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A UK foresight study of materials in decarbonisation technologies: the case of traction motors

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A UK foresight study of materials in decarbonisation technologies: the case of traction motors

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

Editors

A G Gunn, J M Hannaford

Contributors

G Mudd, A Luce

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British Geological Survey offices

Nicker Hill, Keyworth,
Nottingham NG12 5GG

Tel 0115 936 3100

BGS Central Enquiries Desk

Tel 0115 936 3143
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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/

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1 Introduction to traction motor technology

Traction motors, also referred to as electric motors, serve as the powertrain for electrically driven vehicles and machinery, producing power through the conversion of electrical energy into mechanical energy. These motors find application in electric vehicles (EV), electric trains and in industrial applications such as conveyor belts and pumps (Slemon, 2024). Given their pivotal role in the electrification of transportation, the increasing adoption of traction motors in EVs is anticipated to fuel demand for a variety of raw materials in increasing quantities.

Traditionally, traction motors are categorised into direct current (DC) and alternating current (AC) motors. While DC motors are predominantly used in industry and heavy applications such as trains, AC motors are the most popular type for the EV market, although older and smaller models initially used DC motors. This study focuses on EV traction motors leading up to 2050, thereby concentrating on the predominant AC-motor technologies.

1.1 PRINCIPLES OF OPERATION

EV traction motors operate by generating mechanical torque through the interaction between a conductor supplied with electric current and a magnetic field (Slemon, 2024). These motors typically comprise a non-moving stator and a spinning rotor (Everything PE, 2024) (Figure 1).

The stator consists of windings, which are made of a conducting material, wound around a steel stator core tooth. When electric current flows through the stator windings, it produces a magnetic field that interacts with the rotor, resulting in torque being applied to the drive shaft, thus propelling the vehicle forwards. To regulate the electric current supplied to the motor and convert the DC power provided by the battery into the AC power required for the rotor, the motor requires a motor control system, commonly referred to as the inverter. Additionally, the motor control system monitors and regulates various parameters such as temperature and motor speed (Everything PE, 2024).

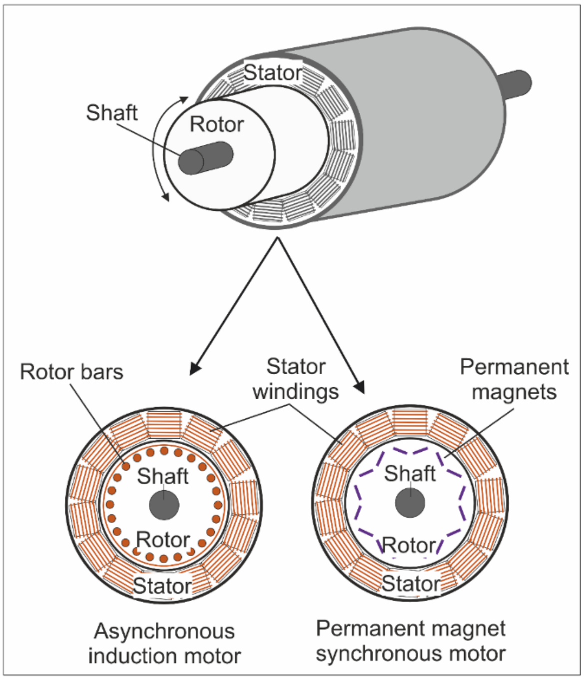


Figure 1 Schematic diagram of an EV traction motor and the cross-section of a typical permanent magnet-based motor and an alternating current induction motor. Wound rotor synchronous motors are not shown. BGS © UKRI 2024.

An essential characteristic of an EV traction motor is its efficiency across a range of speeds and torques, with consideration given to weight and space constraints in the vehicle's design (Chau and Li, 2013, Marscheider-Weidemann et al., 2021).

Key parameters include:

- power density (kilowatt per kilogram, kW/kg), which describes the amount of energy generated by the motor per unit of weight
- torque density (newton metre per kilogram, Nm/kg), which represents the turning force on the motor per unit of weight

Other important parameters influencing the design of traction motors include material costs and noise levels.

Although DC motors were previously prevalent in early models of EVs and are still employed in some micromobility applications, they have become obsolete in the expanding EV market due to significant drawbacks compared to AC motors. Notably, DC motors have limited motor speed and necessitate higher maintenance due to the utilisation of a commutator, responsible for current switching, and brushes for the electrical contact (Chau and Li, 2013, Gobbi et al., 2024).

Alternating current motors are classified as either synchronous or asynchronous motors. Synchronous motors rely on a rotor synchronised to the stator magnetic field, whereas asynchronous motors, commonly referred to as induction motors, have a rotor rotation slower than that of the stator (Marscheider-Weidemann et al., 2021). Synchronous motors can be further classified into permanent magnet synchronous motors (PMSM), wound rotor synchronous motors (WRSM) and reluctance motors, with the latter predominantly being 'switched' (SRM). There are also some hybrid variants such as permanent magnet-assisted reluctance motors. The majority of asynchronous induction motors use a squirrel-cage rotor, which is what was considered in this study, while the wound-rotor induction rotor is now rarely used (Chau and Li, 2013). It is important to note that SRM and hybrid motors were not considered in this study due to insufficient available data.

PMSMs currently dominate the global and UK markets, capturing 74 per cent of the UK market share in 2022 (Advanced Propulsion Centre UK, 2024c). The remaining market is mainly occupied by AC induction motors (ACIM) at 20 per cent and WRSMs at 6 per cent (Figure 2). Consequently, these three motor types are the focus of this study.

While PMSMs are recognised for their efficiency and high performance, concerns have arisen regarding the material cost of rare earth element-based permanent magnets and the permanent magnet supply chain, prompting efforts to reduce or eliminate rare earth elements (REEs) from permanent magnets or explore alternative, permanent magnet-free motor designs (Gobbi et al., 2024, Widmer et al., 2015). Axial flux motors are considered a promising future technology due to their compact design, reduction in material use and high efficiency. These motors can use both permanent magnet or induction designs and are currently undergoing trials in high performance sports cars (E-mobility engineering, 2021, Gobbi et al., 2024, Yasa Ltd., 2024a). Due to lack of data and its unproven commercial viability, this subtechnology was not considered in this study.

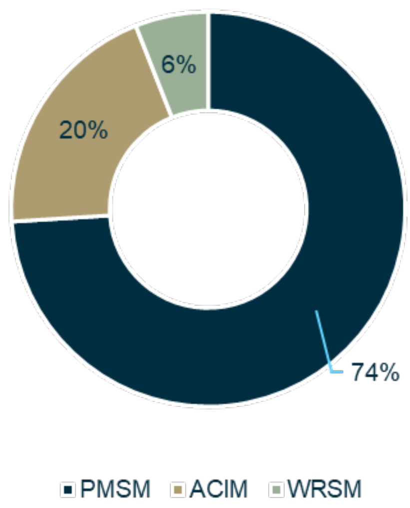


Figure 2 Market share of electric vehicle traction motors in the UK in 2020. PMSM: permanent magnet synchronous motors; ACIM: alternating current induction motors; WRSM: wound rotor synchronous motors (Advance Propulsion Centre, 2024).

1.2 ESSENTIAL COMPONENTS AND MATERIALS

A variety of different traction motors exist or are in development. This study focuses on the three technologies that predominate in the current electric vehicle market (Table 1):

- permanent magnet synchronous motors
- alternating current induction motors
- wound rotor synchronous motors

Table 1 Elements used in traction motor technologies.

Technology	UK critical elements	Other
PMSM	Cobalt (Co), nickel (Ni), rare earth elements (REE): dysprosium (Dy), neodymium (Nd), praseodymium (Pr), samarium (Sm), terbium (Tb); silicon (Si)	Aluminium (Al), barium (Ba), boron (B), chromium (Cr), copper (Cu), iron (Fe), molybdenum (Mo), strontium (Sr), zirconium (Zr)
ACIM	Cobalt (Co), silicon (Si)	Aluminium (Al), chromium (Cr), copper (Cu), iron (Fe), molybdenum (Mo)
WRSM	Cobalt (Co), silicon (Si)	Aluminium (Al), chromium (Cr), copper (Cu), iron (Fe), molybdenum (Mo)

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

All motors require electrical steel for fabricating the stator and rotor core material. This comprises multiple laminations of silicon-based steel, typically containing up to 6.5 per cent silicon (Si), which enhances the electrical resistivity and overall motor efficiency (Hernandez et al., 2017). Si was excluded from this study as it is part of the structural materials in the motor, but it remains a key part of the technology.

The manufacturing process of electrical steel is complex and its production is geographically concentrated. Therefore, supply risks with this material are likely to become apparent with the increase in EV production and electrical steel should be considered in future work.

Additonally, copper (Cu) coil is universally used for the stator windings across all motor types to create the stator magnetic field, due to its high conductivity. There is potential for substituting aluminium (Al) for copper (Cu) in windings within the next 10 years, which could reduce costs and motor weight. However, Al has a lower conductivity than Cu, consequently reducing power density (Advanced Propulsion Centre UK, 2021).

2 Electric motors

2.1 PERMANENT MAGNET SYNCHRONOUS MOTORS

PMSMs integrate permanent magnets following two main designs, either on the surface of the rotor (surface-mounted PMSM) or closer to the rotor core (interior PMSM) (Agamloh et al., 2020). Permanent magnets enable a high power density and a reduction in material use (for example, Cu), resulting in a more efficient, lighter and smaller motor compared to other motor designs (Chau and Li, 2013).

The main permanent magnet type used in PMSM is the neodymium-iron-boron (NdFeB) magnet, due to its optimal magnetic properties (Nordelöf et al., 2018). The heavy REEs dysprosium (Dy) and terbium (Tb) are commonly added to the magnet in minute quantities to increase its thermal stability, as demagnetisation can otherwise occur at temperatures exceeding 150°C (Nordelöf et al., 2018). Samarium-cobalt (SmCo) magnets are another type with similar but partly weaker magnetic properties. They are more expensive than NdFeB magnets as they contain both a REE (samarium (Sa)) and cobalt (Co). SmCo magnets have a higher temperature tolerance to demagnetisation and higher resistance to corrosion, making them a preferred choice for more extreme applications (Stanford Magnets, 2024).

Ferrite-based magnets, dominantly containing iron (Fe) with minor additions of barium (Ba), strontium (Sr) or Co to tailor their properties to the environment of use, are the only other type of magnet widely used in motors (Widmer et al., 2015). These have the advantage of not containing REEs and are cheaper to produce. However, their low remnant flux density leads to lower torque density in the motor, making them less efficient and generally uncompetitive compared with NdFeB and SmCo magnets. Recent developments have improved performance, with Tesla announcing plans to use a REE-free PMSM in their future vehicle assembly lines; these are likely to be ferrite-based (Adamas Intelligence Inc., 2023).

We consider brushless DC motors under PMSMs as they have the same design and material use and, despite their name, are considered an AC motor, although they are powered in a different way (Erdmann et al., 2015). Brushless DC motors are used in Volkswagen's ID-model series (Kane, 2019).

2.2 ALTERNATING CURRENT INDUCTION MOTORS

The ACIM is the most mature technology and is a simple but robust and low-cost alternative to PMSMs. Unlike PMSMs, which rely on permanent magnets to create a magnetic field, ACIMs generate a magnetic field by inducing an electric current onto the rotor. One notable advantage is their ability to avoid producing an electrical current when switched off, thus mitigating issues such as cogging torque, which is the change in torque resulting from the interaction of the permanent magnet slots on both the rotor and stator, common with PMSMs at low speeds. A significant drawback of ACIMs is the efficiency loss associated with the induction process (for example, rotor resistance and leakage) (Widmer et al., 2015).

The primary rotor type used in ACIMs is known as a 'squirrel cage'. This consists of Al or Cu bars, with Cu being favoured by the largest ACIM car manufacturer, Tesla (Lu and Parker, 2023). Although ACIMs were initially used in all Tesla models, Tesla has increasingly been adopting PMSMs alongside ACIMs in its models, with a PMSM often serving as the secondary motor for all-wheel drive configurations (Evspecifications.com, 2024, Widmer et al., 2015). Note that the Cu rotor cage in ACIMs results in increased Cu usage compared to PMSM.

2.3 WOUND ROTOR SYNCHRONOUS MOTORS

WRSMs represent a relatively mature technology, commonly used in a range of applications such as water pumps or compressors (Mabhula, 2019). These motors feature Cu windings in both the rotor and stator to create a magnetic field by inducing electric current. The transfer of current to the rotor is typically facilitated through brushes on a slip ring. However, prolonged use of these brushes can lead to wear and tear, resulting in increased maintenance requirements and potential electrical faults. Moreover, WRSMs require an additional power inverter, increasing system complexity and cost (Widmer et al., 2015). Nevertheless, these motors have been successfully deployed by manufacturers such as Renault (Widmer et al., 2015), whilst BMW’s new generation of EV motor incorporates this technology, promising high energy density and high motor speeds without the need for permanent magnets (Banner, 2022).

3 Supply chain mapping of traction motors

This study focuses on materials used in the manufacturing of permanent magnet-based traction motors, which are the predominant type used in EVs. This includes elements integral to permanent magnets, such as REEs (Dy, Tb, neodymium (Nd) and praseodymium (Pr)), and boron (B), as well as Cu for the windings. The different supply stages of traction motors and the material transformation steps are presented in Figure 3.

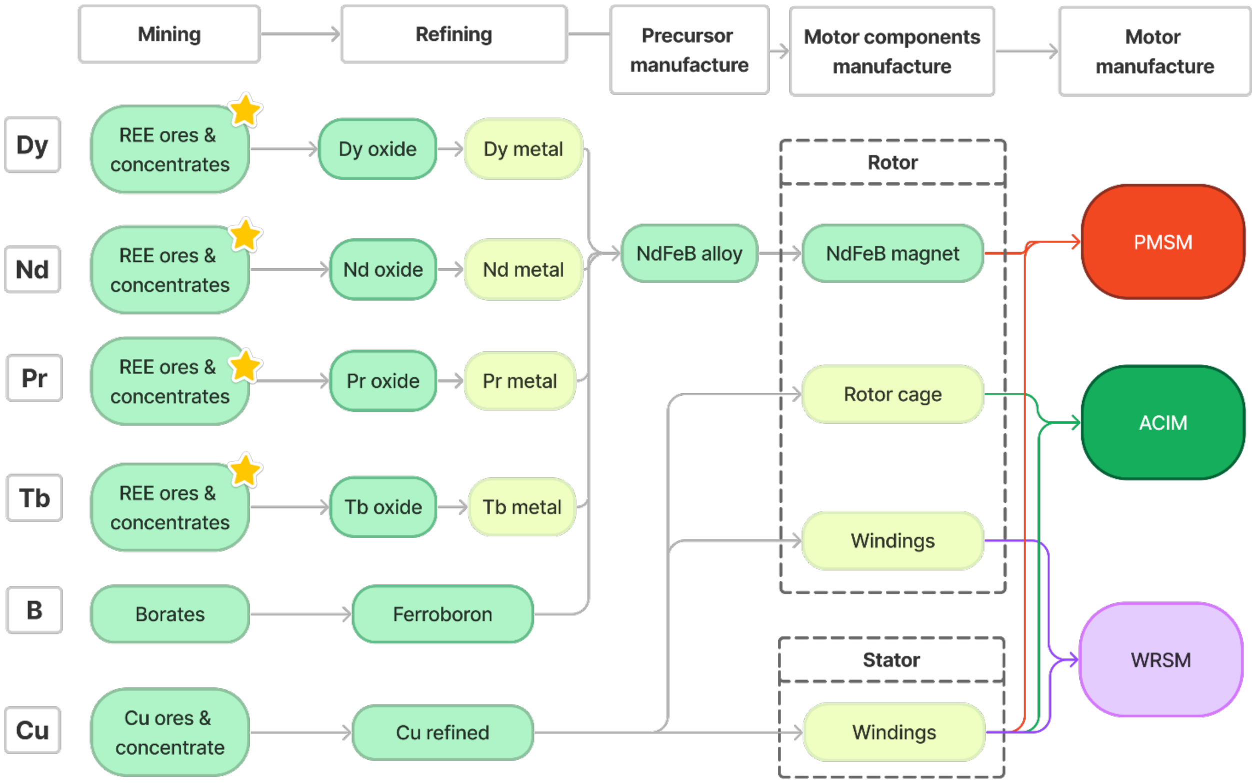


Figure 3 Supply chain mapping of traction motors, key raw materials and components. The green shading indicates materials that have been included in the analysis. A star indicates a material produced as a co-product. The yellow shade indicates a material that was only partially analysed (REE: rare earth elements; PMSM: permanent magnet synchronous motors; ACIM: alternating current induction motors; WRSM: wound rotor synchronous motor). BGS © UKRI 2024.

3.1 THE RARE EARTH ELEMENTS

The REEs are a group of 17 elements, including the lanthanides alongside yttrium (Y) and scandium (Sc), that occur together in different deposits with individual elements present in varying concentrations. The REEs are mined and processed into rare earth oxides (REOs) from rare earth mineral concentrate (Wall, 2014). Most REEs are produced from carbonatites, ion-adsorption deposits and alkaline igneous rocks (for example, Bayan Obo in China and Mount Weld in 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, physical separation and chemical separation, whilst the production of individual REOs (such as neodymium oxide, Nd_2O_3) and subsequent refining into individual metals require additional hydrometallurgical steps.

REE separation is a very challenging process owing to the very small differences in physical and geochemical properties within this group of elements. 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 Fe to form NdFeB alloy. NdFeB alloy is used to manufacture sintered permanent magnets or NdFeB powder, which in turn are used 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 (Smith et al., 2022). These are ultimately installed into the rotor of PMSM.

Cu is required in all traction motor types and is used in different parts in varying quantities. Cu ore is processed by smelting, hydrometallurgical processing and further refined by electrowinning into Cu metal (Mudd and Jowitt, 2018). The main consumption of Cu in all three motors is in the making of stator windings, particularly for WRSM designs, while ACIMs may also use it in the rotor cage (IDTechEX, 2020, Widmer et al., 2015).

4 Supply chain bottlenecks

The supply chain for the complex processing and manufacturing steps required to produce traction motors is concentrated in a few countries. This high level of production concentration is a risk to the secure supply of traction motors (Figure 4).

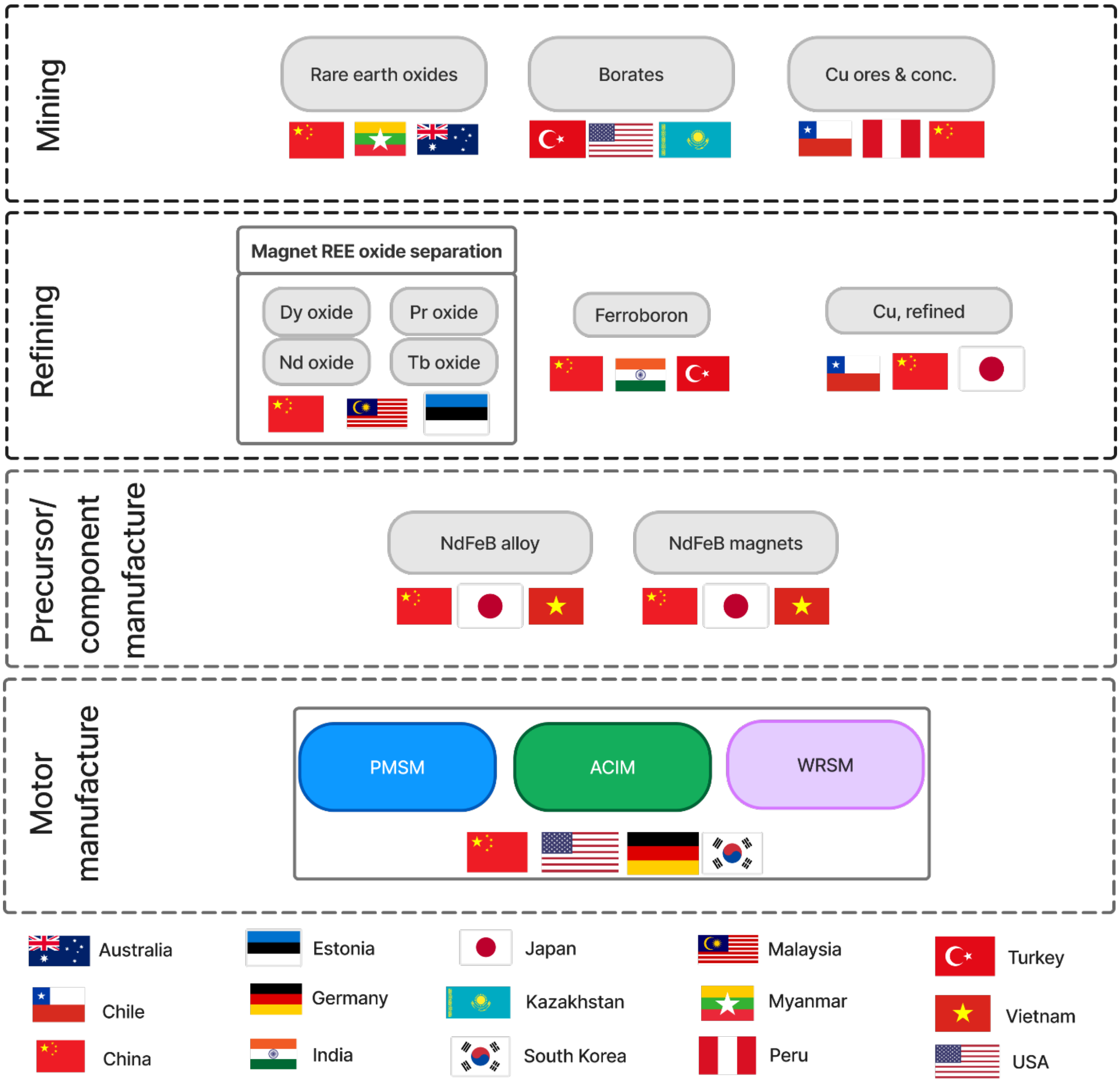


Figure 4 Geographical production concentration in the traction motor supply chain. All steps show the top three producers, from left to right, except for ferroboron and the motor manufacturing stage, where the flags only highlight key producers and their order does not reflect their respective market share. The data for mine production and for refined copper is based on quantitative data for 2017 to 2021 from the BGS World Mineral Statistics Database (BGS, 2023). The top three producing countries of REEs at the refining stage and the NdFeB alloy production are from Adamas Intelligence Inc. (2022) and magnet manufacturing are based on data from Smith et al. (2022). The analysis of the motor manufacturing stage is based on data from Lu and Parker (2023), Mobility Foresights (2023). NB: the rotor cage and windings are manufactured at the motor manufacturing stage and are, therefore, not shown separately. Secondary supply from recycling is not included. REE: rare earth elements; PMSM: permanent magnet synchronous motors; ACIM: alternating current induction motors; WRSM: wound rotor synchronous motor. BGS © UKRI 2024.

The mined raw materials considered in this report originate from various countries across the world:

- REOs are dominantly supplied by China
- borates come from Central Asia and the USA
- Cu ores dominantly come from Chile and Peru

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 the accessed magnet REOs are separated in China, with minor activity in Malaysia and Estonia (Adamas Intelligence Inc., 2022). This Chinese dominance in the market also applies to REE metal refining.

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

Several other minor producers exist, but their production share is uncertain and was therefore not included in the supply chain analysis.

NdFeB alloy 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 ('swarf'). However, secondary production was not considered in this analysis.

In contrast, traction motor production and assembly are distributed across numerous locations globally, often associated with major EV manufacturing countries.

4.1 MINING AND REFINING

4.1.1 Production concentration

The global production share of materials used in the manufacture of permanent magnets used in traction motors 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 due to 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
- REOs

However, it should be noted that REO is a proxy for individual REEs, including Dy, Nd, Tb and Pr. 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.

The mine production of borates exhibits a high level of concentration with the top three producers (Türkiye, USA and Kazakhstan) collectively contributing more than 80 per cent of global supply. However, it is noteworthy that the share of production held by the single largest producer (Türkiye) 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. 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 5 per cent Pr, 15 per cent Nd, 0.1 per cent Tb and 1 per cent Dy by mass. In contrast, the mass of contained cerium (Ce) and lanthanum (La) is about 25 to 43 per cent. This highlights an additional challenge in mine 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 Tb, Dy, Pr and Nd.

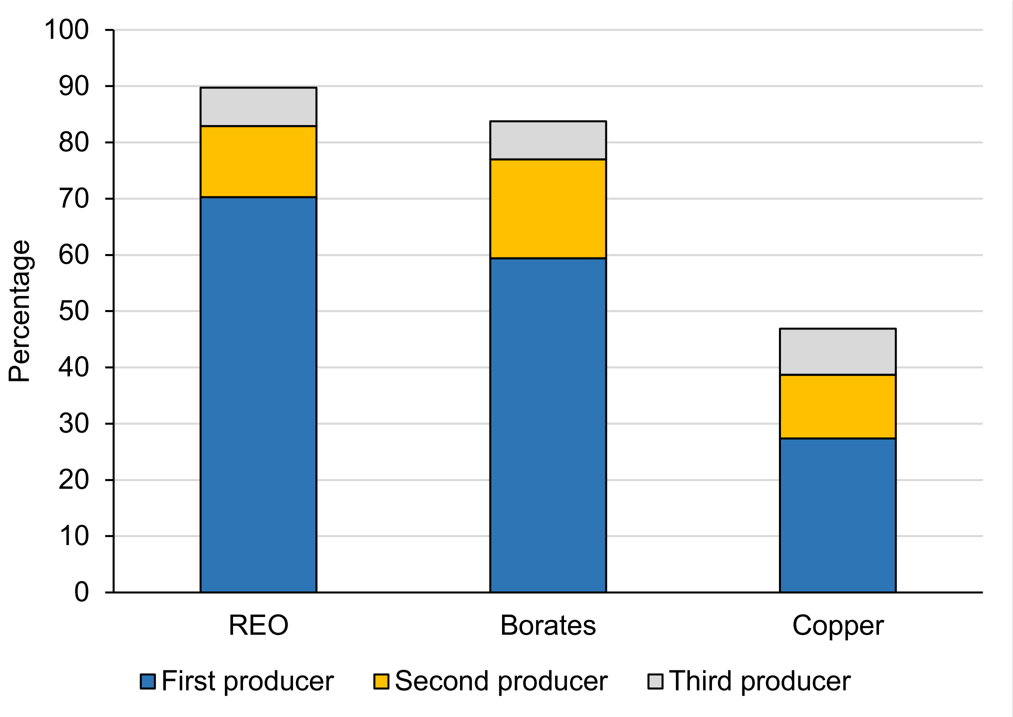


Figure 5 Global mine production of REOs, borates and Cu ores and concentrates, showing the production shares of the top three producing countries. Data from the British Geological Survey World Mineral Statistics Database (BGS, 2023). BGS © UKRI 2024.

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 individual rare earth metals are not available. While it remains impracticable to quantify the production concentration of ferroboron, it is acknowledged that China, India and Turkey are the foremost producers (Smith et al., 2022). The production of refined copper is moderately concentrated with the top three producers (China, Chile and Japan) accounting for 56per cent of the global total and the single largest producer (China) 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.

For Cu, the production concentration scores are relatively low at both the mining and refining stages, 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 rare earth 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.

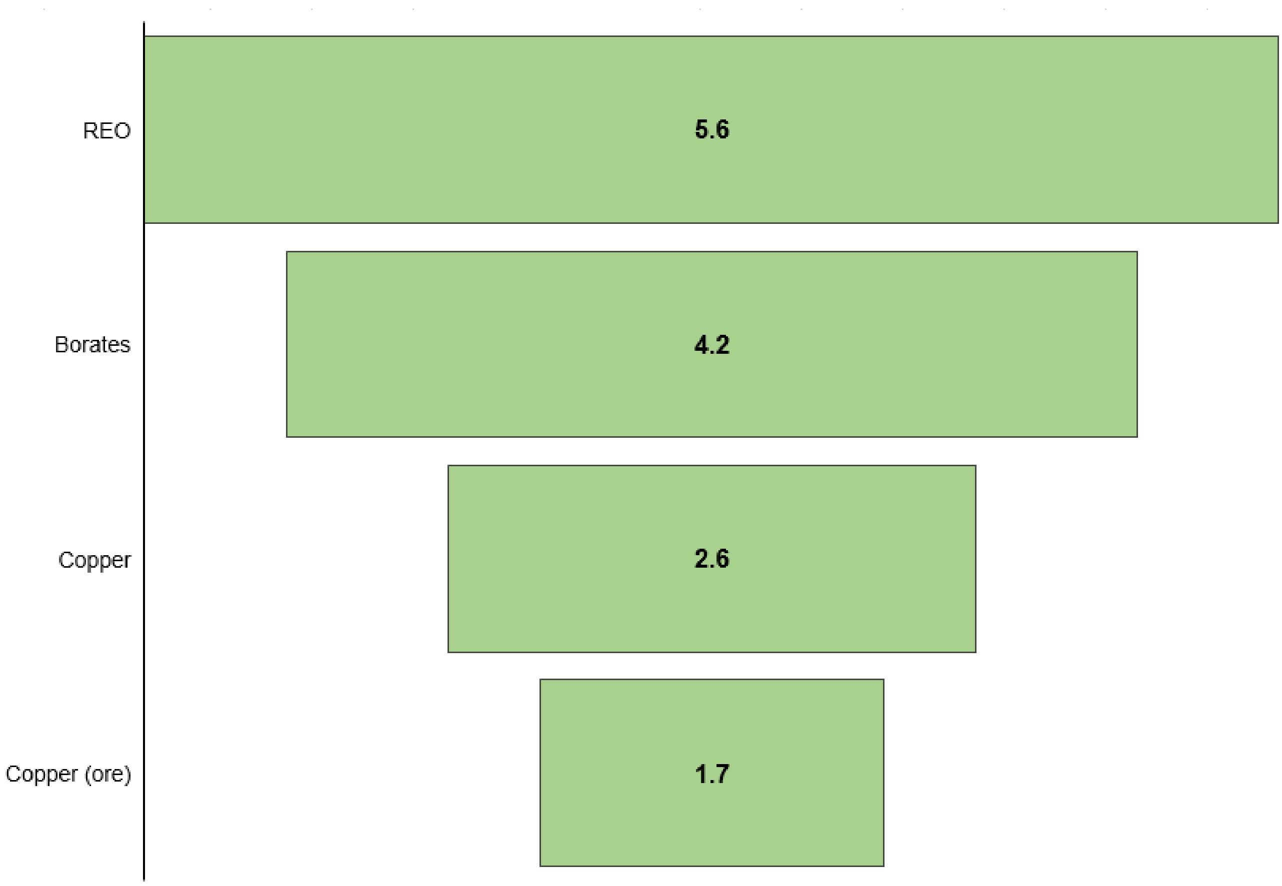


Figure 6 Ranked production concentration scores for key materials (mined and refined) used in traction motors based on an ESG-weighted Herfindahl–Hirschman index (HHI) for each of the top three producing countries. BGS © UKRI 2024.

4.1.2 Global trade concentration and trade restrictions

The trade of mined and refined materials used in the manufacture of permanent magnets is geographically concentrated and may be subject to restrictions imposed by trading nations. It is important to acknowledge that the trade data for certain evaluated permanent magnet materials, including ores and refined metals, either remain unavailable or are reported at insufficient resolution to offer meaningful insights. For instance, trade data for some permanent magnet materials are aggregated and typically disclosed under a single trade code. Notably, ferroboron is reported alongside ferrophosphorus and ferro-silico-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 (for example, alunite, pozzolana and mineral pigments), making it very difficult to extract data that specifically relates to REE ores and concentrates. Although eight- and ten-digit trade codes exist for REE ores and concentrates (for example, HS 25309050), not all countries report trade data at this level of detail and such data are not typically publicly available. Consequently, these trade flows are 'hidden'.

The HS trade codes employed to assess trade concentration are listed in Table 2.

Table 2 The six-digit HS trade codes used to assess trade concentration of materials used in the manufacture of traction motors.

HS code	Description	Stage
252800	Borates, natural and concentrates thereof, whether or not calcined, and natural boric acids containing <= 85 per cent of H_3BO_3 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	Refining
740200	Copper, unrefined; copper anodes for electrolytic refining	Refining

Trade of borates is moderately to highly concentrated, with 57 per cent of global imports shared between China, Brazil and India (Figure 7). Turkey 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.

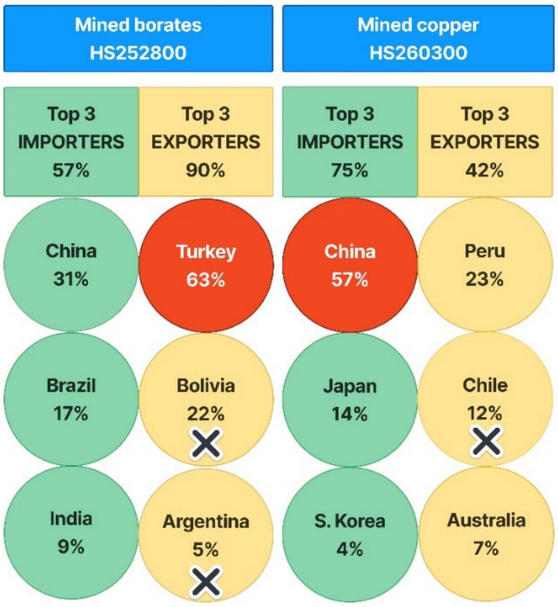


Figure 7 The top three importing and exporting countries for mined (ores and concentrates) borates and Cu, with the share of global trade flows shown for each country. Countries highlighted in red are dominant exporters or importers (where global share exceeds 40 per cent) and countries with a cross have active trade restrictions. Compiled from data derived from United Nations (2023) and Organisation for Economic Co-operation and Development (2020). BGS © UKRI 2024.

The trade of Cu ores and concentrates demonstrates a moderate to high level of concentration, with 42 per cent of exports shared among the top three countries, namely 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). It is also important to highlight that Chile imposes a 10 per cent fiscal tax on its exports of Cu ores and concentrates.

Exports of borates are also subject to active trade restrictions: Argentina levies a 4.5 per cent tax on its exports, while Bolivia mandates a license agreement alongside a fiscal tax equivalent to 0.05 per cent of the total trade value on its exports.

The trade of refined (separated) rare earth compounds is moderately concentrated, with the top three exporting nations (USA, Malaysia and Russia) accounting for 54 per cent of the global total (Figure 8). Of these, the USA is the single largest exporter, accounting for 30 per cent of the total. Imports of rare earth compounds are less concentrated, with the top three importers (China, Germany and Japan) accounting for only 28 per cent of the global total.

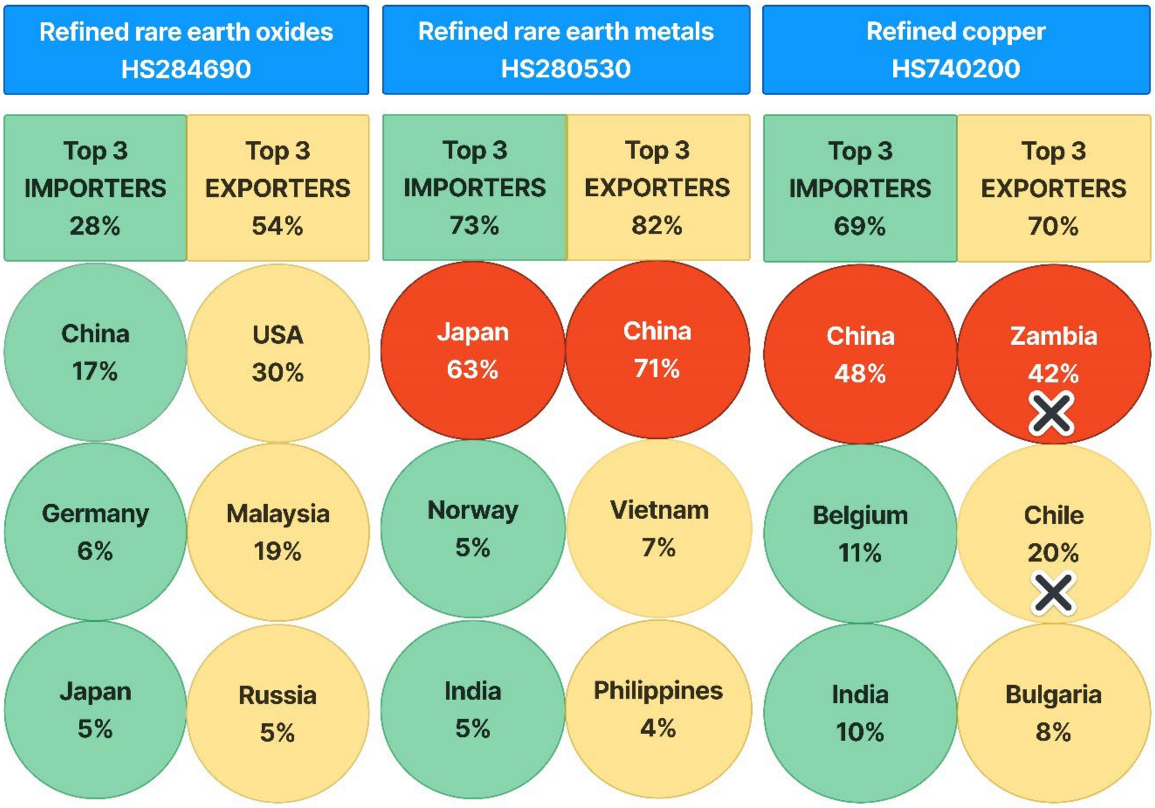


Figure 8 The top three importing and exporting countries for refined rare earths (metals and compounds) and Cu, with the share of global trade flows shown for each country. Countries highlighted in red are dominant exporters or importers (where global share exceeds 40 per cent) and countries with a cross have active trade restrictions. Compiled from data derived from United Nations (2023) and Organisation for Economic Co-operation and Development (2020). BGS © UKRI 2024.

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

The trade in refined rare earth metals and in refined Cu are both highly concentrated. Specifically, 69 per cent of global imports of refined Cu are distributed among the top three trading countries, while 73 per cent of global imports of refined rare earth metals are controlled by the top three trading countries. (It should be noted that trade data for Malaysia for refined rare earth metals have been excluded from the analysis, as it appears the reported trade data actually represent imports of rare earth 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. For global exports of refined rare earth metals, 82 per cent are controlled by China, Vietnam and the Philippines, 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 rare earth metals, Chile and Zambia have imposed restrictions on their exports of refined Cu in the form of export taxes, fiscal taxes and licensing agreements.

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

- China is the largest importer of mined Cu and borates; it is also the largest importer of refined rare earth metals and compounds and refined Cu
- global trade of refined rare earth 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 rare earth metals) and the 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)

4.2 COMPONENT AND PRODUCT MANUFACTURE

China is the dominant actor at the precursor and component stage, 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). Furthermore, numerous magnet-producing companies headquartered outside China 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 that have expanded over the last year to reflect the increasing market and demand, in addition to restrictions on the exports of REE products, REE refining and REE-processing technologies.

The production of traction motors is preferably conducted by car manufacturers in-house given their integral role within EVs, the required complex and capital-intensive infrastructure, and related high-value intellectual property (Challen, 2021). Approximately three-quarters of all EV traction motors are produced by EV manufacturers themselves, including:

- BYD (the largest EV producers) in China
- Tesla and General Motors in the USA
- Volkswagen and BMW in Germany
- Hyundai in South Korea

(Lu and Parker, 2023, Mobility Foresights, 2023)

Therefore, a significant proportion of all EV traction motors are likely to be produced in these four countries, but production is not highly concentrated and can also be found in other parts of the world.

5 UK supply chain in traction motor technology

The UK has several active participants in the traction motor supply chain. They cater to the UK automotive industry, which is an important part of the UK economy, and are primarily positioned downstream at the motor manufacturing stage.

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 UK, there are 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 and recently published a positive preliminary economic assessment, although the available resources are minor compared to top-producing countries (Cornish Metals Inc., 2024, Szebor and Chesher, 2023). 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 REE in the UK and no resources are known (Currie and Elliott, 2024, Deady et al., 2023). There are also no known resources of B.

There is currently limited refining of the raw materials used in traction motors in the UK. There are, however, some notable ongoing developments. Pensana is constructing an REO separation facility at Humber Freeport, East Yorkshire (BEIS, 2022b). The plant is projected to have an annual capacity to produce 12 000 tonnes (t) of total REOs and 4400 t of 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, including Nd and Nd-Pr metal and NdFeB alloy, both needed for magnet manufacturing. Their facility at Ellesmere Port, 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).

Permanent magnets are manufactured by SG Technologies in Greater London and have supplied the automotive industry and other industries since the 1940s (SG Technologies, 2024a). The company is now an important global supplier of NdFeB magnets, producing over 25 million units per year, and offer magnetic assembly in rotors (SG Technologies, 2024b).

Other UK companies, including Bunting-Berkhamsted in Hertfordshire and Arnold Magnetic Technologies in Sheffield, South Yorkshire, assemble permanent magnets into motor components to be used in various applications including the incorporation into rotors for automotive traction motors (Arnold Magnetic Technologies, 2024, Bunting Europe, 2024). Both companies also offer consultation services regarding design and material choice. Other permanent magnet assemblers and suppliers in the UK include Eclipse Magnetics, Cermag and Greenwood Magnetics, but not all are involved in the automotive industry (Cermag Ltd, 2024, Eclipse Magnetics, 2024, Greenwood Magnetics, 2024).

Many car manufacturers have outlined plans to produce EVs in the UK, with a focus on in-house traction motor manufacturing. Ford's plant at Halewood is currently undergoing conversion into an EV production facility, including manufacturing traction motors for the European market, with production due to start in 2024 (Advanced Propulsion Centre UK, 2024b). Similarly, Jaguar Land Rover (JLR) is converting its Wolverhampton engine manufacturing plant into an electric motor manufacturing centre as part of a $15 billion investment into electric vehicles for JLR brands (JLR, 2023). Current engine manufacturing already includes the assembly of electric drive units for mild hybrid vehicles (JLR, 2020).

Yasa Ltd., headquartered in Oxford and wholly owned by Mercedes-Benz, specialises in the manufacturing of axial flux motors used in high-performance cars such as hybrid sports cars (for example, Ferrari and Koenigsegg) (Yasa Ltd., 2024b). However, these motors do require REE permanent magnets (Yasa Ltd., 2024b). Advanced Electric Machines, a spin-off from Newcastle University, is manufacturing switched reluctance motors without the use of permanent magnets in Tyne and Wear.

There are several other UK motor manufacturers that produce motors dominantly for speciality applications, including electric buses, heavy-duty vehicles, two and three wheelers, aircraft and customised motors (Denis Ferranti Group, 2024, Deregallera, 2024, Equipmake, 2024, Magnetic Systems Technology Limited, 2024, PMW Dynamics, 2024). A full list of manufacturers and suppliers is provided by the Society of Motor Manufacturers and Traders (SMMT, 2024).

The UK is developing recycling capabilities for REEs found in permanent magnets. HyProMag initiated the production of NdFeB magnets by recycling magnet scrap materials. 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 aims for a target capacity of 20 t of 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 plant to a larger demonstration plant (Ionic Technologies, 2023), aiming to recover 30 t per annum of waste magnets and swarf, to produce over 10 t of separated magnet REOs (Ionic Technologies, 2024).

6 UK future demand

6.1 MARKET SHARE SCENARIOS AND MODELLING CONDITIONS

The future demand for the raw materials needed for the manufacture of traction motors used in EVs requires an in-depth understanding of future technological trends, their market penetration and associated bill of materials. The technological evolution of the electric motors market has previously been modelled in a range of scenarios up to 2050 (European Commission et al., 2020, Liang et al., 2023).

In this analysis, the future metal requirements for the UK are estimated based on several key factors:

- the gradual transition of electric motor types used in EVs from 2020 onwards, informed by current trends and developments from mass market original equipment manufacturers (OEMs). This transition accounts for the shift away from REE-permanent magnets, a preference expressed by some OEMs due to concerns regarding cost volatility and environmental impact (Figure 9) (Advanced Propulsion Centre UK, 2024c, Gear, 2022)
- projection of EV sales in the UK as provided by National Grid (2023) (Figure 10)
- the materials intensity of each electric motor, measured in kilograms of metal per vehicle (Ballinger et al., 2019, Liang et al., 2023). The assumption is made that technological optimisation in the future may lead to changes in material usage intensity. For instance, while the absolute consumption of raw materials might increase with larger equipment sizes, this effect could potentially be mitigated by higher energy production resulting from resource-efficient designs

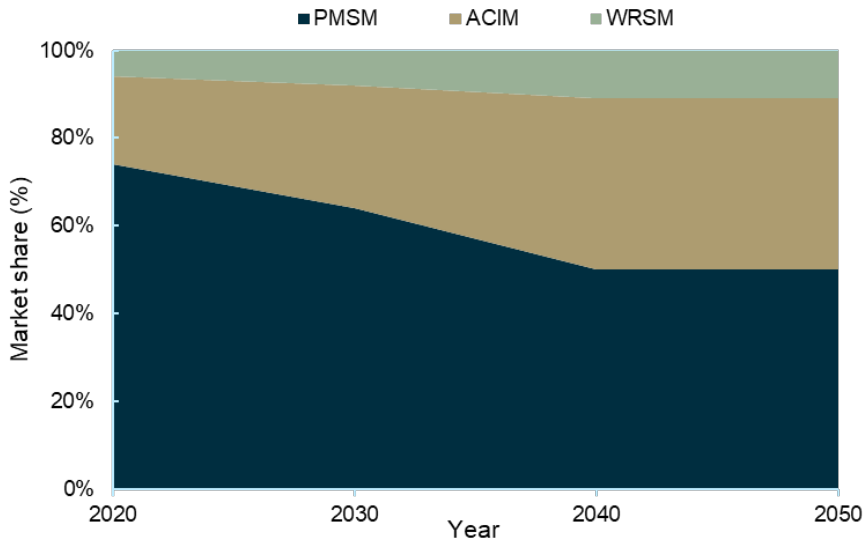
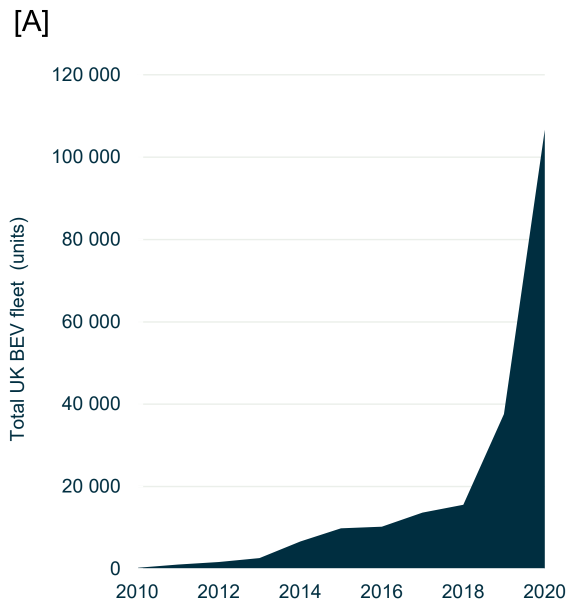


Figure 9 Evolution of the EV traction motors market between 2020 and 2050 showing the technology transformation that is likely to take place (data from Advanced Propulsion Centre UK (2024c)). The market shares shown were used in the material demand calculations. PMSM: permanent magnet synchronous motors; ACIM: AC induction motors; WRSM: wound rotor synchronous motor. BGS © UKRI 2024.



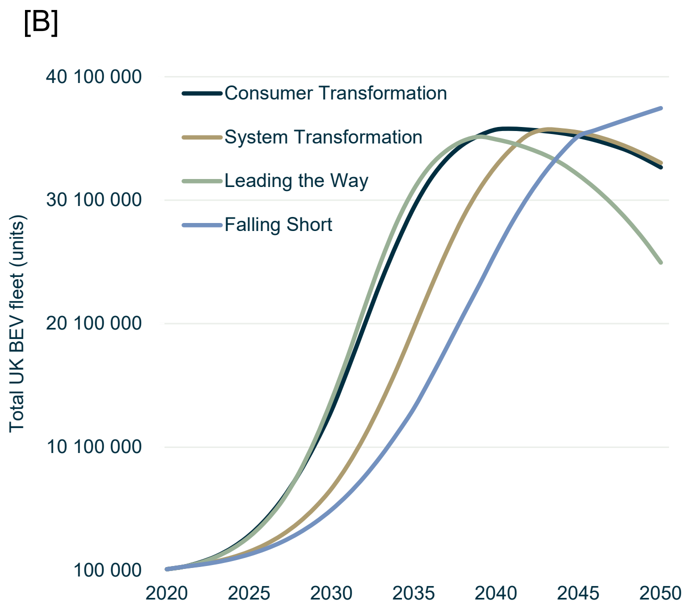


Figure 10 A: total number of battery electric cars (BEV) (passenger vehicles and vans) in the UK up to 2020 (Department for Transport, 2022); B: future UK fleet of electric vehicles under the various Future Energy Scenarios (National Grid, 2023).

PMSMs dominate the global and UK markets, with a UK market share of 74 per cent in 2022 (Advanced Propulsion Centre UK, 2024c). The remaining market is occupied by ACIMs at 20 per cent and WRSMs at 6 per cent. The market is expected to undergo significant changes in coming decades, with manufacturers increasingly shifting away from REE permanent magnets due to concerns about the environmental impact of extraction and cost volatility (Advanced Propulsion Centre UK, 2024c, Gear, 2022). As a result, the market share of PMSMs is expected to decline to 64 per cent by 2030, further dropping to 50 per cent by 2040, after which it stabilises until 2050.

ACIM and WRSM motors are rare-earth-free alternatives to PMSM and are used by some of the leading manufacturers such as BMW, Volkswagen, Audi and Renault (Gear, 2022). The market penetration of these motors is expected to increase significantly to 28 per cent and 8 per cent in 2030, respectively. This trend is expected to continue, with ACIM and WSRM reaching shares of 39 per cent and 11 per cent, respectively, by 2040. Beyond 2040, the market share for both motors is assumed to remain stable.

Future demand and material challenges associated with a gradual technological transition have been analysed. This is considered to provide a reliable indication of potential bottlenecks in the EV electric motors supply chain.

6.2 FUTURE UK RAW MATERIAL NEEDS FOR TRACTION MOTORS

The number of EVs (including vans) in the UK between 2010 and 2020 is derived from data reported by the Department for Transport (2022). Subsequently, data for 2021 to 2050 are derived from the National Grid's Future Energy Scenarios (National Grid, 2023). The forecast models are predicated on the average weight of the traction motor across the range of EV models. Vehicles reaching the end of their lives are assumed to be on average 14 years old and their replacements are accounted for in the modelling. Plug-in hybrid and hybrid vehicles are excluded from this analysis.

The future demand in the UK for the selected elements embedded in the EV's electric motors is presented in two ways:

- as the quantity (in tonnes) required from 2020 to 2050 for each of the National Grid Future Energy scenarios ('Leading the way', 'Falling short', 'Consumer transformation' and 'System transformation')
- as the percentage of current global metal production (based on average production between 2017 and 2021) (Table 3)

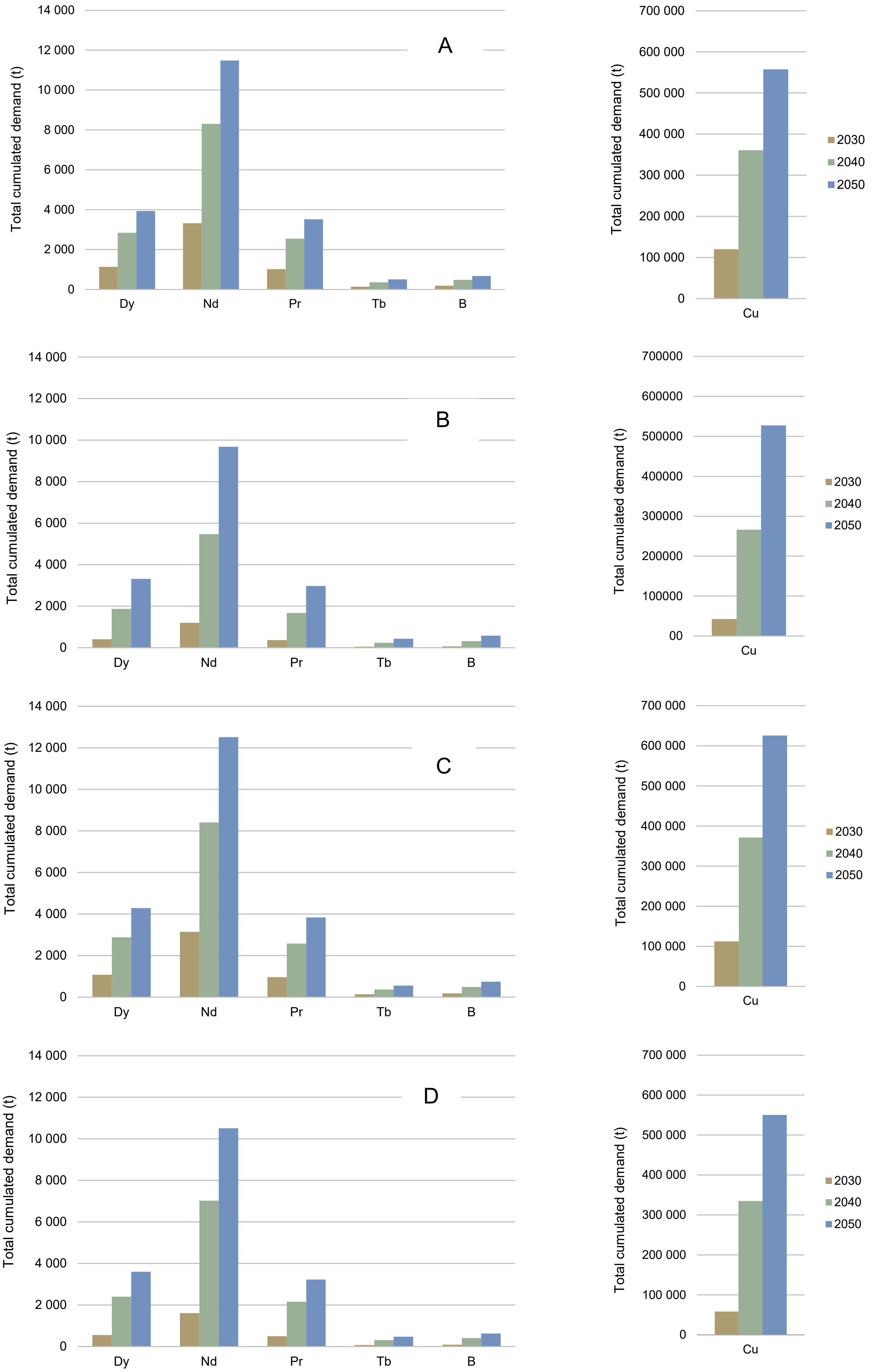
Table 3 Global metal production (five-year average, 2017 to 2021) for the elements assessed in this analysis. (REO data from BGS (2023) modified by in-house calculations for individual metals).

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

The forecasts in Figure 11 and Figure 12 show the cumulative UK demand between 2020 and 2050 and the annual demand as a percentage of current global metal production over the same period, respectively. Annual demand for each element has also been quantified to illustrate temporal fluctuations (Appendix B).

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 traction motors.



A
Total cumulated demand (t)
14 000
12 000
10 000
8 000
6 000
4 000
2 000
0
Dy
Nd
Pr
Tb
B
700 000
600 000
500 000
400 000
300 000
200 000
100 000
0
Cu
2030
2040
2050
B
Total cumulated demand (t)
14 000
12 000
10 000
8 000
6 000
4 000
2 000
0
Dy
Nd
Pr
Tb
B
700000
600000
500000
400000
300000
200000
100000
00
Cu
2030
2040
2050
C
Total cumulated demand (t)
14 000
12 000
10 000
8 000
6 000
4 000
2 000
0
Dy
Nd
Pr
Tb
B
700 000
600 000
500 000
400 000
300 000
200 000
100 000
0
Cu
2030
2040
2050
D
Total cumulated demand (t)
14 000
12 000
10 000
8 000
6 000
4 000
2 000
0
Dy
Nd
Pr
Tb
B
700 000
600 000
500 000
400 000
300 000
200 000
100 000
0
Cu
2030
2040
2050

Figure 11 Cumulative forecast UK traction motor demand (tonnes) for the elements considered in this study between 2020 and 2050 under four different scenarios. A: 'Leading the way'; B: 'Falling short'; C: 'Consumer transformation'; D: 'System transformation'. BGS © UKRI 2024.

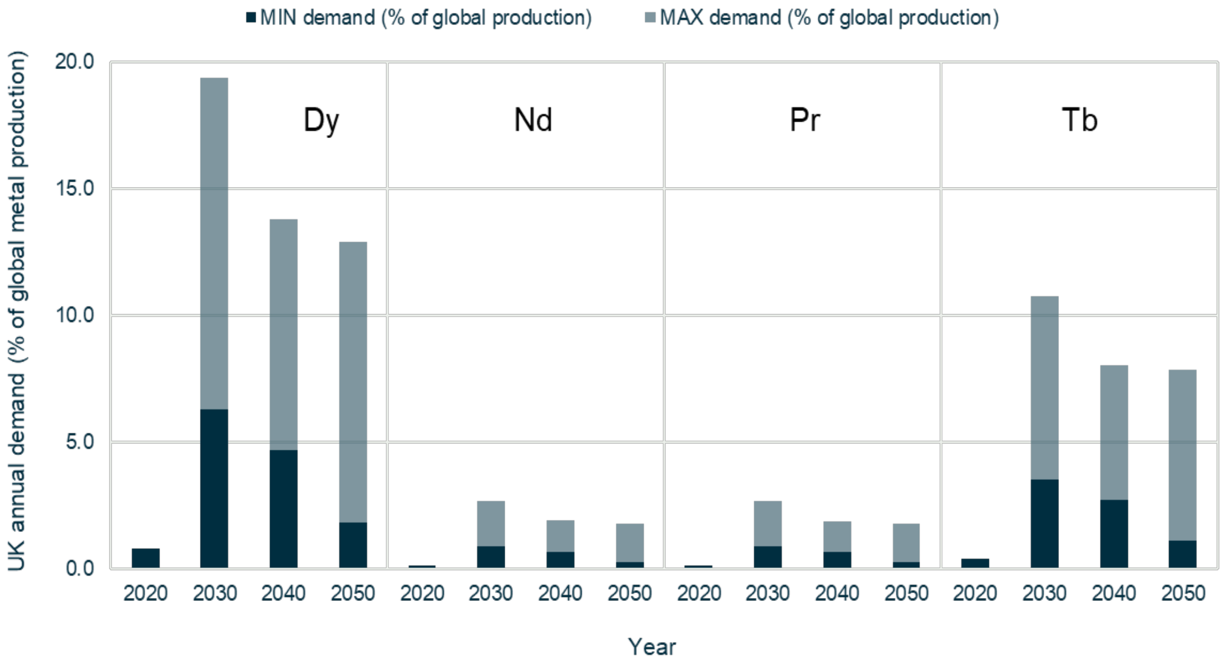


Figure 12 Annual UK demand in 2030, 2040 and 2050 as a percentage of current global metal production (five-year average, 2017 to 2021). Data from the BGS World Mineral Statistics Database (BGS, 2023) with our own calculations on individual metals. The minimum and maximum values represent the outputs of the different scenarios. BGS © UKRI 2024.

The individual demand for Dy, Nd, Pr, Tb and B is forecast to be approximately two times higher between 2030 and 2040 compared with demand between 2020 and 2030. The demand for Cu is expected to triple between 2030 and 2040 (Figure 11).

Between 2040 and 2050, the demand for all metals except Cu decreases by approximately 20 per cent compared to the previous decade. The annual demand for all elements is expected to peak by 2030 to 2040 in scenarios such as 'Leading the way' and 'Consumer transformation', while the 'System transformation' scenario indicates a continuous increase in annual demand until 2050. In contrast, the demand for the 'Falling short scenario' is forecast to peak by 2040, followed by a minor decline by 2050 (Appendix B).

Comparing these demand projections with current global production levels underscores the magnitude of future demand increases expected for materials utilised in electric motor technologies (Figure 12). The situation for Dy and Tb is particularly concerning. By 2030, the UK alone would require 6 to 19 per cent (minimum to maximum) of the current global production of Dy and 4 to 1 per cent for Tb. By 2040, these percentages are estimated to be 5 to 14 per cent for Dy and 3 to 8 per cent for Tb (Figure 12). UK demand for Nd and Pr is of less concern as they never exceed 2.5 per cent of annual global production. However, this level of demand remains significant, particularly when comparing the market size of the UK with other major centres of consumption where permanent magnet manufacture exists.

6.3 GLOBAL DEMAND VS UK DEMAND PROJECTIONS

The global material demand projections used in this analysis are sourced from the 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 scenarios used by the IEA (‘Stated policies’, ‘Announced pledges’ and ‘Net zero’ scenarios) (Figure 13).

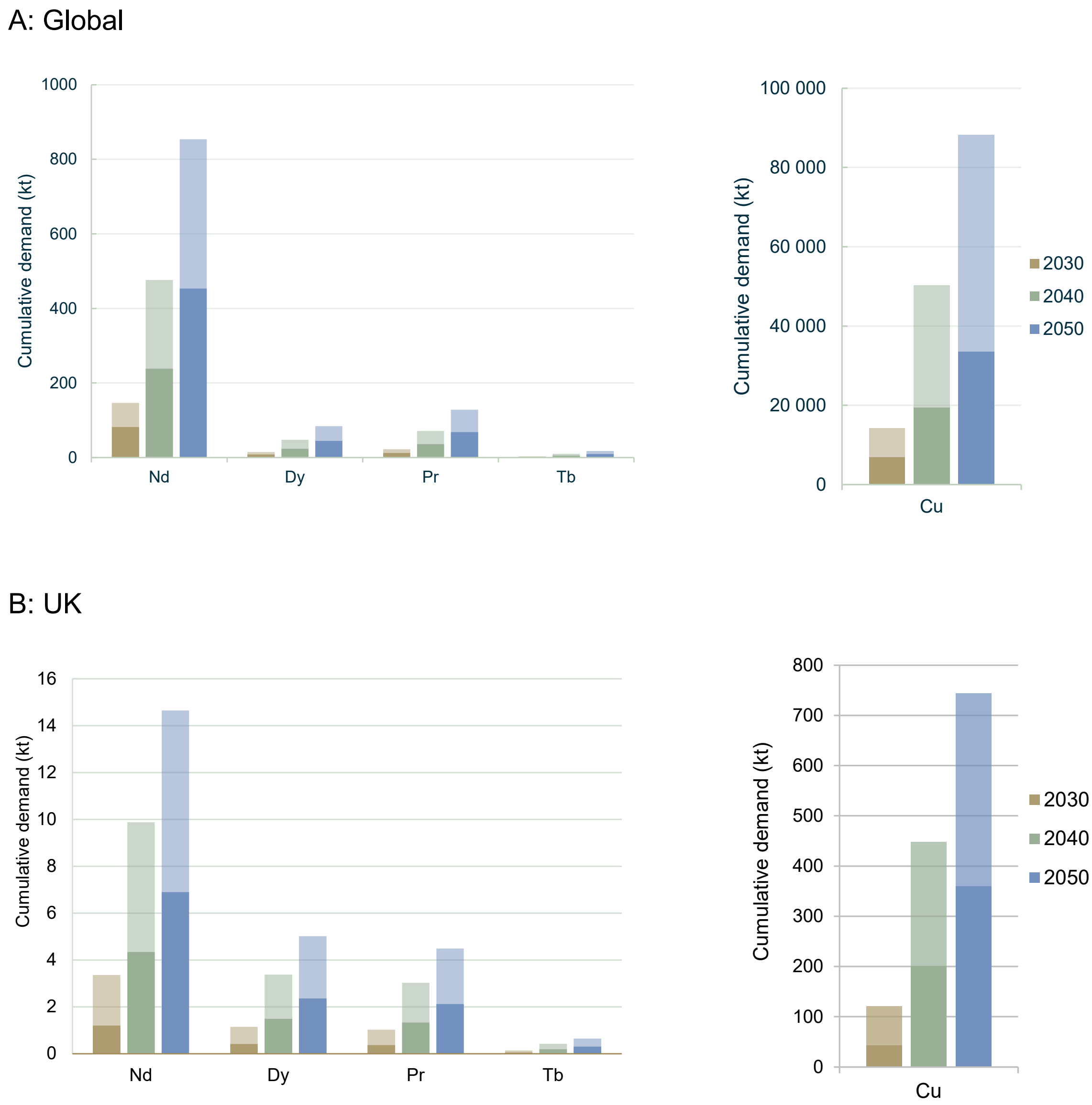


Figure 13 Material demand between 2020 and 2050 for selected elements (in kilotonnes, kt) embedded in EV traction motors globally (A) and in the UK (B). A: data for the global demand projections based on the IEA estimates for different scenarios (International Energy Agency, 2023). The maximum and minimum values derived from the following scenarios are shown: ‘Stated policies’; ‘Announced pledges’; ‘Net zero emissions by 2050’. B: UK materials demand for EVs. The maximum and minimum values derived from the following scenarios are shown: ‘Leading the way’; ‘Falling short’; ‘Consumer transformation’; ‘System transformation’. (National Grid, 2023)

The results illustrate that the demand for all elements evaluated is unsurprisingly higher (nearly two orders of magnitude for Nd) at the global level due to the size of the population and market compared to the UK. When comparing these projections, it is evident that the UK's demand for Dy, Pr and Tb is significant, ranging from 5 to 8 per cent, 3 to 5 per cent, and 3 to 5 per cent, respectively, of the global demand between 2020 and 2030, and maintaining similar proportions between 2030 to 2040 and 2040 to 2050. On the other hand, the UK's demand for Nd and Cu is much less, ranging from 1 to 2 per cent of global demand between 2030 and 2050 for traction engine application.

Demand for B cannot be compared due to a lack of data in the IEA projections.

7 Discussion and conclusions

EVs require not only batteries, but also electric powertrains, which are very different to the internal combustion engine (ICE). The transition to EVs has forced the automotive sector to adapt its manufacturing practices and designs, and to develop new supply chains. The current UK EV supply chain is small, but transferable skills and knowledge from the ICE supply chain could be utilised to advance its development.

Access to materials and components will be crucial to the success of the electrification transition. Current barriers to the material supply chain are many and varied, resulting from competing global demand, geopolitics and market conditions, but most importantly our need to tackle climate change, which imposes a rapid scale-up of decarbonisation technologies and their associated supply chains.

In this assessment, we estimated the UK demand for key elements embedded in traction motors of three different types:

- permanent magnet synchronous motors (PMSM)
- the alternating current induction motors (ACIM)
- wound rotor synchronous motors (WRSM)

The current dominant traction motor type in the UK is the PMSM (74 per cent share of the UK market), followed by the ACIM (20 per cent share) and WRSM. PMSMs use NdFeB magnets in their operation, whereas ACIMs and WRSMs are permanent magnet-free motors.

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

- boron (B)
- copper (Cu)
- dysprosium (Dy)
- neodymium (Nd)
- praseodymium (Pr)
- terbium (Tb)

The UK material demand forecasts were produced using the National Grid Future Energy scenarios. 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 utilised 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 traction motor 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 (Tb, Dy, Nd and Pr) 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 Türkiye 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 global magnet manufacturing market). It is important to note that most magnet producers operating outside China also have facilities in China and their supply chains are therefore highly dependent on the Chinese market (Smith et al., 2022).

Traction motors are mostly produced by automotive EV manufacturers in China, Europe and North America, so the current leading producers are likely to continue to dominate the market for several years. However, the EV supply chain is undergoing rapid development and expansion across the globe and new participants in this sector can be expected in the future.

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 rare earth metal stage from China is significant and a potential risk to the traction motor supply chain, if supply of oxides and metal from other jurisdictions does not grow rapidly enough to meet demand. The prominence of China in permanent magnet manufacture is likely to grow 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 rare earth compounds, metals and permanent magnets, any escalation in supply risk is likely to be detrimental to any industry dependent on these materials and will deter future investment. The traction motor market is very dynamic and expected to undergo significant changes up to 2050. For example, PMSMs are likely to become less dominant by 2050, with a market share of 50 per cent, whilst advances in induction motor technology will strengthen their market, with a share close to 30 per cent by 2040. These changes will lead to a lower pace of demand increase for permanent magnet REEs. In contrast, demand for Cu will accelerate in response to this change. However, the resource base for Cu is large and geographically diversified, so attendant supply risks should be relatively minor.

Analysis of future UK demand for traction motors and embedded materials was derived from the size of the UK fleet reported by the Department for Transport (2022) and future projections based on the National Grid's Future Energy scenarios (National Grid, 2023). Material intensity data for an average traction motor were used to calculate the embedded material flows. Between 2030 and 2040, the cumulative UK demand for Dy, Nd, Pr, Tb, B and Cu is expected to grow considerably. Demand for Cu will grow most rapidly, with a cumulative demand 5.4 times greater than in the previous decade. The rate of demand increase slows between 2040 and 2050, but the quantities of materials required will be broadly similar to the previous decade. For example, UK demand for Nd will amount to 3500 tonnes between 2030 and 2040, and 3800 tonnes between 2040 and 2050.

The comparison of global and UK demand highlights that the global demand is about two orders of magnitude greater than the UK demand, primarily due to global demographics and market size. The UK alone would require around 19.4 per cent of the current global production of Dy, 10.8 per cent of Tb and 2.7 per cent of Nd and Pr by 2030. These numbers are significant considering the small quantities of these elements that are currently produced globally, the market size of the UK and the competing demand from the predominant industry participants.

The UK share of global demand for Dy, Pr and Tb is significant, ranging from 3 to 8 per cent between 2020 and 2050, with Dy having the largest share in 2030. The UK demand for Nd and ranges between 1 and 2 per cent of world demand between 2030 and 2050. This demand is led by China in the upstream and midstream traction motor supply chain. However, automotive OEMs from USA, Germany and South Korea, which are currently leading the production of traction motors, are also important participants in the supply chain. Ensuring the UK has access to secure and sustainable material supplies in such a highly competitive environment will be a major challenge.

8 Recommendations

This assessment leads to the following key recommendations for the traction motor sector in the UK.

8.1 ENSURE THE SECURITY OF SUPPLY FOR ELECTRIC VEHICLES IN THE UK

A range of objectives has been highlighted in the Critical Minerals Strategy aimed at strengthening the UK security of supply (BEIS, 2022a). However, the urgency for specific actions that will ensure the UK automotive sector plays a key role in the national and global electrification of the transport transition should be stressed.

The UK, with its heritage in automotive manufacture and related research and innovation, is well-placed to develop a domestic EV supply chain. Its success will be critically dependent on the ability of the UK to access the materials in the forms and quantities required, at competitive prices and following sustainable and responsible supply principles. Government funding to strengthen innovation and research capabilities related to traction motors and their supply chains will be essential.

The provision of support for investment will also be crucial: for example, through the Automotive Transformation Fund (Advanced Propulsion Centre UK, 2024a) and the Circular Critical Minerals Supply Chains (CLIMATES) fund (DBT et al., 2023) and by increased international cooperation such as trade agreements and strategic partnerships (for example, Less Common Metals' strategic partnership with Rainbow Rare Earths) (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 electric powertrain value chain underpinned by secure and sustainable material supplies.

8.2 MEET THE UK'S DEMAND FOR MATERIALS

The UK demand for all the elements assessed is large relative to current levels of global production and especially problematic for those REEs required to manufacture permanent magnets. Therefore, diversification of the REE value chain through investment in projects aiming to scale up material supply would reduce UK and global supply risks.

There is an urgent need for new mining and refining projects to increase the supply of all the permanent magnet REEs outside China. The provision of investment in Cu projects is equally critical, as Cu is essential not just for the manufacture of the functional elements of traction motors, but also for structural parts and the connection of EVs to the grid. Furthermore, Cu utilisation in other clean-energy applications is set to increase greatly.

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

8.3 SUPPORT A PERMANENT MAGNET ECOSYSTEM

The midstream stage of the value chain, which produces rare earth alloys and permanent magnets, is dominated by China. Although the UK is actively participating in this part of the value chain, further investment and incentives are required to strengthen this sector. The absence of permanent magnet manufacturing means that alloys produced in the UK are exported elsewhere, chiefly to China, for the production of magnets, which are then re-imported for use in traction motors and other applications. It is therefore crucial that the development of a permanent magnet ecosystem in the UK is supported. This would also facilitate the development of reverse supply chains from magnets that will become available from end-of-life traction motors and other applications. The provision of subsidies and tax incentives could support the establishment of a domestic sector and de-risk manufacturing investment.

This assessment provides many useful insights into potential material bottlenecks associated with the expansion of traction motors and the electrification of transport. However, the robust estimation of future material demand and the identification of potential supply issues depend on reliable supply chain analyses 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.

Like other decarbonisation technologies, the traction motors 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 development of data observatories (UK Technology Metals Observatory, 2024), together with the development of stocks and flows models supported by scenarios 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.

Acronyms and abbreviations

AC	Alternating current
ACIM	AC induction motor
BGS	British Geological Survey
DC	Direct current
ESG	Environmental, social and governance
EV	Electric vehicle
HS	Harmonized System
ICE	Internal combustion engine
IEA	International Energy Association
OEM	Original equipment manufacturer
PMSM	Permanent magnet synchronous motor
NdFeB	Neodymium-iron-boron (permanent magnet)
REE	Rare earth element
REO	Rare earth oxide
SmCo	Samarium-cobalt (permanent magnet)
WRSM	Wound rotor synchronous motor

Appendix A

Traction motor raw materials and components excluded from the analysis. ACIM: alternating current induction motor; EV: electric vehicle; PMSM: permanent magnet synchronous motors.

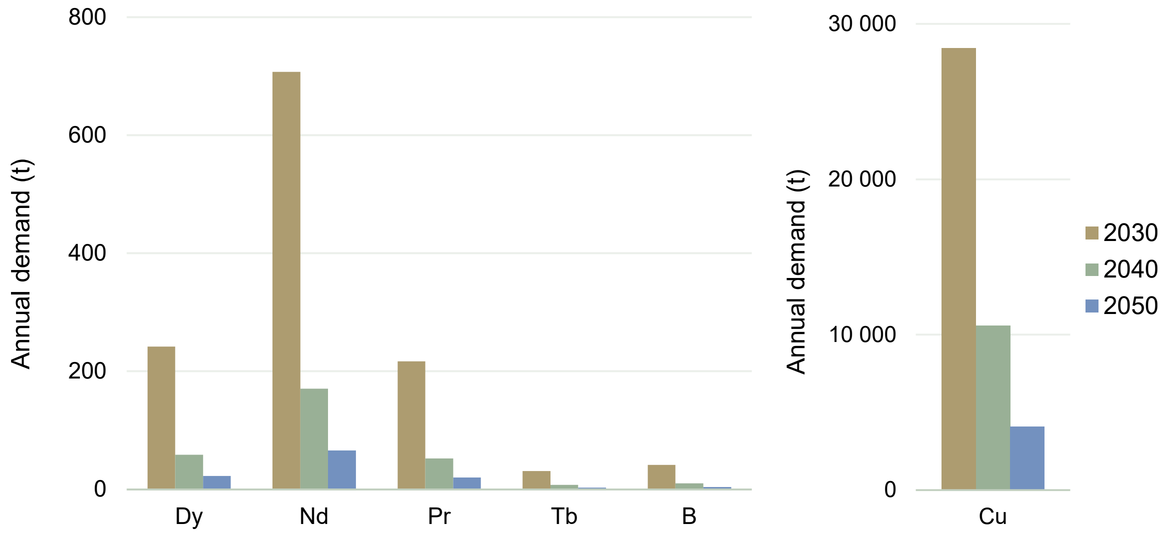
Component	Function	Reason for exclusion
Raw materials		
Al	Alternative to copper for windings in all motors or in the ACIM rotor cage	Currently not commonly used in EV traction motors
Ba	Used in ferrite permanent magnets	Ferrite magnets are not commonly used in current permanent magnet motors
Co	Used in samarium-cobalt (SmCo) permanent magnets	SmCo magnets are not commonly used in current permanent magnet motors
Cr	Used in steel in some motor components	Not part of the main technology
Ni	Used in coatings for permanent magnets	Lack of data
Fe	Neodymium-iron-boron (NdFeB) and ferrite permanent magnets	Demand in permanent magnets is negligible compared to iron use in structural components (steel), which is not considered
Mo	Used in steel in some motor components	Not part of the main technology
Sm	Used in SmCo permanent magnets	SmCo magnets are not commonly used in current permanent magnet motors
Si	Used in electrical steel to make the stator and rotor core	Not part of the main technology
Sr	Used in ferrite permanent magnets	Ferrite magnets are not commonly used in current permanent magnet motors
Zr	Used in ferrite permanent magnets	Ferrite magnets are not commonly used in current permanent magnet motors
Precursor materials and components		
Ferrite permanent magnet	Other type of permanent magnet used in PMSM	Currently not used in EV traction motors
SmCo permanent magnet	Other type of permanent magnet used in PMSM	Currently not used in EV traction motors
Electrical steel	Used to make rotor and stator core	Not part of the main technology

Component	Function	Reason for exclusion
Motor sub technologies		
Switched reluctance motors	Future technology with similar efficiency to PMSM, while using low-cost raw materials	Future uptake is uncertain
Axial flux motors	Future technology with high efficiency and lower material requirements	Future uptake is uncertain
High temperature superconductor motors	Future technology with high efficiency and lower material requirements	Early stage in development, future uptake is uncertain

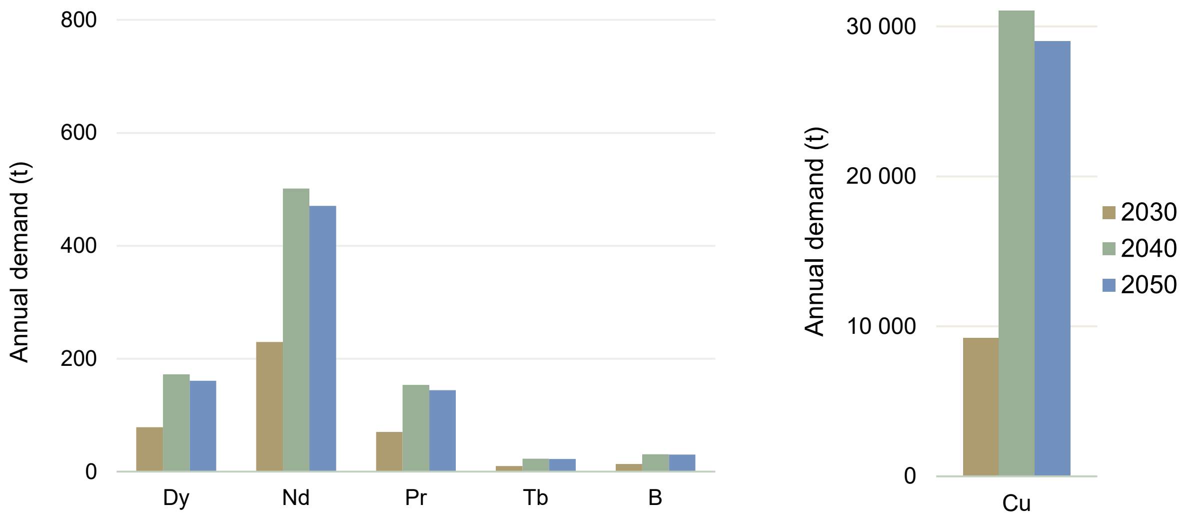
Appendix B

Annual forecast demand (tonnes) for the elements considered in this study up to 2050 and compared with 2020 under four different scenarios. A: ‘Leading the way’ scenario; B: ‘Falling short’ scenario; C: ‘Consumer transformation’ scenario; D: ‘System transformation’ scenario.

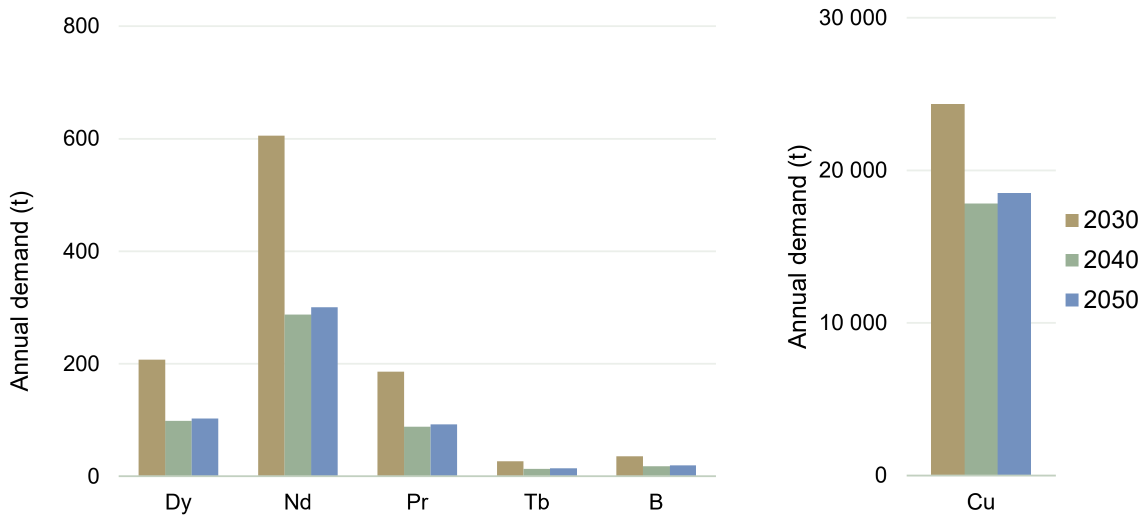
A



B

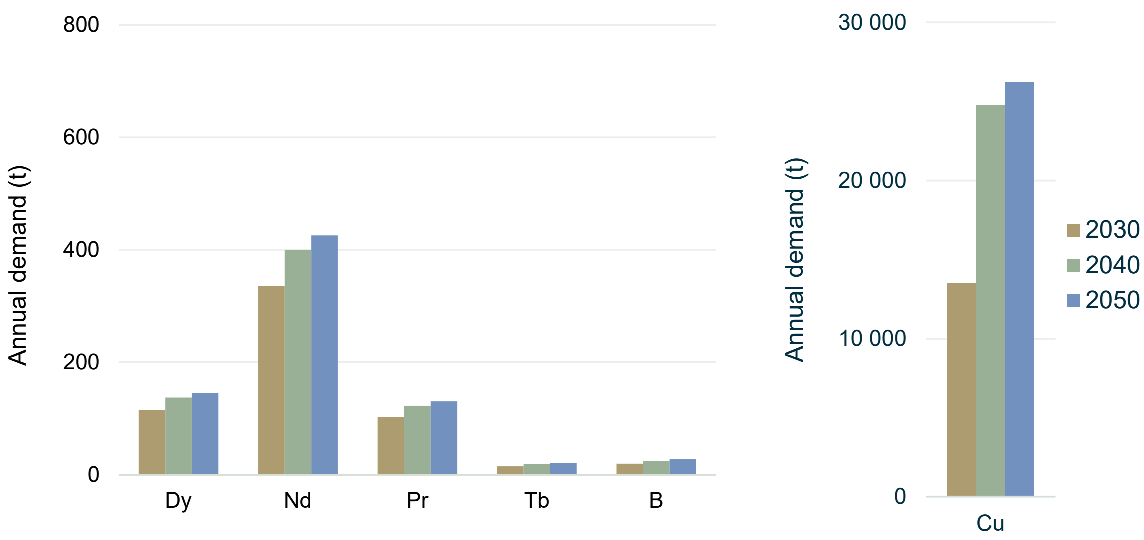


C



Annual demand (t)
800
600
400
200
0
Dy
Nd
Pr
Tb
B
Annual demand (t)
30 000
20 000
10 000
0
Cu
2030
2040
2050

D



Annual demand (t)
800
600
400
200
0
Dy
Nd
Pr
Tb
B
Annual demand (t)
30 000
20 000
10 000
0
Cu
2030
2040
2050

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