS	Harmonized System (trade codes)
NdFeB	Neodymium-iron-boron alloy
PMSG	Permanent magnet synchronous generator
REE	Rare earth element
REO	Rare earth oxide

References

Adamas Intelligence Inc. 2022. Rare Earth Magnet Market Outlook to 2035. *Adamas Intelligence Inc.,* (Online: *ADAMAS INTELLIGENCE INC.*) Available: https://www.adamasintel.com/rare-earth-magnet-market-outlook-to-2035/ [Accessed: 20 May 2023].

Arnold Magnetic Technologies. 2024. *Capabilities*. (Online: *Arnold Magnetic Technologies*.) Available: https://www.arnoldmagnetics.co.uk/capabilities/ [Accessed: 07 March 2024].

Ballinger, B, Stringer, M, Schmeda-Lopez, D R, Kefford, B, Parkinson, B, Greig, C & Smart, S 2019. The vulnerability of electric vehicle deployment to critical mineral supply. *Applied Energy*. 255**,** 113844. Available: https://doi.org/10.1016/j.apenergy.2019.113844.

BBC News. 2023. Vestas: Wind turbine jobs boost for Isle of Wight factory. *BBC News*. 23 March 2023. (Online: *BBC.*) Available: https://www.bbc.co.uk/news/uk-england-hampshire-60848933 [Accessed: 15 March 2024].

BEIS. 2022. UK's first magnet refinery given huge financial boost as first ever strategy for supply of critical minerals published. 22 July 2022 (Online: *Department for Business, Energy & Industrial Strategy (BEIS) & the RT Hon Kwasi Kwarteng, HM Government.*) Available: https://www.gov.uk/government/news/uks-first-magnet-refinery-given-huge-financial-boost-as-first-ever-strategy-for-supply-of-critical-minerals-published [Accessed: 07 March 2024].

BGS. 2023. *World mineral statistics data*. (Online: *British Geological Survey (BGS)*.) Available: https://www2.bgs.ac.uk/mineralsuk/statistics/wms.cfc?method=searchWMS [Accessed: 08 December 2023].

Bunting Europe. 2024. *Automotive*. (Online: *Bunting Europe*.) Available: https://www.bunting-berkhamsted.com/industries/automotive/ [Accessed: 07 March 2024].

Centre for Sustainable Energy 2017. Common concerns about wind power – 2nd edition. *Centre for Sustainable Energy,* (Online: *CENTRE FOR SUSTAINABLE ENERGY*.) Available: https://www.cse.org.uk/my-community/community-projects/common-concerns-about-wind-power/ [Accessed: 06 February 2025].

Cermag Ltd. 2024. *Permanent Magnets*. (Online: *Cermag Ltd*.) Available: http://www.cermag.co.uk/permanent%20magnets.htm [Accessed: 07 March 2024].

Committee on Climate Change 2020. The Sixth Carbon Budget The UK's path to Net Zero. (Online: *COMMITTEE ON CLIMATE CHANGE*.) Available: https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf [Accessed: 26 April 2024].

Copper Development Association Inc. 2024. *Renewables*. (Online: *Copper Development Association Inc.,*.) Available: https://www.copper.org/environment/sustainable-energy/renewables/ [Accessed: 14 March 2024].

Cornish Metals Inc. 2024. Cornish Metals reports positive preliminary economic assessment results for South Crofty Tin Project. 30 April 2024 (Vancouver: *Cornish Metals Inc.*) Available: https://investors.cornishmetals.com/announcements/6315981 [Accessed: 21 May 2024].

Currie, D & Elliott, H 2024. The potential for rare earth elements in the UK. *British Geological Survey, Critical Minerals Intelligence Centre* (Online: *DEPARTMENT FOR BUSINESS AND TRADE*.) Available: https://ukcmic.org/downloads/reports/the-potential-for-rare-earth-elements-in-the-uk-2024.pdf [Accessed: 22 May 2024].

DBT, Innovate UK & Ghani, N M. 2023. £15 million funding boost to strengthen supply of critical minerals. 27 February 2023 (Online: *Department for Business and Trade (DBT).*) Available: https://www.gov.uk/government/news/15-million-funding-boost-to-strengthen-supply-of-critical-minerals

Deady, E A, Goodenough, K M, Currie, D, Lacinska, A, Grant, H, Patton, M, Cooper, M, Josso, P, Shaw, R, Everett, P & Bide, T 2023. Potential for Critical Raw Material Prospectivity in the UK. *British Geological Survey* (Keyworth: *BRITISH GEOLOGICAL SURVEY*.) Available: https://ukcmic.org/reports/ukcmic-potential-for-critical-raw-material-prospectivity-in-the-uk-cr23024.pdf

DESNZ. 2024a. Energy Trends: UK renewables - Energy Trends renewables tables (ODS). (Online: *Department for Energy Security and Net Zero (DESNZ)*.), https://www.gov.uk/government/statistics/energy-trends-section-6-renewables [Accessed: 17 May 2024].

DESNZ. 2024b. Energy Trends: UK renewables, Table 6.1. Renewable electricity capacity and generation. (Online: *Department for Energy Security and Net Zero (DESNZ)*.) Available: https://www.gov.uk/government/statistics/energy-trends-section-6-renewables [Accessed: 02 April 2024].

DESNZ 2024c. Proposed amendments to Contracts for Difference for Allocation Round 7 and future rounds. *Department for Energy Security and Net Zero (DESNZ)* (Online: Available: https://www.gov.uk/government/consultations/proposed-amendments-to-contracts-for-difference-for-allocation-round-7-and-future-rounds#:~:text=The%20Contracts%20for%20Difference%20(%20CfD,towards%20our%20net%20zero%20ambitions [Accessed: 17 May 2024].

DESNZ 2023. Offshore Wind Net Zero Investment Roadmap. *Department for Energy Security and Net Zero and Department for Business and Trade (DESNZ)* (Online: *HM GOVERMENT*.) Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1167856/offshore-wind-investment-roadmap.pdf [Accessed: 26 April 2024].

Eclipse Magnetics. 2024. *About us*. (Online: *Eclipse Magnetics*.) Available: https://www.eclipsemagnetics.com/company/about-us/ [Accessed: 07 March 2024].

EERE. 2024. (Online: *Office of Energy Efficiency & Renewable Energy (EERE); US Department of Energy*.) Available: https://www.energy.gov/eere/wind/how-do-wind-turbines-work [Accessed: 27 March 2024].

Energy Voice. 2016. Babcock wins contract for Beatrice offshore transformer modules. 09 September 2016. (Online: *Energy Voice.*) Available: https://www.energyvoice.com/renewables-energy-transition/118899/babcock-wins-contract-beatrice-offshore-transformer-modules/ [Accessed: 15 March 2024].

European Commission, Joint Research Centre, Alves Dias, P, Bobba, S, Carrara, S & Plazzotta, B. 2020a. *The role of rare earth elements in wind energy and electric mobility – An analysis of future supply/demand balances. Publications Office*.) Available: doi/10.2760/303258.

European Commission, Joint Research Centre, Carrara, S, Alves Dias, P, Plazzotta, B & Pavel, C 2020b. Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system. *European Commission, Joint Research Centre* (Luxembourg: *PUBLICATIONS OFFICE OF THE EUROPEAN UNION*.) Available: https://doir.org/10.2760/160859 [Accessed: 14 March 2024].

Farina, A & Anctil, A 2022. Material consumption and environmental impact of wind turbines in the USA and globally. *Resources, Conservation and Recycling.* 176**,** 105938. Available: https://doi.org/10.1016/j.resconrec.2021.105938.

Frangoul, A. 2023. The world's largest offshore wind farm produces its first power. *CNBC*. 9 October 2023. (Online: *CNBC LLC.*) Available: https://www.cnbc.com/2023/10/09/the-worlds-largest-offshore-wind-farm-produces-its-first-power.html [Accessed: 18 March 2024].

Greenwood Magnetics. 2024. *About us*. (Online: *Greenwood Magnetics*.) Available: https://www.greenwoodmagnetics.com/about-us/ [Accessed: 07 March 2024].

Hsu, W-T, Petavratzi, E, Zils, M, Einarsson, S, Morasae, E K, Lysaght, O & Hopkinson, P 2024. Mapping the flows and stocks of permanent magnets rare earth elements for powering a circular economy in the UK. *Sustainable Production and Consumption.* 47**,** 37-46. Available: https://doi.org/10.1016/j.spc.2024.03.027.

Hutchinson, M & Zhao, F 2023. GWEC - Global Wind Report 2023. *Global wind energy council* (Online: *GLOBAL WIND ENERGY COUNCIL*.) Available: https://gwec.net/wp-content/uploads/2023/04/GWEC-2023_interactive.pdf [Accessed: 14 March 2024].

Idoine, N, Raycraft, R, Price, F, Hobbs, S, Deady, E, Everett, P, Shaw, R, Evans, E & Mills, A 2023. World mineral production 2017-2021. *British Geological Survey* (Keyworth:

BRITISH GEOLOGICAL SURVEY.) Available: https://nora.nerc.ac.uk/id/eprint/534316 [Accessed: 27 October 2022].

Innovation News Network. 2024. Metal and alloy production in the Western World: A supply chain alternative. 7 February 2024. (Online: *Innovation News Network.*) Available: https://www.innovationnewsnetwork.com/metal-and-alloy-production-western-world-supply-chain-alternative/43186/ [Accessed: 07 March 2024].

International Energy Agency 2024. Global critical minerals outlook 2024. *International Energy Agency (IEA)* (Online: *IEA*.) Available: https://iea.blob.core.windows.net/assets/ee01701d-1d5c-4ba8-9df6-abeeac9de99a/GlobalCriticalMineralsOutlook2024.pdf [Accessed: 4 June 2024].

International Energy Agency 2023. Global EV Outlook 2023 - Catching up with climate ambitions. *International Energy Agency* (Online: *INTERNATIONAL ENERGY AGENCY*.) Available: https://www.iea.org/reports/global-ev-outlook-2023 [Accessed: 17 January 2023].

Ionic Technologies. 2024. *Our Plant*. (Online: *Ionic Technologies*.) Available: https://ionictechnologies.com/process/

Ionic Technologies. 2023. Belfast company's innovative magnet recycling technology makes UK's energy transition and decarbonisation ambitions a reality. 4 July 2023 (Online: *Ionic Technologies.*) Available: https://ionictechnologies.com/news/belfast-companys-innovative-magnet-recycling-technology-makes-uks-energy-transition-and-decarbonisation-ambitions-a-reality/ [Accessed: 11 March 2024].

IRENA. 2024. *Wind energy*. (Online: *International renewable energy agency (IRENA)*.) Available: https://www.irena.org/Energy-Transition/Technology/Wind-energy [Accessed: 19 March 2024].

JDR Cable Systems Ltd. 2024. *About JDR*. (Online: *JDR Cable Systems Ltd.*) Available: https://www.jdrcables.com/about/ [Accessed: 15 March 2024].

Josso, P, Lusty, P A J, Gunn, A G, Shaw, R A, Singh, N, Horn, S & Petavratzi, E 2023. Review and development of the methodology and data used to produce the UK criticality assessment of technology-critical minerals *British Geological Survey* (Online: *BRITISH GEOLOGICAL SURVEY*.) Available: https://ukcmic.org/downloads/reports/ukcmic-review-and-development-of-the-methodology-and-data-used-to-produce-the-uk-criticality-assessment-of-technology-critical-minerals.pdf [Accessed: 20 December 2023].

Lacal-Arántegui, R 2015. Materials use in electricity generators in wind turbines – state-of-the-art and future specifications. *Journal of Cleaner Production.* 87**,** 275-283. Available: https://doi.org/10.1016/j.jclepro.2014.09.047.

Lee, J & Zhao, F 2024. Global Wind Report 2024. *Global Wind Energy Council* (Online: *GLOBAL WIND ENERGY COUNCIL*.) Available: https://gwec.net/global-wind-report-2024/#:~:text=The%20report%20finds%20the%20wind,triple%20renewable%20energy%20by%202030. [Accessed: 17 May 2024].

Less Common Metals. 2023. LCM enters into strategic supply agreement with Rainbow Rare Earths to bolster an ethical western supply-chain for rare earth elements. 12 September 2023 (Online: *Less Common Metals,*.) Available: https://lesscommonmetals.com/lcm-enters-into-strategic-supply-agreement-with-rainbow-rare-earths-to-bolster-an-ethical-western-supply-chain-for-rare-earth-elements/ [Accessed: 07 March 2024].

Liang, Y, Kleijn, R & van der Voet, E 2023. Increase in demand for critical materials under IEA Net-Zero emission by 2050 scenario. *Applied Energy.* 346**,** 121400. Available: https://doi.org/10.1016/j.apenergy.2023.121400.

Marscheider-Weidemann, F, Langkau, S, Eberling, E, Erdmann, L, Haendel, M, Krail, M, Loibl, A, Neef, C, Neuwirth, M, Rostek, L, Shirinzadeh, S, Stijepic, D, Espinoza, L A T, Baur, S-J, Billaud, M, Deubzer, O, Maisel, F, Marwede, M, Rückschloss, J & Tippner, M 2021. Raw materials for emerging technologies 2021 - a commissioned study. *German Mineral Resources Agency (DERA) at the Federal Institute for Geosciences and Natural Resources (BGR)* (Berlin, Germany: *BGR*.) Available: https://publica.fraunhofer.de/handle/publica/301094 [Accessed: 05 June 2023].

Memija, A. 2023. Siemens Gamesa Produces First 108-Metre Wind Turbine Blades for Moray West. 15 December 2023. (Online: *Offshorewind.biz.*) Available: https://www.offshorewind.biz/2023/12/15/siemens-gamesa-produces-first-108-metre-wind-turbine-blades-for-moray-west/

MMTA. 2023. China's Ga, Ge export controls may deter EU trade. 5 October 2023 (Online: *Minor Metals Trade Association (MMTA).*) Available: https://mmta.co.uk/chinas-ga-ge-export-controls-may-deter-eu-trade/ [Accessed: 17 January 2024].

Mudd, G M & Jowitt, S M 2018. Growing Global Copper Resources, Reserves and Production: Discovery Is Not the Only Control on Supply. *Economic Geology.* 113**,** 1235-1267. Available: https://doi.org./10.5382/econgeo.2018.4590 [Accessed: 1/30/2023].

National Grid. 2024. *How does a wind turbine work?* (Online: *National Grid*.) Available: https://www.nationalgrid.com/stories/energy-explained/how-does-wind-turbine-work [Accessed: 26 April 2024].

National Grid. 2023. Future Energy Scenarios 2023. (Online: *National Grid*.) Available: https://www.nationalgrideso.com/future-energy/future-energy-scenarios/documents [Accessed: 20 December 2023].

National Grid. 2022. Onshore vs offshore wind energy: what's the difference? Available: https://www.nationalgrid.com/stories/energy-explained/onshore-vs-offshore-wind-energy [Accessed: 18 March 2024].

National Grid ESO. 2024. Britain's Electricity Explained: 2023 Review. 09 January 2024 (Online: *National Grid.*) Available: https://www.nationalgrideso.com/news/britains-electricity-explained-2023-review [Accessed: 18 March 2024].

Organisation for Economic Co-operation and Development 2020. Methodological note to the Inventory of Export Restrictions on Industrial Raw Materials. *Organisation for Economic Co-operation and Development (OECD)* (Online: *OECD*.) Available: https://www.oecd.org/trade/topics/trade-in-raw-materials/documents/methodological-note-inventory-export-restrictions-industrial-raw-materials.pdf [Accessed: 19 April 2023].

Pavel, C C, Lacal-Arántegui, R, Marmier, A, Schüler, D, Tzimas, E, Buchert, M, Jenseit, W & Blagoeva, D 2017. Substitution strategies for reducing the use of rare earths in wind turbines. *Resources Policy.* 52**,** 349-357. Available: https://doi.org/10.1016/j.resourpol.2017.04.010.

Pensana Plc 2024. Pensana Plc Corporate Presentation. *Pensana Plc,* (Online: *PENSANA PLC*.) Available: https://pensana.co.uk/wp-content/uploads/2024/01/Corporate-Presentation-January-2024.pdf [Accessed: 07 March 2024].

Rabe, W, Kostka, G & Smith Stegen, K 2017. China's supply of critical raw materials: Risks for Europe's solar and wind industries? *Energy Policy.* 101**,** 692-699. Available: https://doi.org/10.1016/j.enpol.2016.09.019.

Richardson, J. 2023. Wind Turbine Manufacturers. Available: https://www.renewableenergyhub.co.uk/main/wind-turbines/manufacturers-of-wind-turbine#:~:text=Marlec%20(UK)%20Marlec%20produce%20a,in%20renewable%20energy%20since%201978. [Accessed: 15 March 2024].

SG Technologies. 2024. *Company*. (Online: *SG Technologies*.) Available: https://www.sgtec.com/company/about/ [Accessed: 28 March 2024].

Siemens Gamesa. 2021. Powering ahead in the UK: Siemens Gamesa to double offshore blade facility. (Online: *Siemens Gamesa.*) Available: https://www.siemensgamesa.com/newsroom/2021/08/210809-siemens-gamesa-double-blade-facility-offshore-hull-uk [Accessed: 15 March 2024].

Smith, B J, Riddle, M E, Earlam, M R, Iloeje, C & Diamond, D 2022. Rare earth permanent magnets: supply chain deep dive assessment. *U.S. Department of Energy* (Washington D.C.: *U.S. DEPARTMENT OF ENERGY*.) Available: https://doi.org/10.2172/1871577 [Accessed: 26/02/2024].

Szebor, N & Chesher, R 2023. South Crofty Tin Project – Mineral Resource Update NI 43-101 Technical Report - Cornish Metals Inc. *AMC consultants,* (Online: *CORNISH METALS*.) Available: https://cornishmetals.com/site/assets/files/5449/south_crofty_tin_project_mineral_resource_update_ni_43-101_technical_report_sedarb.pdf

Tang, L. 2024. China boosts quota for first batch of rare earth production in 2024. 7 February 2024. (Online: *S&P Global Inc.*) Available: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/metals/020724-china-boosts-quota-for-first-batch-of-rare-earth-production-in-2024 [Accessed: 04 June 2024].

The Crown Estate 2023. Offshore wind report 2022. (Online: *THE CROWN ESTATE.*) Available: https://www.thecrownestate.co.uk/media/4382/11720_owoperationalreport_2022_tp_020523plusaccessibility.pdf [Accessed: 4 June 2024].

UK Technology Metals Observatory. 2024. *UK Technology Metals Observatory*. (Online: *UKRI*.) Available: https://techmetalsobservatory.org/ [Accessed: 02 April 2024].

Ukpanah, I. 2024. UK's Wind Power: A Gust of Growth in the Renewable Energy Sector. Available: https://www.greenmatch.co.uk/green-energy/wind [Accessed: 26 April 2024].

United Nations. 2023. United Nations Commodity Trade Statistics Database. (Online: *United Nations*.), https://comtradeplus.un.org/ [Accessed: 20 December 2023].

University of Birmingham. 2023. First production of recycled magnets at Tyseley Energy Park, Birmingham. 18 December 2023 (Online: *Univeristy of Birmingham.*) Available: https://www.birmingham.ac.uk/news/2023/first-production-of-recycled-magnets-at-tyseley-energy-park-birmingham# [Accessed: 11 March 2024].

Wall, F. 2014. Rare earth elements. 312-338 in*: Critical Metals Handbook.* Edition: 1st. (Chichester: *John Wiley & Sons, Ltd.*) Available: https://doi.org/10.1002/9781118755341.ch13.

Wind Europe. 2023. NZIA: act now or Europe's wind turbines will be made in China. 14 June 2023 (Online: *Wind Europe.*) Available: https://windeurope.org/newsroom/press-releases/nzia-act-now-or-europes-wind-turbines-will-be-made-in-china/ [Accessed: 17 May 2024].