UK Critical Minerals
Intelligence Centre

A UK foresight study of materials in decarbonisation technologies

Decarbonisation and Resource Management Programme

Open Report OR/24/005

Department for Business & Trade

British Geological Survey

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BRITISH GEOLOGICAL SURVEY

DECARBONISATION AND RESOURCE MANAGEMENT PROGRAMME

OPEN REPORT OR/24/005

A UK foresight study of materials in decarbonisation technologies

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Keywords: foresight, critical minerals, decarbonisation

Front cover: EdWhiteImages. 2022. wind-energy-7342177_1280. pixabay. PublicDomainPictures. 2012. alternative-21581_1280. Pixabay. Hydrogen refuelling, ©Microsoft 365

Bibliographical reference: Petavratzi, E, Horn, S, Shaw, R, and Josso, P. 2024. A UK foresight study of materials in decarbonisation technologies. *British Geological Survey Open Report*, OR/24/005. 73pp.

Keyworth, Nottingham British Geological Survey 2024

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Foreword

This report is the published product of a study by the UK Critical Minerals Intelligence Centre (CMIC), hosted by the British Geological Survey (BGS), which was commissioned by the Department for Business and Trade (DBT) as part of the 2024 work programme for CMIC.

Acknowledgements

The synthesis study has been completed by a team in BGS following the publication of a series of individual foresight technology reports compiled by BGS, Decision Analysis Services (DAS) and the University of Exeter. The authors would like to acknowledge the assistance of several people who helped to deliver this report and, in particular, the following BGS staff:

- Gavin Mudd (scientific support)
- Gus Gunn (scientific editor)
- Annabelle Luce (project coordinator)
- Debbie Rayner (graphics designer)

Many external stakeholders assisted the delivery of the synthesis and individual foresight reports by providing advice, information, data and feedback. We would like to thank them all for their great support and commitment.

Finally, the authors would also like to thank the DBT's critical minerals team for their feedback and advice during the development of the synthesis and individual foresight reports.

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Executive summary

The UK's net zero commitment is driving demand for renewable energy, energy storage and electrified transport. This analysis examines UK demand up to 2050 and global supply challenges for 36 materials critical to the following eight decarbonisation technologies:

- batteries
- electrolysers
- fuel cells
- heat pumps
- nuclear energy
- photovoltaics
- traction motors
- wind turbines

This report synthesises the findings of foresight studies on these decarbonisation technologies, each being the subject of a separate published report. With limited UK-based supply chains, reliance on international markets and growing global competition poses supply risks and material bottlenecks. Evaluating current and future supply constraints is therefore essential to mitigate risks to the UK's decarbonisation targets.

The analysis methodology involved five steps:

1. defining boundaries: identifying relevant decarbonisation technologies, sub-technologies and critical materials
2. material allocation: mapping materials essential to the function of specific technologies
3. supply risk evaluation: assessing risks based on production and trade concentration, and on UK value chains
4. quantifying UK demand: projecting material demand to 2050 using National Grid scenarios and global comparisons
5. assessing the scale of the UK demand relative to global demand

DEMAND ANALYSIS INSIGHTS

- Batteries will see the fastest growth, with significant demand increase projected for graphite, nickel (Ni), lithium (Li) and cobalt (Co)

- Heat pumps, traction motors and wind turbines will drive demand for copper (Cu) and rare earth elements (REEs), requiring close market monitoring

- Photovoltaics (PVs) will increase demand for silicon (Si), Cu and silver (Ag), with emerging technologies requiring new materials like bismuth (Bi)

- Nuclear energy is likely to face supply chain pressures as the UK aims to quadruple capacity by 2050, demanding careful monitoring of uranium (U), gadolinium (Gd), indium (In) and niobium (Nb)

- Demand for fuel cells used in transport and electrolysers for green hydrogen production is anticipated to grow considerably, which will result in increased need for platinum group metals (PGMs), particularly iridium (Ir), which would requiring close monitoring

- Projected cumulative UK demand to 2050 is led by graphite (5.6 Mt), Ni (2.5 Mt) and Cu (2.4 Mt), with dramatic increases from 2024 levels (30- to 40-fold for graphite, Ni, Cu and Li; 15-fold for Co and Si)

- Demand for most materials will peak between 2030 and 2040

- High-risk materials for the UK include Li (15 to 40 per cent of global production by 2030, depending on the scenario) and graphite (10 to 29 per cent); the UK's share of global demand for REEs, Ni, Co and Cu will also rise significantly

- Li faces the greatest supply risk, with the UK alone requiring up to 40 per cent of current global production by 2030: global supply would need a 32-fold increase by 2030 to meet demand, posing major challenges for securing stable supplies amidst intense international competition

GLOBAL SUPPLY ASSESSMENT INSIGHTS

- Geographical concentration of mine production is low to moderate for most materials, but is highly concentrated for Nb, Ir, REEs and platinum (Pt), and refining shows significant concentration, with China dominating as the leading producer for 29 of 49 materials analysed

- Global trade is dominated by three or fewer countries for most mined and refined materials, with China playing a key role as both a major importer of raw materials and an exporter of refined products

- Midstream supply chains are highly concentrated for certain intermediate products, such as polysilicon, Si metal, Ag paste and permanent magnets (key for wind turbines and traction motors), primarily in China, and limited midstream production capacity outside south-east Asia creates a bottleneck for batteries

- Some technologies, including fuel cells, electrolysers, nuclear applications and heat pumps, benefit from more diverse manufacturing sources at the component stage

- In the UK:
  - involvement in decarbonisation technology supply chains is concentrated in downstream stages of manufacturing, assembly and research and development, with limited upstream activity such as mining and refining
  - key sectors include electric vehicles (EVs), where the UK has capabilities in traction motor and battery manufacturing and established plans for future developments in both areas
  - Large-scale production of most technologies takes place abroad
  - exploration is taking place for domestic resources, such as Li in Cornwall, as well as planning to develop refining capacity in northern England to strengthen the supply chain
  - there is significant expertise in hydrogen (fuel cells and electrolysers), nuclear and next-generation battery technologies, while recycling activities for batteries and permanent magnets are emerging but remain limited at present

RECOMMENDED ACTIONS

- Ongoing monitoring: establish data observatories, like the UK Technology Metals Observatory, for continuous supply chain analysis and risk mitigation

- Supply diversification: prioritise domestic and international mining and refining projects that can increase production quickly, ideally within five years

- Funding and collaboration: encourage partnerships between industry and research organisations through initiatives like the Circular Critical Minerals Supply Chains fund to address raw material and supply chain challenges

- Midstream investment: support UK companies to build midstream capabilities, such as precursor material and component manufacturing, to reduce vulnerabilities in value chains

- Skilled workforce development: ensure development of a skilled workforce essential to support the growth of UK manufacturing capacity in decarbonisation technologies; expand expertise in areas like fuel cells and electrolysers, and invest in training to grow the UK manufacturing workforce

- Circular economy:
    - ensure development of a circular economy
    - promote re-use, refurbishment, remanufacture and recycling to secure future material supply
    - address gaps in reverse supply chains, industrial capacity and investment to enable future growth in circular economy activities and allow the UK to assume a prominent global role

- Demand reduction: minimise reliance on high-risk materials and technologies facing supply bottlenecks through circular economy actions; for example, product lifetime extension, enhanced material efficiency, improved product design and consumer behaviour change

- Policy leadership:
    - integrate materials supply and sustainability into a UK industrial strategy, using tools such as product passports to enable circular practices
    - invest in a comprehensive raw materials strategy, in international trade agreements and promote international diplomacy to improve resilience

INSIGHT FROM THE FORESIGHT STUDIES

These foresight studies provide vital insight into future material needs and supply-and-demand dynamics for emerging technologies. Expanding their scope to include economic factors and environmental, social and governance (ESG) considerations would provide important additional validity. Expanding their scope to include other sectors, such as digital technologies and communication, artificial intelligence, robotics and aerospace, would provide a more comprehensive understanding of future material challenges. A horizon-scanning exercise should be undertaken to identify priority areas for future assessments.

Technology-specific recommendations are detailed in the corresponding individual reports. To stay aligned with the rapid advances in decarbonisation technologies and progress towards net zero goals, these foresight studies should be updated regularly, preferably at intervals of no more than two years.

1 Introduction

The decarbonisation transition relies on scaling-up green technologies that depend on numerous materials, including critical raw materials, for their manufacture and connection to the grid. The short timescale set by the UK's net zero ambition (HM Goverment, 2021) for the adoption of these technologies, which is in line with similar timelines set globally, means that material demand will escalate rapidly, leading to supply challenges as we race towards climate change mitigation. This is endorsed by many, including the Climate Change Committee, the IEA, the World Bank and COP28. The transition to net zero, however, is not mono-dimensional: it demands a sustainable, fair and equitable transition.

Establishing sustainable and responsible supply chains for materials used in renewable technologies is crucial to prevent adverse trade-offs and mitigate their effects across their value chains. Failure to address these challenges could jeopardise the long-term availability and accessibility of raw and processed materials, as well as products derived from them.

The UK Critical Minerals Strategy sets out plans for:

- security of supply
- improving domestic capabilities
- collaborating with international partners to ensure diversification of global supply

The strategy also highlights the need for the UK to participate in the resolution of global challenges, for example on the responsible and equitable supply of critical minerals and the development of market transparency through better data and traceability (BEIS, 2022). The role of long-term material forecasts is crucial to identify potential supply issues and to enable planning for timely policy and mitigation actions.

This study analyses future UK demand for key materials used in eight selected decarbonisation technologies up to 2050:

- batteries
- electrolysers
- fuel cells
- heat pumps
- nuclear applications
- photovoltaics
- traction motors
- wind turbines

Detailed analyses for each of the assessed technologies are presented in individual reports, which outline the assessment criteria and key findings in depth. These reports are released alongside this synthesis report and offer comprehensive evaluations and data on the technologies examined. All reports are accessible on the CMIC website (Critical Minerals Intelligence Centre, 2024).

This report synthesises the results of the studies on individual technologies to provide a holistic overview of future UK material demand. It examines the UK's material demand and supply from a global perspective and provides recommendations to mitigate supply risks and help to ensure that the UK meets its net zero ambitions.

It is important to stress that the analyses undertaken for individual technologies are not exhaustive. Only selected functional materials and specific applications were considered. Other industry sectors and technologies that use many of the assessed materials were excluded. The overall UK material demand is, therefore, likely to be larger than is presented here. Additional complementary studies should be carried out that focus on other sectors and applications in order to better quantify overall material demand.

2 Methodology

The methodology used in this study follows a systemic approach by taking into consideration the value chain activities associated with these technologies, from raw material production to product manufacture. This approach was applied consistently across all technologies to ensure comparable results.

The assessment process consisted of five key steps (Figure 1). The analysis started by defining the decarbonisation technologies and sub-technologies (Table 1) and the materials used in each (Table 2). Only materials essential to the functionality of each technology were considered. Other non-essential materials were not included in the analysis; for example, materials used in supporting infrastructure such as aluminium (Al), which is found in PV cells and widely used steel-alloying elements. An assessment of supply risks was then undertaken together with an evaluation of the UK value chain for each technology. This was followed by the quantification of UK demand for the selected elements and technologies, together with an assessment of its scale relative to global demand.

Further information regarding the materials excluded from the analysis is found in Appendix A of each report.

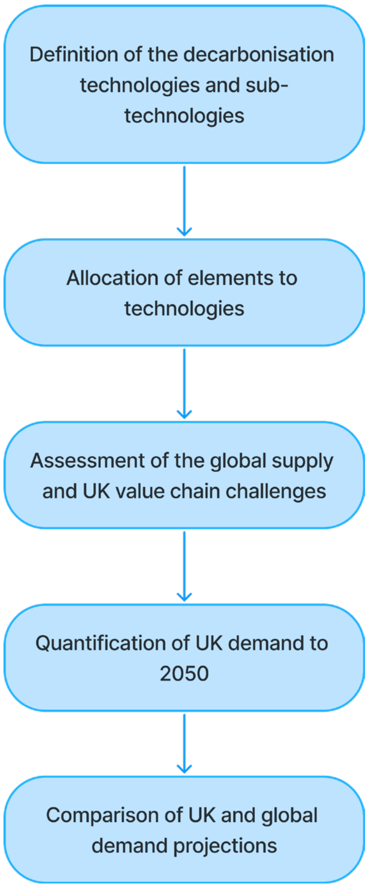

Figure 1 Key stages of the foresight methodology. BGS © UKRI.

In some instances, however, it was necessary to modify the approach in some way, generally due to the absence of relevant data or underpinning scenarios. Details of the departures from the standard approach are provided in the following sections of this report.

Table 1 Decarbonisation technologies and sub-technologies considered in this study.

Batteries	Wind turbines	Traction motors	Fuel cells	Electrolysers	Photovoltaic	Nuclear	Heat pumps
Lithium-ion batteries (LIB)	Gearbox-Double-fed Induction generator (GB-DFIG)	Permanent magnet synchronous motors (PMSM)	Proton Exchange Membrane (or Polymer electrolyte) fuel cells (PEMFC)	Alkaline electrolysers (AEL)	Passivated emitter and rear contact (PERC)	Pressurised Water Reactors (PWR)	Air-Source Heat Pumps (ASHP)
Sodium ion batteries (SIB)	Gearbox-Permanent Magnet Synchronous Generator (GB-PMSG)	Alternating current induction motors (ACIM)		Proton Exchange Membrane electrolysers (PEM)	Silicon heterojunction (SHJ)	Small Modular Reactors (SMR)	Ground-Source Heat Pumps (GSHP)
	Direct Drive-Permanent Magnet Synchronous Generator (DD-PMSG)	Wound rotor synchronous motors (WRSM)		Solid Oxide electrolysers (SOEC)	CIGS and CdTe thin film cells		
	Direct Drive-External Excitation Synchronous Generator (DD-EESG)			Anion Exchange Membrane electrolysers (AEM)	III-V/Si thin film tandem solar cells		

The technologies and sub-technologies considered in this study are shown in Table 1. They were determined using market analysis information and data on future technology trajectories to ensure that significant technological changes are accounted for. A range of reports, peer-reviewed papers, technology roadmaps and stakeholder consultations were used to inform the future market shares of sub-technologies. In most cases, specific components in each sub-technology were selected for detailed assessment, for example, the cathodes in batteries and the permanent magnets in the rotors of traction motors. The materials used in these components were analysed in terms of future demand and supply risk. This is discussed in detail in each of the individual foresight technology reports.

Table 2 Elements included in the foresight studies. UK critical minerals are those identified by Lusty et al. (2021).

	UK critical minerals																												
	Bi	C	Co	Ga	In	Li	Nb	PGM	REE	Si	Sn	Te	Ag	Al	B	Cd	Cr	Cu	Mn	Mo	Na	Ni	P	Se	Ti	U	Zn	Zr	As
Batteries		●	●			●				●									●		●	●	●						
Wind turbines									●						●			●											
Traction motors									●						●			●											
Fuel cells		●						●																					
Electrolysers								●	●													●			●			●	
Photovoltaics	●			●	●					●	●	●	●			●		●						●					●
Nuclear					●		●		●	●	●		●		●	●	●		●	●		●			●	●		●	
Heat pumps									●					●	●			●									●		

● Elements included in the analysis

2.1 DECARBONISATION TECHNOLOGIES

2.1.1 Batteries

A battery is a device that produces electrical energy from the conversion of chemical energy (European Union, 2023). They are used in numerous applications, such as portable electronic devices, EVs, medical equipment and power tools. Batteries are an important enabler for the electrification transition and a detailed foresight study for batteries is available in (Petavratzi et al., 2024b).

The foresight study focused on rechargeable batteries used in EVs. Two sub-technologies were included: lithium-ion batteries (LIB) and sodium-ion (SIB) batteries. LIBs are the dominant technology up to 2050, with SIBs' market share increasing steadily to 15 per cent by 2050.

The battery cathode and anode were the key components in the analysis, as cathode and anode active materials are the main determinants of the performance of the battery cell. LIB technologies for automotive batteries are mainly differentiated by the cathode active materials, which are used in a variety of cathode chemistries. Li is essential in all cathode types.

The main battery chemistries currently in use are:

- nickel-manganese-cobalt (NMC)
- nickel-cobalt-aluminium (NCA)
- lithium-iron phosphate (LFP)

This analysis considered not only these chemistries but also included variants such as lithium-manganese-iron phosphate and other, less prominent, cathode chemistries such as lithium-manganese oxide. In addition, a range of different configurations within the NMC group was considered (for example, NMC111; NMC 622).

The main anode active material currently in use is graphite, which is expected to remain predominant up to 2050. Accordingly, only graphite-based anodes were included in the assessment. Future innovative technologies that include doping graphite anodes with Si, Si anodes, Nb and niobium-tungsten anodes are in development but are not yet in commercial use. Information about their future market shares in the UK and suitability for the automotive sector are not available. They have, therefore, been excluded from the assessment.

SIBs are an alternative battery technology that is relatively cheap and uses fewer critical materials than LIBs: for example, sodium (Na) replaces Li and hard carbon replaces graphite (Degen et al., 2023). While there are several cathode materials in development for SIBs, we only consider Prussian blue analogues and nickel-manganese layered oxides in this analysis as these have the greatest commercial potential. Hard carbon is currently the dominant type of anode material in SIBs and is manufactured from various biomass sources, such as cellulose, sugar and resins (Degen et al., 2023).

2.1.2 Electrolysers

Hydrogen has a critical role in the UK's net zero transition (HM Goverment, 2021). Hydrogen use can help reduce carbon emissions and decarbonise sectors that are difficult to transition, such as transport. Hydrogen can be produced in various ways, including electrolysis, biochemical conversion and thermochemical conversion. In this assessment, the focus is on electrolysis processes, which enable green hydrogen production. (Zils, 2024a) is a detailed foresight study for electrolysers.

Electrolysis is the process of breaking down water into hydrogen and oxygen using electricity. An electrolyser comprises essentially a direct current source and two electrodes (an anode and a cathode) coated with noble metals, such as Pt. The electrodes are separated by an electrolyte, which can be a liquid such as potassium hydroxide in the case of alkaline electrolysis, or a solid-state membrane, as in proton-exchange electrolysis.

There are four main types of electrolyser technology:

- alkaline electrolysers (AEL)
- proton-exchange membrane electrolysers (PEM)
- solid oxide electrolysers (SOEC)
- anion exchange membrane electrolysers (AEM)

AELs and PEMs are the dominant electrolyser types installed globally. All four types are included in this assessment.

2.1.3 Fuel cells

Fuel cells convert chemically bound energy in hydrogen into electrical energy and heat. In a fuel cell, hydrogen, as a dihydrogen molecule (H_2), is recombined with oxygen (O_2). The reaction releases a direct electric current and produces water (H_2O) as a waste product. (Zils, 2024b) is a detailed foresight study for fuel cells.

A fuel-cell system, comprising a series of individual fuel cells organised in stacks, is the focus of this analysis. A typical fuel-cell stack comprises two porous, catalyst-doped electrodes (anode and cathode), an electrolyte placed between the two electrodes and a gas diffusion layer.

There are five main types of fuel cell technology currently in use:

- alkaline fuel cells (AFC)
- proton exchange membrane (or polymer electrolyte) fuel cells (PEMFC)
- phosphoric acid fuel cells (PAFC)
- molten carbonate fuel cells (MCFC)
- solid oxide (or oxide ceramic) fuel cell (SOFC)

PEMFCs are the most widely used (European Commission et al., 2020b) and are considered likely to continue to be the leading type in the future. This analysis, therefore, focuses on PEMFCs as they are likely to dominate the road transport sector (DOE, 2022, European Commission et al., 2020b, Shell & Wuppertal Institut, 2017).

2.1.4 Heat pumps

Heat pumps are an important low-carbon heating technology and they are expected to play a significant role in decarbonisation of the heating and hot water provision in the UK in conjunction with improved building insulation. (Zils, 2024c) comprises a detailed foresight study for heat pumps.

Heat pumps transfer heat from one place to another by using a small amount of energy. The operation of a heat pump is based on the thermodynamic principle that heat naturally flows from warmer to cooler spaces. A heat pump operates on a refrigeration cycle involving compression, condensation, expansion and evaporation of a refrigerant fluid. The cycle can be reversed to either absorb heat from the outdoor environment and release it indoors (for heating) or absorb heat from indoors and release it outdoors (for cooling) (McQuiston et al., 2023).

Heat pumps can be classified according to the source of the ambient heat into three types:

- air-source heat pumps (ASHP)
- ground-source heat pumps (GSHP)
- water-source heat pumps (WSHP)

(Energy Saving Trust, 2024, International Energy Agency, 2022a, McQuiston et al., 2023)

ASHPs are currently the dominant technology globally.

In terms of size and application, heat pumps are commonly categorised into residential (5 to 15 kW for an average house or above 15 kW for larger residential buildings) and commercial (25 to 70 kW) heat pumps.

Despite the different heat pump types, their core components are similar in terms of material requirements. This study has, therefore, focused on four core components:

- compressor (consisting essentially of an electric motor)
- condenser (heat exchanger)
- evaporator
- expansion valve

2.1.5 Nuclear

Nuclear fission is a key energy source for many countries and will become increasingly important in global decarbonisation. (Jackson et al., 2024) offers a detailed foresight study for nuclear energy.

Nuclear fission involves the splitting of atoms in a nuclear reactor, resulting in the release of lighter atoms and large amounts of energy. The key components of the reactor core include:

- fuel rods, comprising pellets of fissile material, commonly ^{235}U
- neutron moderator, which slows down the initial release of fast neutrons from nuclear fission
- control rods, which are inserted into the nuclear reactor to absorb neutrons and reduce the rate of, or stop, the nuclear chain reaction
- coolant, where the thermal energy generated by nuclear fission is absorbed and pumped through a closed-loop circuit to generate steam, which is used by a turbine for electricity generation

The scope of materials that make up the fuel, moderator, control rods and coolant vary according to the type of nuclear sub-technology. Stakeholder engagement and evidence from the UK Government Civil Nuclear Roadmap (DESNZ, 2024a) strongly suggests that large-scale pressurised water reactors (PWR) and small modular reactors (SMR) will make the largest contributions to the civil on-grid nuclear capacity between now and 2050. These sub-technologies are, therefore, the focus of this analysis.

PWRs are large-scale reactors that use water as both the moderator and coolant. They typically have a power capacity greater than 700 MW. SMRs are smaller versions of conventional water-cooled reactors (like PWRs) and have a capacity of less than 500 MW.

2.1.6 Photovoltaics

The conversion of energy from the Sun into electricity requires the use of PV technologies. A PV cell comprises essentially very thin wafers of semiconductor material that convert incident energy to electrons when exposed to sunlight. Individual cells are linked together to make a panel, each installed in a metal frame within a glass casing. (Petavratzi et al., 2024c) is a detailed foresight study for PVs.

A range of sub-technologies was considered in the analysis:

- passivated emitter and rear solar cells: currently the most widely used technology
- Si heterojunction solar cells: with the second-largest share in the PV market at present, their importance is expected to increase in the future
- thin film cells, such as copper-indium-gallium diselenide (CIGS) and cadmium-telluride (CdTe): more bendable than crystalline Si cells and can potentially be used in a wide range of applications, but efficiency is lower and tend to be relatively expensive to manufacture
- III-V/Si thin film tandem solar cells: currently only used in high-specification applications, such as space technologies, but are likely to become available commercially after 2035 (Boyer-Richard et al., 2023, Gervais et al., 2021)

2.1.7 Traction motors

Traction motors, also referred to as electric motors, represent the powertrain for electrically driven vehicles and machinery, producing power through the conversion of electrical energy into mechanical energy. They are used in EVs, electric trains and in various industrial applications, such as pumps. Traction motors typically comprise a non-moving stator and a spinning rotor

(Everything PE, 2024). A detailed foresight study for traction motors is given in (Petavratzi et al., 2024a).

Permanent magnet synchronous motors (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 (ACIMs) at 20 per cent and wound rotor synchronous motors (WRSMs) at 6 per cent. These three types of traction motor were considered in this study.

PMSMs integrate permanent magnets in the rotor. The main permanent magnet type used in PMSM are neodymium-iron-boron magnets, due to their optimal magnetic properties (Nordelöf et al., 2018). ACIMs are the most mature motor technology: they are simple, robust and lower cost than PMSMs as they do not rely on permanent magnets to create a magnetic field. Instead, they generate a magnetic field by inducing an electric current onto the rotor. WRSMs are a relatively mature technology commonly used in a range of applications such as water pumps or compressors (Mabhula, 2019). Whilst WRSMs do not represent the dominant technology for EV applications, their use by manufacturers such as Renault and BMW has been reported (Banner, 2022, Widmer et al., 2015). In the future, the market share of ACIMs and WRSMs is expected to increase while PMSMs' market share is expected to decrease to 50 per cent.

2.1.8 Wind turbines

Wind turbines are a well-established renewable technology that harness energy from wind. 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). This capacity expansion will likely continue, with the Climate Change Committee suggesting that the UK may require up to 125 GW by 2050 (Committee on Climate Change, 2020). Petavratzi et al. (2024d) is a detailed foresight study for wind turbines.

The kinetic energy imparted to the blades of a wind turbine is converted into electricity by the rotation of a rotor within a generator (IRENA, 2024). The primary components of a wind turbine include the foundation, tower, nacelle and rotor blades. The nacelle contains the generator, together with a gearbox in some turbine types and several other functional components.

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

- 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)

GB-PMSGs and DD-PMSGs are commonly used in offshore wind farms, while GB-DFIGs and DD-EESGs usually find use in onshore wind applications. In the future, GB-PMSGs and DD-PMSGs are expected to monopolise the market both in offshore and onshore applications.

2.2 ELEMENTS SELECTED FOR ANALYSIS

The elements evaluated for the different technologies are shown in Table 2. The selection of materials for this assessment was guided by two key criteria:

- materials essential to the core function of the technology: only materials critical to the operation of each technology were included in the analysis; for example, cathode active materials were assessed for batteries and only the materials in the semiconductor layers were analysed for PVs, while structural materials, such as glass, aluminium, steel and copper, for which the demand from such technologies is minor compared to other industries, were excluded
- materials classified as critical: materials that are classified as critical in the UK criticality assessment (Lusty et al., 2021) were included in the analysis

2.2.1 Limitations to material selection

As stated, certain materials were excluded because they are not essential to the function and performance of the selected technology. However, other factors also contributed. These include:

- the absence of appropriate, authoritative data
- lack of clarity of the role of a material in a component
- lack of detailed bills of materials (BOMs) for components or products

Further information on the exclusion of materials is given in the individual technology reports.

2.3 THE VALUE CHAIN OF DECARBONISATION TECHNOLOGIES

It is important to fully understand the value chains of each material involved in order to fully evaluate the supply chains for decarbonisation technologies. This ensures the right material forms are considered and the assessment boundaries (mining to product manufacture) are clearly and transparently defined.

The key stages considered in this analysis to identify potential supply chain bottlenecks are:

- mining
- refining
- production of precursor materials and components
- manufacturing

The value chain mapping traces the transformation of raw materials from extraction by mining to their incorporation into components and final products (Figure 2).

At the mining stage, ore is extracted and initially processed to produce a concentrate. Refining then produces purified metals or chemical compounds, which commonly serve as precursor materials for the manufacture of components such as permanent magnets and battery cathodes. The decarbonisation technologies examined in this study require several components to be manufactured and assembled in a final product.

Our value chain analysis tracks these material transformations across the life cycle stages, providing quantitative insights for the mining and refining stages. While there is adequate data to assess the raw materials at these stages, the midstream of the value chain (precursors and components) can be assessed only in a qualitative manner due to its extreme complexity and limited data availability. The analysis also includes an assessment of the geographical distribution of the supply chain, identifying the dominant players for each material at each stage and thus contributing to the evaluation of supply risks for the UK.

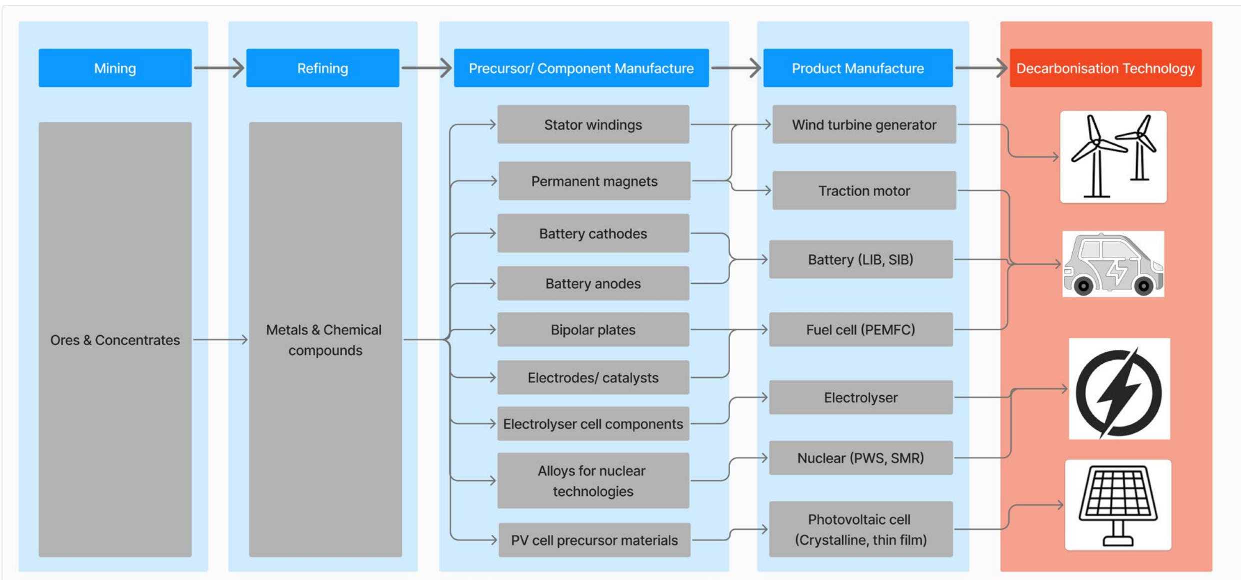

Figure 2 The system boundaries of the value chain analysis. BGS © UKRI.

2.4 MODELLING FUTURE UK MATERIAL DEMAND

Assessment of future UK material demand for decarbonisation technologies is crucial for making informed strategic decisions. Ensuring a secure, sustainable and responsible UK supply of these materials will depend on the development of long-term models and continuous monitoring of changes in technologies, markets and value chains. Forecasting UK demand for eight key decarbonisation technologies up to 2050 requires an understanding of how these technologies will evolve over time and how that will affect material consumption.

In this study, we developed a methodology to forecast UK material demand up to 2050, which uses scenarios and technology transformation assessments from multiple sources. Details of the underpinning data sources and scenarios used are provided in the individual foresight technology reports.

2.4.1 Future energy scenarios

Given that this analysis focuses on decarbonisation technologies, understanding their future deployment is important. To effectively quantify the material demand associated with these technologies, scenarios projecting the growth of clean energy systems are essential. These scenarios provide a basis for estimating the resources required to support the anticipated expansion of decarbonisation technologies.

This assessment used the Future Energy Scenarios (FES) developed by National Grid (National Grid, 2023a). They provide pathways that the UK can follow to achieve net zero by 2050. They take account of the whole energy system and therefore provide projections for all the decarbonisation technologies considered in this assessment, following a consistent methodological framework and scenario conditions.

The FES provides four different pathways for the evolution of the entire energy system through to 2050 (Figure 3). Each scenario explores projected energy demand and potential energy sources to build a comprehensive view of how net zero goals can be achieved.

The four scenarios are:

- falling short
- consumer transformation
- system transformation
- leading the way

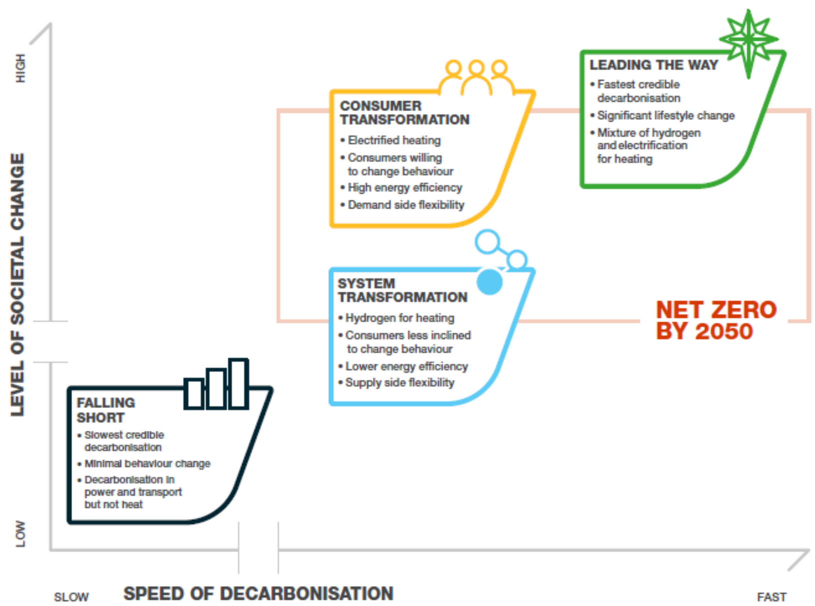

Figure 3 The scenario framework of the National Grid Future Energy Scenarios (National Grid, 2023b).

2.4.1.1 Falling short

This is the only scenario that does not meet the net zero by 2050 target. It assumes that annual carbon emissions remain significant in 2050. Overall progress to decarbonisation is taking place, but at a slower pace than in the other three scenarios. Reliance on natural gas for domestic heating continues to be significant and passenger EV uptake is growing slowly. Decarbonisation of other vehicles is slower than for passenger cars.

2.4.1.2 Consumer transformation

This scenario assumes that the net zero target is met by 2050. Consumers have a high level of engagement in the transformation of the energy system, with improvements in home energy efficiency, smart monitoring of electricity demand, and uptake of heat pumps and EVs. The energy systems are expected to have peak electricity demand managed through various technologies, including energy storage, demand-side response and smart energy management.

2.4.1.3 System transformation

This scenario assumes that the net zero target is met by 2050. Significant changes have taken place prior to 2050 in the supply of the energy system, while the role of the consumer in this scenario is less significant. However, it is expected that consumers will use hydrogen boilers within existing heating systems and move towards using an EV (battery or fuel cell). This scenario assumes an increase in hydrogen demand, which is mostly met by natural gas, coupled with carbon capture, use and storage.

2.4.1.4 Leading the way

This is the most aggressive of all scenarios assuming that net zero is met by 2046. In this scenario, decarbonisation takes place rapidly, with investment in several clean energy technologies and a high level of engagement from consumers who are willing to decarbonise their houses and transport. Hydrogen plays a key role in decarbonising industrial processes that are otherwise difficult to decarbonise. Hydrogen production is by electrolysis powered by renewable energy.

2.4.1.5 FES data used in the analyses

In our analyses, we used the following data from the forecast FES models for each technology in the UK up to 2050:

- batteries: size of the EV fleet
- wind turbines: offshore and onshore wind power generation capacity
- traction motors: size of the EV fleet
- fuel cells: hydrogen demand in transport
- electrolysers: installed electrolyser capacity
- photovoltaics: installed PV operational capacity
- nuclear: level of nuclear power deployment
- heat pumps: number of heat pumps (domestic and non-domestic)

A separate scenario was used to forecast material demand for the future UK battery manufacturing sector, based on projected UK battery manufacturing capacity as provided by Benchmark Minerals.

For nuclear technologies, an additional fifth scenario, derived from the UK civil nuclear roadmap to 2050, was included, to reflect the UK's nuclear ambitions (DESNZ, 2024a). Stakeholders considered this crucial, as the FES focuses exclusively on the broader UK energy system and does not incorporate the specific goals of the UK's nuclear strategy.

Further information about the use of FES in the analysis of each technology is given in the foresight technology reports.

2.4.2 Technology transformation and material needs

Understanding technology transformation is critical for projecting embedded material demand, as the bill of materials (BOM) and the market penetration of new and improved technologies is likely to shift in the future. The trajectories of technological innovation, unique to each decarbonisation technology, are discussed in the respective reports. Estimation of the future market shares of individual sub-technologies, each with its own BOM, allows the material demand to be adjusted according to future technological changes.

Figure 4 illustrates the market evolution of emerging technologies in EV traction motors and offshore wind turbines from 2020 to 2050. In the case of EV traction motors, the market share of PMSMs is projected to decline over time, being replaced by ACIMs. WRSMs are expected to see a slight increase in market share during the same period.

For offshore wind turbines, the market is currently dominated by DD-PMSG, followed by GB-PMSGs and a smaller share by GB-DFIG. By 2030, the GB-DFIG is anticipated to become obsolete, while the GB-PMSG is expected to gradually decline, becoming obsolete by 2050. As a result, DD-PMSG are forecast to dominate the market by 2050.

These shifts in technology dynamics significantly affect material requirements, particularly in relation to REE permanent magnets. The analysis suggests that the automotive sector is moving towards electric motors that do not rely on REE permanent magnets. However, this is not the case for offshore wind turbines, where the DD-PMSG technology, which is reliant on REE magnets, is expected to dominate by 2050.

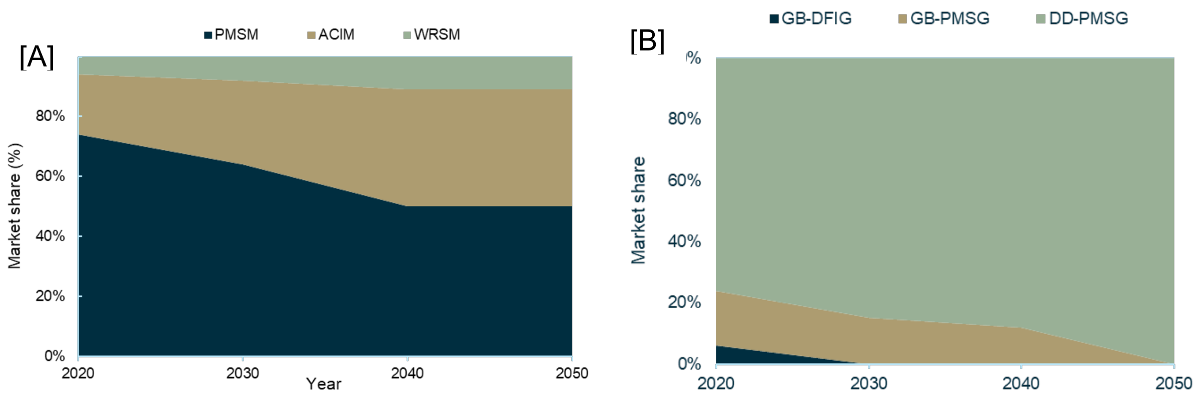

Figure 4 Evolution of the markets between 2020 and 2050 for A: EV traction motors (Advanced Propulsion Centre UK, 2024c); B: offshore wind turbines (European Commission et al., 2020c, Liang et al., 2023) showing the technology transformation that is likely to take place. Traction motors: PMSM: permanent magnet synchronous motors; ACIM: AC induction motors; WRSM: wound-rotor synchronous motor. Wind turbines: GB-DFIG: gearbox double-fed induction generator; GB-PMSG: gearbox permanent magnet synchronous generator; DD-PMSG: direct drive-permanent magnet synchronous generator. BGS © UKRI.

An analysis of technological evolution and its impact on material requirements is provided in the individual reports. These trends vary between different elements and technologies. This detailed analysis has enabled a better understanding of how technological advancements will influence future material demand. This is then embedded in the forecast demand calculations.

2.4.3 Modelling future UK demand

Modelling future UK demand involved integrating various datasets and conditions.

- Clean energy demand forecasts based on the FES developed by the National Grid (Section 2.4.1)
- Market evolution analysis results, which outlined the market shares of sub-technologies between 2020 and 2050
- Product lifespan data (for example, for EVs) to account for material obsolescence and the replenishment required in the future demand model
- Material intensity data for those materials included in the analysis

The clean energy demand forecasts from the FES (such as the projected number of EVs in the UK between 2020 and 2050) along with average lifespan data were used to estimate the number of new products (for example, new vehicles) entering the UK product stock each year. Following this, market evolution analysis and material intensity data were combined to calculate the demand for specific materials in any given year. This method was applied across all other technologies to model material demand.

The projected UK demand for key elements embedded in specific technologies is presented in two formats:

- total quantity (in tonnes) required from 2020 to 2050 for each FES, with both cumulative and annual demand figures
- demand expressed as a percentage of current global metal production, based on average production data from 2017 to 2021

2.4.4 Modelling future global demand

The global material demand forecasts in our analysis use scenarios and data from the IEA (International Energy Agency, 2023a), which align with the UK's net zero pathways.

We compared UK projections with global demand using, in most cases, three IEA scenarios (International Energy Agency, 2024b):

- stated policies scenario: this scenario assesses current governmental policies and their actions to meet set targets, considering regulatory, market, infrastructure and financial factors.
- announced pledges scenario: this scenario assumes that governments fulfil their climate commitments, leading to a 1.5°C temperature increase by 2100
- net zero emissions by 2050 (NZE): this scenario assumes net zero by 2050, stabilising temperatures below 1.5°C above pre-industrial levels (with at least 50% probability). It also assumes advanced economies achieve net zero before developing nations and that key energy-related UN Sustainable Development Goals, such as universal energy access by 2030, are met

In cases where global demand data from the IEA scenarios were unavailable, alternative scenarios were employed for specific technologies to ensure comprehensive analysis. For example, in the case of fuel cells, the global demand was modelled using historic IEA figures (International Energy Agency, 2023b) and the worldwide fuel cell vehicle estimates provided by Samsun et al. (2022). The global electrolyser demand was modelled using the IEA sustainable development scenario (SDS) (1400 GW by 2050) (International Energy Agency, 2021) and the IRENA 1.5°C Pathway scenario data (International Renewable Energy Agency, 2022). Finally, the global demand for heat pumps was modelled using, in addition to the IEA NZE scenario, the EU foresight (world) scenarios (European Commission et al., 2023).

2.4.5 Limitations to modelling future demand

Modelling future demand for eight decarbonisation technologies is challenging, particularly when attempting to apply a unified assessment framework to produce comparable results. Each technology presented distinct issues, which are outlined in the individual reports.

The primary challenge was data availability and quality. Detailed information on the evolution of the UK market for different technologies was often incomplete or unavailable. Generating this data would have required comprehensive technology roadmaps and foresight studies, which do not exist. In the absence of UK-specific data, we relied on global or European studies to fill these gaps although, in some cases, these data may not accurately reflect the UK market.

The second major challenge was acquiring material intensity data for the various elements, semi-manufactured components and products examined in this study. This information is not readily accessible and required extensive analysis of published literature and stakeholder engagement to develop reasonable estimates.

2.5 MODELLING SUPPLY: ANALYSIS AND BOTTLENECKS

Most supply chain bottlenecks are linked to a high degree of concentration in one or several parts of the supply chains. An individual country or company may predominate, thus increasing the likelihood of supply disruptions. This may be further exacerbated by trade restrictions.

Such constraints may take many forms, including:

- export control applied by the producing country
- import restrictions in the form of a preferential trade agreement
- domestic production protectionism
- sanctions due to geopolitical tensions (for example, EU and UK sanctions against Russia)
- constraints related to responsible sourcing rules that require adherence to guidelines on human rights and sustainability (for example, the EU's conflict minerals regulation (European Union, 2017))

Risk due to production concentration is not only geographical in origin: an additional threat to supply arises where the production of a key component in the supply chain is controlled by a small number of companies operating in multiple countries.

The by-product nature of a particular raw material also contributes to supply risk. A by-product metal is produced as a secondary output during the extraction or refining of a primary metal or mineral. These by-products are not the main target of the mining operation but are recovered from the same ore due to their economic value or demand need. The lack of collected and published information on the resource endowment and potential recovery of these by-products adds to the uncertainty of their supply.

Examples of by-products include:

- the recovery of Co from Cu or Ni mining
- the recovery of gallium (Ga) from Al (bauxite) or zinc (Zn) refining
- the recovery of tellurium (Te) from Cu refining

2.5.1 Production concentration

The production concentration data are modified by ESG standards in the producing countries, following the proposed revision of the methodology for UK criticality assessment (Josso et al., 2023). Each material is evaluated by calculating the degree of production concentration using the Hershman-Herfindahl Index (HHI) weighted by the integrated ESG score. The ESG scores are derived by combining the scores of the key producing countries for the environmental performance index, the human development index and the world governance index. The combined scores for each material were then ranked between 1 and 10, with a score of 10 being of greatest concern (having the greatest likelihood of supply disruption) and a score of 1 being of least concern (Josso et al., 2023).

Secondary materials such as waste and scrap have not been included in the assessment. This study explores the mining to product manufacture supply chain only, so end-of-life stages are not included. In addition, information about the availability of secondary supply is a major data gap, which requires additional modelling and in-depth analysis.

2.5.2 Global trade concentration and trade restrictions

The global trade concentration was calculated using six-digit Harmonized System (HS) code trade data from the United Nations Comtrade (UN Comtrade) database (United Nations, 2023). Total global imports and exports were calculated for each material for the period 2017 to 2021. Average net imports and net exports were calculated for the same period, for the top five trading nations in each case. The percentage share of the global total held by each of the top five trading nations was then calculated.

The presence and severity of trade restrictions placed on traded materials was assessed using data held in the Organisation for Economic Co-operation and Development (OECD) Inventory of Export Restrictions on Industrial Raw Materials (Organisation for Economic Co-operation and Development, 2020). The restrictions themselves were not used to weight the results of the global trade concentration calculations, because the data are too complex and their effects not well known enough to be used in this way. Rather, the data were used in a qualitative manner, highlighting countries and materials where restrictions may further add to supply disruption.

2.5.3 UK value chain analysis

The analysis of the UK value chain was conducted in a qualitative manner and focused on the roles of key players across the various stages. Where quantitative data, such as manufacturing capacity, was available, it was incorporated into the discussion and compared with projected demand. Specifically for batteries, planned UK gigafactory capacities were included in the calculations and tailored demand forecasts were created to reflect the evolving battery market. These estimates are distinct from the broader UK EV fleet demand.

2.5.4 Limitations to supply modelling

Supply modelling attempted to build a picture of the global and UK value chains for the materials included in the analysis. The main issues relate to data availability.

- Production concentration: while total mine and refinery production data are published, data for specific forms of materials, such as battery-grade cathode and anode materials, are not publicly available

- Global trade concentration and trade restrictions: there are many issues concerning the availability, quality, scope and relevance of trade data for the purposes of this analysis. These vary by country and commodity. Although some data may be available, their resolution is commonly inadequate for detailed analysis as individual HS trade codes commonly represent data aggregated for multiple commodities and material forms

3 Results: future UK material demand

3.1 DECARBONISATION TECHNOLOGIES

The aggregated UK demand projections for selected elements in eight decarbonisation technologies are summarised in Figure 5. Detailed demand results for the full range of elements for each technology are provided in the individual reports. Here, the key findings are illustrated using selected examples of the materials analysed. The demand projections are based on the 'Clean energy demand forecasts' FES of the National Grid (Section 0).

Figure 5 shows the cumulative demand for these commodities up to 2030, 2040 and 2050. The horizontal dimension of the figure illustrates the demand for each commodity across all technologies, while the vertical dimension shows the demand for various commodities within each technology. The symbol size indicates the projected demand (in tonnes) for each material.

Among the different decarbonisation technologies, batteries stand out due to their rapidly increasing demand profile for several key materials, including graphite, Ni, Li, Co and Si. It is also important to note that Cu demand in batteries was not assessed, as the focus was on active materials for cathodes and anodes. Cu is used in the current collectors of Li-ion battery cells (anode collector).

In a typical EV, battery pack Cu content represents between 10 to 15 per cent of the weight of the battery (ElectraMet, 2024). Heat pumps, traction motors and wind turbines exhibit significant demand growth for Cu and REEs, highlighting the need for close monitoring as these rapidly growing technologies evolve. Similarly, PVs demonstrate substantial demand growth for several elements and are undergoing significant technological transformations. This reinforces the importance of tracking material requirements across all emerging technologies.

By 2050, graphite is projected to have the highest cumulative demand, with an estimated 5.6 million tonnes (t). This is followed by Ni in batteries, with a projected demand of 2.5 million t. Cu also has significant demand growth across various technologies, including 1.35 million t for heat pumps, 626 kilotonnes (kt) for traction motors and 402 kt for wind turbines. For Li, demand in 2050 is expected to reach 674 kt, predominantly for batteries. Co demand is also centred on battery technologies, reaching 302 kt by 2050. Si demand is primarily driven by PV technologies, projected at 192 kt, with an additional 91 kt anticipated for use in batteries. In the nuclear sector, U demand is estimated at 62 kt. REEs, particularly those used in permanent magnets, are expected to see demand of 28 kt for wind turbines, 21 kt for traction motors and 8 kt for heat pumps in 2050. Ag demand, dominated by PV technologies, is projected at 500 t. PGMs, which are mainly required for fuel cells and electrolysers, have a total demand of 3 t by 2050.

Figure 6 and Figure 7 show the projected decade-by-decade demand increases for various elements. For most of the selected materials, demand growth is anticipated to peak between 2030 and 2040. The cumulative demand between 2040 and 2050 for most of the commodities remains at similar, or slightly higher, levels than in the previous decade. However, U and PGMs are exceptions, with their greatest demand growth expected between 2040 and 2050. This difference is attributed to varying technology-readiness levels: technologies like nuclear energy, fuel cells and electrolysers are likely to become commercially viable later in the transition, so the demand for essential materials will accelerate as they are adopted more widely.

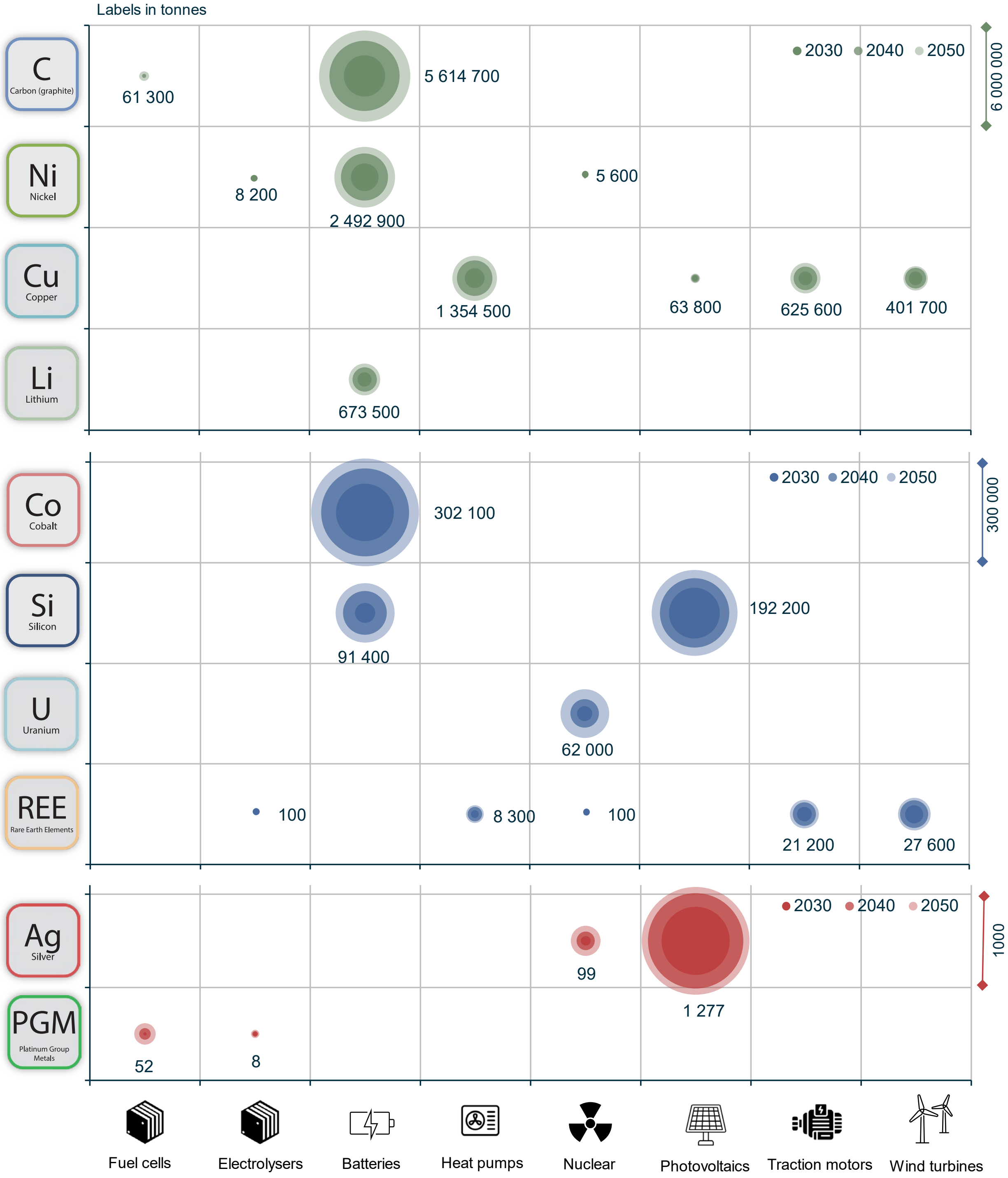

Figure 5 Cumulative demand for selected elements in the UK in 2030, 2040 and 2050 in each technology assessed in this study. Only the maximum demand of all National Grid scenarios is shown (National Grid, 2023a). Data labels indicate the maximum demand in 2050 in tonnes. For clarity, when the demand is less than 50 000 t, the size of the green bubble symbol remains constant. Similarly, where demand is less than 1000 t, the size of the blue bubble remains constant. BGS © UKRI.

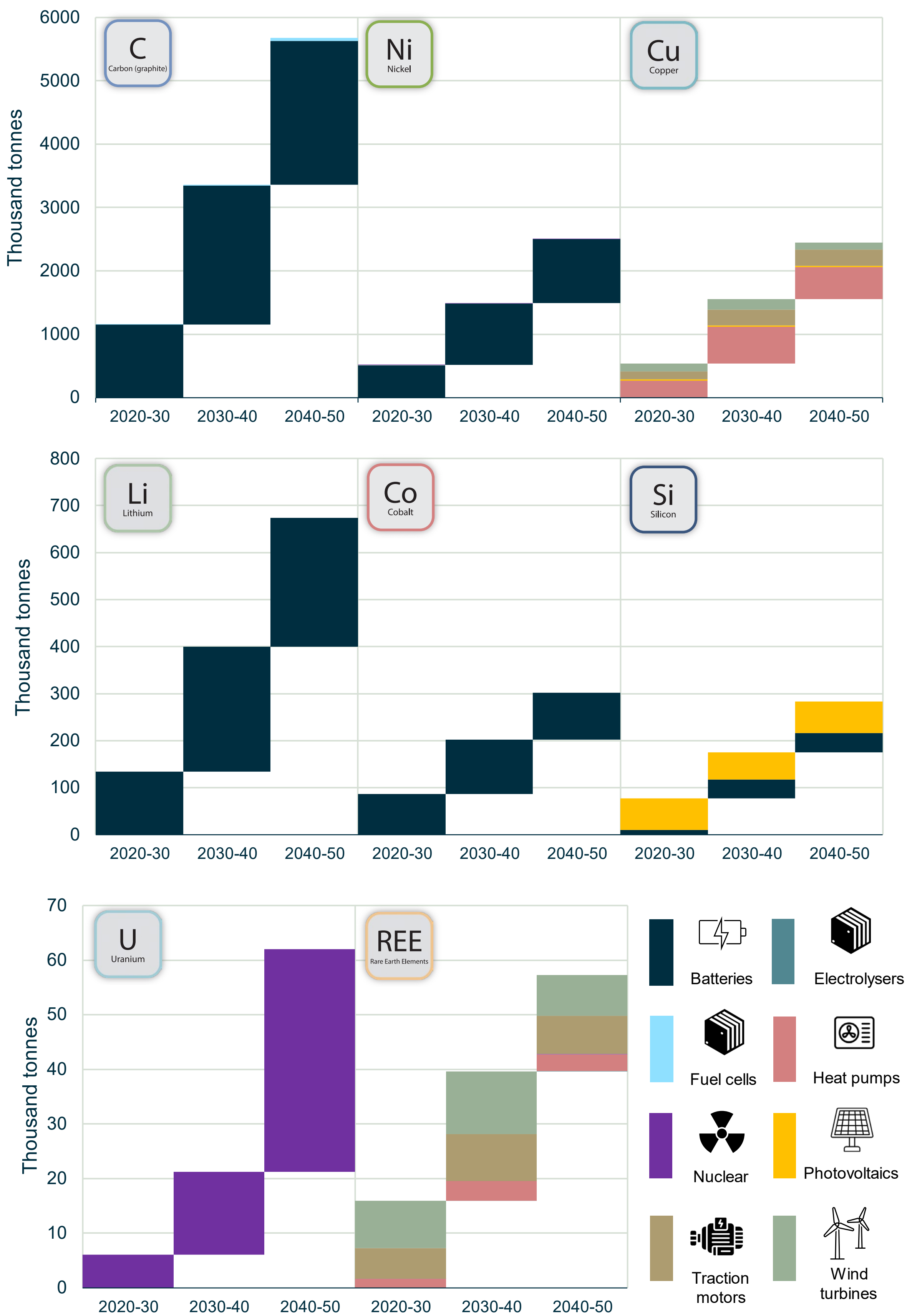

Figure 6 Cumulative UK demand in each decade for key elements in the technologies evaluated. Only the maximum demand of all National Grid scenarios is shown (National Grid, 2023a). Demand figures are in thousands of tonnes. BGS © UKRI.

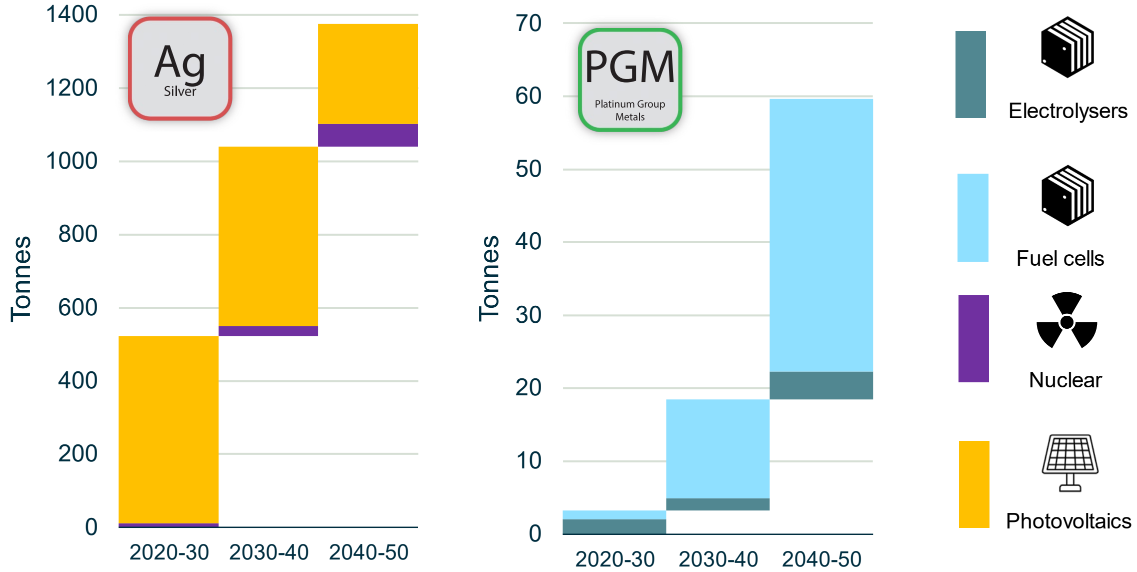

Figure 7 Cumulative UK demand in each decade for Ag and PGMs in the technologies evaluated. Only the maximum demand of all National Grid scenarios is shown (National Grid, 2023a). Demand figures are in tonnes. BGS © UKRI.

3.1.1 UK demand for the battery manufacturing sector

The UK has set ambitious targets for establishing battery gigafactories, which will significantly increase material demand as not all batteries produced domestically will be used in the UK EV fleet. The material demand assumptions outlined in Section 3.1 pertain only to the future UK EV fleet; a separate assessment was conducted to quantify the additional material demand driven by UK battery manufacturing.

The demand projections for UK battery manufacturing are based on an incremental increase in gigafactory capacity, projected to reach approximately 40 GWh by 2030 and 66 GWh by 2050, according to data provided by Benchmark Minerals (Talbot, 2024).

The results shown in Figure 8 indicate a demand trend similar to that of the UK EV fleet presented in Section 3.1. By 2050, graphite is expected to have the highest cumulative demand, at 1.37 million t, followed by Ni at 1 million t, Li at 169 kt and Co at 97 kt.

There is a notable surge in demand for all materials between 2030 and 2040, with demand stabilising during the subsequent decade. For example, cumulative graphite demand is projected at 574 kt between 2030 and 2040, and 630 kt between 2040 and 2050.

This analysis highlights the trend in UK material demand for most materials evaluated, with rapid growth projected by 2050. For instance, graphite demand is expected to grow from less than 200 000 t in 2030 to 1.37 million t by 2050, representing a sevenfold increase in 20 years. Similarly, Li demand is set to rise from 20 kt in 2030 to 169 kt by 2050, a near-ninefold increase. Ni demand is anticipated to expand tenfold, while Co demand is projected to increase fivefold over the same period. These figures underscore the significant challenges and opportunities ahead for resource supply chains.

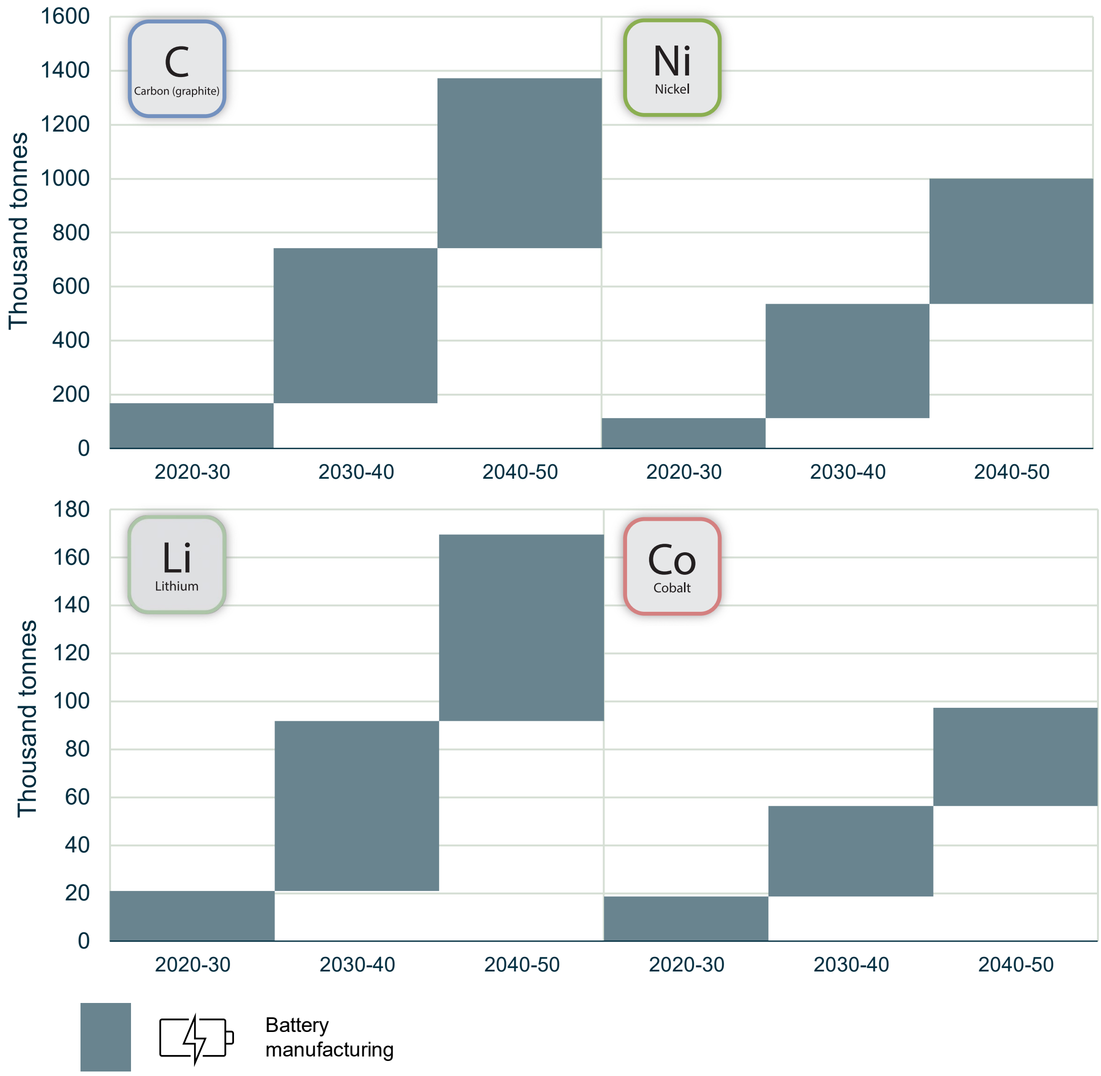

Figure 8 Cumulative UK demand in each decade for key elements used in battery manufacturing. Only the maximum demand of all National Grid scenarios is shown (National Grid, 2023a). Demand figures are in thousands of tonnes. BGS © UKRI.

3.2 COMPARISON OF UK DEMAND AND GLOBAL SUPPLY

In order to provide a different perspective, the projected UK demand was compared with the current global supply of the materials analysed.

From 2030 onwards, based on our analysis, the UK demand for key materials would represent a substantial portion of global supply. For example, although UK battery demand for Li is not the largest in terms of actual tonnage, it shows the most rapid increase in its required share of global supply, depending on the scenario considered. From 2030, the UK's Li demand could account for 15 per cent of global supply under the 'Falling short' scenario and up to 40 per cent under the 'Net zero' scenario. Similarly, UK graphite demand is projected to account for 10 to 29 per cent of global supply, Co for 5 to 14 per cent, REEs for 3 to12 per cent, and Ni for 2 to 6 per cent. Given the UK's ambitious decarbonisation targets, it is more likely that the upper end of these ranges will be required, corresponding to high-adoption scenarios, rather than the lower estimates tied to slower decarbonisation efforts.

It is notable that UK demand for battery raw materials as a percentage of global supply is expected to plateau from 2030 onwards, remaining at similar levels through to 2050. This highlights potential global supply constraints for materials like Li, graphite, Co and Ni, and underscores the critical need for new supply streams to be operational by 2030.

In the case of REEs, UK demand is projected to peak around 2030 but then decline and stabilise at approximately 5 per cent of global supply by 2040. This represents a significant share and will necessitate new REE sources, both primary and secondary, to be available by 2030. Similarly, the UK's U demand is expected to account for 3 to 10 per cent of global supply, but this demand will primarily arise after 2045. For Cu and Si, despite their overall significant demand (Section 3.1), the UK demand for each is expected to constitute only a small fraction of global supply.

Further details on the other materials considered in this study are available in the individual technology reports.

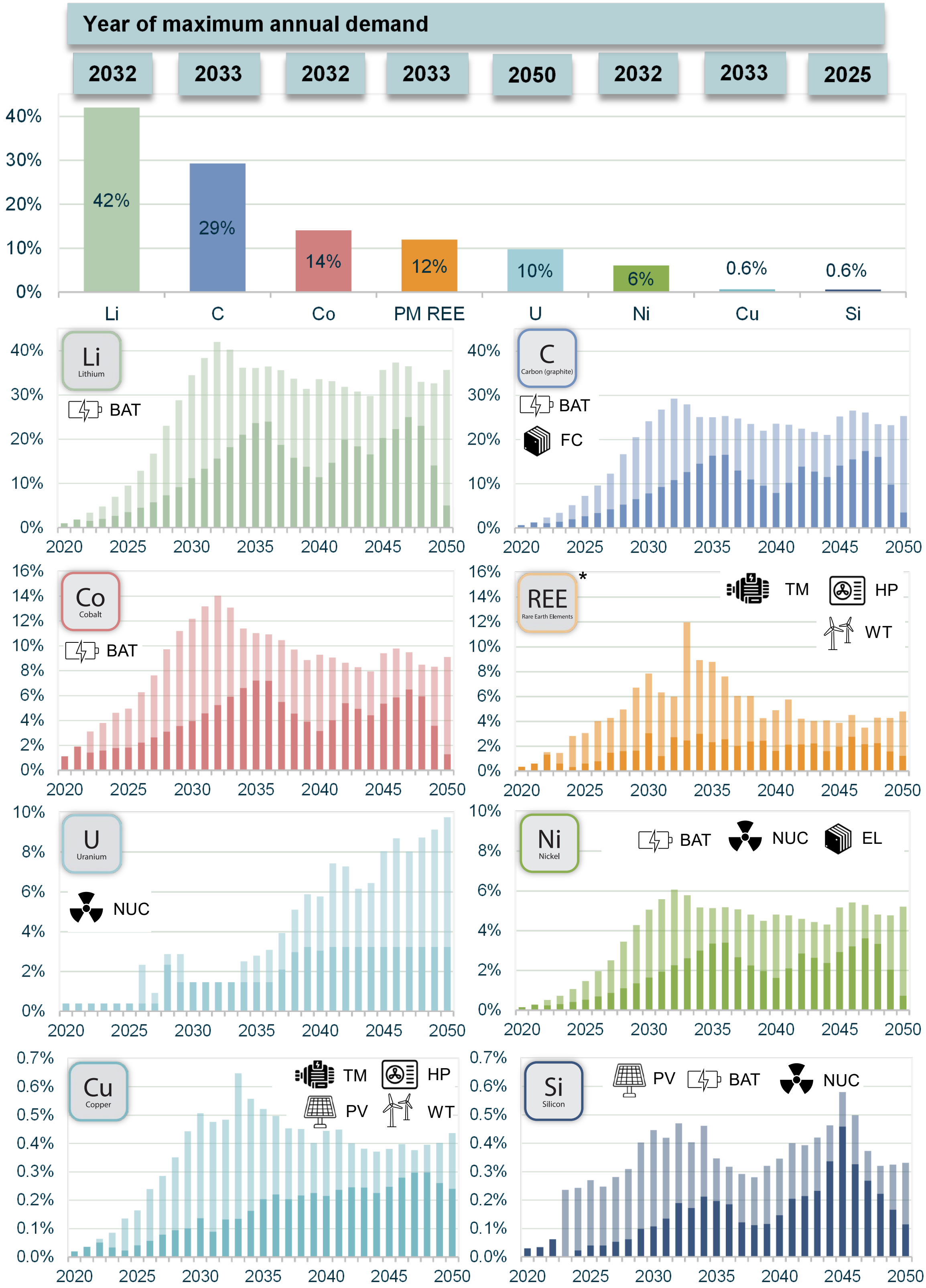

Figure 9 Annual UK demand as a percentage of global production for selected elements, shown as the minimum (dark shade) and maximum (light shade) demand of the National Grid scenarios (National Grid, 2023a). The top graph shows the maximum demand in individual years for each element. Global production figures are the five-year average (2017 to 2021) from the BGS World Mineral Statistics Database (Idoine et al., 2023). Data for REEs are demand and production levels for the permanent magnet REEs: dysprosium, neodymium, praseodymium and terbium. BAT: batteries; EL: eletrolysers; FC: hydrogen fuel cells; HP: heat pumps; NUC: nuclear; PV: photovoltaics; WT: wind turbines. BGS © UKRI.

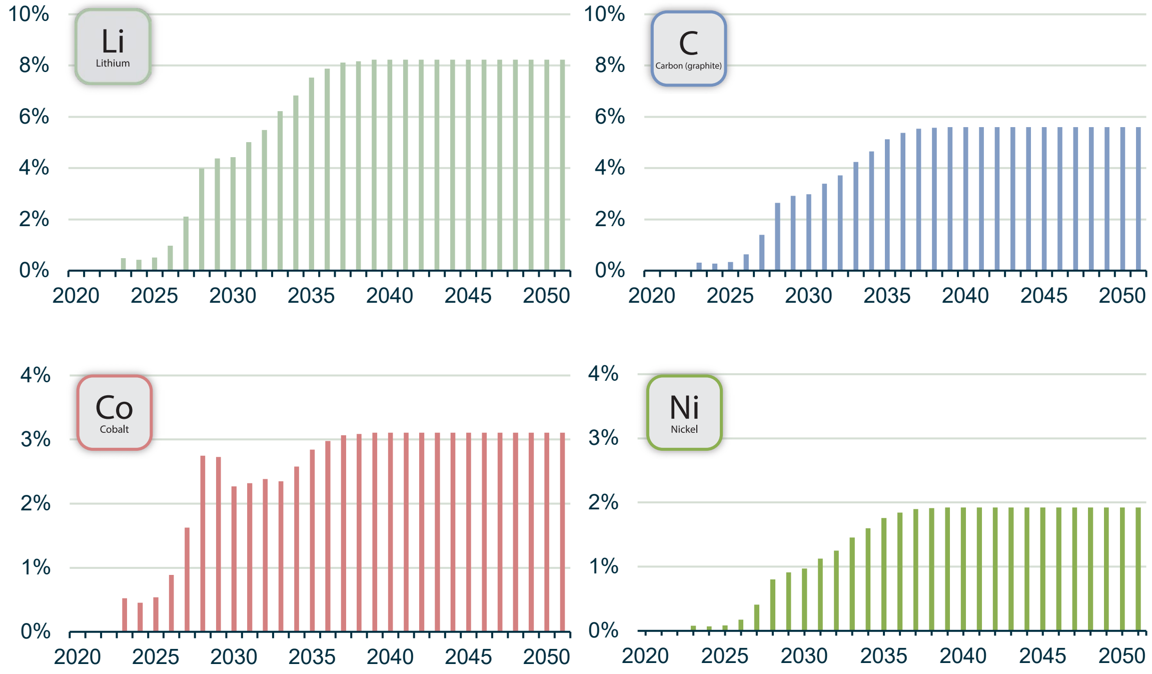

Figure 10 Future annual UK demand as a percentage of current global production for selected elements used in battery manufacture. Global production figures are the five-year average (2017 to 2021) from the BGS World Mineral Statistics Database (Idoine et al., 2023). BGS © UKRI.

3.3 COMPARISON OF UK AND GLOBAL DEMAND

The UK is competing with numerous countries for access to materials critical to decarbonisation technologies, a situation that could lead to significant global supply bottlenecks. Figure 11 compares the UK demand for these materials against global demand for the technologies analysed.

Among these materials, REEs represent the largest share of UK demand relative to global demand, ranging from 12.5 per cent in 2030 to 15 per cent in 2050. This substantial share reflects the UK's rapid decarbonisation objectives, where REEs play a key role in electric motors, wind turbines and heat pumps.

Similarly, the UK demand for Ni, Co, graphite and Cu accounts for significant portions of global demand: Ni represents 7 to 9 per cent, Co 5 to 6.5 per cent, and both graphite and Cu between 5 and 6 per cent. The high demand for Ni, Co and graphite is driven by the UK's plans to electrify its vehicle fleet, while Cu's importance spans all decarbonisation technologies, emphasising its essential role in the transition to a low-carbon economy.

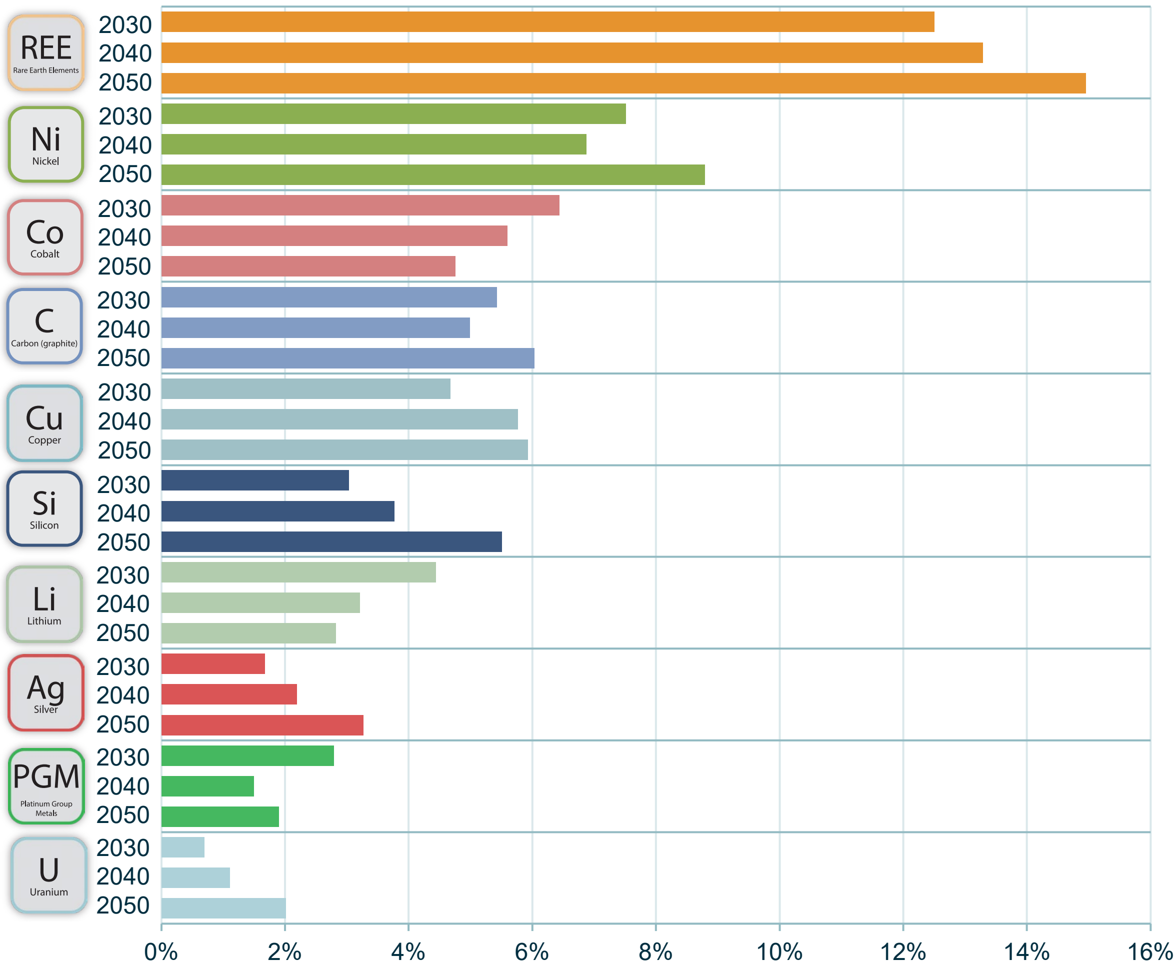

Figure 11 UK demand as a percentage of global demand for selected elements in 2030, 2040 and 2050. Only the maximum demand of all National Grid scenarios is shown (National Grid, 2023a). PGMs included in the analysis are Pt and Ir; included REEs are dysprosium, gadolinium, lanthanum, neodymium, terbium and yttrium. Data from European Commission et al. (2020b), International Energy Agency (2021), International Energy Agency (2023a), International Renewable Energy Agency (2022), IRENA (2019), Samsun et al. (2022). BGS © UKRI.

The UK's demand for Li is projected to account for 3 per cent of global demand in 2030, rising to 4 per cent by 2050. Global cumulative Li demand is estimated to reach 3 million t by 2030 (Table 3) and the annual global demand in 2030 is estimated at about 591 kt, compared to the current supply of approximately 94.6 kt (Idoine et al., 2023). This means global Li supply would need to increase sixfold to meet the projected demand in 2030. This dramatic surge in demand highlights the significant challenges relating to global Li availability and the vulnerability of the UK in competing for a secure and reliable supply of this critical resource.

Si and Ag are mainly used in PV technologies. The UK's demand for Si is projected to account for 3 per cent of global demand by 2030, increasing to 5.5 per cent by 2050. For Ag, UK demand is expected to reach 1.8 per cent by 2030 and 3 per cent by 2050.The highly concentrated nature of global Si production could pose a serious risk to UK supply security in the future. In contrast, Ag production is more diversified, which reduces the risk of supply shortages for the UK.

Table 3 Cumulative global demand up to 2030, 2040 and 2050 for selected elements in all technologies analysed in this study (in tonnes). Material demand data compiled from European Commission et al. (2020b), International Energy Agency (2021), International Energy Agency (2023a), International Renewable Energy Agency (2022), Samsun et al. (2022).

Elements	2030	2040	2050
Co	1 343 900	3 605 940	6 356 620
Cu	48 902 330	131 561 200	209 870 870
Graphite	22 283 540	75198 620	115 023 360
Li	3 024 440	12 451 380	23 839 360
Ni	13 321 170	45 775 260	80 111 030
PGMs: Pt, Ir	680	4360	7340
REEs: Dy, Gd, La, Nd, Tb, Y	439 880	1 223 050	1 988 280
Si	16 347 070	42 369 380	65 008 680
Ag	70 440	143 230	172 660
U	873 370	1 912 090	3 085 040

3.4 ASSUMPTIONS AND LIMITATIONS OF THE FUTURE DEMAND PROJECTIONS

In addition to the methodological challenges discussed in Section 2.4.5, it is also important to highlight some important additional assumptions.

3.4.1 Different scenario basis for UK and global demand

The scenarios for future UK and global demand are not the same. The primary aim of this project was to quantify future UK demand and we used the National Grid scenarios as the underpinning data in the assessment. For global demand, we used existing projections from well-established global scenarios, such as those developed by the IEA, for comparison. While these scenarios are based on different criteria and methodologies to the National Grid scenarios, their common focus on decarbonisation ensures alignment in scope and objectives.

3.4.2 Use of current global supply as a proxy

In comparing UK demand to global supply, current global production levels are used as a proxy. The development of forward-looking supply scenarios was outside the scope of this study. Accordingly, it remains unclear how global supply will evolve in the future. Creating supply scenarios would require the acquisition of large amounts of additional data, much of which is not in the public domain, together with extensive expert analysis.

3.4.3 Use of static lifetime data in demand calculations

The UK demand assessment incorporates material flows that become obsolete over time by factoring in the average lifetime of products. This approach does not model future changes in product lifetimes. Instead, it relies solely on average lifetime figures. This simplification can impact the accuracy of demand projections, as it does not account for variations in product lifetimes across different applications or technologies.

4 Results: assessment of supply

The supply of materials required for the selected decarbonisation technologies was assessed to identify potential future bottlenecks. This assessment examined various factors, including production and trade concentrations, export restrictions and monopolistic control at each stage of the value chain, from raw material extraction to manufacturing, across all technologies.

4.1 PRODUCTION CONCENTRATION

The production concentration of 49 raw materials used in eight key decarbonisation technologies was calculated for the top three producing countries in each case for the period 2017 to 2021 (see Josso et al., 2023 for method details). Of the 49 materials considered, 20 were assessed at the mining stage, with the remainder being evaluated at the refining stage. The production concentration data are modified by the ESG standards in the producing countries (Josso et al., 2023). The data were normalised so that the production concentration for each material is between 1 and 10, with higher values representing greater degrees of concentration.

Materials at the mining stage typically have lower production concentration scores, with 12 of the 20 having scores of under three; this is largely due to the lower production shares held by the top producers — production is more diversified. Exceptions include Nb (7.9), Ir (7.2), REE oxides (REOs) (5.6) and Pt (5.6), all of which have high scores that reflect the significant share of production held by a single country. For example, 98 per cent of Nb is mined in Brazil and 91 per cent of Pt is mined in South Africa.

The production of refined materials is typically much more concentrated, with 18 of the 29 refined materials having a production concentration score above three. The highest scores, exceeding 8.5, are reported for spherical graphite, refined Ga, cobalt sulfate and high-purity manganese sulfate monohydrate (HPMSM). These values reflect the extreme levels of production concentration (for example, 100 per cent for spherical graphite) but also the intermediate ESG score of China, which is the top producer in each case. It is notable that China is the leading producer of 29 of the 49 materials assessed; its dominance is especially strong on the refining side, where it is the main producer of 21 refined materials (Figure 12).

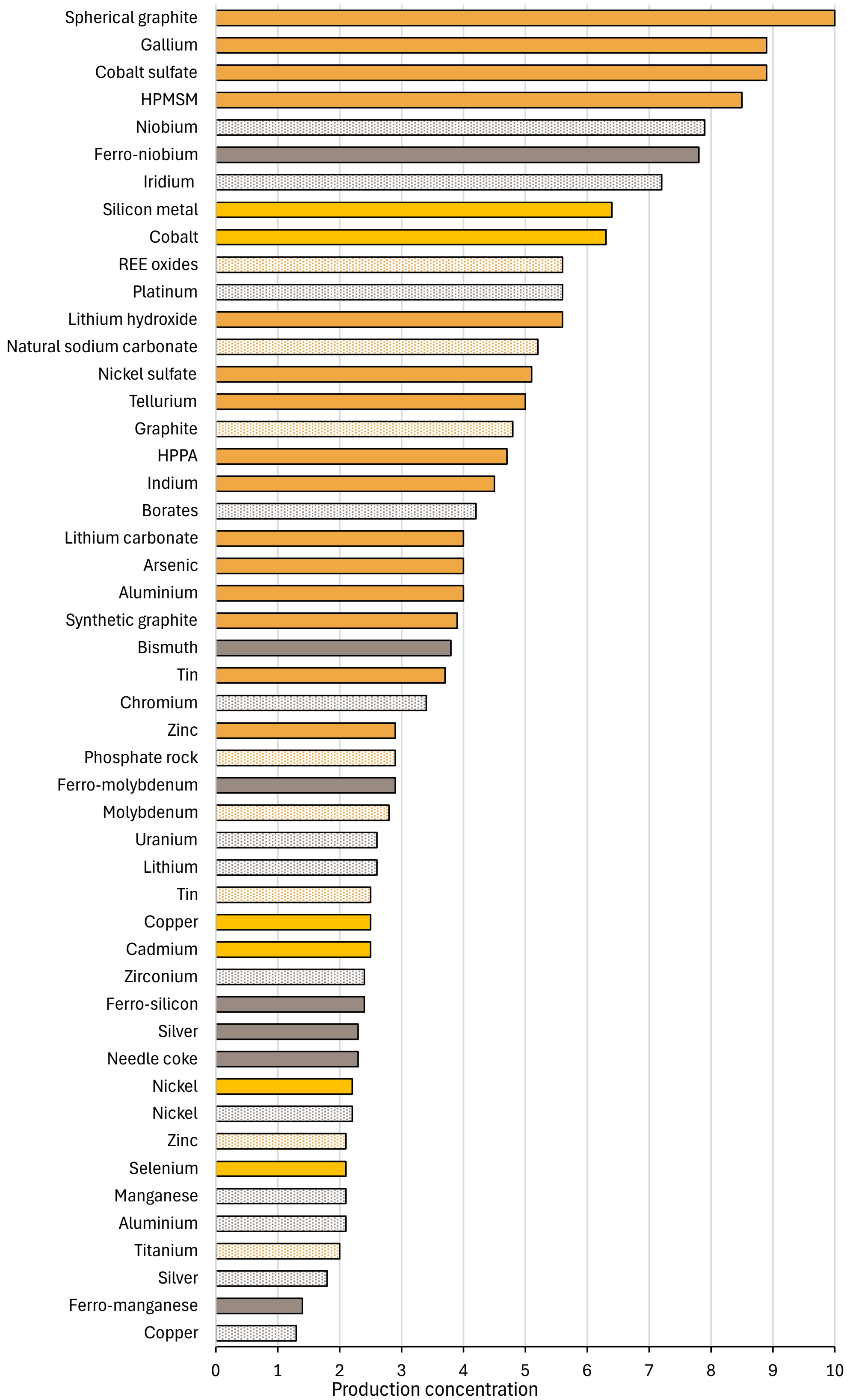

Figure 12 Ranked production concentration scores for key materials (mined and refined) based on an ESG-weighted HHI for each of the top three producing countries in the period 2017 to 2021. Mined materials (patterned bars) typically have lower scores on account of their more diverse supply base. Amber bars (solid and patterned) indicate that China is the leading global producer.

4.2 GLOBAL TRADE CONCENTRATION AND TRADE RESTRICTIONS

As with the production of mined and refined materials used in decarbonising technologies, 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 materials assessed (ores and refined metals) are not available or are reported at too low a resolution to be useful. For example, trade data for Ga, In and Bi (used in PV technologies) are heavily aggregated and are typically reported under a single HS trade code that cannot be disaggregated.

Global imports of chromium (Cr), Co, Ni, Ag and tin (Sn) at the mining stage are highly concentrated with the top three trading nations accounting for more than 80 per cent of imports in the five-year period from 2017 to 2021 It is noteworthy that, for 12 of the 16 mined materials assessed for global trade concentration, China is one of the top three importers, which highlights its global dominance in securing raw materials.

Exports of the ores of borate, phosphate, manganese (Mn), Al (bauxite), Co, Fe, Ni and Ag are highly concentrated, with the top three trading nations accounting for 80 per cent or more of global exports. Additionally, nine of the 16 materials assessed are subject to some sort of trade restriction (Figure 13). For example, the export of Ni ores and concentrates from the Philippines is subject to a licensing agreement and a fiscal tax, while the export of Ni ores and concentrates from Indonesia has been prohibited since 2020. Similarly, Co ores and concentrates from the Democratic Republic of the Congo (DRC) are subject to various licensing agreements and export taxes that, combined with the high level of trade concentration, significantly increase the risk of supply disruption.

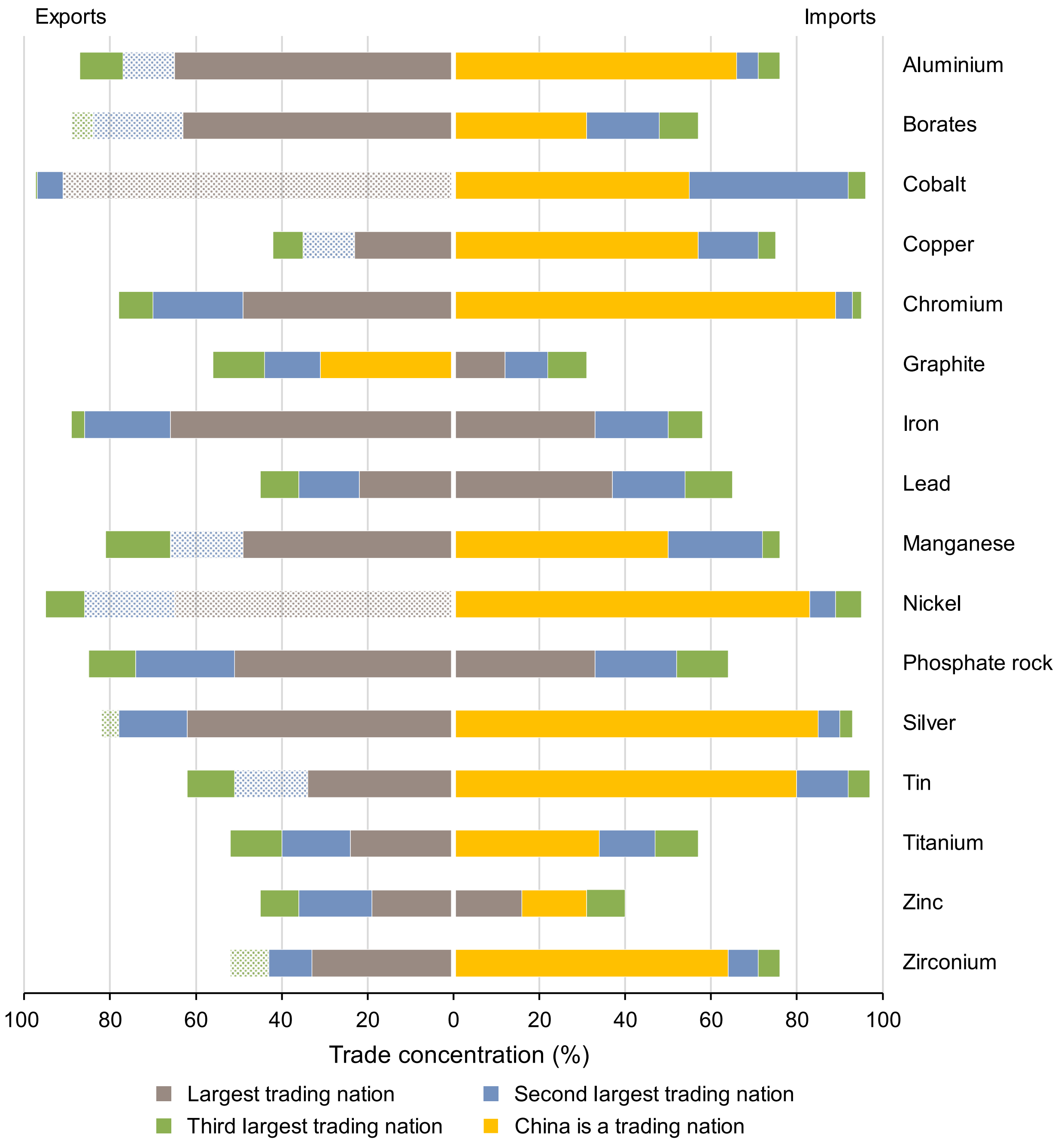

Figure 13 Global trade concentration of mined materials essential for the technologies evaluated in this study, showing the export and import shares of the top three trading nations between 2017 and 2021. Patterned bars indicate that there is a trade restriction (for example, tax, tariff or quota) currently in place. Compiled from data derived from United Nations (2023) and Organisation for Economic Co-operation and Development (2020). BGS © UKRI.

Global imports of cadmium (Cd), Cu, REEs, Ag powder, Si metal and Li hydroxide and carbonate at the refining stage are highly concentrated with the top three trading nations accounting for 60 per cent or more of the global trade share. Of these, China is the top importer of Si metal, Ag powder and refined Cu, accounting for more than 40 per cent of the global trade share.

China is also the single largest importer of:

- boric acid (26 per cent)
- ferroniobium (32 per cent)
- refined Ni (26 per cent)
- REOs (17 per cent)
- refined selenium (Se) (16 per cent)
- refined Pt (16 per cent)

Exports of 12 of the 27 refined materials shown in Figure 14 are also highly concentrated, with the top three trading countries accounting for 60 per cent or more in each case in the same five-year period (2017 to 2021). China is a major exporter (more than 40 per cent of the global trade share) of arsenic (As), lithium hydroxide, REE metals and synthetic graphite. It is also an important (one of the top three) exporter of:

- refined Se (eight per cent)
- refined Ag (ten per cent)
- refined zirconium (Zr) (seven per cent)

China also applies a trade restriction to its exports of synthetic graphite in the form of export permitting.

Other nations that apply trade restrictions to exports of refined materials include Tunisia (phosphoric acid), Argentina (lithium hydroxide), Zambia and Chile (Cu), Indonesia (Sn) and Namibia (As). These data further demonstrate China’s dominant role in the global trade of a range refined materials required for decarbonising technologies.

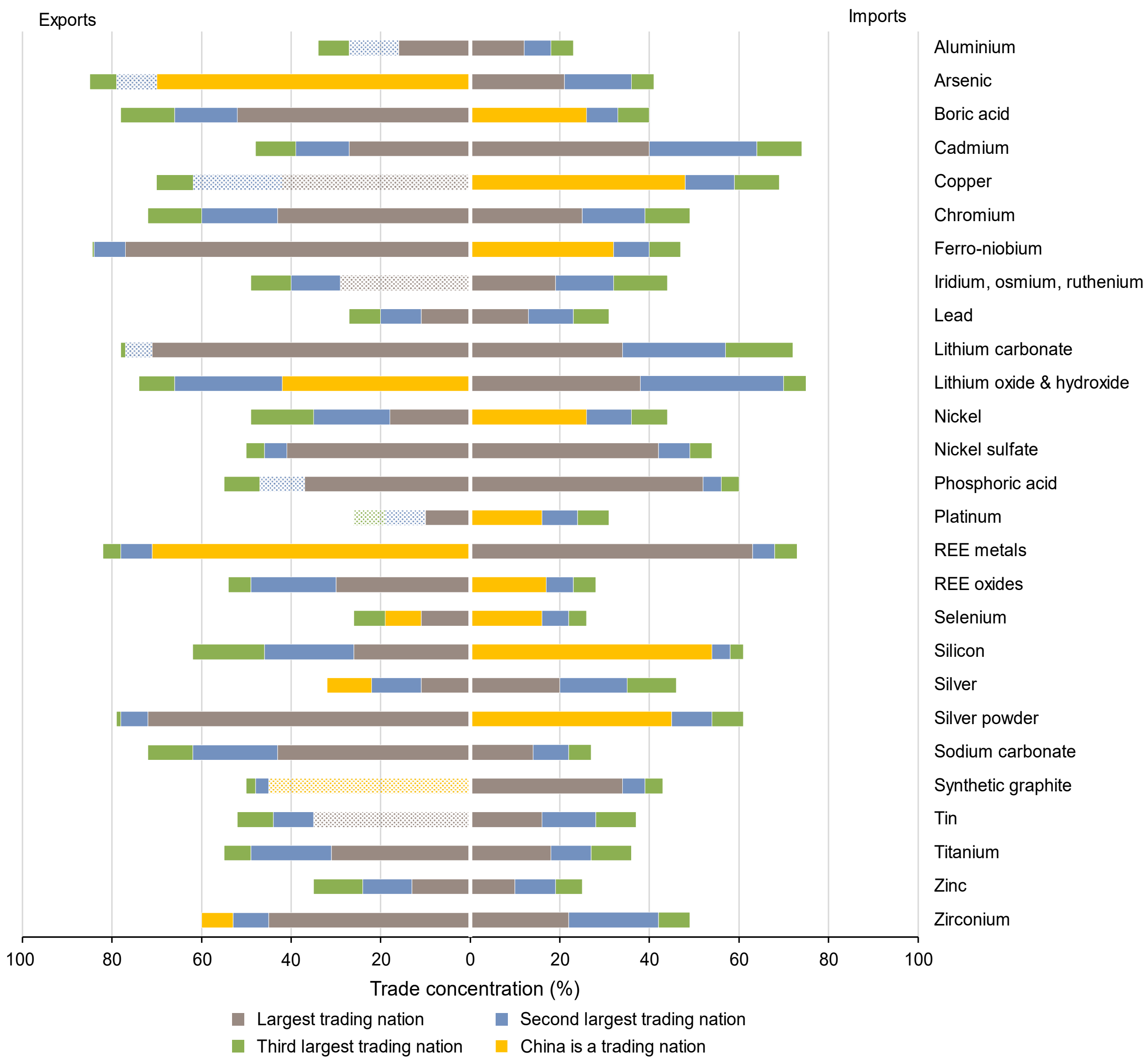

Figure 14 Global trade concentration of refined materials essential for the technologies evaluated in this study, showing the export and import shares of the top three trading nations between 2017 and 2021. Patterned bars indicate that there is trade restriction (for example, tax, tariff or quota) currently in place. Compiled from data derived from United Nations (2023) and Organisation for Economic Co-operation and Development (2020). BGS © UKRI.

Mapping significant trade flows, where a single country accounts for 40 per cent or more of the global trade share, highlights the dominance of a relatively small number of countries in the global trade of raw materials. Only 13 countries account for the bulk of global trade of 34 raw materials required for decarbonisation technologies (Figure 15). Of these, China is the single largest importer and exporter of several materials; in contrast, many other countries dominate the trade of only one or two materials. The trade of several of these commodities is also affected by trade restrictions, including taxes, licensing agreements and quotas. For example, Zambia accounts for 42 per cent of global exports of refined Cu and applies a ten per cent tax and licencing agreement to its exports.

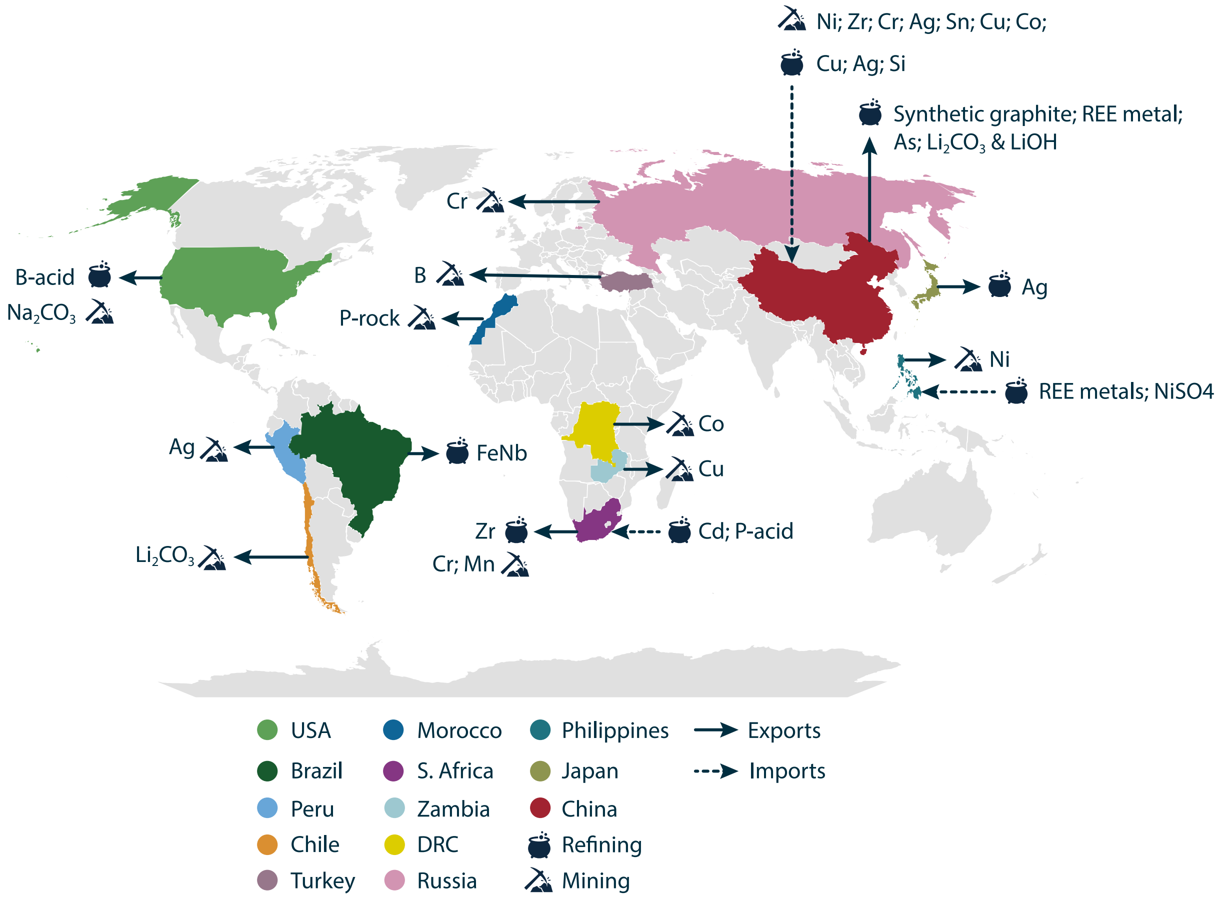

Figure 15 The global distribution of trade in key mined and refined materials used in the technologies evaluated in this study. Countries that account for 40 per cent or more of the global trade in these materials are shown. Base map created using Microsoft Excel.

The analysis of the global trade of materials required for decarbonising technologies produced several notable points.

- The global trade of mined and refined materials is highly concentrated, with the top three trading nations generally accounting for 60 per cent or more of the global trade
- China is the single largest importer of at least 20 key materials at both the mining and refining stages
- China is also a significant exporter of materials, especially at the refining stage
- Where trade restrictions are imposed, they are almost always applied to exports, with the most common restrictions being licence agreements and export taxes; the use of trade prohibitions is limited to a few countries such as Indonesia)
- It is difficult to assess the direct impact of a particular trade restriction as this will depend on its type, magnitude and duration. Imposition of a trade embargo or quota is likely to have a greater effect than levying an export tax for a short period. The dynamic character of export restrictions also contributes additional uncertainty to the supply chain

- The most significant risk to supply is where global trade is dominated by a few countries (for example, China accounts for 85 per cent of global imports of mined Ag). The risk may increase if restrictions are applied to trade: for example, China recently applied export licensing to refined Ga, which led to price increases and some international traders being cut out of the market (Minor Metals Trade Association, 2023)

4.3 SUPPLY CHAIN ANALYSIS FOR DECARBONISATION TECHNOLOGIES

A comprehensive analysis of the value chain for each decarbonisation technology is presented in the individual reports. The following summary highlights the key players and monopolies identified across the various stages of the value chain (mining, refining, component manufacturing and product manufacturing) specific to the elements included in this study.

4.3.1 Batteries

The key countries participating in the battery value chain were identified using a quantitative approach where data was available. Figure 16 illustrates the top three global producers of raw materials for batteries at the mining and refining stages. It also gives a qualitative summary of the principal nations involved in component manufacturing (such as cathode and anode active material production) and battery manufacturing.

Both the mining and refining stages are dominated by a few countries that have significant shares in global production. With the exceptions of needle coke, Mn and Ni, a single producer dominates all other battery raw materials each with a market share exceeding 40 per cent. For example, Australia dominates mine production of Li (57 per cent of total), while 67 per cent of Co production is from DRC. In the refining stage, China's dominance is clear: it accounts for most of the refined material production for all assessed materials, with market shares ranging from 48 per cent for lithium carbonate to 100 per cent for natural graphite. This heavy concentration of refining capacity in China highlights the country's critical role in the global battery supply chain.

The manufacturing of key battery components, particularly cathode active materials (NCA; NMC) and anode materials (graphite and hard carbon for Na-ion batteries), is strongly concentrated in three Asian countries: China, Japan and South Korea. China also leads in the production of LFP cathode active materials, although some other nations, such as Australia, Canada and Germany, also have some limited manufacturing capacity for LFP.

For Na-ion battery cathode active materials, the market is still in the early stages of commercialisation, with China again playing a dominant role. However, other countries, including Sweden, Switzerland and the USA, are also developing their own production capabilities, signalling potential diversification in the future.

Li-ion battery manufacturing is dominated by China, Japan and South Korea, with these three countries leading global production. Similarly, several countries are working to build production capacity in the emerging market of Na-ion batteries. However, China remains the clear leader in this sector as well. It has a significant lead over other nations and is the only country that currently manufactures Na-ion batteries on a commercial scale.

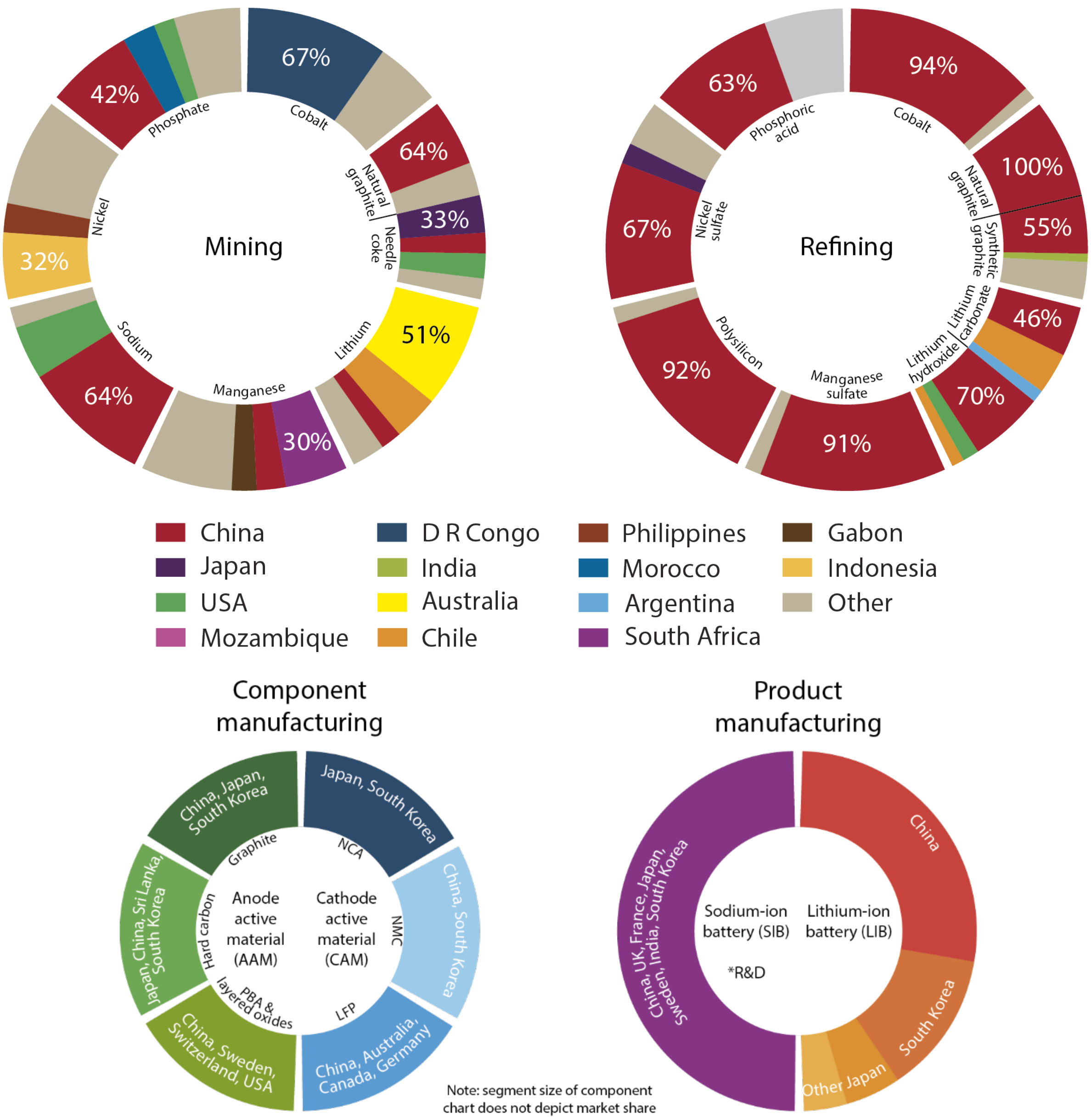

Figure 16 Key players in the global battery value chain (material to product manufacture) for the five-year period 2017 to 2021. Mining and refining shares are based on quantitative data. The component and product manufacturing are represented qualitatively. Natural graphite refining shows the production of high-purity spherical graphite. The leading countries in component and product manufacturing are shown, although the shares held by each are only known for Li-ion batteries. Data sources: Benchmark Mineral Intelligence (2024), Degen et al. (2023), Hampel (2023), Idoine et al. (2023), International Energy Agency (2022b), Liu et al. (2022), Obayashi and Evans (2023), Venditti et al. (2022), Volta Foundation (2023). BGS © UKRI.

4.3.2 Electrolysers

Figure 17 shows the top three global producers of mined and refined materials essential for electrolysers. The key countries involved in component and product manufacturing are also shown. The analysis reveals that China leads in REE mining with a 70 per cent share of global production, while South Africa dominates Pt and Ir mining with 71 per cent and 84 per cent, respectively. Indonesia is the largest Ni producer with a 32 per cent share; China leads in titanium (Ti) production at 31 per cent, and Australia in Zr with a 39 per cent share. In refined materials, China controls 90 per cent of global REE refining and 30 per cent of Ni refining. Data limitations prevent assigning refined Pt market shares to specific countries. Data limitations also restrict quantitative market share allocation for key component manufacturers.

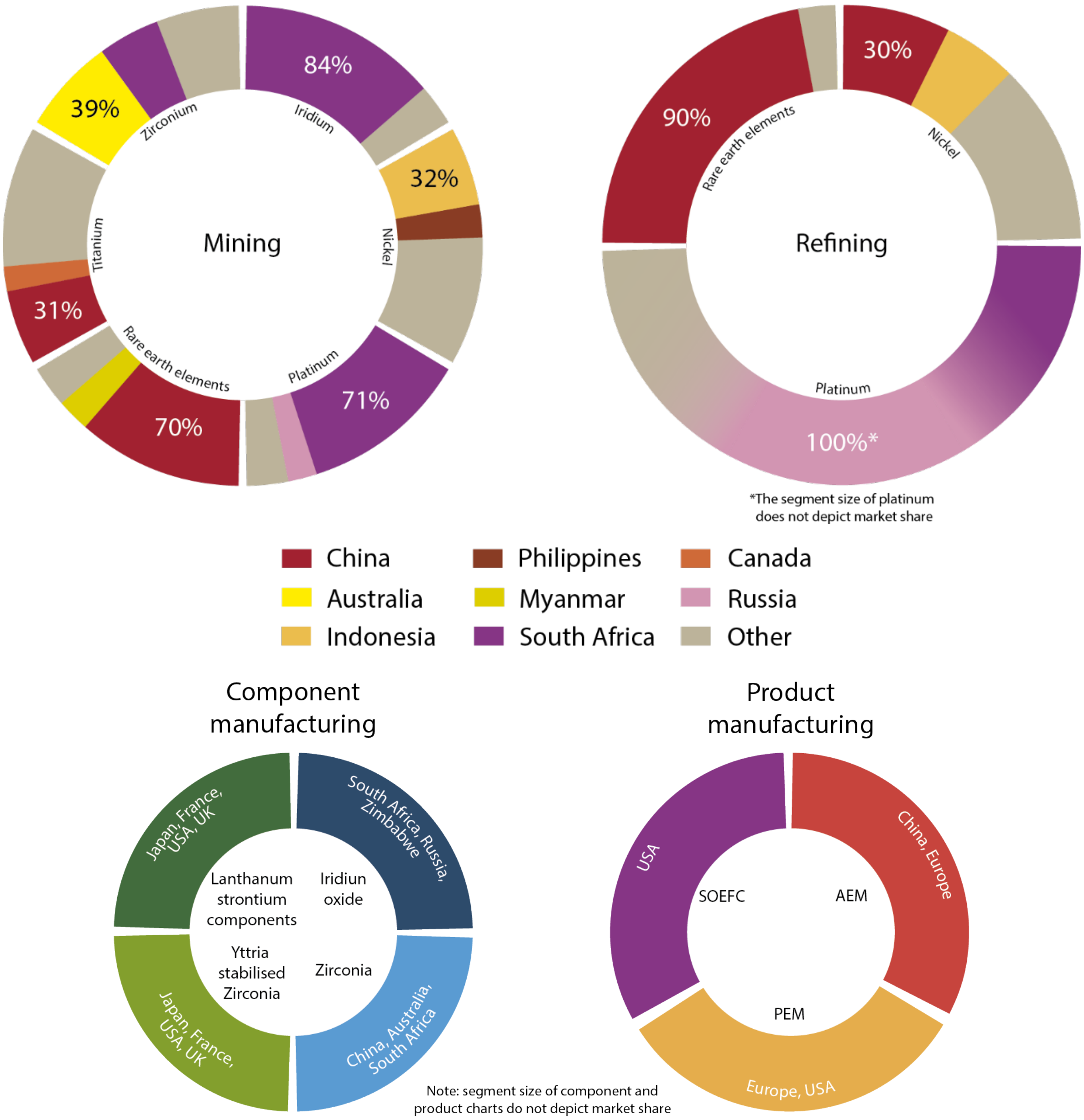

Figure 17 Key players in the global electrolysers value chain (material to product manufacture) for the five-year period 2017 to 2021. The leading countries in component and product manufacturing are shown, although the shares held by each are not known. Data sources: DataM Intelligence (2024), Idoine et al. (2023), MWR (2023), Zirconium-Association (2022). BGS © UKRI.

Lanthanum (La) and strontium (Sr) component manufacturing is undertaken mainly in Japan, France, the USA and the UK, while production of zirconia, which is used in the electrolyte layer of SOECs, is dominated by China, Australia and South Africa. Iridium oxide, used in as a catalyst in PEMs, is produced mainly in South Africa, Russia and Zimbabwe, and yttria-stabilised zirconia manufacturing is concentrated in Japan, France, the USA and the UK. China and Europe lead AEM electrolyser manufacturing, Europe and the USA dominate PEM electrolyser production, and most SOEC electrolyser production is carried out in the USA.

4.3.3 Fuel cells

Figure 18 shows the top three global producers of mined and refined materials used in fuel cells. It also includes a qualitative summary of the countries dominant in PEMFC manufacturing. The analysis indicates that China leads in natural graphite production and South Africa in Pt, while needle coke production is more evenly distributed among Japan, China and the USA.

Refined natural and synthetic graphite production is largely monopolised by China. Due to limited data on refined Pt production, market shares cannot be attributed to individual countries. PEMFC manufacturing is widely distributed in China, Europe, Japan, Canada and the USA, although the capacity installed in each country is not known.

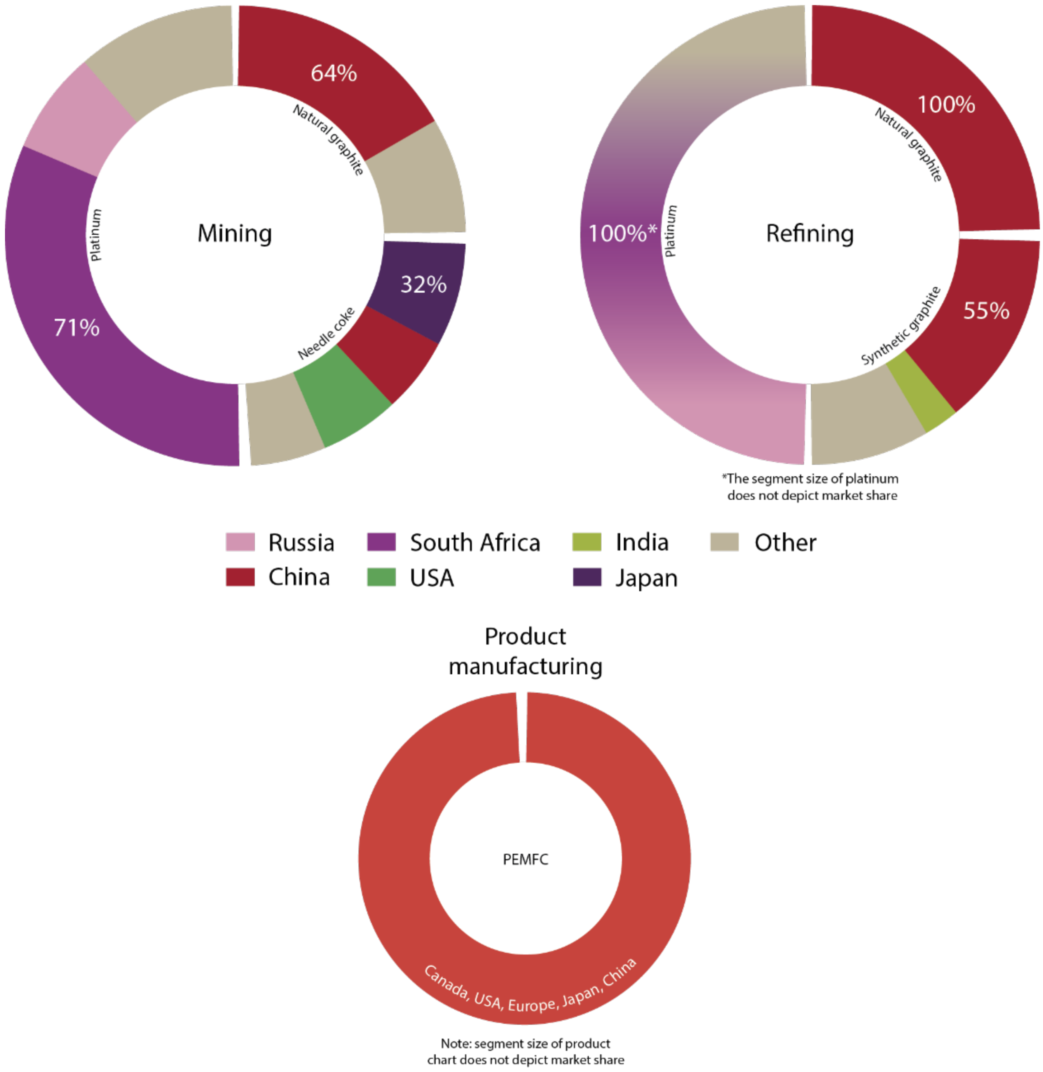

Figure 18 Key players in the global fuel cells value chain (material to product manufacture) for the five-year period 2017 to 2021. Natural graphite refining shows the production of high-purity spherical graphite. The leading countries in product manufacturing are shown, although the shares held by each are not known. Data sources: European Commission et al. (2020a), European Commission et al. (2023), Fortune Business Insights (2021), Idoine et al. (2023). BGS © UKRI.

4.3.4 Heat pumps

Figure 19 shows the main participants in the heat pump value chain. In raw material production, China holds a near-monopoly on REEs, with a 91 per cent share of the global total, while Türkiye leads borate production with a 59 per cent share. For other materials, the top-producing countries each hold market shares of about 30 per cent. At the refined material stage, China is the dominant supplier of all the functional materials analysed, with market shares ranging from 30 per cent to 90 per cent. Other notable players include Indonesia for Ni and Sn, Chile for Cu and Myanmar for Sn.

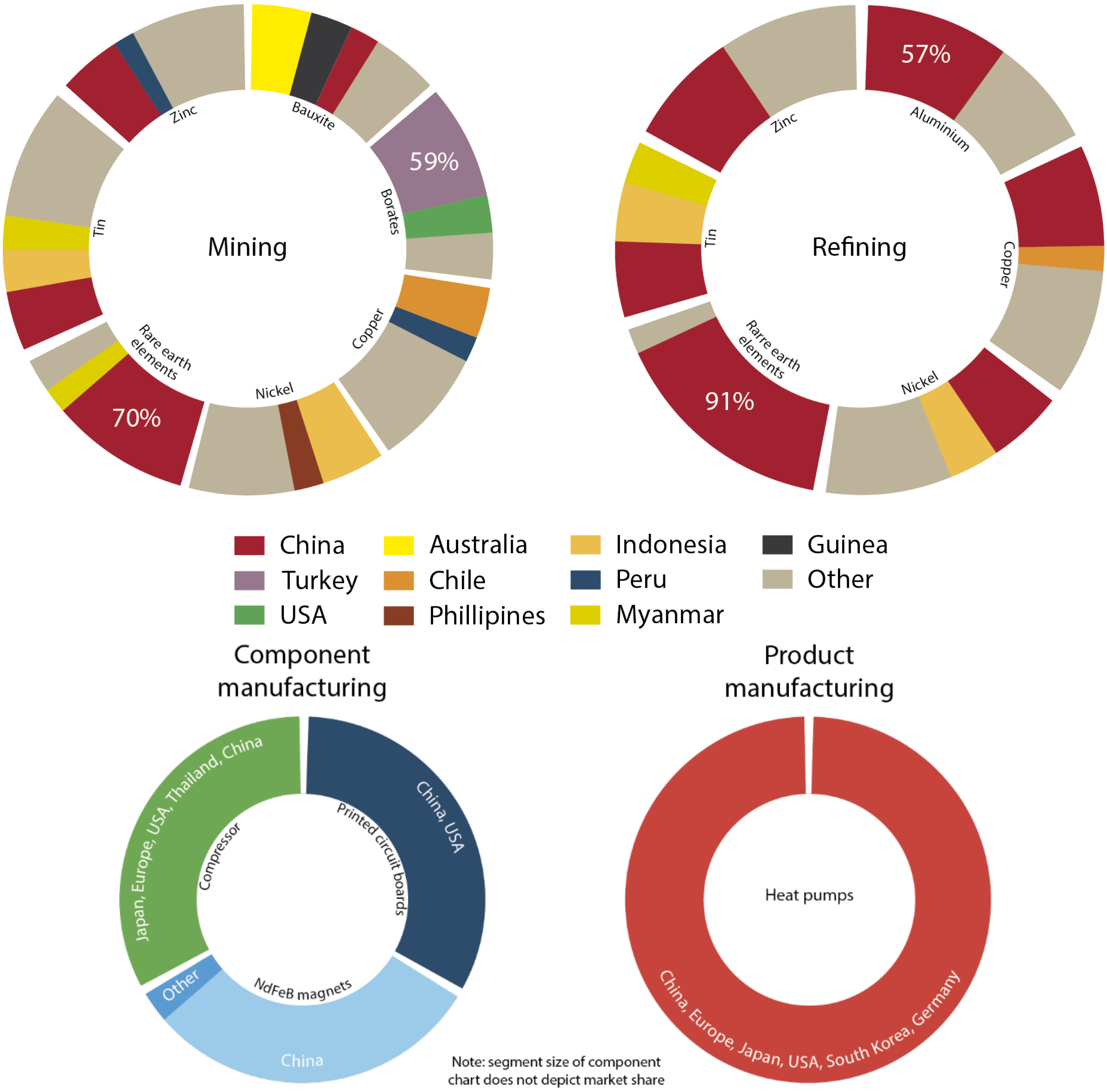

Figure 19 Key players in the global heat pumps value chain (material to product manufacture) for the five-year period 2017 to 2021. The leading countries in component and product manufacturing are shown, although the shares held by each are not known. Data sources: European Commission et al. (2020b), Idoine et al. (2023), International Energy Agency (2023a), Adamas Intelligence Inc. (2022), European Commission et al. (2023), GMI (2023), Idoine et al. (2023), Smith et al. (2022). BGS © UKRI.

In component manufacturing, China leads in permanent magnet production, while printed circuit boards are mostly produced in China and the USA. Compressor manufacturing is more dispersed, with production in Japan, Europe, the USA, Thailand and China. The final assembly and manufacture of heat pumps are also globally distributed, with major production centres in China, Europe, Japan, the USA and South Korea.

4.3.5 Nuclear technologies

Figure 20 shows the three largest global producers of raw materials essential for nuclear technologies, including U, various steel-alloying elements, Zr, Ti, REEs, Ag, Sn and borates.

For some materials, mine production is dominated by a few countries: China for REEs, Brazil for Nb and Türkiye for borates, each with more than 50 per cent of the global total. Kazakhstan leads in U production with a 41 per cent market share; South Africa holds 48 per cent of Cr production, and China accounts for 40 per cent of molybdenum (Mo) output. Steel alloying elements, such as Ni, Ti and Mn, along with Sn and Ag, are mined in several countries, with the dominant producers accounting for about 30 per cent of the global market. Australia leads in Zr mining with a 39 per cent share of global production.

In refining, the supply landscape shifts, with China emerging as the top producer of several materials including REEs, Cd, In, Ni and Sn. Chinese production of refined REEs accounts for almost 90 per cent of the global total, while for the other elements, China's market share ranges from 30 per cent to 50 per cent. Refining of ferroniobium is almost exclusively controlled by Brazil (90 per cent share), while Russia leads ferrosilicon production (40 per cent) and Chile dominates ferromolybdenum production (47 per cent).

Component manufacturing for nuclear technologies is concentrated in countries with established nuclear industries, notably the USA, France, Russia, Germany, China and the UK, each holding significant roles across various stages of nuclear technology production and supply. These countries are also involved in the production of precursor materials used in these components (Figure 20). For example, it is important to note that Russia and China feature prominently in the production of U fuel, Zr alloy cladding and Ag-In-Cd control rods. Further information is provided in the separate nuclear report.

Figure 20 Key players in the global nuclear value chain (material to product manufacture) for the five-year period 2017 to 2021. The leading countries in component and product manufacturing are shown, although the shares held by each are not known. Data sources: Idoine et al. (2023), World Nuclear Association (2024). BGS © UKRI.

4.3.6 Photovoltaics

The key countries involved in PV value chains (Figure 21) were identified using quantitative data for the mining and refining stages. In the absence of data for component and product manufacturing, these stages were evaluated in a qualitative manner. Figure 21 highlights the top three global mine producers of key functional raw materials used in PVs, such as Sn, Ag and Cu. China leads in Sn mining with 30 per cent of global production; Mexico in Ag with 25 per cent, and Chile in Cu with 27 per cent.

The refining stage involves a broader set of elements, many obtained as by-products. With the exception of Bi and Ag, China dominates refining of most materials, controlling over 50 per cent of the global market for refined Ga, Si metal, Te, Sn and In. Vietnam is the largest Bi producer with a 40 per cent share, closely followed by China at 37 per cent. Japan leads refined Ag production with 54 per cent of the global total.

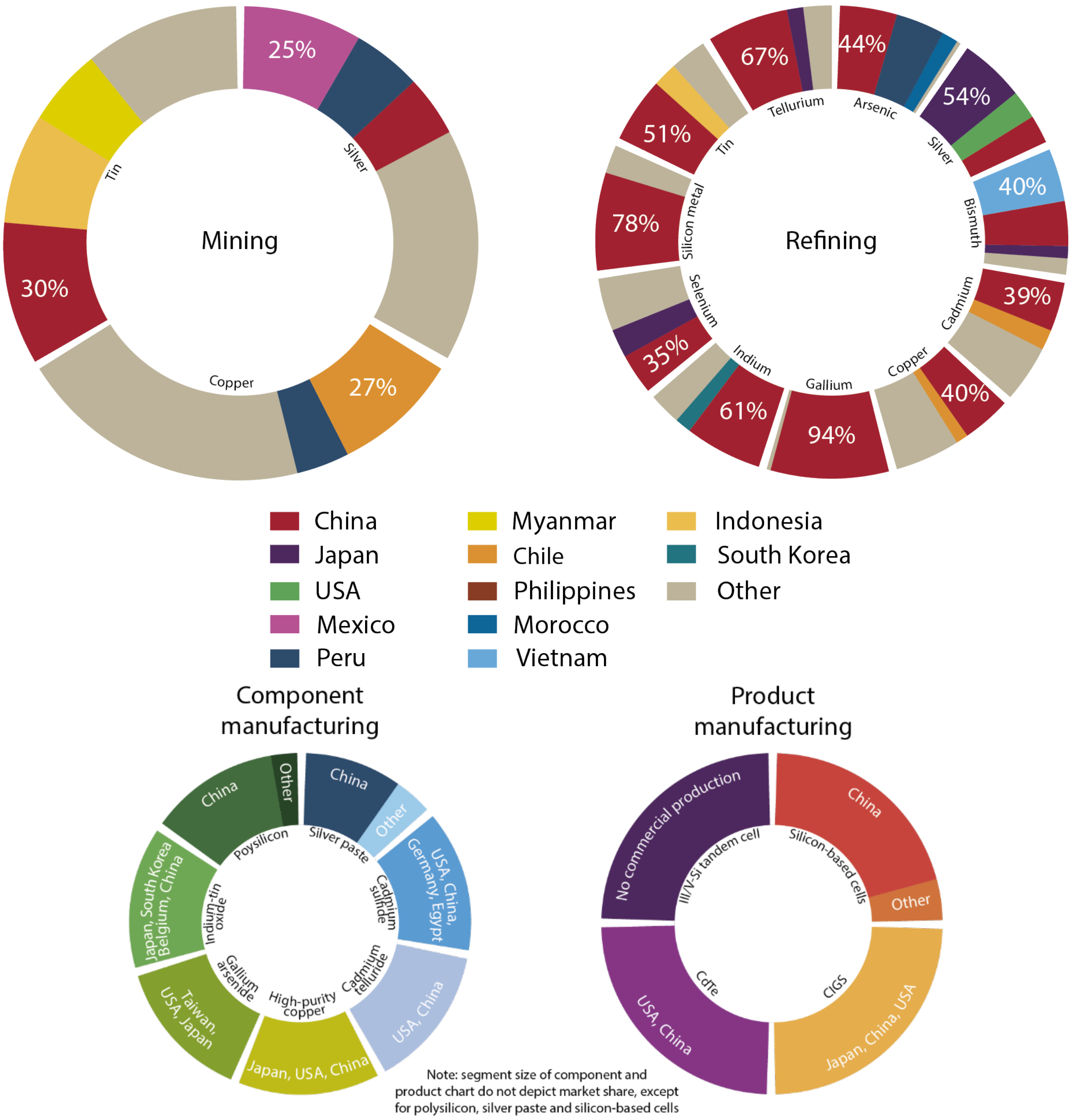

Figure 21 Key players in the global PV value chain (material to product manufacture) for the five-year period 2017 to 2021. The leading countries in component and product manufacturing are shown, although the shares held by each are only known for polysilicon, Ag paste and Si-based cells. Data sources: Gervais et al. (2023), Idoine et al. (2023), International Energy Agency (2022c), Scarpulla et al. (2023), ZSW (2019). BGS © UKRI.

PV component manufacturing is carried out in several countries. However, China, Japan and the USA are the dominant producers of many essential compounds and components. In particular, China monopolises polysilicon and Ag paste production, both of which are vital for Si-based PV technologies. In terms of product manufacturing, China leads in Si-based cell production, the dominant PV technology. Thin-film PV technologies, such as CIGS and CdTe, are mostly produced in Japan, China and the USA, with CIGS led by Japan, China and the USA, and CdTe by the USA and China. Tandem cell technology has not yet reached commercial-scale production.

4.3.7 Wind turbines and traction motors

The key countries involved in the wind turbine and traction motor value chains were assessed using a quantitative approach where data were available. Figure 22 shows the three leading global producers of raw materials for wind turbines and traction motors at both the mining and refining stages. It also provides a qualitative overview of leading nations in component manufacturing, including permanent magnet and magnetic alloy production for traction motors and wind turbines, as well as generator production for wind turbines. Final product assembly (traction motor manufacturing and nacelle assembly for wind turbines) is also depicted in a qualitative manner.

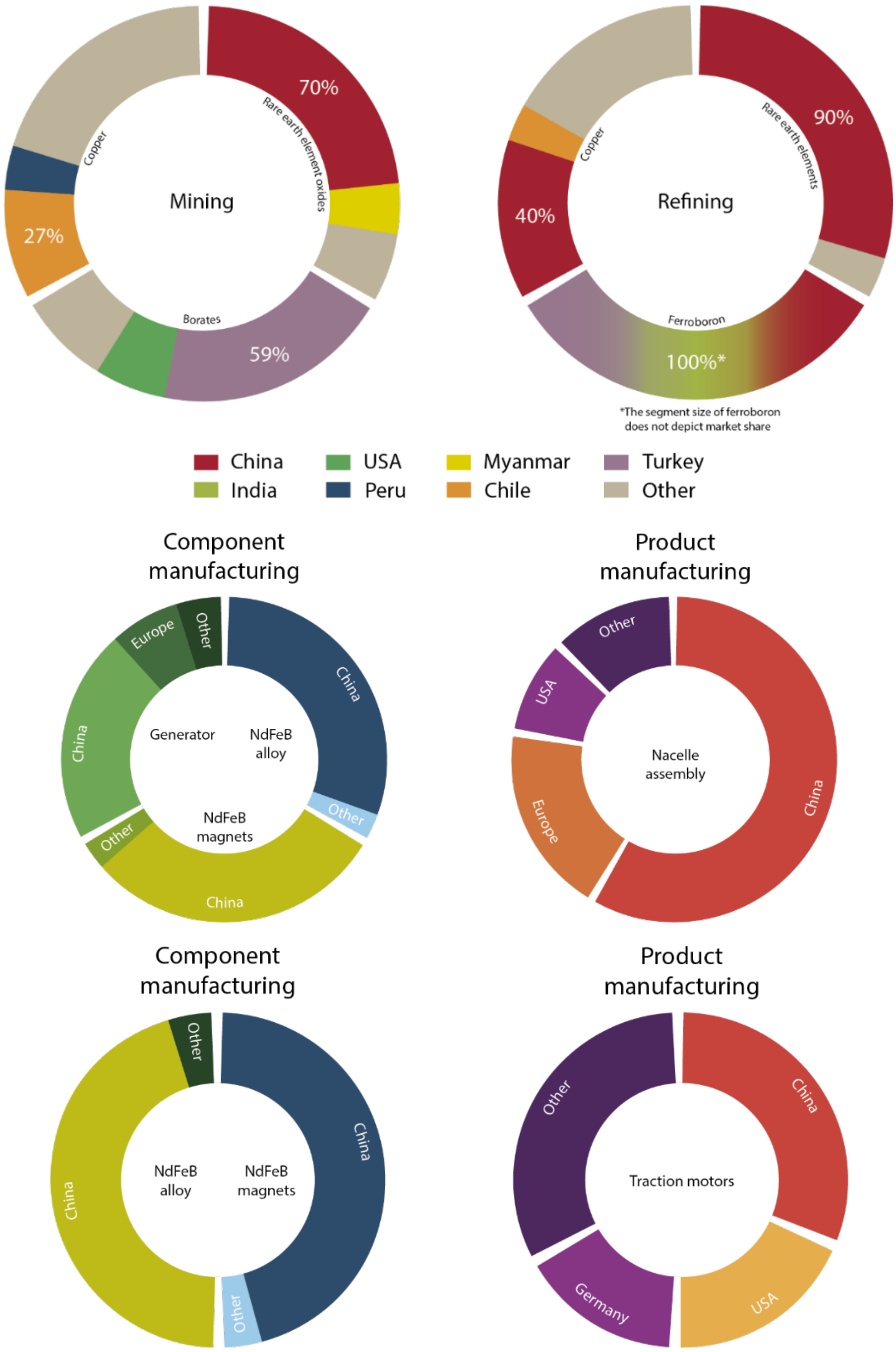

Figure 22 Key players in the global wind turbine and traction motor value chain (material to product manufacture) for the five-year period 2017 to 2021. Data sources: Adamas Intelligence Inc. (2022), Hutchinson and Zhao (2023), Idoine et al. (2023), Lu and Parker (2023), Mobility Foresights (2023), Smith et al. (2022). BGS © UKRI.

At the mining and refining stages, the REE value chain is dominated by China, which controls 70 per cent of global mining and 90 per cent of refining. Chile is the largest global producer of mined Cu, holding a 27 per cent share, while China leads in refined Cu production with 40 per cent of the market. For boron (B), Türkiye has the largest share of borate production at 59 per cent; however, due to restricted data availability, it is difficult to identify a single dominant producer of ferroboron, with China, India and Türkiye all active.

China also dominates the production of key components such as permanent magnets, magnet alloys and generators for wind turbines. The nacelle assembly for wind turbines is largely monopolised by China, demonstrating the country's vertical integration from REE sourcing to nacelle production. As most traction motors are manufactured in-house by EV producers, China is also the lead producer of traction motors, although the USA and Germany have notable shares in this market as well.

4.3.8 UK value chain for decarbonisation technologies

The UK's involvement in the supply chains of decarbonisation technologies varies between individual stages. There is a limited presence in upstream activities, such as mining and refining, but greater focus on the downstream stages of manufacturing, assembly, installation and research and development. Large-scale manufacturing is generally undertaken overseas, while UK companies specialise in small-scale production of customised products in speciality applications and niche markets. Given the significance of the automotive sector to the UK economy, there is strong involvement in the EV supply chain, including battery and traction motor manufacturing. However, other decarbonisation technology supply chains, such as those for heat pumps and PV cells, are less developed in the UK.

There is no current primary extraction in the UK of the key materials analysed in this study. However, ongoing exploration for Li in Cornwall and north-east England and for Ni-Cu and Co in north-east Scotland have potential to support the battery supply chain. Moreover, there are plans to re-open the South Crofty Sn-Cu mine in Cornwall, which could supply Sn to the PV and nuclear supply chains and Cu to the wind turbine, traction motor, battery and heat pump supply chains (Cornish Metals Inc., 2024).

There is some existing refining capacity in the UK, together with several projects under development. These are located at major trading ports in the north of England, including Ellesmere Port in Cheshire as well as in Merseyside, Humberside and Teesside. Amongst these, an oil refinery (Philips 66) produces battery-precursor needle coke as a by-product. However, this is currently exported due to lack of domestic synthetic graphite production (Green Finance Institute, 2023). Other important operations include a Li refinery in Merseyside (Arcadium Lithium, 2024) and a REE metal and alloy refinery at Ellesmere Port (Less Common Metals, 2023). At the Ellesmere Port site, additional facilities are in development to support the battery and permanent magnet supply chains. There is no refining capacity in the UK for raw materials used in PV cells and nuclear technologies.

At the precursor and component level, the UK is home to some globally significant players, particularly in the hydrogen and nuclear sectors. For example, Johnson Matthey, a global leader in fuel cells and electrolysers with its headquarters in London, manufactures key components for the hydrogen industry at Swindon in Wiltshire (Johnson Matthey Plc, 2024). The UK also operates significant U-enrichment facilities, which account for approximately eight per cent of global U-enrichment capacity. This operation, which supports the domestic nuclear power industry, is undergoing further development to reduce dependency on foreign suppliers (DESNZ, 2024c, World Nuclear Association, 2024). In contrast, there is limited UK production capacity for producing Li-ion battery and PV cell precursors. Specialised manufacturers instead focus on niche markets and next-generation technologies; for example, Echion Technologies and Nyobolt are developing Nb-based battery anodes (Echion Technologies (2024); Nyobolt (2024) and ilika is developing solid-state batteries (ilika, 2024).

In product manufacturing, the UK is best positioned in the EV market, with one battery gigafactory already in operation (2 GWh capacity) and published plans for additional plants that could expand this capacity to 80 GWh by 2030 (Mckelvie and Bennett, 2023, Tata Sons, 2023, West Midlands Gigafactory, 2023). Moreover, two major car manufacturers, Ford and Jaguar

Land Rover, plan to produce their EV traction motors domestically (Advanced Propulsion Centre UK, 2024b, JLR, 2023).

In the energy sector, there are important UK producers and developers of nuclear technologies, including EDF Energy and Rolls Royce SMR (EDF Energy, 2024, Rolls-Royce SMR, 2024) and manufacturers of heat pumps such as Grant UK (Grant UK, 2024). However, for solar and wind energy technologies, the role of the UK is chiefly in installation and servicing, with most product manufacture and assembly taking place overseas. Most PV cells are assembled in China and imported as complete units for installation in the UK.

The future end-of-life management of products and materials from decarbonisation technologies in the UK remains uncertain. However, there are significant opportunities to develop circular ecosystems and recycling infrastructure to secure secondary domestic supply and ensure sustainable resource management. Several new start-ups are working on battery cell and permanent magnet recycling. For example, Recyclus in Wolverhampton started recycling Li-ion batteries in 2023. It will process 8300 t in the first year to be turned into 'black mass' (Dawkins, 2023). Altilium Clean Technology aims to go further and process 50 000 t of black mass per year into new battery components at its planned facility at Teeside (Jolly, 2023). Recovered black mass is likely to be exported overseas in the near-term, because key parts of the value chain are not currently available in the UK, for example refining and battery precursor manufacture. However, Altilium aims to develop some of this capability in-house in the future.

Two UK-based recycling start-ups, HyProMag and Ionic Technologies, are planning to process permanent magnet scrap into recycled magnets and REOs for new magnets. Both already operate demonstration plants, located in Tyseley Energy Park in Birmingham (HyproMag) and in Belfast (Ionic Technologies) (Ionic Technologies, 2024, University of Birmingham, 2023). However, large-scale recycling remains absent and most end-of-life products are currently collected and exported for treatment overseas.

5 Discussion

The UK's commitment to achieving net zero (DESNZ, 2023) is driving growing demand for renewable energy production, energy storage and transport electrification. This foresight analysis was conducted to evaluate the projected UK demand up to 2050 and the global supply challenges for 36 materials (Table 2) essential to eight decarbonisation technologies:

- batteries
- electrolysers
- fuel cells
- heat pumps
- nuclear energy
- photovoltaics
- traction motors
- wind turbines

Only a small part of the supply chains of these technologies is currently based in the UK, resulting in a strong reliance on international markets. In addition, the rapid growth in global decarbonisation is increasing competition for materials, components and products, leading to potential supply bottlenecks. Assessing both present and future material demand and supply constraints is crucial for mitigating risks to achieving the UK's decarbonisation targets.

The methodology used in the analysis comprises five main steps.

1. Defining boundaries: identifying decarbonisation technologies, their subtechnologies and associated materials. The selection of materials was based on their importance to the technology's core function and whether they are deemed to be critical or not
2. Material allocation: mapping key materials and elements to specific technologies and subtechnologies
3. Supply risk evaluation: assessing supply risk on the basis of three parameters:- production concentration, trade concentration and an evaluation of the UK's value chain for each technology
4. Quantifying UK demand to 2050: projecting demand for selected materials and technologies based on National Grid FES, including analysis of demand relative to global requirements
5. Comparing UK to global demand: assessing the scale of the UK demand relative to global demand

The materials evaluated are those essential to the function or performance of a technology, with other, non-functional materials excluded. Although consistent application of the methodology to individual technologies and materials was given a high priority, the availability of reliable data presented challenges to authoritative analysis. For example, high-quality data on trade, material intensities and production were commonly unavailable, especially for precursor materials and midstream value chains, so comprehensive quantitative analysis of supply risks for these stages could not be undertaken. Gaps also exist in data on individual REEs, REE alloy production and permanent magnet manufacturing.

Other exclusions arose from data limitations (for example, lack of granular information on future technology mixes), uncertainty about the role of a material within a particular component and the unavailability of detailed BOMs for specific components and products.

The demand analysis highlights batteries as the most rapidly expanding decarbonisation technology, with significant increases projected for materials such as graphite, Ni, Li and Co. Heat pumps, traction motors and wind turbines also exhibit substantial demand growth, particularly for Cu and REEs, emphasising the importance of monitoring the markets as these technologies develop. Similarly, PVs are expected to see notable demand increases for key elements such as Si, Cu and Ag, with technological advances likely to introduce new materials (for example, Bi) to support next-generation PV applications.

Nuclear technologies are likely to face supply chain pressures, driven by the UK's goal to quadruple nuclear capacity by 2050 (from 6 GW to 24 GW). Supply chains for critical materials like U, Gd, In and Nb will require close monitoring to identify potential bottlenecks. Fuel cell demand, particularly in road transport, is also anticipated to grow, while electrolysers will be crucial for producing green hydrogen, an essential step to net zero. Although the UK's projected demand for fuel cell and electrolyser materials remains relatively modest compared to global production, Ir is an exception: due to its limited production, the UK's demand is expected to account for approximately 5 per cent of global Ir output by 2050, necessitating ongoing supply chain vigilance.

In terms of cumulative demand to 2050 for the 36 elements assessed, graphite ranks highest (5.6 million t), followed by Ni (2.5 million t), Cu (2.4 million t), Li (674 kt), Co (302 kt) and silicon (284 kt). These figures represent dramatic growth compared to 2024 levels: a 39-fold increase for graphite, 38-fold for Ni, 30-fold for Cu, 40-fold for Li, and a 15-fold increase for both Co and Si. The majority of high-demand elements are essential for battery manufacturing. For most materials evaluated, demand is projected to peak between 2030 and 2040. It will then plateau in the subsequent decade.

Comparison of projected UK demand and global supply highlights elements that may face future supply challenges. Li is particularly high risk, with the UK projected to need between 15 and 40 per cent of global production from 2030, depending on the scenario. Graphite follows, with UK requirements estimated at 10 to 29 per cent of global production. Other materials, such as Co, REEs and Ni, will also require significant shares of global output, ranging from 2 to 14 per cent by 2030. For battery raw materials, the UK demand as a percentage of global production will plateau beyond 2030 and remain at similar levels up to 2050.

In contrast, demand for materials such as U is projected to continue to rise rapidly after 2030, with UK requirements potentially reaching 10 per cent of global supply by 2050. Given the UK's net zero ambitions, demand is likely to lie at the upper end of the ranges identified in this analysis. This highlights an urgent need for new supply sources to become operational by 2030 to mitigate risks of resource shortages and to support the UK's decarbonisation goals.

While other elements may require a smaller proportion of global supply, this does not eliminate the need for close monitoring. Even a modest share of the materials produced globally in small quantities, or those with highly concentrated production, could lead to significant supply constraints. In these cases, the supply chain dynamics may present similar challenges to those associated with materials in higher demand, underlying the need for proactive supply security measures across the board.

Many nations have set ambitious decarbonisation targets that rely on the same technologies the UK aims to deploy, creating significant competition for essential materials. When comparing projected UK and global demand, REEs stand out, with the UK's share expected to reach 12.5 per cent of the global total by 2030 and 15 per cent by 2050. Similarly, UK demand for Ni, Co, graphite and Cu represents a substantial portion of global requirements (Figure 11).

Li supply is likely to face the most significant supply bottlenecks. By 2030, the UK alone is projected to require approximately 40 per cent of current global Li production. However, global demand by 2030 would require a 32-fold increase of current global supply to avoid market deficit, which is likely to be difficult to achieve. Given that many countries will be competing for Li, each with much higher volume requirements, securing a stable supply is likely to be particularly challenging for the UK.

The estimation of UK material demand is based on National Grid scenarios, which forecast the growth of the UK EV fleet up to 2050. These projections vary, but indicate that, beginning in 2030, annual EV registrations will range from just over one million to more than three million, with the net zero scenarios anticipating the higher end of this range. This projected increase is significantly higher than recent recorded UK sales, where total car registrations were 1.6 million in 2022 and 1.9 million in 2023. Whether such a sharp rise in new cars is realistic remains uncertain; it also raises the question of whether expanding the UK's EV fleet is the best path forward for achieving a net zero transport sector.

The global supply assessment reveals that mining of most of the evaluated materials has a low to moderate concentration of production. Notable exceptions include Nb, Ir, REEs and Pt, for which mine production is highly concentrated in a few countries. However, production concentration intensifies significantly during refining for most materials. The highest concentration scores are reported for spherical graphite, refined Ga, cobalt sulfate, HPMSM and lithium hydroxide.

China plays a dominant role in refining, emerging as the leading producer of 29 of the 49 materials assessed (in both mining and refining), with 21 of these being refined materials. The marked concentration of refining capacity in China highlights that country's crucial role in this stage of the raw materials supply chain globally.

Several of the materials assessed are recovered solely as by-products of the production of major primary commodities such as Cu, Ni and Zn. These include:

- Ga, In and Te for PV cells
- Co for battery cathodes
- In and Mo for nuclear technologies
- REEs for traction motors and wind turbines

As a result, their future supply will be closely tied to the markets for the primary commodities from which they are extracted. The availability of adequate capacity to recover these by-products will also be significant for securing future supply. Current recovery capacity is limited and is concentrated in only a few countries, posing a significant risk to future supply stability.

The global trade analysis reveals that trade in both mined and refined materials is generally dominated by three (or fewer) countries that together account for over 60 per cent of the global total. China's role in this trade is substantial, both as a major importer of raw materials and a key exporter at the refining stage. While some countries impose export restrictions on raw materials, the majority of these restrictions are license agreements and export taxes rather than trade prohibitions.

More stringent restrictions, such as export bans, are relatively rare. Indonesia is an example of an export ban introduced in 2020 with the aim to increase the value of mineral exports by shifting from exporting raw material to processed goods. Effects on the Ni price, global supply chains for Ni ore availability and disruption to the EV battery value chain were observed as a consequence of this ban. Other more recent restrictions, such as the special export licenses introduced by China for specific Ga and germanium (Ge) products resulted in price spikes and a decline in material exports (International Energy Agency, 2024a, Minor Metals Trade Association, 2023).

The most significant supply risk arises when a small number of countries control global trade and can further concentrate this control by imposing trade restrictions. However, accurately assessing the impact of these restrictions is challenging due to the lack of consistently updated and detailed data, as well as the need to understand the specific types and durations of restrictions. Existing resources, like the OECD Inventory of Export Restrictions on Industrial Raw Materials, capture only part of these complex trade dynamics. Policy initiatives such as the US Inflation Reduction Act and the EU Critical Minerals Act are effectively restrictions on imports. Consequently, they also have direct implications for critical raw material trade, yet they are rarely factored into assessments of the effects of trade restrictions. This highlights an important gap in current analyses.

The midstream supply chain, where key compounds and components are produced, is also highly concentrated for certain intermediate products. For example, China strongly dominates the production of polysilicon, Si metal and Ag paste. Similarly, permanent magnet manufacturing for wind turbines and traction motors is heavily concentrated in China. For batteries, a major bottleneck exists in midstream production capacity (cathode and anode manufacture), which remains limited outside south-east Asia. In contrast, technologies such as fuel cells, electrolysers, nuclear applications and heat pumps benefit from a more diverse range of producers at the component manufacturing stage. Product manufacturing is more geographically dispersed, with significant production centres for many of the technologies analysed in China, Japan, the USA and Europe.

The UK is heavily dependent on imports for intermediate products in technologies like wind turbines and batteries, leaving it exposed to potential disruptions, geopolitical tensions and trade restrictions. Strategic initiatives to diversify supply chains or develop domestic capabilities will be crucial. The UK's industrial strategy should focus on onshoring some midstream supply chain activities, such as cathode and anode manufacturing, to reduce dependence on south-east Asia. Partnerships with like-minded countries could also mitigate risks by diversifying supply.

It is also important to note that this assessment focused on specific key applications in selected technologies. However, the overall demand, taking account of all potential applications and products involving the elements evaluated, is likely to be significantly higher. For instance, Li-ion batteries are not only used in the decarbonisation technologies analysed in this study; they are also key to a wide range of products including, amongst others:

- consumer electronics
- energy storage systems
- data communication
- telecoms infrastructure
- defence technologies
- aerospace systems

At the same time, Li also has important uses in the manufacture of glass, ceramics and lubricating greases. This suggests that the demand for battery raw materials is likely far greater than the estimates provided in this assessment. To develop a more comprehensive understanding of overall demand, foresight assessments should broaden their scope to include additional markets and applications. This principle applies to most of the technologies evaluated in the study, underlining the need for a holistic approach in future assessments.

6 Recommendations

Technological developments are continually reshaping the material requirements of the UK economy. This makes it essential to monitor developments in rapidly evolving and emerging technologies to anticipate future material supply challenges. Each decarbonisation technology examined is influenced by a dynamic mix of factors, such as market conditions, geopolitical events, technoeconomic shifts, and social and environmental considerations that can quickly disrupt supply chains. Continual monitoring of these supply chains can offer valuable insights into future market dynamics and support strategies for effective risk mitigation and responsible material sourcing.

Such monitoring should include detailed stocks and flows models supported by scenario analysis. Establishing and maintaining data observatories that provide ongoing monitoring of supply chains and forward-look analysis, such as the UK Technology Metals Observatory (2024), can be instrumental in centralising data, models and scenario analyses, thus avoiding the need for dispersed and unconnected assessments taking place in governments, research and innovation and industry. These resources inform stakeholders across the supply chain of materials and products, helping to identify supply bottlenecks and facilitating active decision making across the supply chain.

Given the market concentration observed at various stages of the supply chains for key decarbonisation technologies, diversifying supply is essential to enhance resilience and reduce the risk of the UK's participation in these critical markets. To achieve this, the UK Government should prioritise support for new mining and refining projects both in the UK and overseas, aiming to bring additional production online as soon as possible, preferably within the next five years.

Based on the findings of this study, certain commodities, including Li, graphite, Co, REEs, Ni, U and Cu, should receive particular attention. Additionally, the UK Government should facilitate technical assistance for capacity building, training and knowledge transfer, especially in partnership with developing nations. Further support for overseas investment by UK companies through grants and tax breaks would also strengthen supply chain security and contribute to the diversification strategy.

Several funding initiatives have provided valuable support to specific sectors and decarbonisation technologies, strengthening the UK's innovation and research landscape. Examples include:

- Contracts for Difference scheme, which supports new, low-carbon energy infrastructure by giving UK project developers protection against wholesale price volatility (DESNZ, 2024b)
- Automotive Transformation Fund, which advances the EV supply chain (Advanced Propulsion Centre UK, 2024a)
- Faraday Battery Challenge, which focuses on building a domestic battery technology industry (UK Research and Innovation, 2024)

However, these initiatives have often lacked sufficient emphasis on supply chain and raw material challenges, creating a disconnect between the development of innovative technologies and the materials needed to scale them up effectively. Future funding initiatives should adopt a more holistic approach, supporting an integrated assessment of each sector's challenges. For instance, in battery development, funding should address raw material supply issues alongside technological innovation.

The challenges of UK security of supply for battery raw materials, most of which must be sourced from overseas, remain significant. Despite the urgency of this issue, there has been minimal allocation of research and innovation funding to address these supply chain vulnerabilities effectively.

Commercial operators should also be encouraged to collaborate with research organisations to ensure that industry benefits from new data, emerging technologies and research findings. The Circular Critical Minerals Supply Chains fund provides a useful model for this approach, fostering collaboration between researchers and industry to address specific supply chain challenges (Innovate UK, 2024).

The lack of midstream industrial activities in the UK, such as precursor materials (for example, PV cells and cathode active materials) and component manufacturing (such as permanent magnets), poses significant risks to the value chains of key decarbonisation technologies. To mitigate these midstream supply vulnerabilities, investment by UK companies should be actively encouraged and supported. For instance, projects funded through Innovate UK should receive additional support to demonstrate commercial feasibility, fostering a stronger domestic midstream sector. The work that has already started on permanent magnet recycling, for instance, has proven economic feasibility and should be supported further to reach commercial status.

Similarly, battery manufacture cannot progress without a midstream sector in place. The development of precursor material manufacture (cathode and anode manufacture) should become a priority for the UK. The provision of subsidies and tax incentives would support the domestic sector and de-risk manufacturing investment. Additionally, establishing trade agreements with major producing nations and promoting collaborative research and development initiatives would further strengthen supply chain resilience.

The development of a skilled workforce would be essential to support the growth of UK manufacturing capacity in this sector. Maintaining and strengthening this position is essential in areas where the UK already holds expertise, such as in fuel cells and electrolysers. This should also include mitigating risks associated with sourcing PGMs, which are essential to current fuel cell and electrolyser technologies. While the majority of global PGM supply comes from South Africa, the UK also plays a significant role in processing PGMs from waste and scrap. However, this recycling stream is likely to decline over time as the transition from internal combustion engine vehicles to EVs reduces the availability of catalytic converter scrap, which is a major source of recycled PGMs.

To ensure the sustainable growth of the fuel cell and electrolyser market, it is imperative to adopt a strategic approach to securing future feedstock. This includes conducting detailed studies on the future stocks and flows of PGMs and exploring alternative sources. Additionally, strengthening international cooperation, formalising trade agreements and developing strategic partnerships will be essential for securing reliable access to raw materials. These efforts, combined with a forward-thinking strategy for supply chain resilience and resource efficiency, will be key to sustaining the UK's leadership in this sector.

Developing a circular economy across the assessed technologies could significantly enhance secure future supply through the re-use, refurbishment, remanufacturing and recycling of components and materials. This is a strategy in which the UK could gain a leading position, providing policy, infrastructure and technological advancements align. At present, however, the UK lacks the reverse supply chains needed for these activities, including industrial capacity, skilled labour and sustained investment in circular projects. Building this infrastructure will require reshaping existing supply chains to support circular business models that ensure that the maximum value is extracted from resources by using them effectively and efficiently. Such models can create new revenue streams for businesses, promote sustainable material use and strengthen supply chain resilience.

A circular economy could improve supply security for critical raw materials by providing domestic material sources and reducing dependency on imported primary resources. Current efforts in areas like REE recycling should receive full support from Government and investors, employing a range of measures such as funding initiatives, tax incentives, public/private partnerships and collaborative research programmes to accelerate scale-up.

A key aspect of advancing the development of a circular economy is reducing demand for high-risk technologies and materials, particularly those likely to face future supply bottlenecks.

Several strategies can support this goal:

- improvements in material efficiency and product design
- extending product lifespan and encouraging modular design
- promoting circular economy practices and prioritising re-use, refurbishment and remanufacturing to keep products and components in their higher value and use for longer
- advancing resource efficiency through process optimisation
- encouraging consumer behaviour change

Policy plays a critical role in shaping the future of materials supply and sustainability. While often overlooked, it should be integral to the development of new strategies in technology, innovation, decarbonisation, critical minerals and the circular economy. Emerging requirements, such as product passports, can provide better understanding of material compositions and facilitate circular economy practices. Additionally, a comprehensive industrial strategy (Department for Business and Trade, 2024b), ideally underpinned by a raw materials strategy to identify and mitigate supply chain risks in a timely manner, is essential to guide the UK's trajectory in decarbonisation and other sectors.

As the UK's reliance on external markets is unlikely to diminish, maintaining strong international relationships and trade agreements will be vital. Tools like the Critical Imports and Supply Chains Strategy (Department for Business and Trade, 2024a) will be instrumental in developing effective risk mitigation strategies and strengthening supply chain resilience.

The foresight studies conducted here provide valuable insights into the future material needs for emerging technologies, serving as a vital complement to criticality assessments. Expanding this work to include both demand and supply forecasts would enhance its value, providing a fuller picture of potential supply and demand imbalances. Incorporating analyses of economic factors, price volatility and ESG issues would also add valuable context to these projections. Future additional foresight studies should broaden their scope to include other emerging sectors and horizon-scanning exercises would help identify priority sectors for these assessments. Such emerging sector may include, among many others:

- digital technologies
- artificial intelligence
- power electronics
- robotics
- aerospace

Recommendations specific to each individual technology assessed are given in the respective individual reports. These foresight studies should be updated regularly, ideally at intervals not exceeding two years, to reflect the rapid evolution of decarbonisation technologies and the progression toward net zero goals.

Appendix 1 Global metal production (2017 to 2021)

Global metal production (five-year average, 2017 to 2021) for the materials assessed in this analysis. (REO data from Idoine et al. (2023) modified by in-house calculations for individual metals.) REE: rare earth elements, PGM: platinum group metals.

Material	Global production (tonnes)	Material	Global production (tonnes)
Al (refined)	64 334 168	Nd (REE)	28 420
As	54 374	Ni (refined)	242 3024
Bi	4910	Nb	114 096
Borates	7 370 822	Phosphate rock	231 398 413
Cd	25750	Pt (PGM)	184 356
Cr	34967765	Pr (REE)	8684
Co (refined)	132 017	Se	3549
Cu	24 228 142	Si metal	3 035 036
Dy (REE)	9710	Ag (mined)	27 251 690
Gd (REE)	2208	Na_2CO_3 (natural)	44 058 697
Ga	379	Te	530
Graphite (natural)	11 25 388	Tb (REE)	1184
In	813	Sn (smelter)	372 476
Ir (PGM)	7656	Ti	6 558 489
La (REE)	51 311	U	52 731
Li	94 570	Y (REE)	5669
Mn	54 566 982	Zn	12 572 822
Mo	294 154	Zr	1 227 641

Acronyms and abbreviations

AC	Alternating current
ACIM	Alternating current induction motor
AEL	Alkaline electrolyser
AEM	Anion exchange electrolyser
ASHP	Air-source heat pump
BOM	Bill of materials
CdTe	Cadmium-telluride solar cell
CIGS	Copper-indium-gallium diselenide solar cell
COP	Conference of the Parties
DD-EESG	Direct drive-external excitation synchronous generator
DD-PMSG	Direct drive-permanent magnet synchronous generator
ESG	Environmental, social and governance
EU	European Union
EV	Electric vehicle
FES	Future Energy Scenario(s) (National Grid)
GB-DFIG	Gearbox double fed induction generator
GSHP	Ground-source heat pump
HPMSM	High-purity manganese sulfate monohydrate
IEA	International Energy Agency
III-V/Si	Tandem solar cell
LFP	Lithium-iron-phosphate cathode
LIB	Lithium-ion battery
NCA	Nickel-cobalt-aluminium cathode
NMC	Nickel-manganese-cobalt cathode
NZE	Net zero emissions scenario
OECD	Organisation for Economic Cooperation andDevelopment
PEM	Proton exchange membrane electrolyser)
PEMFC	Proton exchange membrane for fuel cell
PGM(s)	Platinum group metal(s)
PMSM	Permanent magnet synchronous motor
PV	Photovoltaic
PWR	Pressurised water reactor
REE(s)	Rare earth element(s)S
SIB	Sodium-ion battery
SMR	Small modular reactor
SOEC	Solid oxide electrolyser

WRSM	Wound-rotor synchronous motor
WSHP	Water-source heat pumps

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