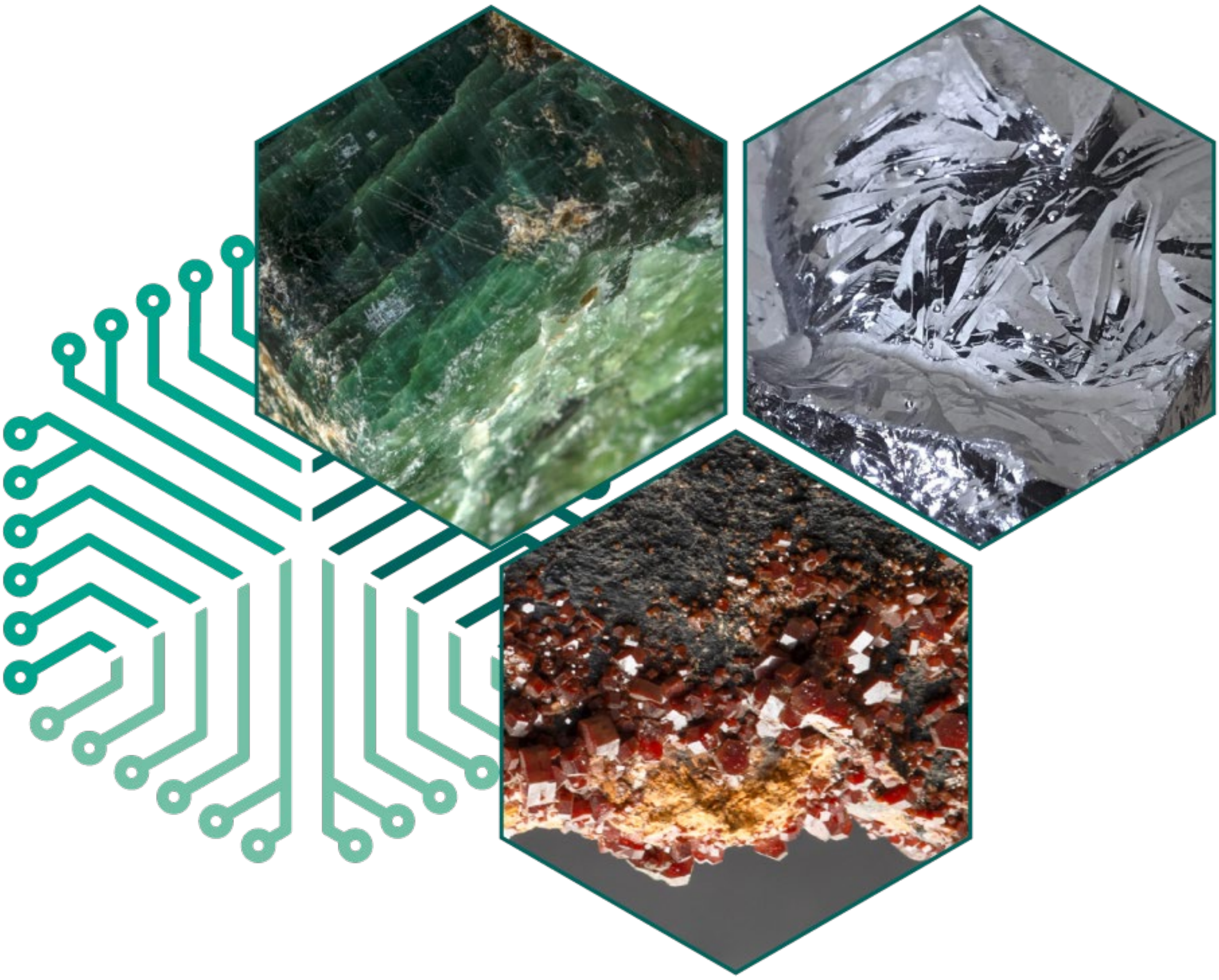
UK Critical Minerals
Intelligence Centre

UK 2024 Criticality Assessment

Decarbonisation and Resource Management Programme

Open Report OR/24/047



Department for Business & Trade

British Geological Survey

BRITISH GEOLOGICAL SURVEY

Decarbonisation and Resource Management Programme

Open report OR/24/047

Keywords: critical minerals; UK criticality assessment.

UK 2024 Criticality Assessment

G Mudd, P Josso, R Shaw, A Luce, N Singh, S Horn, T Bide, D Currie, H Elliott, H Grant, R Halkes, N Idoine, C Mitchell, I Watkins, F Price, E Petavratzi

Editors

A G Gunn, J M Hannaford

Graphic designers

C Woodward, D Rayner

Bibliographical reference: Mudd, G, Josso, P, Shaw, R, Luce, A, Singh, N, Horn, S, Bide, T, Currie, D, Elliott, H, Grant, H, Halkes, R, Idoine, N, Mitchell, C, Watkins, I, Price, F, and Petavratzi , E. 2024. UK 2024 Criticality Assessment. *British Geological Survey Open Report*, OR/24/047. 235pp.

Keyworth, Nottingham British Geological Survey 2024

BRITISH GEOLOGICAL SURVEY

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

The London Information Office also maintains a reference collection of BGS publications, including fossils, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from the BGS shop.

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

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

British Geological Survey offices

Nicker Hill, Keyworth,
Nottingham NG12 5GG
Tel 0115 936 3100

BGS Central Enquiries Desk
Tel 0115 936 3143
email enquiries@bgs.ac.uk

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

The Lyell Centre, Research Avenue South,
Edinburgh EH14 4AP
Tel 0131 667 1000
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road,
London SW7 5BD
Tel 020 7589 4090
Tel 020 7942 5344/45
email bgslondonstaff@bgs.ac.uk

Cardiff University, Main Building, Park Place,
Cardiff CF10 3AT
Tel 029 2167 4280

Maclean Building, Crowmarsh Gifford,
Wallingford OX10 8BB
Tel 01491 838800

Geological Survey of Northern Ireland, 7th Floor,
Adelaide House, 39-49 Adelaide Street, Belfast, BT2 8FD
Tel 0289 038 8462

www2.bgs.ac.uk/gsni/

Natural Environment Research Council, Polaris House,
North Star Avenue, Swindon SN2 1EU
Tel 01793 411500   Fax 01793 411501
www.nerc.ac.uk

UK Research and Innovation, Polaris House,
Swindon SN2 1FL
Tel   01793 444000
www.ukri.org

Website: https://www.bgs.ac.uk
Shop online: https://shop.bgs.ac.uk/

Foreword

This report is the published product of a study by the UK Critical Minerals Intelligence Centre (CMIC), hosted at 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

This study has been completed by a large team at BGS through CMIC. The authors would like to acknowledge the assistance of numerous people who have helped along the way. In particular, the following BGS staff: Michelle Bentham, Joseph Mankelow, Kathryn Goodenough, Corinna Abesser, Eimear Deady and Karen Hanghøj. The BGS Minerals admin staff and BGS Communications team deserve recognition for their support and help at all stages of the project.

The authors would also like to sincerely thank the critical minerals team at DBT, for constant advice, guidance and feedback throughout this study.

There are many groups or organisations that responded to requests for data and information, clarification or general advice; all are duly thanked and acknowledged.

Finally, a special thanks to the BGS Graphics team, especially Craig Woodward and Debbie Rayner, and to Gus Gunn (scientific editor), for their hard work in helping to bring this report to fruition.

Contents

FIGURES

TABLES

Summary

As the UK moves to net zero greenhouse gas emissions, a wide variety of raw materials will be needed in increasing quantities to meet demand for the energy transition and for other modern technologies, industrial sectors and societal goals. These raw materials, which are crucial to the UK economy, often have complex supply chains originating in mines around the world. It should be noted that industrial strategies are underpinned by secure and sustainable raw material supply chains.

The minerals and metals with the greatest economic importance and the highest risk of supply disruption are characterised as 'critical minerals' to the UK. In this report, the term 'raw materials' is used in a general sense to refer to all metals, minerals and gases used in any sectors of the economy. The term 'critical minerals' is used to describe the subset of raw materials that are identified as critical through a criticality assessment.

This report provides the 2024 update of the UK's raw material criticality assessment (CA), undertaken by the British Geological Survey (BGS)-hosted Critical Minerals Intelligence Centre (CMIC) as commissioned by the Department for Business and Trade (DBT). The assessment aims to identify the raw materials that are crucial for the economic prosperity, national security and ongoing technological development of the UK, but have a significant risk of supply disruption.

Identification of raw materials critical to the UK enables the mitigation of risk by:

- strengthening international and domestic supply chains
- developing sustainable trade relationships
- supporting domestic mineral production
- increasing the use of secondary resources and other circular economy strategies

This assessment replaces the original UK Criticality Assessment (December 2021), incorporating the latest data (2018 to 2022) and expanded methodology. The number of evaluated ('candidate') materials has grown significantly, from 26 in 2021 to 82 in 2024. Candidates include most raw materials used in the UK manufacturing sector, energy, technologies, transport, aerospace and defence applications, and in information and communication technologies. The methodology incorporates environmental, social and governance standards and improved criticality quantification to deliver an impartial assessment of available data. Importantly, this methodology is based on quantitative data and thus describes the criticality of raw materials at the time of publication. The assessment does not take account of supply and demand forecasts or any other changes that may take place in minerals markets in the coming years, as such changes cannot be accurately quantified.

Key features

- Global supply risk: assessed using the country-level concentration of mining or refining activities, global trade flows through net imports, the scale of recycling and how much is produced as a co-/by-product of another raw material
    - All aspects are quantified from data sourced from BGS World Mineral Production statistics, trade databases (UN Comtrade; UK Trade Information), industry and academic literature
- UK economic vulnerability: based on apparent consumption value, net import reliance and gross (or economic) value added by a specific raw material
    - All aspects are quantified from trade databases (UN Comtrade; UK Trade Information) and UK economic statistics (Office of National Statistics)

- Each candidate raw material was plotted using the derived global supply risk and UK economic vulnerability scores, which were combined to calculate an overall criticality score
- Stakeholder consultation: engagement with industry, academia and Government representatives helped to inform the position of the criticality threshold, separating critical from non-critical minerals
- The process is based on integrating data and evidence from a variety of sources, making the assessment robust and objective and leading to confidence in the outcomes

The updated 2024 UK list (Table 1) comprises 34 critical minerals, with 17 new additions to the 2021 UK critical minerals list. This increase reflects the greater number of assessed candidate raw materials. Whilst most previous critical minerals retained their status, palladium (Pd) now falls just below the criticality threshold due to its relatively wider geographical distribution of supply compared to other platinum group elements (PGEs), which remain critical.

Table 1 UK critical minerals list 2024.

UK critical minerals list 2024			
Aluminium (Al)	Indium (In)*	Niobium (Nb)*	Tantalum (Ta)*
Antimony (Sb) *	Iridium (Ir)	Phosphorus (P)	Tellurium (Te)*
Bismuth (Bi) *	Iron (Fe)	Platinum (Pt)*	Tin (Sn)*
Borates	Lithium (Li)*	Rare earth elements (REEs)*	Titanium (Ti)
Cobalt (Co) *	Magnesite	Rhenium (Re)	Tungsten (W)*
Gallium (Ga)*	Magnesium (Mg)*	Rhodium (Rh)	Vanadium (V)*
Germanium (Ge)	Manganese (Mn)	Ruthenium (Ru)	Zinc (Zn)
Hafnium (Hf)	Natural graphite (C)*	Silicon (Si)*	
Helium (He)	Nickel (Ni)	Sodium (Na) (compounds)	

* Appeared on the UK critical minerals list 2021.

The 2024 UK critical minerals list aligns with similar worldwide assessments, such as that produced by the European Union in 2023, highlighting the global nature of commodity markets and competition to access raw materials, whilst reflecting the UK's specific geopolitical and economic environment.

The report makes a range of recommendations, including the need for further research and capacity building in the midstream and manufacturing sectors, especially recycling, continuing to build international trade partnerships to reduce the risks and impacts of trade barriers, deep dive studies on important commodities, such as copper, iron, tungsten and tantalum, and technologies (information and computing technologies, especially quantum computing and artificial intelligence), continuing to invest in the pre-competitive geoscience data to underpin the potential for domestic production (such as geophysical surveys), continuing efforts to enhance the methodologies used for criticality assessment, and finally continuing support to maintain UK expertise in critical minerals, supply chains and circular economy opportunities.

It is important to note, as this report demonstrates, that many non-critical raw materials will remain important for a variety of technologies and societal goals (e.g. digital transformation, evolution of the electrical grid and other infrastructure), meaning that they will require different policy approaches than those pursued for critical minerals. All materials below the criticality threshold for this assessment should be maintained as a watch list, ensuring that any changes can be identified quickly and actioned accordingly.

Global commodity markets are highly dynamic in nature, reflecting continuous technological improvements, market expansion and global competition in an increasingly divided geopolitical landscape. Regular reassessment is advised to track changes in criticality status and monitor the impact of risk management policies. A comprehensive update is recommended for 2027, incorporating forward-looking analyses to anticipate the material demands for key UK industrial sectors in response to the evolving technological and geopolitical circumstances.

Addressing the risks identified through CAs requires a balanced approach, combining:

- primary supply
- secondary (recycling) capacity
- planning a strong industrial strategy
- maintaining the expertise to analyse and assess the numerous material supply chains, technologies and their links to the UK economy

This will require ongoing support for criticality-related research, associated data needs (mining and refining; trade data; economic data; material flows; etc.) and increasing the extent of international collaboration. This report provides the foundation for future such planning and policy in the critical minerals field, especially with regards to the emerging industrial strategy for the UK.

1 Introduction

Critical minerals are those that are important to modern technology and societal needs but are at risk of supply disruption, leaving the UK economically vulnerable. The process of determining which materials are critical and those that are not is called a ‘criticality assessment’ (CA).

The purpose of a CA is to assist in the development of appropriate mitigation by identifying which raw materials are of the most strategic importance to a country’s economy and national security, and which are vulnerable to supply disruption due to their being mined or refined in a small number of countries.

This report describes the process and results of the UK 2024 Criticality Assessment undertaken by the British Geological Survey (BGS)-hosted Critical Minerals Intelligence Centre (CMIC) as commissioned by the Department for Business and Trade (DBT). In this study, we use ‘raw material’ to encompass all material forms (metals; minerals; gases) and ‘critical minerals’ for those identified by this assessment.

The identification of critical minerals is essential to guide policies aimed at securing the supply of materials required for the functioning of society. The strategic importance of metals and mineral resources as raw materials has become ever-more pronounced as the need for an energy transition has risen to political prominence worldwide, and a variety of raw materials are used in other important technologies such as communication, transport, construction, aerospace, digital and defence. The advancement and resilience of these industries depend on a steady and secure supply of specific raw materials, minerals, metals, alloys and manufactured components. For example, renewable energy technologies, electric vehicles and batteries for energy storage are all manufactured using a variety of raw materials that are sourced from and processed across the world. Some raw materials, such as lithium, are experiencing very rapid growth rates as many countries accelerate the uptake of related technologies.

This reliance on a broad spectrum of raw materials that may be mined or refined in only a few countries has highlighted the complexity and lack of transparency in many global supply chains. There is a significant risk of supply disruption for the raw materials essential to meet decarbonisation goals — to sustain the development of infrastructure, information and communication technologies — whilst maintaining sovereignty and national security. The energy transition is highlighting the need to secure raw materials to electrify, reduce dependency on fossil fuels and achieve energy security. At the same time, demand for raw materials from existing industrial sectors will continue to require adequate and sustainable supplies.

The raw materials considered in this report are those produced by mining natural resources that have been formed in specific locations by geological processes within the Earth’s crust. Such raw materials have a complex supply chain that starts with exploration, followed by mining and initial processing. Subsequent further processing and refining yields materials that are sold to manufacturers for use in their products. Finally, at the end of product life, recycling may generate a supply of secondary raw materials.

The increasing demand for raw materials has led many regions, nations and industry sectors to develop their own critical mineral lists (European Commission, 2023; U.S. Geological Survey, 2022b; Yan et al., 2021). The results of a CA help governments to actively develop policies aimed at securing raw material supplies and enhancing economic resilience. This can be achieved in many ways:

- investment in exploration, mining and processing, both at home and overseas
- development of alternative materials (where feasible)
- improved recycling technologies and a more circular economy
- optimisation of material use
- diplomatic efforts to secure stable trade relationships

Although substantial research and innovation are ongoing to develop circular economy approaches such as recycling, at present the majority of critical (and non-critical) minerals must be derived from primary sources given that there are not enough metal stocks in the urban and industrial system yet. The development of a critical minerals list is an important first step in understanding the unique economic and industrial landscape of a nation. For many reasons, not all raw materials have the same importance across different economies or industries. This nuanced, in-depth understanding ensures that policy interventions are tailored to address the specific needs and strategic priorities of a country.

The classification of certain raw materials as critical minerals is consistent with the growth in demand for technologies, such as renewable energy (wind turbines; solar photovoltaics, etc.), electric vehicles (especially the batteries needing lithium and drive trains requiring rare earth elements) and technologies supporting existing applications such as catalytic converters in internal combustion vehicles (platinum and palladium, which ensure cleaner exhaust fumes and improved urban air quality).

Resource-rich countries may consider some raw materials critical because they can be produced in large enough quantities to supply consumers. Other consuming nations may deem a raw material critical because of its essential role in a specific sector of the national economy. Criticality therefore depends on perspective and scale; the list of critical minerals should reflect the specific needs of the nation or industry that is conducting the exercise.

A CA typically uses two dimensions to identify critical minerals: the demand side of an economy, commonly referred to as the ‘economic importance’ or ‘economic vulnerability’, and the supply side, which assesses the likelihood of supply disruption.

This study constitutes an update of the UK Criticality Assessment of technology-critical minerals and metals published in 2021 (Lusty et al., 2021). The analysis builds on lessons learned from the previous exercise and expands the scope to incorporate a broader range of industrial sectors and candidate raw materials. DBT commissioned CMIC to complete this report as part of the work programme for 2024.

A review of global CA best practice and methodologies was published in 2023 by CMIC (Josso et al., 2023) and serves as a guide for this assessment. The methodology has been further developed here to improve the reliability and relevance of the assessment for the UK.

Given the highly complex and dynamic nature of global material supply chains (such as rapid growth periods), any assessment is dependent on the availability of reliable, relevant and timely data. Consequently, there is no single, correct or fixed list of critical minerals. Criticality can change at any time in response to market conditions. A robust critical minerals list can flag up the possibility of potential supply risks and highlight the need for additional in-depth studies of particular raw materials. Importantly, a rigorous criticality assessment does not take account of supply and demand forecasts or any other changes that may take place in minerals markets in the coming years, as such changes cannot be accurately quantified.

2 Methodology

Criticality assessments are similar to risk assessments in that they aim to produce an evaluation of the potential for the disruption of the supply of candidate materials and the resulting economic impact of any supply disruption. The CA presented here has two dimensions: global supply risk and UK economic vulnerability. These two dimensions are generally evaluated through the quantification of various measurable indicators that reflect them in some way. Each indicator is quantified using a range of metrics derived from reliable and publicly available datasets.

A detailed discussion of the merits of the indicators commonly employed in raw materials CAs and justifications for the selection of those used is provided in a dedicated methodology report and in published literature (Josso et al., 2023; Schrijvers et al., 2020). In this assessment, a small number of changes to the recommended methodology have been implemented following detailed consideration and stakeholder consultation. A summary of each indicator, data used, calculations and limitations is provided.

2.1 Candidate material list

Any CA must start with the identification of the candidate materials that will be considered. The 82 candidate materials evaluated in this study are listed in Table 2. They cover most elements of the periodic table and a broad range of industrial minerals, thereby encompassing almost all technologies and economic sectors.

Notable raw materials excluded from this assessment include (Josso et al., 2023):

- all hydrocarbons and derivatives
- biotic materials, such as rubber and wood
- gases except natural hydrogen (H) and helium (He), which are included
- highly processed materials, such as radionuclides
- construction minerals such as aggregates, sand and gravel

The lanthanoids plus scandium (Sc) and yttrium (Y), commonly referred to as the rare earth elements (REEs), are treated as a single entity in this assessment because many aspects of their supply chains are not publicly available and most of the traded forms include multiple REEs, making reliable individual assessment difficult (Josso et al., 2023).

Table 2 Candidate materials for this CA.

Individual elements (56)			
Aluminium (Al)	Gallium (Ga)	Molybdenum (Mo)	Sodium (Na)
Antimony (Sb)	Germanium (Ge)	Nickel (Ni)	Strontium (Sr)
Arsenic (As)	Gold (Au)	Niobium (Nb)	Sulphur (S)
Barium (Ba)	Hafnium (Hf)	Palladium (Pd)	Tantalum (Ta)
Beryllium (Be)	Helium (He)	Phosphorus (P)	Tellurium (Te)
Bismuth (Bi)	Hydrogen (H) (natural)	Platinum (Pt)	Thallium (Tl)
Boron (B)	Indium (In)	Potassium (K)	Thorium (Th)
Cadmium (Cd)	Iridium (Ir)	Rhenium (Re)	Tin (Sn)
Caesium (Cs)	Iron (Fe)	Rhodium (Rh)	Titanium (Ti)
Carbon (C) (as graphite)	Lead (Pb)	Rubidium (Rb)	Tungsten (W)
Chromium (Cr)	Lithium (Li)	Ruthenium (Ru)	Uranium (U)
Cobalt (Co)	Magnesium (Mg)	Selenium (Se)	Vanadium (V)
Copper (Cu)	Manganese (Mn)	Silicon (Si)	Zinc (Zn)
Fluorine (F)	Mercury (Hg)	Silver (Ag)	Zirconium (Zr)
REEs (15 lanthanoids plus yttrium and scandium assessed as a single group)			
Lanthanum (La)	Samarium (Sm)	Dysprosium (Dy)	Ytterbium (Yb)
Cerium (Ce)	Europium (Eu)	Holmium (Ho)	Lutetium (Lu)
Praseodymium (Pr)	Gadolinium (Gd)	Erbium (Er)	Scandium (Sc)
Neodymium (Nd)	Terbium (Tb)	Thulium (Tm)	Yttrium (Y)
Promethium (Pm)			
Industrial minerals (25)			
Barite	Garnet	Perlite	Talc
Bentonite clay	Gypsum	Phosphate rock	Vermiculite
Borate	Kaolin clay	Pumice	Wollastonite
Diamonds	Kyanite	Pyrite	Zeolite
Diatomite	Limestone	Pyrophyllite	
Feldspar	Magnesite	Rock salt	
Fluorspar	Natural graphite	Silica sand	

2.2 Global supply risk dimension

No single country is self-sufficient in its capacity to domestically produce all the raw and refined materials and processed products required to sustain its key industrial sectors. The global supply risk dimension for each candidate material is estimated from four indicators reflecting the overall supply chain bottlenecks:

- production concentration indicator (PCI)
- companionality (C)
- global trade concentration (GTC)
- recycling rates

2.2.1 Production concentration indicator

This study deals with mined raw materials, which are produced across the world in areas where geological processes have led to their concentration in a mineral deposit. When a deposit is sufficiently well-characterised that it is considered potentially economic to extract, it is called a mineral resource.

Although geological availability of mineral resources historically dictated centres of production, national policies, globalisation and economies of scale have now become major influences and have led to increased centralisation of production of some raw materials in a small number of countries. This greater production concentration increases the exposure of supply chains to disruption from many diverse causes, both artificial and natural. Artificial changes include government policies and regulations, such as trade restrictions, taxation and resource ownership. Supply disruption related to environmental and social parameters, such as civil unrest, global conflict, pollution, disease and disasters, also becomes more likely with increased concentration of production. The PCI characterises the level of production concentration for each candidate material at the mining stage and, where data is available, at the refining stage. In this study, average annual global production data for the five-year period 2018 to 2022, derived from BGS World Mineral Production statistics (Idoine et al., 2024), was used in the calculation of the PCI (Idoine et al., 2024). This data is complemented by other specialised sources and compilations when required, to ensure quality and fill gaps (for example, SCRREEN (2023d); U.S. Geological Survey (2024b)).

The first step in calculating the PCI is to identify the top three producing countries and their proportional market share. Each share is then squared and multiplied by an environmental, social and governance (ESG) indicator to reflect the additional risk represented by countries with lower standards due to poor governance, civil unrest or pollution risks. The ESG indicator, defined in Equation 1, is derived by calculating the geometric mean of:

- United Nations Development Programme’s human development index (HDI) (Conceição et al., 2022)
- Yale University’s environmental performance index (EPI) (Block et al., 2024)
- World Bank’s world governance index (WGI) (World Bank, 2024)

Data is provided in Appendix 1.

$$ESG(i) = \sqrt[3]{(EPI(i) * HDI(i) * WGI(i))}$$

Equation 1 Calculation of ESG indicator, where ESG = environmental, social and governance; EPI = environmental performance index; HDI = human development index; WGI = world governance index; (i) = country being assessed.

The final PCI calculation, shown in Equation 2, is completed for both the mining and refining stages of a raw material's supply chain, resulting in a modified Hirschman-Herfindahl index (HHI)[1]. These results are normalised on a 1 to 10 scale for equivalence with other indicators in the CA. The final PCI score used in estimation of the global supply risk dimension is based on whichever is the higher of the two values calculated for the mining and refining stages.

$$PCI = \sum_{1}^{3}(5\ yr\ avg.\%\ of\ global\ production(i,n)^2 * ESG(i))$$

Equation 2 Final PCI calculation, where PCI = production concentration indicator; ESG = environmental, social and governance.

2.2.2 Companionality and companion metal fractions

Many metal ores contain more than one metal and hence some metals are produced as a co- or by-product of others (similarly true for minerals and gases). The share of production of a material that is a co- or by-product derived from the mining and refining of a primary material is referred to as the companion metal fraction (CMF). In the context of global mineral production, only a limited number of raw materials are considered 'primary' products: these materials will be the focus of a mining project and generate the revenues to sustain commercial viability. Examples of primary products include metals such as copper (Cu), iron (Fe), aluminium (Al), tin (Sn) and gold (Au), which are mined due to their long-established demand and significant economic value. Other materials are mostly obtained as co-products or by-products (Nassar et al., 2015). Co-products, such as zinc (Zn) and lead (Pb), are commonly mined together in significant quantities, each with substantial economic value. By-products, in contrast, are typically much lower value and are only extracted during the processing of primary commodities or co-products. For example:

- cobalt (Co) can be a co- or by-product of Cu or nickel (Ni) mining
- tellurium (Te) can be a by-product of Cu or Au refining
- indium (In) and germanium (Ge) are by-products of Zn refining

Understanding whether a material is a primary product, a co-product or a by-product is crucial for analysing supply chains and market dynamics. The availability of co- and by-products is inherently tied to the production levels of the primary products with which they are associated. If the demand for Cu decreases, the production of Te as a by-product may also drop, regardless of the market demand for Te itself. This dependency introduces supply constraints and price volatility for many co- and by-products, which can impact industries that rely on them.

By-products are typically only extracted in the refining stage, with mining operations rarely being compensated. Consequently, their supply is less responsive to changes in demand compared to primary commodities. This can lead to supply bottlenecks, where the availability of a by-product is insufficient to meet growing industry needs, especially if the demand for the primary material is stable. Additionally, if a co- or by-product relies entirely on the market of a single primary material, its supply will be seriously affected by any change in the primary material market. In contrast, if a material is produced as a by-product from multiple primary materials, a major market disruption of one of the primary materials will have a proportionally smaller impact as alternative supplies remain operational. Understanding these relationships is essential for anticipating market fluctuations, establishing secure supply chains and planning strategic interventions to mitigate risks associated with the supply of these materials.

[1] See www.investopedia.com/terms/h/hhi.asp

Many companion metals are found as substitute elements in the host minerals containing the primary material. For example, most rhenium (Re) is extracted during smelting of the mineral molybdenite (MoS_2) since the Re substitutes for molybdenum (Mo) in small quantities (Millensifer et al., 2014; Werner et al., 2023).

The CMF values for many commodities are reasonably well documented (Nassar et al., 2015); however, these values can change rapidly when mines open or close down. For example, PGEs were primary products of alluvial placer deposits from the late 18th to the early 20th century. Most PGEs were then obtained as by-products of Ni-Cu mining until the middle of the 20th century. Since the mid-20th century, primary hard-rock sources became predominant, notably from South Africa (Mudd, 2023). Additionally, the global supply of REEs has shifted from being a by-product of mineral sands mining before the 1970s, to development of primary sources (for example, Mount Weld, Australia) and co-product REE mines (for example, Bayan Obo, China).

This highlights the importance of understanding co- and by-product sourcing and identifying alternative resources that could support future supply.

In this assessment, CMF shares are estimated using global mine production statistics and by allocating mineral deposit types to each producing country, allowing the proportion of primary, co- and by-product status to be determined for each material. In this study, we have adopted one of the following approaches to estimating CMF shares for each candidate material:

- 100 per cent assigned to materials known to be primary production only (for example, Fe; Al; kyanite)
- calculation based on fractions of a co- or by-product in different types of mineral deposits using either global studies (for example, Co (Mudd et al. (2013)) or assigning mineral deposit types by each country (for example, Re produced in some countries is derived from Cu processing; for others, it is from Mo smelting)
- If one of the above is not possible, we adopt CMF fractions from Nassar et al. (2015), Graedel et al. (2022) and other literature

The companionality score is calculated by summing all the squares of each share of co- or by-production, taking the log of this sum, and multiplying by the total CMF (Equation 3). This yields scores on a 0 (100 per cent primary) to 400 (100 per cent co-or by-product from a single source) scale, which are then normalised to a 1 to 10 scale. An example calculation for Co is provided in Table 3.

$$Companionality = \ companion\ metal\ fraction * \log \sum_{1}^{n} (\text{co or byproduct shares})^2$$

Equation 3 Calculation of companionality score for Co.

Table 3 Calculation of cobalt (Co) companionality score by assigning mineral deposit types within each country producing Co. Copper (Cu), nickel (Ni), Platinum groups elements (PGEs) Shares based on world mining production statistics (Idoine et al., 2024).

Candidate material	Primary production		Co- or by-production		
	Primary deposit of candidate material	Share (%)	Host commodity	Major deposit types	Share (%)
Co	Co-Ni-As (-Au-Ag) mineralisation	1.4	Cu	Stratiform sediment-hosted Cu-Co	69.4
			Ni-Co	Ni-Co laterites	17.6
			Ni-Cu	Magmatic Ni-Cu (-Co-PGE)	11.6

According to data in Table 3, only 1.4 per cent of world Co production is from primary sources (the Bou Azzer mine in Morocco (Leblanc and Billaud, 1982)), whilst 98.6 per cent is derived from three major types of mineral deposit exploited chiefly for the production of Ni or Cu. On this basis, the companionality score for Co is calculated as:

$$\text{Companionality (Co)} = (69.4 + 17.6 + 11.6) * \log(69.4^2 + 17.6^2 + 11.6^2) = 367$$

This yields a score of 9.25 for Co companionality when normalised on a scale of 1 to 10.

This methodology extends the work of Nassar et al. (2015). It provides more comprehensive and realistic estimates of companionality and the extent to which materials are produced as co- or by-products. The approach relies on extensive geological knowledge of each material and the mines or deposits in each country. Typical co- and by-products and their host primary commodities are given in Table 4, noting that these are typical only and based on key literature and the expert knowledge of BGS and CMIC staff.

Table 4 Typical co-/by-products and their host primary product developed from (Nassar et al., 2015; U.S. Geological Survey, 2024b) and expert knowledge of BGS staff.

Primary product	Typical co- or by-products
Aluminium (Al)	Ga
Copper (Cu)	Au; Mo; Ag; Co; Fe ore; pyrite; Te; Se; As; Bi; Re
Gold (Au)	Ag; Cu; Te; Sb; Hg; As
Iron (Fe) ore	REEs; Ti; V; Mn
Lead (Pb)	Sb; Ag; Bi; Cu; Zn; Te; Au
Molybdenum (Mo)	Re; W
Nickel(Ni)	Cu; Pt; Pd; Rh; Co; Au; Ag; Sc; Se
Platinum (Pt)-Palladium (Pd)	Pd; Rh; Ru; Os; Ir; Ni; Cu; Co; Cr; Au
Tin (Sn)	REEs; W; Ag; Sc; In; Bi; Sb
Titanium (Ti)-Zirconium (Zr)	REEs; Hf
Zinc (Zn)	Cd; Ge; In; Ag; Au; Cu; Pb; Tl; Ga; Sn

2.2.3 Global trade concentration

No country is completely self-sufficient in all materials required for modern technologies and to support economic growth. Consequently, global trade has evolved to facilitate the supply of such materials, with many countries completely reliant on imports to meet their needs. Furthermore, countries with a relatively large share of global imports can exert influence on that material's supply chain, especially in downstream manufacturing and, therefore, product availability. In this context, we use GTC in the global supply risk dimension.

Main data sources

- United Nations Comtrade (Comtrade)
- UKTrade Information (UKTI)

Supplementary data sources

- International Trade Centre (ITC)
- Observatory of Economic Complexity (OEC)
- European Union's Eurostat

Internationally, UN Comtrade is based on the 'Harmonized commodity description and coding system' or HS codes. The HS codes are up to 10 digits in length, with the first six digits applied at the global level and the last four at a national level, if desired. The first two digits represent chapters or general product categories; the second and third digit pairs provide increasing levels of detail and specificity.

For example, HS code 3924101000 corresponds to:

- chapter 39: 'Plastics and rubber articles'
- heading 24: 'Tableware and kitchenware'
- subheading 10: 'Salt, pepper, ketchup and similar dispensers'
- the last 10 and 00 are used by some countries for further classification

In general, trade data has been synthesised at four- or six-digit code levels in this study, although a more detailed breakdown was required for some specialist commodities.

The trade database for each candidate material was established as follows:

1. Identify all relevant raw material trade codes for each candidate material (HS codes)
2. Download trade data from various sources (HM Revenue & Customs, 2024; International Trade Centre, 2024; United Nations Department of Economic and Social Affairs, 2024)
3. Perform quality-control checks on the data (similar price values; realistic trends over time with no extreme changes; consistent magnitude and units of reporting, and that the source of trade is realistic with operating mines or refineries known to exist)
4. Upload data to the candidate material spreadsheet template, which calculates the five-year average net import for each country and the fraction of global trade this represents
5. Identify the top three net importers and calculate the HHI (Equation 4)
6. Normalise the HHI score using a scale of 1 to 10

$$Global\ trade\ concentration = \sum_{1}^{3} share\ of\ import(n)^2$$

Equation 4 Hirschmann-Herfindahl Index (HHI) calculation, where n is n^{th} country (of 3).

Although trade data are extensive, there are some common issues to be considered when it is used for detailed analysis. For example, different materials may be aggregated in a single trade code (for example, HS 811299 includes Ge, In, gallium (Ga), niobium (Nb) and vanadium (V). This makes it difficult, if not impossible, to reliably discern the quantities of each material reported under that code. In addition, trade data may be incomplete from some countries or for certain years, whilst some HS codes allow for monthly data as opposed to others that report annually.

It is also important to be aware of potential errors in trade code data, including incorrect magnitudes (for example, stated as kilograms when the data is in tonnes) and the application of an incorrect code (for example, reporting refined metal rather than metal-rich concentrates that still require refining). In a few cases, there is no realistic basis for the reported trade data (for example, a country reporting exports of Ge when they have no Zn mining or refineries).

2.2.4 Recycling rates

The recycling of materials from end-of-life (EoL) products is potentially an important way to complement primary supply. Recycling, also known as secondary supply, effectively diversifies the supply base, thereby reducing supply risks and import dependence. Secondary supply also contributes to resource conservation, lowers the environmental impacts and energy use linked to primary extraction and reduces the need for imports, thereby improving economic outcomes and resilience and reducing vulnerability.

A review of the literature on recycling rates and a wealth of terminology associated with the recycling of materials has been described in the revised methodology report (Josso et al., 2023). A conceptual representation of material flows along a supply chain is given in Figure 1, including how two key metrics for recycling are estimated: the end-of-life recycling rate (EoLRR) and the end-of-life recycling input rate (EoLRIR). The EoLRR represents how much material is collected for recycling rather than disposal, whilst EoLRIR estimates how much recycled material is used within a new material or product.

In an ideal world, both EoLRR and EoLRIR would reach 100 per cent. In practice, both parameters seldom approach this value. The reasons for this are numerous and include:

- regulatory issues
- consumer behaviour, especially cross-contamination of materials, which affects the ability to recycle or the quality of a recycled material
- system design leading to losses, such as process losses leading to waste disposal
- lack of technological capacity to recycle certain products and materials
- product design that mixes materials, which makes them harder to recycle
- the long time it can take to build sufficient stocks in urban and industrial systems to provide flows for recycling

(United Nations Environment Programme et al. (2013).)

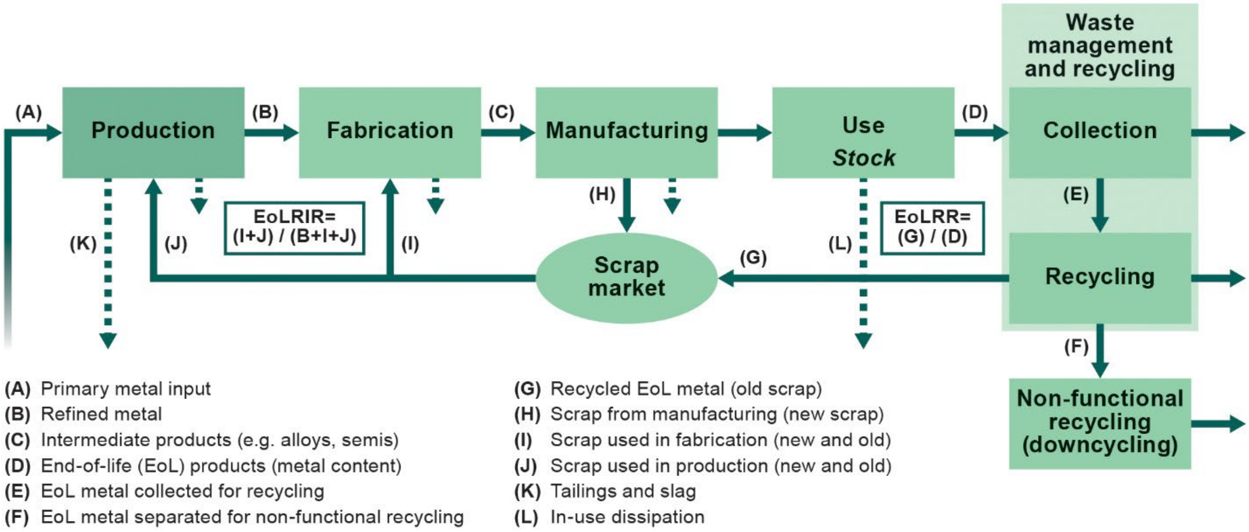


Figure 1 Typical supply chain and life cycle of materials, including the definition of end-of-life recycling collection rate (EoLRR) and end-of-life recycling input rate (EoLRIR). (Redrawn from United Nations Environment Programme et al. (2013)). Copyright © United Nations Environment Programme 2013.

EoLRIR is the most commonly used recycled content indicator (European Commission et al., 2020a; Lusty et al., 2021) and, in principle, is the best indicator to use in CAs. However, it is difficult to obtain consistent and reliable RIR values at either the global or UK level for all candidate materials. This is due largely to data gaps and inconsistencies, together with variations in the methods used to calculate the recycling rates highlighted in Figure 1 (Josso et al., 2023).

The EoLRIR and EoLRR values describe different parts of a material's supply chain (Figure 1). The EoLRIR represents the secondary feedstock share in a production process, whereas the EoLRR is a measure of the efficiency in waste management. An efficient collection and recovery system leads to higher EoLRR (for example, Fe, Cu, Pb and Au), but does not necessarily translate into higher EoLRIR due to the dynamics of primary supply, stocks, technologies involved in secondary supply chains and consumer and industry choices. In other words, the contribution of secondary material may still be low relative to primary sourcing despite a high EoLRR. For this study, we adopt EoLRR as it is more widely documented at a whole-system level.

Recycled materials, particularly minor metals, are commonly downcycled to a lower-quality use or product, rather than contributing to the feedstock requirements for their original applications. Whilst this provides an additional source of supply for downcycled end-use applications, it does not contribute to supply of typically higher-purity and commonly higher-specification material. Although the materials may not be recovered in their pure form, recycling allows many materials to be effectively re-used many times, thus supporting the development of a circular economy.

The calculation of the EoLRR for the end-use applications of each candidate material is based on the methodology outlined by Graedel et al. (2022) using Equation 5, combined with various sources for the shares of end-use applications. An example is given in Table 5.

$$EoLRR_i = \sum_{J=1}^{n} end\_use_{i,j} * EoLRR_{i,j}$$

Equation 5 Where $EoLRR_i$ indicates the EoLRR of the i^{th} material; $end\_use_{i,j}$ denotes the percentage of the j^{th} end use of the i^{th} material; $EoLRR_{i,j}$ indicates the end-of-life recycling rate of the j^{th} end use of the i^{th} material.

This approach reflects global recycling rather than UK EoLRR, hence the indicator forms a component of the global supply risk dimension. In general, the uses of major metals and industrial minerals tend to change slowly over time, meaning the available EoLRR data provides reasonable insights into the global recycling rate of individual candidate materials.

Table 5 Calculation of the EoLRR: using Cu as an example. Data from Baldé et al. (2024); EuRIC AISBL (Undated); International Copper Association (2022)).

Application or sector	Global market share of Cu (%)	EoLRR (%)
Power generation, distribution and transmission	44	90
Construction	20	90
Electric appliances	14	60
Transport	12	90
Others	10	0
Global total	**100**	**77**

2.2.5 Further considerations for assessing global supply risk

Ideally, global supply risk would be assessed for the complete supply chain, including primary production, refining, processing and manufacturing, to provide a comprehensive evaluation of bottlenecks at each stage. However, for most candidate materials, available data of adequate quality for the refining, processing and manufacturing stages are incomplete or entirely absent. In addition, numerous raw materials are combined at the manufacturing stage into compounds, components and products of varying complexity. This makes tracking the complete supply chain for even a single material very challenging. Dedicated studies focusing on specific technological sectors would be a complementary measure to enable a deeper understanding of production concentration.

The level of production concentration at each stage of the supply chain could also be investigated at the company level to determine how many companies operate in each commodity market, irrespective of the locations of the centres of production or refining. If production is concentrated in the hands of only a few companies, even if their activities are widespread geographically, the risk of supply disruption is relatively high. Similarly, the ownership and source of financing for these companies should ideally be evaluated (for example, (UNSGPCETM, 2024)) because of their importance in market dynamics and governance.

Reliable information of this type is not easily found and verified. Ownership and funding sources are also likely to change, especially during periods of rapid growth and technological change, meaning that such information must be current and old studies should not be relied upon. These aspects are beyond the scope of the current study.

2.3 UK economic vulnerability dimension

The UK economic vulnerability dimension is determined from three indicators evaluated for each candidate material:

- UK apparent consumption (AC)
- UK net import reliance (NIR)
- contribution to UK gross value added (GVA)

2.3.1 UK apparent consumption

The UK AC indicator quantifies the economic value of a candidate material to the UK economy. It combines all imports into and exports from the UK of candidate materials using the HS code system and data from UN Comtrade and UK Trade Info or others as needed (Section 2.4). Based on all relevant global trade code data averaged over 2018 to 2022 inclusive, the value of UK AC is estimated according to Equation 6.

Apparent consumption ($AC_{£}$) = $\Sigma production_{£} + \Sigma imports_{£} - \Sigma exports_{£}$

Equation 6 Estimate of UK AC. All data in £.

For some trade codes where the UK is a net exporter, the calculation returns a negative value since the value of exports exceeds UK production and imports (for example, chromium (Cr); PGEs). This is typically due to the import of waste and scrap, or other low-value material forms, which are either recycled or processed into higher-quality materials and products. These are then exported at higher value.

To normalise the AC values from 1 to 10, raw materials for which the UK is a net exporter default to 1 and the maximum value is set to 10. All other values are scaled as a proportion of the maximum (further explained in Section 2.9.1).

2.3.2 UK net import reliance

The UK NIR indicator quantifies the extent to which the UK is reliant on physical imports of a candidate material. It combines the mass of all imports to and exports from the UK of candidate materials using the HS code system and data from UN Comtrade and UK Trade Info or others as needed (Section 2.2.3). For example, the UK has no operating Cu or Fe mines, meaning it is completely (100 per cent) reliant on imports of these raw materials.

Based on all relevant trade code data averaged over the five-year period 2018 to 2022, UK NIR is estimated according to Equation 7.

NIR = $(\sum imports - \sum exports)\ /\ \sum apparent\ consumption$

Equation 7 Estimation of UK NIR in %, based on data in kilograms.

The apparent consumption is calculated in the same way as described in Equation 6 but uses mass instead of value. In most cases, the UK is 100 per cent reliant on imports, leading to a score of 10 on the normalised scale (further explained in Section 2.9.1). The issue of trade barriers is addressed later in Section 2.13.

2.3.3 UK gross value added

UK GVA is a way to measure the financial value of goods and services in the UK economy, allowing assessment at national and regional levels and across different industries or sectors of the economy. It is calculated from an annual business survey, leading to a comprehensive set of statistics covering all sectors of the UK economy. The allocation of business activity is based on 'Standard industrial classification' (SIC) codes (Office for National Statistics, 2007). These are similar to HS codes in trade data and map business activity to subsections of major industrial sectors. For example, two-digit SIC codes map major industrial sectors (for example, 07 is metal mining; 26 is electronics manufacturing), whilst four-digit SIC codes map to specific parts of each industrial sector (or example, 07.29 is mining of non-ferrous metal ores; 26.51 is manufacture of instruments and appliances for measuring, testing and navigation). The previous UK Criticality Assessment (Lusty et al., 2021) mapped candidate materials to specific economic activities at the two-digit code level.

It should be noted that the CA methodology review (Josso et al., 2023) identified various issues in the division of GVA according to individual materials. These included:

- lack of accurate sector-use data, especially as this changes over time
- difficulty in mapping economic value against manufacturing sectors when such activity or value cuts across multiple sectors
- challenge of attributing economic importance to a candidate material, especially when the mass utilised is small (for example, minor metals, such as Te and Ga)

For example, elements included in the manufacturing of semi-conductors, such as silicon (Si), tantalum (Ta), Ga and Ge, are attributable to the GVA of the electronics manufacturing sector (SIC code 26), rather than the GVA of all the sectors using microchips and other electronic components (for example, computers; phones; cars; planes; financial services, etc.), which represent a wide array of SIC codes far exceeding SIC code 26 alone.

For this study, we incorporate the GVA into the UK economic vulnerability dimension to link a candidate material to the particular economic sectors in which it is used. In general, the same end-use sectors identified in the recycling rate indicator are mapped as closely as possible against SIC codes, or completed with additional details depending upon availability of data (see Appendix 1). We have reviewed previous CAs from the UK (Lusty et al., 2021) and EU (European Commission, 2023) and developed a new schema that maps candidate materials to SIC codes at the four-digit level. This allows for a more direct link between the use of candidate materials to specific economic activities at the four-digit level, thereby giving more realistic GVA estimates for each candidate material.

To develop the GVA indicator, data for end-use sectors is collected, linking economic data for end uses to those from the recycling stage to the extent that the data allows. Next, four-digit SIC codes are allocated against each end use greater than 10 per cent. (Any share smaller than this is considered negligible in the context of this assessment). The total GVA is then calculated as the proportional value of all end-uses and their respective GVA values (Equation 8).

$$GVA_j = \sum_{J=1}^{n} (\%share\ of\ sector_{i,j} * GVA_i)$$

Equation 8 Calculation of total GVA, where i is sector, j is share, n is number of sectors.

The GVA results are then scaled from 1 to 10, further explained in Section 2.9.1). Given the importance of diversified economic sectors across the UK, it was considered important to include GVA in this assessment rather than to exclude it, as was recommended by Josso et al. (2023).

2.4 Future technology-driven demand

The revised CA methodology (Josso et al., 2023) proposed the development of technology-specific foresight studies to represent the increased material demands driven by that technology. For example, a detailed assessment of the future growth in battery demand for electric vehicles would need to evaluate all the key materials of Li-based batteries. Depending on battery chemistry, this could include Ni, manganese (Mn), Co, graphite, Fe and phosphate. Such a study could explore various scenarios for the deployment of electric vehicles over time combined with different assumptions of changing battery chemistry. The derived time series of future material demand compared with data on historical supply would allow this indicator to be quantified. For this study, we did not include demand foresights in in the calculation of UK economic vulnerability and then criticality. The demand foresight studies completed focussed on decarbonisation technologies, leading to demand predictions for 28 raw materials. There are 82 candidate raw materials for this CA, meaning that if we did proceed to include a calculation process for adjusting the 28 demand foresight-related raw materials, the other 56 candidate raw materials would not be adjusted in any way. Some of these 56 raw materials, however, can be expected to see rapid growth, such as V used in redox flow batteries used for grid energy storage. Therefore, to avoid introducing inaccuracies into the calculation of UK economic vulnerability and criticality, an approach of case studies for selected materials was adopted. Further discussion of foresight studies is given in Section 4.3.

2.5 Criticality scores, graphical representation and thresholds

2.5.1 Normalisation of indicator scores

All indicators have been normalised to a scale of 1 to 10 so that they can be integrated into the calculation of the two primary dimensions: global supply risk (S) and UK economic vulnerability (V). This approach ensures that all components are scored in the same way before calculating the S and V dimensions. When possible, the normalisation process aims to use the full range of possible values for the indicator, rather than the observed range in the data, to maintain proportionality and better reflect the true distribution of the data population. The full range can be defined for the EoLRR and NIR indicators, which vary between 0 and 100 per cent, or between 0 and 400 for companionality.

An absolute maximum value for the ESG-weighted mined and refined production concentration, GTC, GVA, and UK AC indicators cannot be produced. Therefore, the minimum and maximum values observed for each indicator, respectively, are used for normalisation to the 1 to 10 scale. This results in an increased spread in the ranking of each candidate material on these indicators, as shown in Table 6.

Table 6 Examples of the conversion from raw to normalised scores (indexed from 1 to 10).

Range	Raw score (0 to 100%)	Normalised score	Raw score (minimum / maximum)	Normalised score
Minimum	0	1.0	1310	1.0
Possible value #1	23	3.1	15512	4.1
Possible value #2	57	6.1	23908	6.0
Possible value #3	75	7.7	34735	8.3
Maximum	100	10.0	42250	10.0

2.5.2 Calculation of supply and vulnerability dimension scores

Combination of indicator values into scores for the S and V dimensions is achieved through the use of a geometric mean (Equation 9). Using this mathematical function, rather than the arithmetic mean or summing the indicator scores, results in a more robust representation of indicator scores expressed in different units and where dimensions contain different numbers of indicators or could be temporally correlated (Josso et al., 2023). This scoring is preferable to binning the data into categories of low/medium/high scores, which leads to a loss of data resolution and artificially inflates differences between categories.

$$\text{Geometric mean} = \sqrt[n]{(x_1 * x_2 * \ldots * x_n)}$$

Equation 9 Combination of n indicator values into scores for the S and V dimensions.

Assuming a set of weighting factors, $w = (w_1; w_2; \ldots ; w_n)$, the weighted geometric means becomes Equation 10.

$$\text{Dimension} = \exp\left(\sum weighting_i * \ln(indicator)_i\right) / \sum weighting$$

Equation 10 Weighted geometric means for i materials.

In this situation, as the weighting factors are percentages adding up to 100 per cent, the last component in this formula equals 1. Equation10 is therefore simplified to Equation 11.

$$\text{Dimension} = \exp\left(\sum weighting_i * \ln(indicator)_i\right)$$

Equation 11 Simplified Equation 10 for i materials.

In this CA, for global supply risk, the following weighting values were adopted:

- PCI: 75 per cent
- GTC: 10 per cent
- CMF: 10 per cent
- recycling: 5 per cent

These weightings were chosen as they highlight that the area of greatest supply risk starts with primary extraction (mining) and subsequent processing (refining). On the other hand, global trade is more dispersed; co- and by-product status cannot be changed; and recycling rates are often low and are difficult to improve. Furthermore, based on expert judgement, world mining and refining data are considered to be excellent quality, whereas global trade and companionality data are more complex (as described above) and recycling data retains some uncertainty given the lack of comprehensive studies. For these reasons, the weightings have been assigned in such a way as to place the focus on global production concentration. Finally, multivariate testing shows that giving a reduced weighting to production concentration tends to reduce the spread in plotting, thereby reducing the ability to clearly distinguish critical from non-critical minerals. In other words, production concentration remains a dominant factor in global supply risk and this needs to be accounted for in its weighting factor.

For UK economic vulnerability, the following weighting values were adopted:

- UK AC: 35 per cent
- UK NIR: 45 per cent
- GVA: 20 per cent

These were chosen to reflect the economic value of consumption (AC) and, if an economy is dependent on imports, this is relatively more important than consumption. A modest weighting is assigned to GVA to account for the link between a material and its economic sector and use. Similar to global supply risk, a lower weighting factor is used for GVA given the uncertainty in how accurately the GVA data actually represents the uses of materials for different economic sectors.

These weightings are similar to those adopted in the 2021 assessment (Lusty et al., 2021). The weightings to be adopted were discussed during stakeholder consultation, where broad agreement was noted on the justification and values adopted. A complete worked example is shown in Table 7.

Table 7 Examples of estimating dimension scores based on normalised indices and incorporated weightings (Equation 11). PCI: production concentration indicator; GTC: global trade concentration; C: companionality; RR: end-of-life recycling collection rate (EoLRR, also referred to as recycling); AC: UK apparent consumption (value basis); NIR: net import reliance; GVA: gross value added.

	Global supply risk (S)				**UK economic vulnerability (V)**			**Dimension scores**		**Criticality score**
	PCI	GTC	C	EoL RR	AC	NIR	GVA	S	V	
Weighting	0.75	0.1	0.1	0.05	0.35	0.45	0.20			
Material #1	1.9	2.6	1.0	10	6.2	5.6	1.4	2.0	4.4	3.0

2.5.3 Criticality score and critical space representation

The plotting of the two dimensions of global supply risk and UK economic vulnerability against each other in graphical form (an X-Y graph) creates a two-dimensional area to plot results. This is also known as the ‘critical space matrix’. In this assessment, it uses convex isocritical contours, or curves of equal value, to separate critical from non-critical minerals. This geometry is adopted from risk management, where risk is the product of the two axes of probability and severity (Josso et al., 2023). In this study, criticality is defined as the product of global supply risk and UK economic vulnerability. To maintain the scale within 1 to 10, the final criticality score for each material is calculated as in Equation 12.

$$\text{Criticality} = \sqrt{(\text{economic vulnerability} * \text{global supply risk})}$$

Equation 12 Final criticality score calculation.

This implies that lines of equal criticality score will be convex, rather than orthogonal (or straight lines). This representation allows a more logical interpretation of the degrees of criticality as a function of global supply risk and economic vulnerability, as shown in Figure 2.

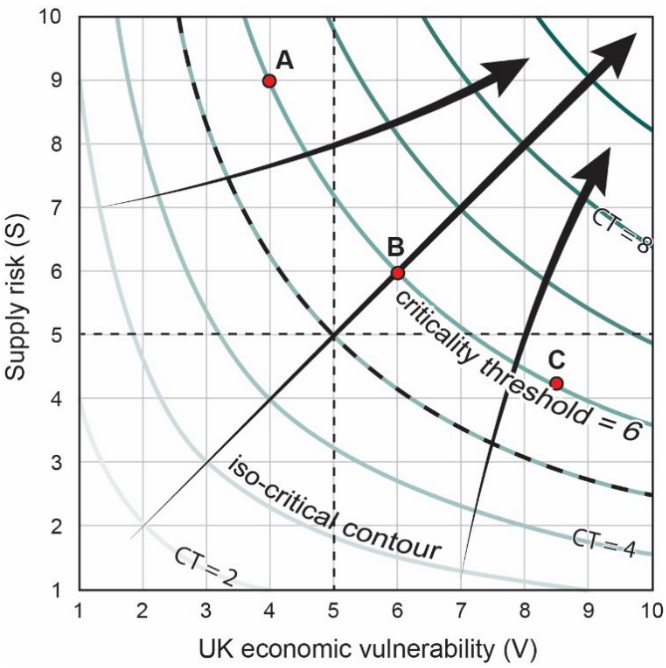


Figure 2 The use of isocritical contours to represent lines of equal criticality (for example, 6 6), also referred to as criticality thresholds (adapted from risk management). (Josso et al., 2023)

For example, materials A, B and C in Figure 2 all have the same criticality score of 6. Using orthogonal criticality threshold lines set at 5 for each dimension (represented by dashed lines on the plot in Figure 2) would lead to only material B being classified as critical, despite materials A and C having the same criticality score of 6.

Defining contours as convex lines has three main advantages over orthogonal thresholds commonly used in previous assessments (European Commission, 2023; Lusty et al., 2021):

- criticality increases in clear, regular steps, demarcated by single lines rather than a pair of lines representing each criticality dimension

- a convex geometry avoids the serious issue in the classification of the degree of criticality where materials plot close to one or other of the orthogonal thresholds commonly utilised in CA. For such materials, a small change in the value of any metric could have a significant impact on the criticality classification, thus diminishing the robustness of the assessment (Figure 2)
- the top-right quadrant (high criticality) resulting from orthogonal thresholds fails to classify candidate materials that do not meet one of the dimension thresholds as critical (such as materials A and C in Figure 2), despite them scoring very highly on one dimension. As such, convex contours allow a more accurate representation of critical space

2.5.4 Definition of criticality threshold

The definition of a criticality threshold is the most subjective stage in the CA process. Scoring all candidate materials is a relatively standard mathematical process, based on quantitative data and resulting in a set of reproducible scores. In contrast, the choice of where to position the threshold that distinguishes critical and non-critical minerals is subjective. This decision is highly significant as the list of critical minerals serves as an essential tool to guide investment, research and development and policy interventions, which are in turn informed by the data synthesised during the CA.

A consultation exercise was undertaken with representatives from Government, industry and academia to discuss the implications of where to position the criticality threshold. Ultimately, this decision needs to reflect the ambition of Government to invest in de-risking the supply chains of the raw materials classified as critical minerals.

During this consultation exercise, participants were presented with results of the CA and asked where the criticality threshold should be positioned. The position of individual candidate materials within the criticality matrix was fixed, whilst the implications of defining a particular contour as the critical threshold were explored. The criticality threshold adopted is discussed after the presentation of results in Section 3.

2.6 Methodology amendments and adopted criticality matrix

In the early stages of this CA, it became apparent that two aspects of the methodology recommended by Josso et al. (2023) should be amended, namely trade barriers and demand foresights. In addition, changes were required to a small number of candidate materials as well as a process to describe data quality.

2.6.1 Changes to the methodology: trade barriers

The incorporation of trade barriers in CA is complex and fraught with numerous methodological and data reliability challenges. Other assessments have used the frequency of embargoes, tariffs and quotas to develop a score for trade barriers (for example, European Commission (2023)). Although this approach is potentially useful, it is based on data of highly variable quality. For instance, trade barriers can be established at any time, even without any historical precedent or tendency to apply such measures. Such barriers may be applied to an entire sector or commodity (such as China's REE export quotas of 2010) or to specific materials, commodities or technologies. Furthermore, the use of a historical dataset (for example, (Organisation for Economic Co-operation and Development, 2020)) is not a reliable predictor of future trade barriers or their potential severity, nor does the dataset cover all countries or candidate materials (Lusty et al., 2021).

The inclusion of trade barriers in the assessment should also take account of international trade agreements, which are designed to facilitate trade. In considering how to incorporate trade barriers in the analysis, it is necessary to distinguish between barriers applied at the country level — in which case any factor would apply to all trade data — and those for specific commodities, products or technologies. Such barriers would have to be assessed for hundreds of trade codes and, in the case of process-related technologies (for example, process technologies for manufacturing REE-based permanent magnets), there are no HS codes against which to apply such trade barriers.

Given the methodological complexity and the lack of sufficiently robust and complete data for all countries, trade codes and candidate materials, trade barriers have been excluded from the calculation of UK economic vulnerability. Instead, selected case studies of trade barriers for different candidate materials are discussed in Section 4.5.

2.6.2 Changes to the methodology: demand foresights

A common challenge for CAs is that they represent a point in time and use recent, but still historical, data. Ideally, CAs should also incorporate a future demand indicator based on past production, expert analysis of future trends and scenarios for demand growth. The data and assumptions underlying these are generally quite variable and uncertain, and they cannot be reliably applied to numerous materials over an extended time period. For example, Drexhage et al. (2017) noted that 'energy storage is regarded as the most difficult to predict and therefore the most uncertain' (p. 16).

A better way to incorporate future demand growth into CA would be to undertake in-depth, top-down foresight studies. For example, various scenarios for the growth of wind turbine deployment over time could be evaluated. Together with associated material intensity models, these would allow estimation of future material demands. An evaluation of this type, allied to those for material demand in other technologies, would be a valuable tool in planning to ensure adequate, secure and sustainable supplies in the future.

To explore the trend in future material demand for the UK related to major decarbonisation technologies up to 2050, CMIC conducted nine foresight studies[2] on:

- solar photovoltaics (Petavratzi et al., 2024e)
- traction motors (Petavratzi et al., 2024b)
- electric vehicle batteries (Petavratzi et al., 2024d)
- nuclear power (Jackson et al., 2024b)
- electrolysers and H-fuel cells (Zils, 2024b; Zils, 2024c)
- wind turbines (Petavratzi et al., 2024c)
- heat pumps (Zils, 2024a)
- the electrical grid (Jackson et al., 2024a)

A synthesis report (Petavratzi et al., 2024a) explores the interactions of cross-sector competition and global demand for 28 materials (for example, Li, Nb, Ni and Co, amongst others). There are many other technological changes underway in both the UK and global economies, including:

- digital transformation, including the rise of artificial intelligence and the emergence of quantum computing
- fossil-fuel phase out
- construction
- grid-scale energy storage systems, such as V redox flow batteries

The CMIC foresight studies do not cover the materials required for such technologies and changes. In other words, the foresight studies cover 28 materials but miss two-thirds of the 82 candidate materials, and so anticipated changes in demand cannot be incorporated in a

---

[2] All CMIC foresight studies, plus the synthesis report, are due for public release in late 2024.

quantitative way for calculating criticality. For this reason, it was decided not to include a demand foresight-related indicator in the UK economic vulnerability dimension. Instead, the findings from the UK demand foresight analyses, combined with available global demand scenarios for selected key materials (Li; permanent magnet-related REEs; Cu) have been explored to determine how economic vulnerability could change under different global demand scenarios (Section 4.3).

2.6.3 Changes to the candidate raw materials list

Several candidate raw materials have been excluded from this analysis for various reasons, chiefly due to lack of data or overlap between individual commodities. The key changes from the candidate materials list (Table 1) are:

- excluded due to lack of production and/or trade data:
    - caesium (Cs)
    - natural H
    - rubidium (Rb)
    - thallium (Tl)
    - thorium (Th)
    - wollastonite
    - zeolite
- mercury (Hg) has been excluded because it is no longer used as a raw material, with modest UK trade activity relating to waste management only. The Minamata Convention on Hg was agreed and signed in 2013 and came into force on 16 August 2017, leading to strict provisions on all uses and trade of Hg and Hg-containing products (United Nations Environment Programme, 2019)
- where there are both mineral and metallic uses of an element (for example, titanium (Ti) in metal form or as the oxide rutile (TiO_2)), we have aligned the analysis based on the dominant forms used. For example, barium (Ba) is almost entirely used in mineral form as barite, meaning all data were synthesised and assessed as barite
- simplification and removal of duplications was carried out for various materials with almost identical production and trade data:
    - Ba included in barite
    - boron (B) included with borates
    - fluorspar included with fluorine (F)
    - phosphate rock included in phosphorus (P)
    - pyrite data attributed to Fe (roasted pyrite) or S (unroasted pyrite)
    - carbon (C) included with graphite (natural)
- name changes were adopted to distinguish industrial process use of these minerals (for example, in chemical plants) from those in the quarrying, aggregates and construction sectors (for example, limestone used as road base or sand used in construction):
    - silica sand was changed to industrial (silica) sand
    - limestone to industrial limestone
    - rock salt (NaCl) to industrial salt
    - sodium (Na) to sodium compounds (includes mostly sodium carbonate (Na_2CO_3), with some sodium nitrate ($NaNO_3$) and minor amounts of Na metal)

2.6.4 Data quality

Much of the data used in this CA can be considered accurate and reliable. However, expert judgement and experience have highlighted concerns about the quality of some published datasets and served to emphasise the need for continual scrutiny of reported data.

There are instances where trade and other data are implausible or incorrect. For example, UN Comtrade data for 2019 shows 6.2 million tonnes (t) of ores and concentrates exported from Mozambique under HS261590 ((United Nations Department of Economic and Social Affairs, 2024), which includes V, Ta and Nb, despite no operating V or Nb mines and only 132 t of Ta in

2019 (Idoine et al., 2024). Total world production of V and Nb in 2019 was 111 000 and 84 000 t, respectively (Idoine et al., 2024), confirming that the Mozambique data is in error.

Another example is provided by the reported export from Peru of almost 1900 t of uranium (U) ores and concentrates in 2019 and 2020. This data is considered incorrect because there is no operating U mine or pilot project in Peru nor any record of U imports that might be available for re-export. Moreover, there is no officially recognised U production reported for Peru at the international level (that is, no production recorded by (Nuclear Energy Agency et al., 2022; World Nuclear Association, 2024a; Idoine et al., 2024)).

As part of quality control and quality assurance (QA/QC), all trade data has been carefully checked for unexpected patterns and trends over time, for unusual or rapid shifts in commodity prices and for major changes in reported volumes, which may reflect the use of incorrect units. Where trade data was missing, alternative sources were checked (Section 2.4) and compared to UN Comtrade and UK Trade Information, using expert judgements on whether to merge such data or leave blank. Given the extent (large data volumes) of some trade codes and their complexity (for example, HS code 811292 includes five elements — Ga, Ge, In, Nb and V — that are mostly geologically exclusive to each other and do not crossover in materials used in modern technologies), together with uncertainty regarding metal contents (for example, waste and scrap; semi-manufactured goods), expert judgement was required to determine how data was used or adjusted.

After all QA/QC checks were completed, a final data-quality categorisation using a traffic light system was adopted (Appendix 2).

- Green: complete, up-to-date, reliable (for example, all five years of data; data consistent and certain)
- Amber: partially useable (for example, data for a single year only; some inconsistencies or uncertainties in data or metal contents)
- Red: unreliable or not available (for example, no data or high uncertainty; apparent errors)

Where a candidate material received four or more amber scores, it was considered of poorer quality but still judged reasonable to include in results; materials with two or more red ticks were excluded from the results and criticality plot.

2.6.5 Criticality matrix and plot

The complete CA methodology used in this study is illustrated in Figure 3 with final equations for each indicator, dimension and key data sources given in Table 8.

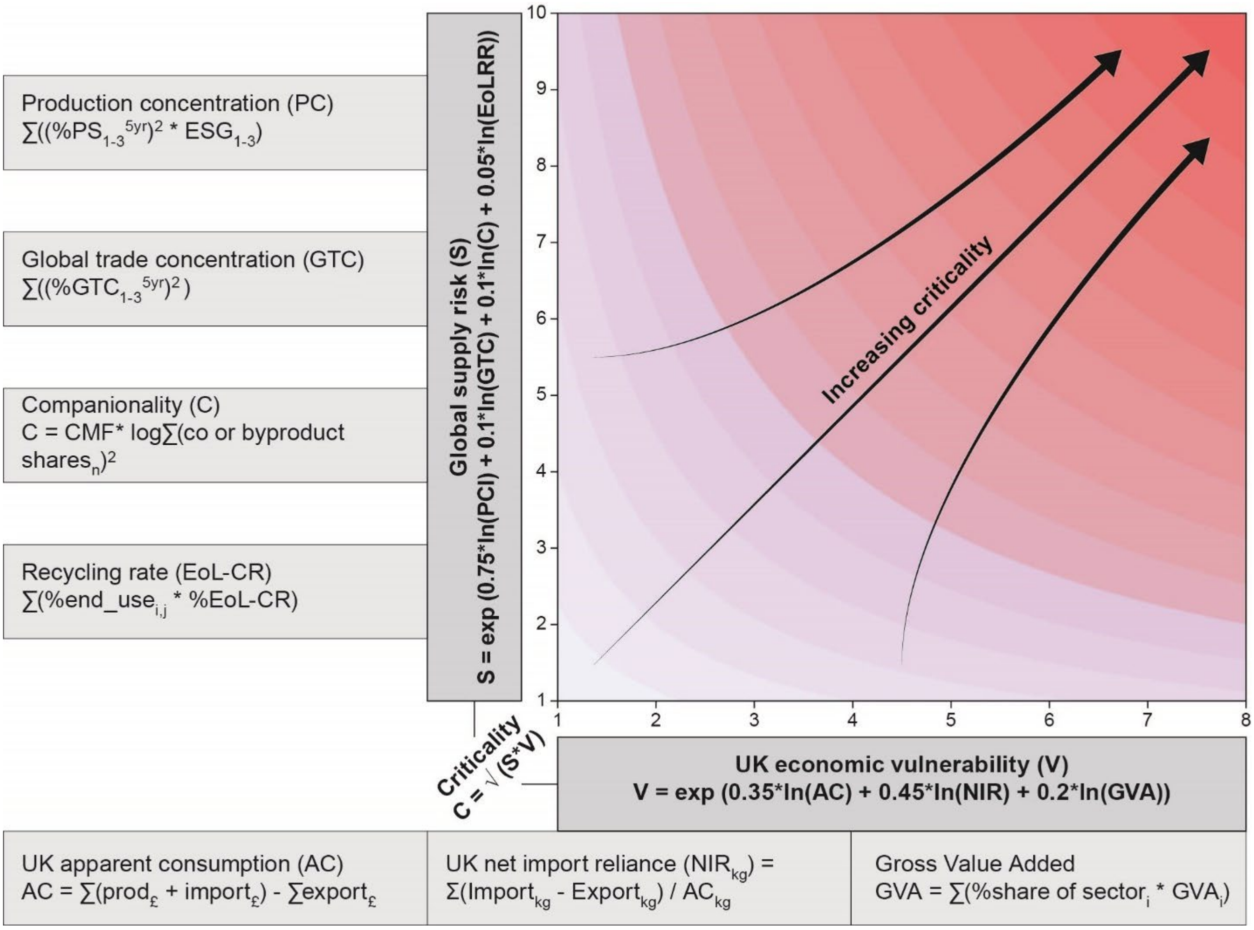


Figure 3 Summary of the UK Criticality Assessment matrix, showing the four indicators used to calculate the global supply risk (S) and the three indicators to calculate UK economic vulnerability (V). The criticality score (C) is the geometric mean of the product of both axis values (Josso et al., 2023). BGS © UKRI.

Table 8 Key indicator equations and data sources for the CA. References: BGS (Idoine et al., 2024; Bide et al., 2024); USGS (U.S. Geological Survey, 2024a; U.S. Geological Survey, 2024b); World Bank – world governance indicators (World Bank, 2024); Yale University – environmental performance index (Wolf et al., 2022); UNDP – human development index (United Nations Development Programme, 2024); UN Comtrade (United Nations Department of Economic and Social Affairs, 2024); UK Trade Info (HM Revenue & Customs, 2024); ITC (International Trade Centre, 2024); OEC (The Observatory of Economic Complexity (2024); UK ONS (Office for National Statistics (2024).

Indicator	Equation	Data sources
Mining concentration	$MI = \sum_{1}^{3}(5\ yr\ avg.\%\ of\ global\ production(i,n)^2 * ESG(i))$	BGS; USGS; specialist sources/syntheses
Refining concentration	$RI = \sum_{1}^{3}(5\ yr\ avg.\%\ of\ global\ production(i,n)^2 * ESG(i))$	BGS; USGS; specialist sources/syntheses

Indicator	Equation	Data sources
ESG index	ESG = $\sqrt[3]{}$ (EPI(i) * HDI(i) * WGI(i))	World Bank (WGI); Yale University (EPI); UNDP (HDI)
Production concentration	PCI = maximum (MI, RI)	This study
Companion-ality	$Companionality = companion\ metal\ fraction * \log \sum_{1}^{n} \text{co or byproduct shares } (n)^2$	BGS; USGS; specialist sources/syntheses
Global trade concentration	$GTC = \sum_{1}^{3} share\ of\ import(n)^2$	UN Comtrade; UK Trade Info; ITC; OEC; BGS
End-of-life collection rate	$EoL - CR_i = \sum_{J=1}^{n} end_{use_{i,j}} * EoL - CR_{i,j}$	Various industry, Government and academic sources
Global supply risk	$S = \exp\ (\sum weighting_i * \ln\ (indicator)_i) / \sum weighting$	This study
UK apparent consumption	$AC_£$ = production$_£$ + imports$_£$ – exports$_£$ (based on £value in trade data)	UN Comtrade; UK Trade Info; ITC; OEC; BGS
UK net import reliance	NIR = (imports$_{kg}$ – exports$_{kg}$) / AC_{kg} AC_{kg} = production$_{kg}$ + imports$_{kg}$ – exports$_{kg}$ (based on mass in trade data)	UN Comtrade; UK Trade Info; ITC; OEC; BGS
Gross value added	$GVA_j = \sum_{J=1}^{n} (\%share\ of\ sector_{i,j} * GVA_i)$	UK ONS
UK economic vulnerability	$V = \exp\ (\sum weighting_i * \ln\ (indicator)_i) / \sum weighting$	This study
Criticality	C = √ (S * V)	This study

3 Results

3.1 Principal results

The normalised scores for all indicators are shown in Table 9. Complete results for each indicator are given in Appendices 3, 4, 5, 6 and 7.

Table 9 Normalised scores for each indicator used in the CA. For the production concentration indicator (PCI), the higher value of the mined and refined scores is used. Abbreviations: M is mining; R, refining; PCI, production concentration indicator; GTC, global trade concentration; C, companionality; EoLRR, end-of-life recycling collection rate; AC, apparent consumption; NIR, net import reliance; and GVA, gross value added; ND, no data; NR, not relevant.

Candidate material	Global supply risk						Economic vulnerability		
	M	R	PCI	GTC	C	EoLRR	AC	NIR	GVA
Aluminium (Al)	2.2	3.8	3.8	6.1	1.0	3.6	7.1	6.1	2.1
Antimony (Sb)	4.1	4.7	4.7	1.7	3.5	8.2	3.7	9.3	1.7
Arsenic (As)	NR	4.2	4.2	2.4	9.1	10.0	1.5	10.0	1.4
Beryllium (Be)	3.7	3.2	3.7	1.9	2.2	9.5	3.2	8.0	1.8
Bismuth (Bi)	4.3	7.5	7.5	2.5	8.7	10.0	1.9	10.0	2.3
Cadmium (Cd)	NR	2.0	2.0	6.3	9.6	8.4	2.0	10.0	1.1
Chromium (Cr)	3.8	2.8	3.8	9.2	1.5	3.0	1.0	10.0	2.6
Cobalt (Co)	7.9	5.6	7.9	10.0	9.3	5.7	5.3	9.8	1.1
Copper (Cu)	1.5	2.0	2.0	6.8	1.3	3.1	5.5	10.0	1.2
Gallium (Ga)	NR	10.0	10.0	1.5	9.9	8.5	1.0	10.0	2.9
Germanium (Ge)	NR	9.5	9.5	3.0	9.4	7.3	2.1	10.0	2.2
Gold (Au)	1.0	ND	1.0	2.5	3.3	1.5	10.0	10.0	1.8
Hafnium (Hf)	NR	3.2	3.2	1.9	10.0	7.5	3.7	10.0	1.2
Helium (He)	NR	2.8	2.8	5.3	10.0	7.6	5.8	10.0	1.7

Candidate material	Global supply risk						Economic vulnerability		
	M	R	PCI	GTC	C	EoLRR	AC	NIR	GVA
Indium (In)	NR	4.8	4.8	1.8	9.8	9.0	1.9	10.0	1.7
Iron (Fe)	1.9	3.6	3.6	2.9	1.0	2.5	7.6	10.0	3.9
Lead (Pb)	2.8	2.5	2.8	2.7	1.5	2.7	4.2	10.2	1.1
Lithium (Li)	2.8	4.6	4.6	5.6	4.3	9.7	4.6	7.7	1.3
Magnesium (Mg)	NR	9.7	9.7	1.0	1.1	5.8	4.4	10.0	2.1
Manganese (Mn)	2.2	1.0	2.2	7.2	1.0	3.3	5.5	10.0	4.2
Molybdenum (Mo)	2.7	2.8	2.8	1.7	6.4	6.1	2.5	10.0	2.2
Nickel (Ni)	2.6	1.8	2.6	8.2	3.0	4.6	6.3	10.0	1.9
Niobium (Nb)	9.6	8.5	9.6	2.4	1.1	9.2	4.8	10.0	3.9
Phosphorus (P)	3.1	6.9	6.9	2.7	1.0	10.0	6.5	9.5	2.5
Potassium (K)	1.9	NR	1.9	2.6	1.0	10.0	6.2	5.6	1.6
REEs	5.6	8.5	8.5	1.8	6.5	10.0	3.5	10.0	3.1
Rhenium (Re)	3.7	1.9	3.7	2.0	9.6	6.1	1.0	10.0	10.0
Selenium (Se)	NR	1.9	1.9	2.1	9.7	9.1	2.6	10.0	2.3
Silicon (Si)	6.0	6.2	6.2	1.6	1.0	8.6	6.6	9.6	2.0
Silver (Ag)	1.8	ND	1.8	2.5	6.3	5.9	6.4	10.0	1.6
Sodium (Na)	3.5	ND	3.5	1.3	1.0	10.0	5.7	10.0	2.4
Strontium (Sr)	3.6	NR	3.6	2.3	1.0	9.8	1.3	10.0	1.0
Sulphur (S)	1.4	NR	1.4	2.8	9.8	10.0	4.6	10.0	2.8
Tantalum (Ta)	3.8	2.5	3.8	5.8	2.1	8.8	3.3	10.0	1.6

Candidate material	Global supply risk						Economic vulnerability		
	M	R	PCI	GTC	C	EoLRR	AC	NIR	GVA
Tellurium (Te)	NR	4.3	4.3	3.7	8.5	6.8	1.9	10.0	2.5
Tin (Sn)	2.6	3.4	3.4	3.9	1.0	7.0	5.7	9.9	2.9
Titanium (Ti)	2.1	3.5	3.5	3.2	5.1	9.1	6.4	9.9	1.4
Tungsten (W)	7.9	ND	7.9	2.8	1.2	7.2	4.6	10.0	1.2
Uranium (U)	2.8	ND	2.8	3.3	1.3	9.4	3.9	10.0	2.8
Vanadium (V)	5.6	3.2	5.6	1.3	8.7	2.4	4.2	10.0	2.4
Zinc (Zn)	1.9	2.5	2.5	3.1	2.3	7.0	6.6	10.0	1.9
Zirconium (Zr)	2.4	2.4	2.4	8.2	9.9	10.0	1.0	10.0	1.5
Platinum (Pt)	6.3	ND	6.3	5.1	2.0	8.4	1.0	10.0	4.7
Rhodium (Rh)	7.8	ND	7.8	3.2	9.7	7.5	1.0	10.0	4.7
Iridium (Ir)	8.3	ND	8.3	3.9	9.8	10.0	1.0	10.0	1.7
Palladium (Pd)	4.1	ND	4.1	2.1	4.7	7.3	1.0	10.0	4.6
Ruthenium (Ru)	10.0	ND	10.0	3.9	9.9	10.0	1.0	10.0	2.6
Barite	2.6	NR	2.6	3.4	1.0	9.4	4.5	5.1	1.8
Bentonite Clay	1.8	NR	1.8	1.2	1.0	7.7	2.2	10.0	1.2
Borates	4.2	NR	4.2	3.9	1.0	8.2	4.4	10.0	2.2
Diamonds	2.2	NR	2.2	4.6	1.0	10.0	4.3	10.0	1.4
Diatomite	2.0	NR	2.0	1.5	1.0	9.6	4.5	10.0	1.3
Feldspar	2.4	NR	2.4	3.5	1.0	9.4	2.7	10.0	1.6
Fluorine	6.1	NR	6.1	1.7	1.0	10.0	4.0	1.0	2.1

Candidate material	Global supply risk						Economic vulnerability		
	M	R	PCI	GTC	C	EoLRR	AC	NIR	GVA
Garnet	3.0	NR	3.0	1.2	1.5	10.0	2.8	10.0	1.0
Graphite (natural)	5.5	NR	5.5	2.2	1.0	8.5	1.9	10.0	1.8
Gypsum	1.0	NR	1.0	1.7	1.0	7.9	5.7	5.0	1.1
Kaolin clay	1.7	NR	1.7	1.6	1.0	6.6	4.7	1.0	3.2
Kyanite	4.0	NR	4.0	1.8	1.0	10.0	3.1	10.0	1.2
Industrial limestone	6.6	NR	6.6	3.4	1.0	4.7	5.5	1.0	1.9
Magnesite	5.0	NR	5.0	2.1	1.0	5.3	3.7	10.0	1.8
Perlite	2.4	NR	2.4	1.3	1.0	10.0	3.1	10.0	1.5
Pumice	2.8	NR	2.8	2.5	1.0	10.0	3.6	10.0	1.7
Pyrophyllite	2.0	NR	2.0	3.2	1.0	9.3	4.2	10.0	1.2
Industrial salt	1.5	NR	1.5	2.7	1.0	10.0	6.3	3.1	2.0
Industrial (silica) sand	2.1	NR	2.1	1.9	1.0	8.6	6.1	1.1	1.9
Talc	2.3	NR	2.3	1.4	1.0	5.9	4.5	9.6	3.1
Vermiculite	2.7	NR	2.7	1.3	1.0	10.0	2.9	10.0	1.4
Average	3.1	3.4	3.7	2.8	3.4	6.8	3.4	7.8	1.9

The results presented in Table 9 highlight certain key points for each indicator.

3.1.1 Production concentration indicator

The highest scaled PCI scores are for Ga and Ru at 10.0, reflecting the dominance of China and South Africa, respectively. The two lowest scores are for Au and gypsum (both 1.0), due to their highly diversified mining sectors. Industrial minerals average 2.9, whilst metals average a score of 4.7; this highlights that industrial minerals are typically mined more widely across the world in contrast to metals, which are generally concentrated in their global supply.

Production data between 2018 and 2022 for the top three producing countries (Appendix 3) clearly underscores the frequency of China as a leading producer, with countries such as the USA, Australia, South Africa, Brazil, Canada and Turkey prominent for particular commodities. In particular, where data is available, China appears as a top three producer in 36 of the mining and 29 of the refining stages.

Other selected examples include:

- China accounts for 94.9 per cent of refined Ga
- China accounts for 92.2 per cent of refined Ge
- Brazil accounts for 90.9 per cent of mined Nb
- South Africa averages 90.5 per cent, 81.6 per cent, 78.8 per cent, 69.0 per cent and 35.4 per cent of mined Ru, iridium (Ir), rhodium (Rh), platinum (Pt) and palladium (Pd), respectively, reflecting the dominance of South Africa in mine production of the PGEs
- Democratic Republic of the Congo (DRC) accounts for 69.1 per cent of mined Co, with China accounting for 70.6 per cent of refined Co
- China accounts for 64.0 per cent of mined REE oxides and 86.8 per cent of refined REE oxides
- Chile accounts for 54.9 per cent of refined Re
- Australia accounts for 49.4 per cent of mined Li, with China 56.6 per cent of refined Li
- Australia accounts for 36.5 per cent of mined Fe ore, with China 55.8 per cent of crude steel and pig iron supplies

Metals, such as Cu, Au and Ag, and many industrial minerals are so widely mined that no single country dominates global supply.

3.1.2 Global trade concentration indicator

The GTC indicator provides a representation of the geographical distribution of demand across the world and has a broad distribution of scores showing the relatively dispersed nature of global trade. The mean for GTC is 2.8, compared to mining concentration at 3.1, refining concentration at 3.4 and PCI at 3.7 (for example, antimony (Sb) scores 4.7 for PCI but 1.5 for GTC). These results demonstrate that global demand for raw materials is widely spread, in contrast to the concentration of primary supply.

3.1.3 Companionality indicator

The extent to which elements can be considered primary, co- and by-product or by-product only is shown in Figure 4, developed from CMIC expert knowledge and key studies such as Nassar et al. (2015) and (Graedel et al., 2022). Of the candidate materials, 31 were quantified using country production data and assigning mineral deposit types at the country level and 47 were assessed using global mineral resource studies. This provides a substantial improvement in the estimates for companionality used in this assessment compared with the previous UK study (Lusty et al., 2021).

It is worth noting that the higher-scoring elements are commonly by-products recovered only at smelters or refineries (for example, cadmium (Cd) 9.6; In 9.8; Ga 9.9; Te 8.5; hafnium (Hf) 10.0). These values contrast markedly with those for the major industrial metals that have low companionality scores (for example, Cu 1.3; Fe 1.0; Sn 1.0; Pb 1.5).

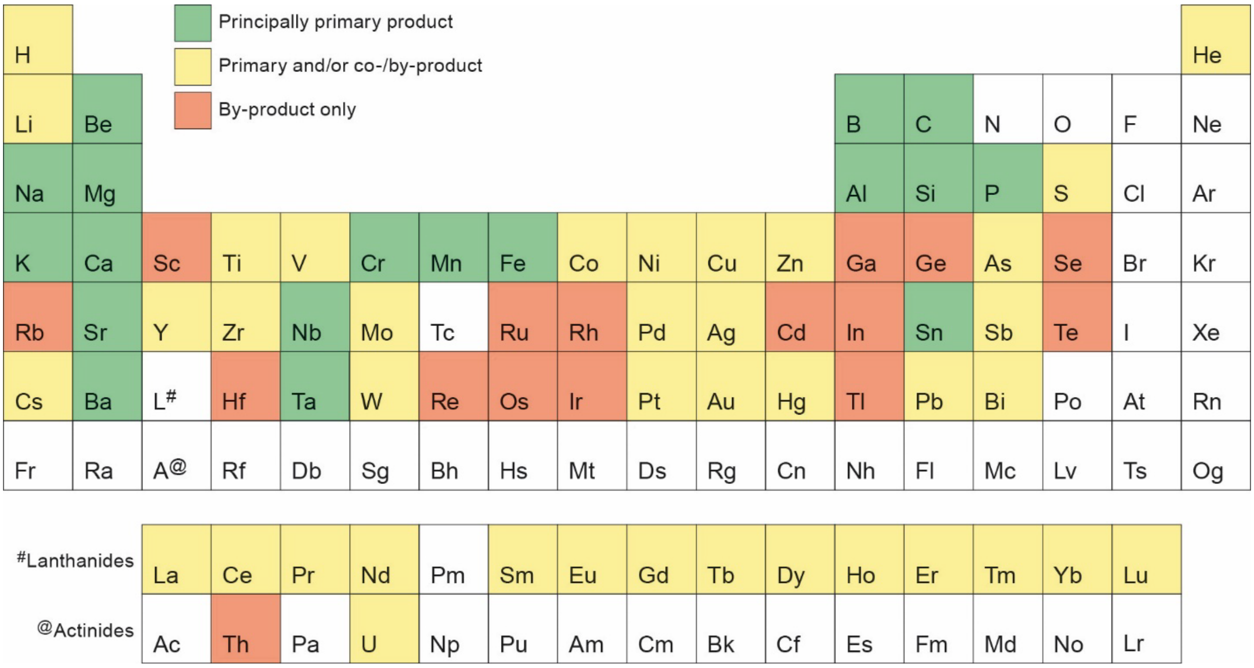


Figure 4 Primary, co-/by-product or by-product only status of most elements, based on expert knowledge of the CMIC team and key studies such as Nassar et al. (2015). BGS © UKRI.

3.1.4 Recycling indicator

Recycling rates for candidate raw materials vary significantly: only 14 per cent, mostly major and precious metals, have relatively high recycling rates (normalised score less than 5.0); 30 per cent have zero recycling (score 10.0). This may be due to a lack of reporting or the fact that no recycling occurs. For example, minor metals used in alloys are not recovered during recycling of those alloys. The remaining 56 per cent of candidate raw materials have recycling rates between 5.0 and 9.9 on the normalised scale.

3.1.5 UK apparent consumption

The UK AC shows wide variation. Low scores (1.0) are calculated for Cr, Ga, Re, zirconium (Zr) and PGEs, with many others, including Cd, In and Mo, having scores between 1.9 and 2.5. More significant consumption is reported for Al, Co, Cu and Fe, with scores in the range 5.3 to 7.6, up to the maximum of 10.0 for Au. The mean value of 3.4 highlights that many candidate materials are typically modest in their AC.

It is worth noting that a low AC value does not necessarily mean low economic value to the UK. For example, PGEs are a major export sector for the UK (based almost entirely on secondary re-processing). In contrast, the high AC value of Au is based on high levels of imports and exports, together with the role of Au financial trading: AC is £13.7 billion, based on imports of £43.2 billion and exports of £29.6 billion.

The second highest AC is for Fe at £716.3 million, significantly lower in value than Au but still very substantial. The UK produced an average of 1000 t of Fe oxides between 2018 and 2022 (Office for National Statistics, 2023), imported 4.2 million t of Fe and produced 5.6 million t of crude steel (UK Steel, 2024). The steel industry also requires a wide variety of additional commodities that are incorporated in various alloys and may contribute to the UK AC calculated for Ni, Mn, Cu, Si, Ti, Co, Mo and tungsten (W) (all used to make different ferroalloys).

The UK currently consumes relatively small quantities of elements more specific to low-carbon technologies and energy storage systems. Co, a key component in the production of batteries for electric cars and renewable energies, has the highest AC at £38.2 million. Li is also used in the production of batteries but, due to recent price drops, Li has a significantly lower AC at £16.2 million. The UK also produced over 72 t of Li in 2021 (Office for National Statistics, 2023). B, a key component of the permanent magnets used in electric vehicles and wind turbines, has an AC of £12.9 million. This is high compared to the REEs, another key component of the same technology, which have an AC of less than £4 million.

All of the PGEs analysed (Ru, Rh, Pd, Ir and Pt) have a highly negative AC, ranging from -£17.4 million for Ru to -£553.2 million for Pd. Despite having no primary production of the PGEs, the UK is a net exporter of these commodities. This results from the global circular economy created by Johnson Matthey, who recover these elements from recycled products and scrap (Johnson Matthey Plc, 2024b).

3.1.6 UK net import reliance

The UK NIR scores show that the majority (49) of candidate materials have a score of 10.0, meaning that the UK is 100 per cent dependent on imports. Eight candidate materials have NIR values in the range 8.0 to 9.9, with seven more between 3.0 and 7.7. Only three candidate materials score 1.0. These are F (in the form of fluorspar), industrial limestone and kaolin clay, whilst industrial (silica) sand scores 1.1.

The mining of fluorspar actually ceased in the UK in late 2023, although this was mostly destined for exports (Bide et al., 2024). This is outside the timeframe of this assessment and current UK fluorspar needs are met by imports. The current NIR score for fluorspar in 2024 is therefore 10.0, highlighting the dynamic nature of such aspects of material supply chains.

The kaolin clay sector is based mostly on exports, with about 94 per cent of UK production exported over the period 2018 to 2022, averaging £121 million per year (Bide et al., 2024).

3.1.7 Gross value added

GVA scores are quite varied, although typically modest with a mean of 1.9. The highest GVA score of 10.0 is Re, which is used in the high-value aerospace sector. The actual quantities of Re are small in mass terms (global refinery production averages 58 t per year; Appendix 1). This demonstrates that small quantities of a particular raw material can have very significant leveraging effects on economic activity. Similarly, Pt, Pd and Rh score 4.7, 4.6 and 4.7, respectively, despite no UK mine production, highlighting the role of secondary processing.

3.2 Synthesising the criticality plot

In order to develop the final criticality plot, weighting factors were applied to each indicator to reflect their relative importance in criticality (Section 2.10). Application of these weighting factors to the normalised indicator scores allows the global supply risk (S), UK economic vulnerability (V) and criticality score (CS) to be calculated for each candidate raw material (Figure 3 and Table 10). Based on stakeholder engagement and feedback, a criticality threshold or isocritical contour of 4.0 was adopted. A small number of candidate raw materials cannot be assessed due to the absence of sufficiently reliable data for the metrics employed in the analysis (Section 2.13.3).

The criticality plot (Figure 5) shows 34 of the 82 candidate raw materials have a criticality score equal to or greater than 4. Many of these are commonly listed as critical minerals in other national and regional assessments, for example Li, REEs, Ga, Ge, W, Pt and Pd (Josso et al. (2023). With the exception of Pd, the 18 critical minerals classified in the previous UK criticality assessment (Lusty et al., 2021) retain the same status in this assessment, despite the methodological changes implemented. Now scoring 3.9, just below the criticality threshold, the downgrade of Pd likely results from its much lower production concentration score, with a more diversified supply across Russia (41.7 per cent), South Africa (35.4 per cent) and Canada (7.35 per cent) compared to other PGEs (for example, South Africa produces 69.0 per cent of global Pt mine supply). It should be noted that this study covers the period 2018 to 2022, with Russia's invasion of Ukraine starting in early 2022. International sanctions against Russia do not currently include Pd, although Russian Pd supply is now more difficult to obtain, highlighting that the global supply risk for Pd would be greater now (November 2024).

This is believed to be the first national CA to rate Fe as a critical mineral. Previous studies by the EU, USA and others have not listed iron as critical (see Josso et al. (2023). The criticality score for Fe is 5.1, which is identical to Li, Sb and borates. The UK economic vulnerability for Fe is high because of its very significant economic importance, being used in the construction, automotive, aerospace and other manufacturing sectors. Although global supply risk is lower, the use of isocritical contours places Fe above the criticality threshold of 4.0. It should be noted that the EU assessment plotted Fe in a similar position (low supply risk, high economic vulnerability) but, due to their use of the linear thresholds, Fe fell outside the critical quadrant. The inclusion of Fe highlights that criticality is not just about modern technology but also about materials fundamental to a broad range of economic sectors such as construction, automotive, aerospace and other consumer-oriented industries.

Many candidate materials have criticality scores between 3 and 4 (for example, Cu, beryllium (Be), U, Ag, Cr, S, Cd, Sr, garnet, selenium (Se), pumice, He, Pb and vermiculite). It is important to note that these values are based on the data synthesised for this study, which reflects the period 2018 to 2022. There are many varied factors that could affect the future classification of these materials, such as changing production concentrations, technological evolution, policy adoption and national security considerations. Some of these issues are explored in the following discussion (Section 4). It is also significant to note that some of the lowest-scoring materials are those where the UK is a significant producer or exporter, such as kaolin clay, gypsum and palladium. This highlights the importance of domestic production in achieving secure supply of raw materials.

Table 10 Normalised scores for the global supply risk (S), economic vulnerability (V) and criticality score (CS) score. Thirty-four candidate materials classified as critical are listed together with those identified in the previous 2021 UK Criticality Assessment (Lusty et al., 2021).

Candidate material	S	V	CS	2024 CA	2021 CA
Aluminium (Al)	3.5	5.2	4.2	Critical	Not assessed
Antimony (Sb)	4.2	4.8	4.5	Critical	Critical
Arsenic (As)	4.4	3.5	3.9	Non-critical	Not assessed
Beryllium (Be)	3.5	5.2	4.2	Non-critical	Non-critical
Bismuth (Bi)	4.2	4.8	4.5	Critical	Critical
Cadmium (Cd)	2.8	3.7	3.2	Non-critical	Not assessed
Chromium (Cr)	3.7	3.4	3.6	Non-critical	Not assessed

Candidate material	S	V	CS	2024 CA	2021 CA
Cobalt (Co)	8.1	5.1	6.4	Critical	Critical
Copper (Cu)	2.2	5.3	3.4	Non-critical	Not assessed
Gallium (Ga)	8.2	3.5	5.3	Critical	Critical
Germanium (Ge)	8.3	4.2	6	Critical	Non-critical
Gold (Au)	1.3	7.1	3	Non-critical	Not assessed
Hafnium (Hf)	3.5	4.6	4	Critical	Not assessed
Helium (He)	4	6.9	5.3	Critical	Not assessed
Indium (In)	4.8	3.9	4.3	Critical	Critical
Iron (Fe)	3	7.5	4.8	Critical	Not assessed
Lead (Pb)	2.6	4.8	3.6	Non-critical	Not assessed
Lithium (Li)	4.8	4.5	4.7	Critical	Critical
Magnesium (Mg)	6	5.5	5.8	Critical	Critical
Manganese (Mn)	2.4	6.8	4	Critical	Non-critical
Molybdenum (Mo)	3	4.6	3.7	Non-critical	Non-critical
Nickel (Ni)	3	6.1	4.3	Critical	Non-critical
Niobium (Nb)	6.7	6.4	6.6	Critical	Critical
Phosphorus (P)	5.3	6.4	5.8	Critical	Not assessed
Potassium (K)	2	4.5	3	Non-critical	Not assessed
REEs	7.2	5.5	6.2	Critical	Critical
Rhenium (Re)	3.9	4.5	4.2	Critical	Non-critical
Selenium (Se)	2.4	4.6	3.3	Non-critical	Not assessed
Silicon (Si)	4.6	6.1	5.3	Critical	Critical

Candidate material	S	V	CS	2024 CA	2021 CA
Silver (Ag)	2.2	5.9	3.6	Non-critical	Not assessed
Sodium (Na)	3	6.2	4.3	Critical	Not assessed
Strontium (Sr)	3.2	3.1	3.1	Non-critical	Non-critical
Sulphur (S)	2.1	5.9	3.5	Non-critical	Not assessed
Tantalum (Ta)	3.9	4.7	4.3	Critical	Critical
Tellurium (Te)	4.6	4.2	4.4	Critical	Critical
Tin (Sn)	3.2	6.4	4.5	Critical	Critical
Titanium (Ti)	3.8	5.7	4.7	Critical	Not assessed
Tungsten (W)	5.9	5	5.4	Critical	Critical
Uranium (U)	2.8	5.5	3.9	Non-critical	Not assessed
Vanadium (V)	4.8	5.5	5.2	Critical	Critical
Zinc (Zn)	2.7	6.2	4	Critical	Not assessed
Zirconium (Zr)	3.4	3	3.2	Non-critical	Not assessed
Platinum (Pt)	5.6	3.8	4.6	Critical	Critical
Rhodium (Rh)	7.3	3.8	5.3	Critical	Not assessed
Iridium (Ir)	7.9	3.1	5	Critical	Not assessed
Palladium (Pd)	4	3.8	3.9	Non-critical	Critical
Ruthenium (Ru)	9.1	3.4	5.6	Critical	Not assessed
Barite	2.6	4	3.2	Non-critical	Not assessed
Bentonite Clay	1.8	3.9	2.6	Non-critical	Not assessed
Borates	3.7	5.5	4.5	Critical	Not assessed
Diamonds	2.4	5.1	3.5	Non-critical	Not assessed

Candidate material	S	V	CS	2024 CA	2021 CA
Diatomite	2	5	3.1	Non-critical	Not assessed
Feldspar	2.4	4.4	3.3	Non-critical	Not assessed
Fluorine	4.6	1.9	2.9	Non-critical	Not assessed
Garnet	2.7	4	3.3	Non-critical	Not assessed
Graphite (natural)	4.3	4	4.1	Critical	Critical
Gypsum	1.2	3.9	2.1	Non-critical	Not assessed
Kaolin clay	1.7	2.2	1.9	Non-critical	Not assessed
Kyanite	3.4	4.3	3.8	Non-critical	Not assessed
Industrial limestone	5	2.1	3.2	Non-critical	Not assessed
Magnesite	3.9	5	4.4	Critical	Not assessed
Perlite	2.3	4.6	3.2	Non-critical	Not assessed
Pumice	2.6	4.9	3.6	Non-critical	Not assessed
Pyrophyllite	2.1	4.8	3.2	Non-critical	Not assessed
Industrial salt	1.6	3.6	2.4	Non-critical	Not assessed
Industrial (silica) sand	2.1	2.2	2.2	Non-critical	Not assessed
Talc	2.1	5.9	3.5	Non-critical	Not assessed
Vermiculite	2.4	4.4	3.3	Non-critical	Not assessed

The 2024 list of critical minerals is shown specifically in Table 11.

Table 11 2024 critical minerals list for the UK.

Critical minerals (34)			
Aluminium (Al)	Helium (He)	Niobium (Nb)	Tantalum (Ta)
Antimony (Sb)	Indium (In)	Phosphorus (P)	Tellurium (Te)
Bismuth (Bi)	Iridium (Ir)	Platinum (Pt)	Tin (Sn)
Borates	Iron (Fe)	REEs	Titanium (Ti)
Cobalt (Co)	Lithium (Li)	Rhenium (Re)	Tungsten (W)
Gallium (Ga)	Magnesite	Rhodium (Rh)	Vanadium (V)
Germanium (Ge)	Magnesium (Mg)	Ruthenium (Ru)	Zinc (Zn)
Graphite (natural)	Manganese (Mn)	Silicon (Si)	
Hafnium (Hf)	Nickel (Ni)	Sodium (Na) (compounds)	

The UK 2024 critical minerals list is compared with other worldwide lists in Table 12. The EU lists 32 critical minerals (this expands to 36 if the PGEs are considered individually) and adds Cu and Ni, which did not meet the criticality criteria, to their strategic list (European Commission, 2023). There are 26 individual critical minerals in common between the EU and UK lists.

The USA also lists 50 critical minerals (noting they split the REEs individually) (U.S. Geological Survey, 2022b), of which 41 are shared with the UK list. Both Canada (Natural Resources Canada, 2022) and Australia (Australian Government, 2024) list 35 critical minerals, both treating the PGEs as a group but expanded here to allow comparison to the UK list. For comparison with the UK, Australia has 22 critical minerals in common whilst Canada has 26. This demonstrates that the new UK list is very similar to leading international peers, but there remain key differences such as Fe, Pd, F and Cr, amongst others. Of these lists, most do not appear to assess industrial minerals, with the exception of graphite and fluorine (as fluorspar), although the EU does include borates, feldspar, S and phosphate rock.

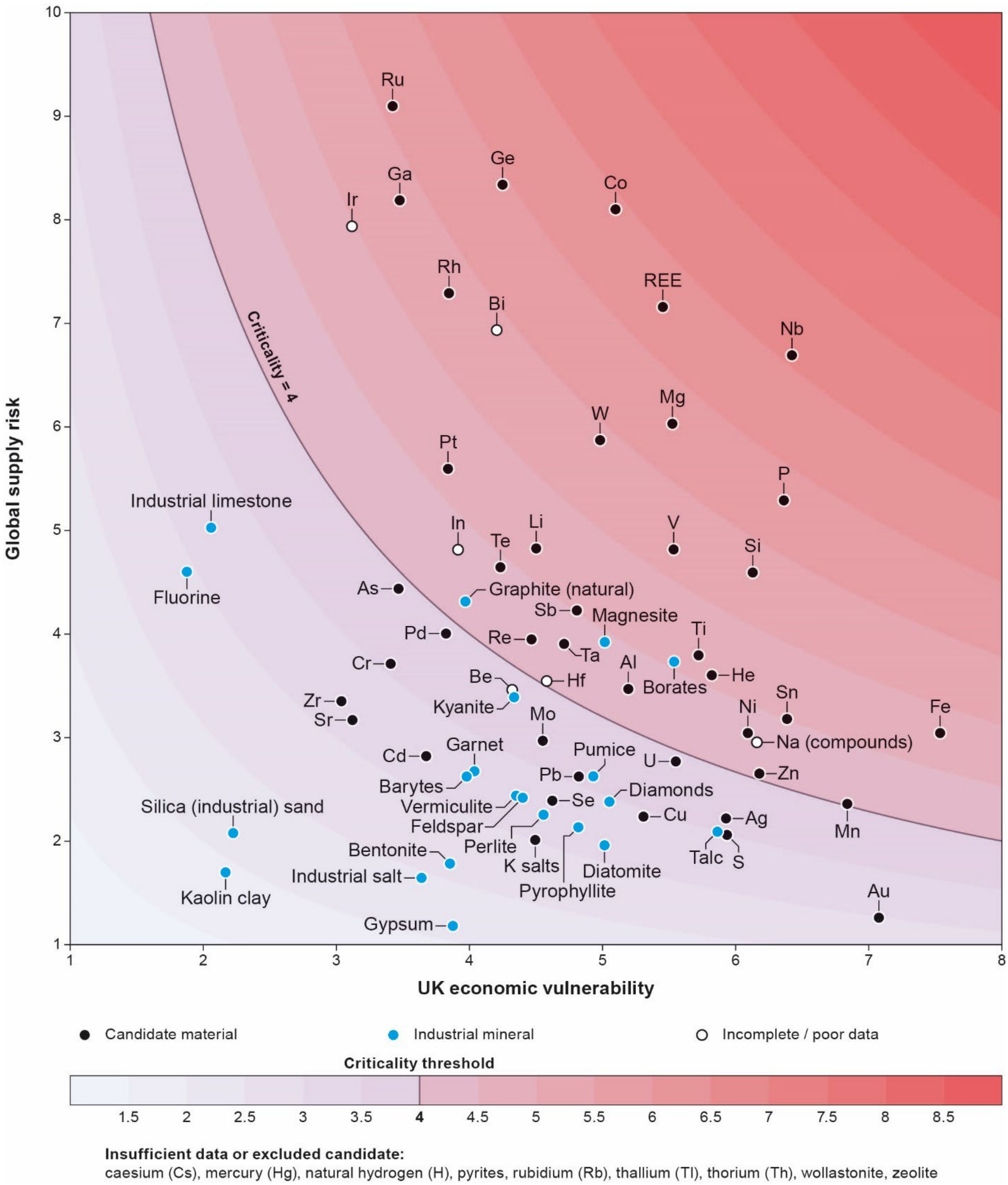


Figure 5 Criticality plot showing the position of all candidate raw materials (shown as circles: black-filled circles are reliable data; blue-filled circles are industrial minerals with reliable data; white-filled circles are low reliability) and the adopted criticality threshold of 4. Thirty-four materials lie above the threshold and are classified as critical. BGS © UKRI.

Table 12 Comparison of the 2024 UK critical minerals with the European Union (EU), USA, Canada and Australia lists (reference given in square brackets).

Candidate material	UK 2024 [this study]	EU 2024 [1]	USA 2022 [2]	Canada 2022 [3]	Australia 2024 [4]
Aluminium (Al)	Critical	Critical	Critical	Critical	Critical[A]
Antimony (Sb)	Critical	Critical	Critical	Critical	Critical
Arsenic (As)	Non-critical	Critical	Critical	-	Critical
Beryllium (Be)	Non-critical	Critical	Critical	-	Critical
Bismuth (Bi)	Critical	Critical	Critical	Critical	Critical
Cadmium (Cd)	Non-critical	Non-critical	-	-	-
Caesium (Cs)	ID	N/A	Critical	Critical	-
Chromium (Cr)	Non-critical	Non-critical	Critical	Critical	Critical
Cobalt (Co)	Critical	Critical	Critical	Critical	Critical
Copper (Cu)	Non-critical	Strategic[B]	-	Critical	-
Gallium (Ga)	Critical	Critical	Critical	Critical	Critical
Germanium (Ge)	Critical	Critical	Critical	Critical	Critical
Gold (Au)	Non-critical	Non-critical	-	-	-
Hafnium (Hf)	Critical	Critical	Critical	-	Critical
Helium (He)	Critical	Critical	-	Critical	-
Indium (In)	Critical	Non-critical	Critical	Critical	Critical
Iron (Fe)	Critical	Non-critical	-	-	-
Lead (Pb)	Non-critical	Non-critical	-	-	-
Lithium (Li)	Critical	Critical	Critical	Critical	Critical
Magnesium (Mg)	Critical	Critical	Critical	Critical	Critical

Candidate material	UK 2024 [this study]	EU 2024 [1]	USA 2022 [2]	Canada 2022 [3]	Australia 2024 [4]
Manganese (Mn)	Critical	Critical	Critical	Critical	Critical
Molybdenum (Mo)	Non-critical	Non-critical	-	Critical	Critical
Nickel (Ni)	Critical	Strategic[B]	Critical	Critical	Critical
Niobium (Nb)	Critical	Critical	Critical	Critical	Critical
Phosphorus (P)	Critical	Critical	-	-	-
Potassium (K)	Non-critical	N/A	-	Critical	-
REEs	Critical	Critical	Critical	Critical	Critical
Rhenium (Re)	Critical	Non-critical	-	-	Critical
Scandium (Sc)	N/A	Critical	Critical	Critical	Critical
Selenium (Se)	Non-critical	Non-critical	-	-	Critical
Silicon (Si)	Critical	Critical	-	-	Critical
Silver (Ag)	Non-critical	Non-critical	-	-	-
Sodium (Na)	Critical	N/A	-	-	-
Strontium (Sr)	Non-critical	Critical	-	-	-
Sulphur (S)	Non-critical	Non-critical	-	-	-
Tantalum (Ta)	Critical	Critical	Critical	Critical	Critical
Tellurium (Te)	Critical	Non-critical	Critical	Critical	Critical
Tin (Sn)	Critical	Non-critical	Critical	Critical	-
Titanium (Ti)	Critical	Critical	Critical	Critical	Critical
Tungsten (W)	Critical	Critical	Critical	Critical	Critical
Uranium (U)	Non-critical	N/A	-	Critical	-

Candidate material	UK 2024 [this study]	EU 2024 [1]	USA 2022 [2]	Canada 2022 [3]	Australia 2024 [4]
Vanadium (V)	Critical	Critical	Critical	Critical	Critical
Zinc (Zn)	Critical	Non-critical	Critical	Critical	-
Zirconium (Zr)	Non-critical	Non-critical	Critical	-	Critical
Platinum (Pt)	Critical	Critical	Critical	Critical	Critical
Rhodium (Rh)	Critical	Critical	Critical	Critical	Critical
Iridium (Ir)	Critical	Critical	Critical	Critical	Critical
Palladium (Pd)	Non-critical	Critical	Critical	Critical	Critical
Ruthenium (Ru)	Critical	Critical	Critical	Critical	Critical
Barite	Non-critical	N/A	Critical	-	-
Bentonite clay	Non-critical	N/A	-	-	-
Borates	Critical	Critical	-	-	-
Diamonds	Non-critical	N/A	-	-	-
Diatomite	Non-critical	N/A	-	-	-
Feldspar	Non-critical	Critical	-	-	-
Fluorine	Non-critical	Critical	Critical	Critical	Critical
Garnet	Non-critical	N/A	-	-	-
Graphite (natural)	Critical	Critical	-	Critical	Critical
Gypsum	Non-critical	N/A	-	-	-
Kaolin clay	Non-critical	N/A	-	-	-
Kyanite	Non-critical	N/A	-	-	-
Industrial limestone	Non-critical	N/A	-	-	-

Candidate material	UK 2024 [this study]	EU 2024 [1]	USA 2022 [2]	Canada 2022 [3]	Australia 2024 [4]
Magnesite	Critical	N/A	-	-	-
Perlite	Non-critical	N/A	-	-	-
Pumice	Non-critical	N/A	-	-	-
Pyrophyllite	Non-critical	N/A	-	-	-
Industrial salt	Non-critical	N/A	-	-	-
Industrial (silica) sand	Non-critical	N/A	-	-	-
Talc	Non-critical	N/A	-	-	-
Vermiculite	Non-critical	N/A	-	-	-

References: [1] European Union (European Commission, 2023); [2] United States of America (U.S. Geological Survey, 2022b); [3] Canada (Natural Resources Canada, 2022); [4] Australia (Australian Government, 2024). ID: insufficient data; N/A: not assessed; -: assessment unknown.

[A] As high-purity alumina only

[B] For the EU, Cu and Ni did not meet the criteria for listing as critical minerals but were included in the EU strategic minerals list

4 Discussion and implications for the UK

This CA has adopted a revised set of indicators to estimate the two key dimensions of criticality: global supply risk and UK economic vulnerability. Lines of equal criticality are depicted by convex isocritical contours. This allows a more robust identification of those materials that can be deemed critical.

Several related issues that may affect the future demand and supply of critical minerals require further discussion, including the effects of future demand changes in the UK from:

- technological evolution
- decarbonisation of the electricity grid
- potential impacts of trade barriers
- climate change risks to global supply resilience

The role of recycling and development of a more circular UK economy are crucial in ensuring secure and sustainable supplies in the future. These are key areas of uncertainty and help to explore the significance of the results of this CA.

4.1 UK policy context

In October 2024, the UK Government launched a consultation process to establish a new industrial strategy for the UK (HM Goverment, 2024). The primary objective was to develop a strategy that drives economic growth by taking advantage of the UK's unique strengths and untapped potential. In particular, the strategy was envisaged to support eight key sectors:

- advanced manufacturing
- clean energy industries
- defence
- digital technologies
- financial services
- life sciences
- creative industries
- professional and business services

It should be noted that critical minerals are fundamental to all these sectors, directly and indirectly. For example, critical minerals are direct inputs for the first four sectors (Section 4.2), whilst the latter four sectors make extensive use of digital, energy and related technologies delivered by the first four sectors: they indirectly rely on the critical minerals used within these technologies. It is anticipated that the new industrial strategy will be developed and released in mid-2025 and that resilient supply chains for critical minerals will be a key enabler of the strategy.

The UK's commitment to achieving a net zero greenhouse gas emissions economy by 2050 has led to a wide range of initiatives and policies that are relevant, since they drive demand for various critical minerals.

The UK Government has invested £200 million as an incentive to decarbonise freight vehicles and the haulage sector through the Zero Emission HGV and Infrastructure Programme. This funding will support the deployment of 370 zero-emission trucks and 57 refuelling and electric charging sites across the country (Department for Transport et al., 2023). Additionally, 955 zero-emission buses are also expected to be added to the UK fleet, funded through the Zero Emission Bus Regional Areas (ZEBRA) fund (International Energy Agency, 2024b).

The UK has seen an annual growth of over 15 per cent in the sale of electric vehicles during the first quarter of 2024, but the 2023 Vehicle Emissions Trading Schemes Order has set a target that 80 per cent of all car sales should be electric by 2030. This is combined with an expected installation of at least 300 000 public charging sites in the UK by 2030 (International Energy Agency, 2024b).

Renewable energy contributed to over 51 per cent of electricity produced in the UK in 2023 to 2024 and installed capacity is increasing steadily (Department for Energy Security and Net Zero, 2024). The new UK Government is also committed to doubling onshore wind energy by 2030 and has removed the development ban that has been in place since 2015 (UK Government, 2024).

On 30 September 2024, the UK's last coal-fired power station, located at Ratcliffe-on-Soar in Nottinghamshire, ceased operation. By-products from coal-fired power stations previously supplied synthetic gypsum and coal combustion products to the construction industry. Synthetic gypsum, produced from flue gas desulphurisation, was utilised by plasterboard manufacturers (Bide et al., 2021). Coal combustion products, primarily used in the construction sector, include coal fly-ash (also known as pulverised fuel ash or PFA) and furnace bottom ash (FBA) (Bide et al., 2021). FBA is primarily used as a lightweight aggregate in concrete blocks, although it can also be used as a lightweight fill and drainage material and a cement clinker additive (Bide et al., 2021). PFA is primarily used in autoclaved aerated concrete (AAC) blocks, blended cements and concrete, grouts and stabilisation materials and as a cementitious material (Bide et al., 2021). Although there remains a significant inventory of historic coal combustion products, the removal of fresh material from coal-fired power stations means raw material demands will have to be met in other ways (Section 4.4).

The UK Government is currently working towards a new industrial strategy, a fundamental component of which will be a critical minerals strategy. As such, it is important that policy development is aware of the following issues and changes occurring, as observed during the conduct of this CA.

4.2 Technology-driven raw material demands

This CA's results represent the current picture of demand and supply risk for the UK based on data for 2018 to 2022. However, many of the materials evaluated will see global changes in their future demand as new technologies enter the market and global policy settings evolve, leading to constant evolution of raw materials demand. For example, grid-scale energy storage batteries are expected to grow substantially in coming years to help balance the intermittency of power supply from renewable energy sources, meaning potentially significant growth for V, Li, and other materials used in such batteries.

To help explore this, we have compiled the principal materials used in selected technologies for the UK economy (energy, aerospace, defence and electronics) in Table 13. We have then overlaid the material requirements for some of these technologies on the criticality plot given in Figure 6. Combined, they show that many technologies will require not only numerous materials that are already listed as critical, but also many that are not, such as Cu, Ag, Cr, Mo, etc.

Aerospace technologies require specialist alloys, made from various metals, that can withstand extreme environments, many of which plot high on the UK criticality matrix. For example, Re is used in rockets and aircraft engines in combination with Ni, Mo or W, allowing the material to withstand high temperatures and increase engine power and fuel efficiency (Singh et al., 2023). However, supply of Re is vulnerable as global production is extremely limited (GSR score 3.9), with annual production of 58 t, the majority as a by-product of Mo and Cu from Chile (Idoine et al., 2024). Global Re demand is expected to increase in the future, leading to growing supply risks to which the UK economy is vulnerable. Furthermore, aerospace engine blades are plated with a platinum-based thermal barrier coating, showing that aviation is also enabled by platinum.

Other materials with an increasing demand from new technologies are in competition with demand from major established industries. For example, most of the world's V is used in steel alloys, commonly in the aerospace industry (90 per cent in 2020) (Graedel et al., 2022). However, V redox flow batteries have emerged in the last decade as a viable stationary energy storage solution to compensate for the weather-dependent supply from renewable energies and support peak electricity demand (Rodby et al., 2023). At the same time, V mine supply is highly concentrated in China (62 per cent). Increased deployment of V redox flow batteries would lead to an increased competition for V between energy storage systems and the steel industry, increasing the pressure on the already vulnerable V supply (GSR score 4.8). Further detailed research and analysis are required to better understand the supply chains of energy storage systems and to predict future global and UK demand for embedded materials, including V.

The fast-evolving digital transformation of our society requires a wide range of specialised materials in increasing quantities. Specific electronic properties are needed to power data transfer networks, data centres and mobile electronic devices. Microchips need semiconductor materials, such as Si and Ga, microcapacitors on integrated circuits require Ta, whilst mobile device screens and displays require In, Sn and other materials (Kumar et al., 2025; Marscheider-Weidemann et al., 2021). Most of these materials have a high criticality score in this UK assessment and are also deemed critical by the European Union and the USA (European Commission, 2023; U.S. Geological Survey, 2022b).

The recent rise of artificial intelligence, which depends heavily on large data centres, has accelerated the need for more of these critical minerals to accommodate the increasing global demand for such technologies. It is crucial to improve our knowledge of the material supply chains in the digital sector since high-purity forms of some needed materials are only available from a few sources. For example, Si metal is produced in over 30 countries, but only three of these can produce the high-purity polysilicon used for high-performance microchips, with more than 90 per cent of production in China (Idoine et al., 2024; International Energy Agency, 2022).

A growing digital technology is quantum computing, which has highly specialised material requirements including high chemical and isotopic purity. Further work is required to assess the future material demand of the digital industry and to improve our understanding of its material supply chains and the challenges of supply security for the UK.

The key point is that there are technological changes occurring globally and in the UK that will require increasing amounts of materials currently plotting below the threshold adopted for this CA, such as Cu and Se. This underlines the continuing and growing importance of such materials to the UK economy and societal objectives such as net zero, defence and the digital transformation.

Table 13 Candidate materials and their use in key technologies. Elements in red are used in new technologies that are currently not widely used; elements in bold are listed as critical in this study. This is not an exhaustive list and reflects the most widely used current components and subtechnologies and the most promising future technologies. Compiled from Compound Interest 2014 (Brunning, 2014), European Union 2023 (European Commission et al. (2023), DERA 2021(Marscheider-Weidemann et al., 2021) and UK CMIC technology foresight studies (marked with *) (Jackson et al., 2024a; Petavratzi et al., 2024a; Petavratzi et al., 2024d; Zils, 2024b; Zils, 2024c; Zils, 2024a; Jackson et al., 2024b; Petavratzi et al., 2024e; Petavratzi et al., 2024b; Petavratzi et al., 2024c).

Key Technologies	Sub technology/component	Elements
Decarbonisation of energy and transport technologies		
Electric vehicle batteries*	Li-ion batteries	**Al**, **graphite**, **Co**, Cu, F, **Fe**, **Li**, **Mn**, **Ni**, **P**, **Si**
	Others (Na-ion, solid-state, etc.)	**Na**, **V**, **Li**, **Nb**, S, **Ti**
Energy storage systems	Redox-flow batteries	Cu, **Fe**, S, **V**
Electric vehicle traction motors*	Permanent magnet motors	**Al**, **B**, **Co**, Cu, **Fe**, **REE** (**Dy**, **Nd**, **Pr**, **Sm** **Tb**), **Si**, Sr, Zr
	Others (alternating current induction motors; wound rotor synchronous motors, etc.)	**Al**, Cu, Cr, **Fe**, Mo, **Si**
Hydrogen electrolysers and fuel cells*	Proton exchange membrane	**Al**, Au, **graphite**, **Co**, Cu, **Ir**, **Pt**, Pd, **Ru**, **Ti**
	Others (solid oxide, etc.)	**Al**, **Co**, **Fe**, **Mn**, **Ni**, **Ir**, Sr, **REE** (**Ce**, **Y**), Zr
Photovoltaic cells*	Crystalline silicon cells	Ag, **Bi**, **In**, **Sb**, **Sn**, **Si**, **Ga**
	Thin-film cells	**Al**, Ag, As, Cd, Cu, **B**, **Bi**, F, **Ga**, **Ge**, Mo, **In**, **Sb**, Se, **Sn**, **Si**, **Te**, **Zn**
Wind turbines*	Generator	**Al**, **B**, **Co**, Cu, **Fe**, **REE** (**Dy**, **Nd**, **Pr**, **Sm** **Tb**), **Si**, Sr, Zr
	Other components	**Al**, Pb, Cr, **Fe**, **Mn**, Mo, **Nb**, **Ni**, **Zn**
Heat pumps*	Compressor; expansion valve; condenser/evaporator	**Al**, **B**, Cu, **Fe**, **REE** (**Dy**, **Nd**, **Pr**, **Tb**), **Zn**

Key Technologies	Sub technology/component	Elements
Thermoelectric devices	Thermoelectric generators	Ag, **Bi**, **Ge**, Pb, **Te**
Nuclear energy*	Advanced modular reactors; small modular reactors	Ag, **Al**, **B**, Cd, Cr, **Fe**, **REE** (**Gd**), Mo, **Nb**, **Ni**, **In**, **Sn**, **Si**, **Ti**, U, Zr
National grid infrastructure*	Cables; inverters; transformers	Cu, **Al**, **Fe**
Other emerging technologies		
Aerospace and defence	Steel and super alloys	**Al**, **Co**, Cr, Cu, **Fe**, **Ge**, **Hf**, **Mn**, Mo, **Nb**, **Ni**, **Nb**, Pb, **Pt**, **Re**, **Ru**, **Ti**, **Ta**, **Te**, **V**, **W**, Zr, (Be, **Mg**, **Sc**)
Digitisation and electronics	Mobile device batteries	Al, Li, Co, graphite
	Microelectronics and chips	Ag, Au, Cu, **Ta**, **Ni**, **REE** (**Dy**, **Gd**, **Nd**, **Pr**, **Tb**), **Si**, **Ga**, As, Pd, **Ru**, **Sb**, **Sn**, Pb
	Screens	**Al**, **In**, **Sn**, K, **REE** (**Dy**, **Eu**, **Gd**, **La**, **Pr**, **Tb**)

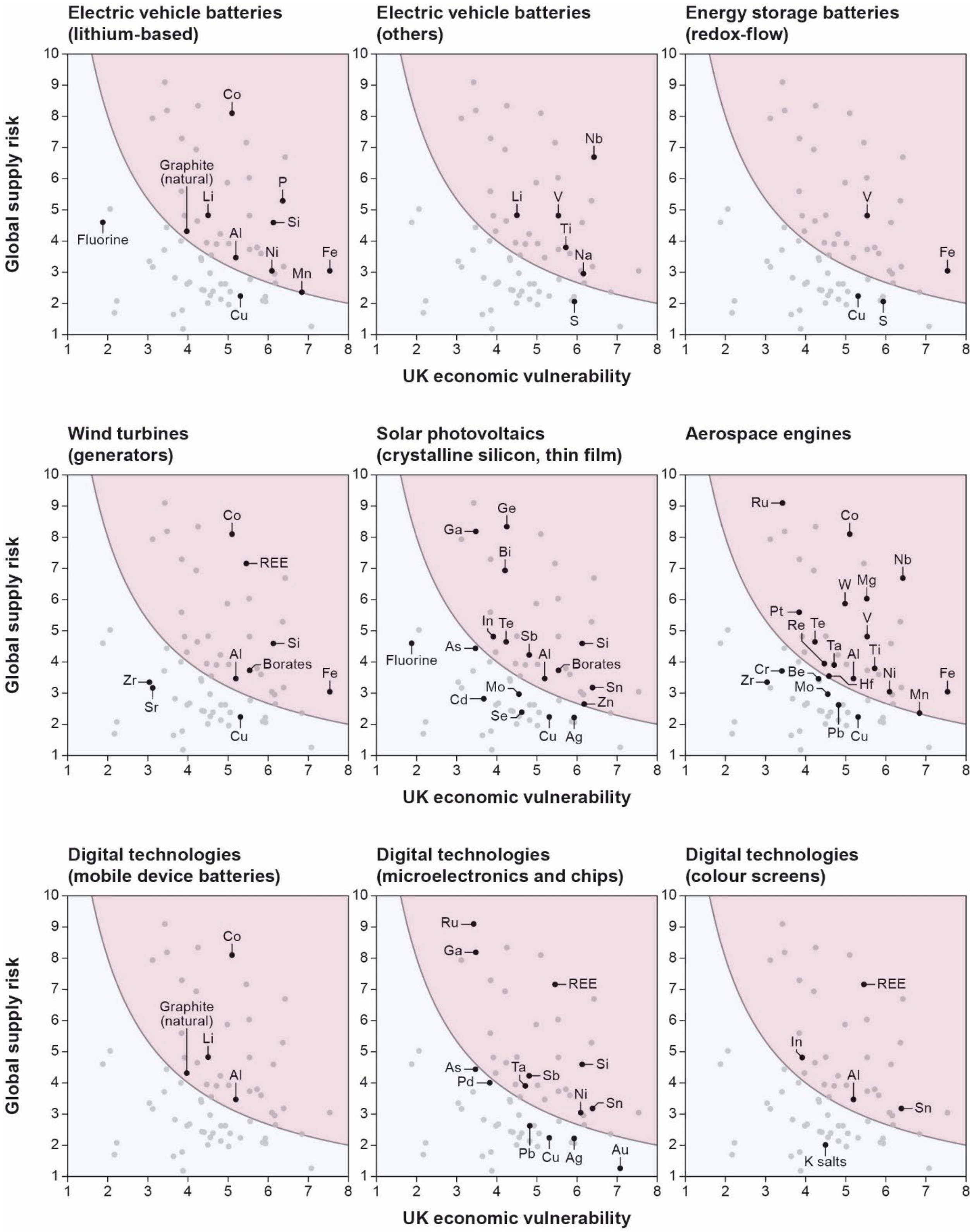


Figure 6 Materials required for selected technologies displayed through the CA plot (based on details in Table 13). BGS © UKRI.

4.3 Foresight studies and future UK critical minerals demand

In alignment with the revised CA methodology, CMIC conducted eight foresight studies (due for release late 2024) that aim to identify the raw material needs for selected decarbonisation technologies in the UK up to 2050, based on the National Grid future energy scenarios (National Grid, 2023b). The analysed technologies are:

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

A synthesis report was also produced and an additional report on Cu and Al for the electrical grid was also produced (both due for release in late 2024).

The results of these studies give insights into the future development of the demand for essential materials in these technologies and are expected to be publicly released by CMIC in late 2024. Whilst we were not able to do this analysis for all candidate materials, the examples of Cu, Li and selected REEs used in permanent magnets are presented in sections 4.3.1, 4.3.2 and 4.3.3 and compared with current global mine production trends.

The International Energy Agency (IEA) have recently developed new assessments of the materials required for the energy transition, with a particular focus on electric vehicles and energy storage batteries. In their Global EV Outlook report for 2018 (International Energy Agency, 2018), the demand for Co in electric vehicle batteries was projected to grow from about 12 000 t in 2017 to between 71 000 to 393 000 t by 2030, depending on battery chemistry and policy scenario. By the 2024 report (International Energy Agency, 2024b), it was noted that lithium iron phosphate ($LiFePO_4$) batteries made up more than 40 per cent of the batteries in electric vehicle sales, meaning that Co demand was considerably reduced from earlier assessments. This reinforces the highly dynamic nature of technological evolution, the uncertainty of predictions in such dynamic contexts (for example, (Drexhage et al., 2017)) and that future projections need to be interpreted carefully, especially assumptions around important factors such as battery chemistry, sales trends, etc.

The IEA have recently launched a new annual report, the 'Global critical minerals outlook', which explores the global status of critical minerals for energy technologies (International Energy Agency, 2024d). In this study, the IEA presents global scenarios for critical minerals demand based on future evolution of energy and transport technologies.

- Stated policies scenario: based on existing policies and strategies and the general direction of the energy transition; 50 per cent probability of achieving a 2.4°C extent of global warming by 2100
- Announced pledges scenario: assumes that governments will implement all policies required to meet their respective climate pledges; 50 per cent probability of achieving a 1.7°C extent of global warming by 2100
- Net zero greenhouse gas emissions scenario by 2050: this develops a pathway for the energy sector to achieve net zero greenhouse gas emissions by 2050 and meet the United Nations Sustainable Development Goals for energy; 50 per cent probability of achieving a 1.5°C extent of global warming by 2100 with limited overshoot

Since the net zero scenario is the most ambitious with respect to global climate goals, it is also the scenario with the greatest global demand growth for critical minerals. The materials included are Cu, Li, Ni, Co, graphite and REEs, which are all key to renewable energy and electric vehicle technologies. We combined the IEA scenarios with simple statistical regressions of past world production in order to explore the way historical patterns of global mine supply contrast with predicted demand increases for Cu, Li and the four REEs used in permanent magnets (neodymium (Nd); praseodymium (Pr); terbium (Tb); dysprosium (Dy)).

4.3.1 Copper

Cu is a material that has recently begun to be added to critical minerals lists despite Cu not meeting the normal thresholds for criticality, such as Australia (Australian Government, 2024) and the EU (European Commission, 2023). This has largely been driven by concerns about the ability of the global Cu mining sector to develop new mines in the near future and increase production (conversion of mineral resources through ore reserves to mine supply (International Energy Agency, 2024d)). Cu has diverse uses including power and electricity, telecommunications and digital technologies, as well as chemicals and infrastructure (especially piping) (Appendix 6).

Given the need to enhance the national electrical grid in the UK to accommodate a higher proportion of renewable energy, electric vehicle charging capacity and large data centres, we review the basics of the IEA Cu demand scenarios and what this could mean for the UK. Figure 7 shows historical world Cu mine and refinery production from 1975 to 2022 (noting refinery production includes secondary Cu scrap), combined with linear regressions from 1994 to 2022 (since this period shows higher growth rates than prior to 1994), which are then projected to 2050 (dashed lines) and the three IEA scenarios for future Cu demand.

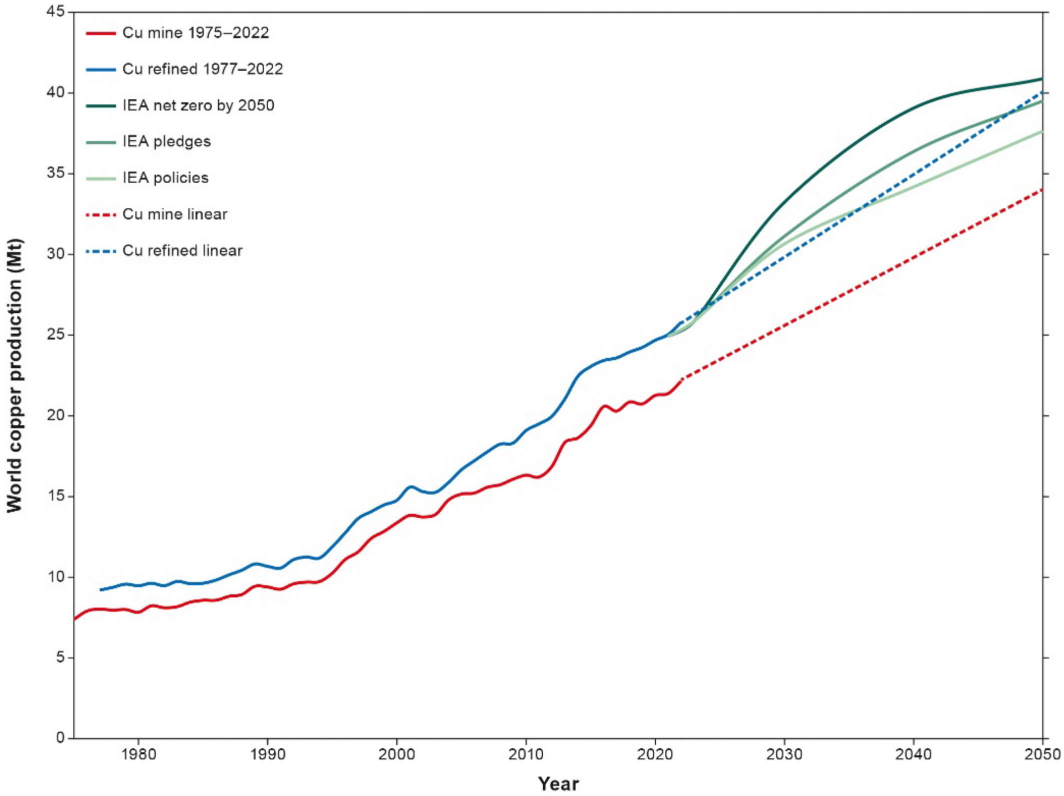


Figure 7 Historical world Cu mine (red) and refinery (blue) production (data combined from (Idoine et al., 2024; U.S. Geological Survey, 2024b; U.S. Geological Survey, 2024a; Mudd and Jowitt, 2018a), including earlier historical editions), with linear regressions to 2050 (red and blue dashed lines for mine and refined Cu production, coefficients of correlation or R^2 values of 0.98 and 0.99, respectively) and the three principal IEA scenarios for future copper demand: stated policies (light green); announced pledges (middle green), and net zero (dark green). BGS © UKRI.

It is clear from the data that projections of refined Cu production are likely to meet Cu demand for the stated policies and announced pledges scenarios, but the net zero scenario requires an increase in Cu production above that projected of about 12 per cent around 2040 and declining to 2 per cent by 2050. This does not mean that such demands cannot be met, just that mine supply needs to grow above recent rates to meet these projected demands. Historically, the annual growth rate on mined and refined Cu production averaged 2.2 and 2.3 per cent, respectively, from 1975 to 2022, ranging from a minimum of -5.9 per cent (decrease) to a maximum of 8.8 per cent (increase; Figure 7). Going back further in history (using the references cited in Figure 7) shows that maximum growth values for mine production can vary:

- 10.6 per cent (1904)
- 29.6 per cent (1916)
- 36.3 per cent (1937)
- 9.8 per cent (1969)
- 8.8 per cent (2013)

(Noting that growth rates in refined Cu were more subdued.)

It should be noted, however, that the confluence of current conditions facing the Cu sector are different to those faced historically, meaning it is difficult to quantify the growth rates that can be achieved. Detailed assessment of these conditions is clearly beyond the scope of a CA, which focuses on recent data to assess global supply risks and not future supply projections.

Given the concerns about the capacity to increase global Cu mine supply, this highlights that there are significant constraints facing Cu that may increase global supply risk in the near future. For example, Zambia and DRC have ambitions to substantially increase their Cu production (Reuters, 2024b; Reuters, 2024a), meaning that as much Cu would be supplied from this region of the world as from Chile. This would lead to an increase in global supply risk due to poorer ESG indices for both Zambia and DRC. The AC and GVA values would also increase, due to greater Cu use in the UK associated with the energy transition, potentially moving Cu above the current criticality threshold of 4.0. Criticality assessment methodology in general, however, does not and is not intended to model global supply risks in detail (for example, mine by mine or country by country). It is simply reasonable to acknowledge that, although Cu remains below the criticality threshold at present, this may change in the near future.

4.3.2 Lithium

Li production has steadily increased since the mid-twentieth century, mainly to meet demand in glasses, ceramics, greases and pharmaceuticals. The past 20 years has also seen a substantial increase in global demand for batteries, particularly for electric vehicles.

The global demand for Li is expected to increase more than tenfold by 2050 to support the net zero energy transition (International Energy Agency, 2024b). Figure 8 shows historical world Li mine production from 1975 to 2022, combined with an exponential regression from 1975 to 2022 and a linear regression from 2016 to 2022 (since this period shows higher growth rates prior to 2016; global market conditions changed due to the rapid rise of electric vehicles), with both regressions projected to 2050 (dashed lines), the three IEA scenarios for future global demand and the maximum projected Li demand from the synthesised UK CMIC foresight studies (Petavratzi et al., 2024a).

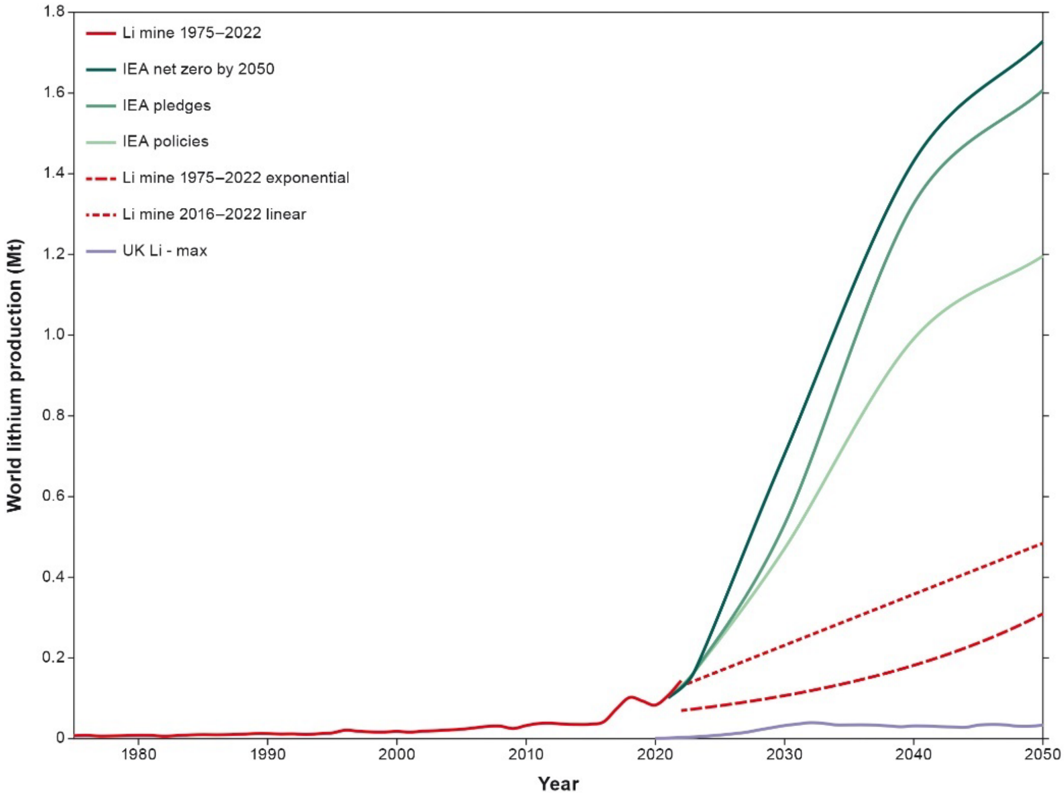


Figure 8 World historical Li production (red line) (Idoine et al., 2024) and estimated future supply based on past production growth rates (exponential regression of data from 1975 to 2022 (dashed red line), coefficient of correlation or R^2 of 0.82; linear regression of data from 2016 to 2022 (dotted red line), coefficient of correlation or R^2 of 0.75) and future demand based on three IEA scenarios: existing policies (light green); policy pledges (middle green), and net zero (dark green) (International Energy Agency, 2024d). The estimated UK annual demand over time (light purple) is also illustrated as the maximum demand of the four National Grid future energy scenarios (National Grid, 2023a). BGS © UKRI.

Both the historical exponential and linear projection suggest that the current trajectories for global Li supply would not be able to meet future demand, reaching between 30 and 40 per cent of the world's demand by 2050 (depending on the IEA scenario). In the UK, Li demand for electric vehicle batteries alone is expected to increase thirtyfold up to 2050, when considering the most extreme scenario. This would represent between two and three per cent of global demand. Therefore, it is expected that Li will become increasingly critical due to an increasing gap between supply and demand for the UK and globally. A similar trend is expected for other major battery raw materials (Co; Mn; Ni; graphite).

As outlined previously, the various UK CMIC foresight studies do not cover all technologies for which projected material demand to 2050 is expected to grow (for example, V redox flow batteries; digital and quantum computing). For Li, hypothetical scenarios to assess the impact on criticality can be explored. If the rapid predicted growth in global and UK Li demand is the highest across all materials, this would lead to a score of 10.0 on a scale of 1 to 10 as a fourth indicator in UK economic vulnerability. That is, for this study, Li included an AC of 4.6, a NIR of 7.7 and GVA of 1.3. If we were to add a fourth factor of 10.0 for demand foresight, this would change the geometric mean of economic vulnerability from 3.6 to 4.6 (without weightings applied, given that no weighting is available for the demand foresight). The increase in economic vulnerability score therefore increases overall criticality for Li due to rapid predicted growth in demand.

In the future, assuming the UK developed a complete Li supply chain of its own from mining through refining to component manufacture and product assembly, this could lead to lower global supply risks, due to the greater diversity of global mine supply or lower production concentration, and increased AC, but zero net import reliance. In other words, Li would likely move both to the left and down in the criticality plot to a position below the criticality threshold. This would be a welcome development, signifying the achievement of self-sufficiency for the UK with respect to Li. The ideas presented here suggest possible pathways for the future evolution of the criticality of Li for the UK.

4.3.3 Rare earth elements

In recent decades the REEs, especially Nd, Pr, Dy and Tb, have become essential to high-performance permanent magnets used in electrical turbines and drive trains for electric vehicles. Supply has come to be dominated by China (Section 3.2) in the mining, refining and manufacturing stages. The IEA has assessed future demand for these four REEs as part of their new 'Critical minerals outlook' series (International Energy Agency, 2024d).

The fraction of Nd, Pr, Dy, Tb constituted 26 per cent of total REE world production in2021 (IEA citation; Nd, Pr, Dy, Tb production of 78, 000 tonnes in 2021 divided by world REE production of 296, 400 tonnes). Historical production of these REE is plotted assuming that this 26 per cent is consistent back to 1975. This approach is a general approximation only and is not intended to be a detailed quantitative assessment. The derived historical Nd+Pr+Dy+Tb production is shown in Figure 9, including exponential and linear regressions of the historical data (1975 to 2022), projections of these regressions to 2050 and the three IEA demand scenarios.

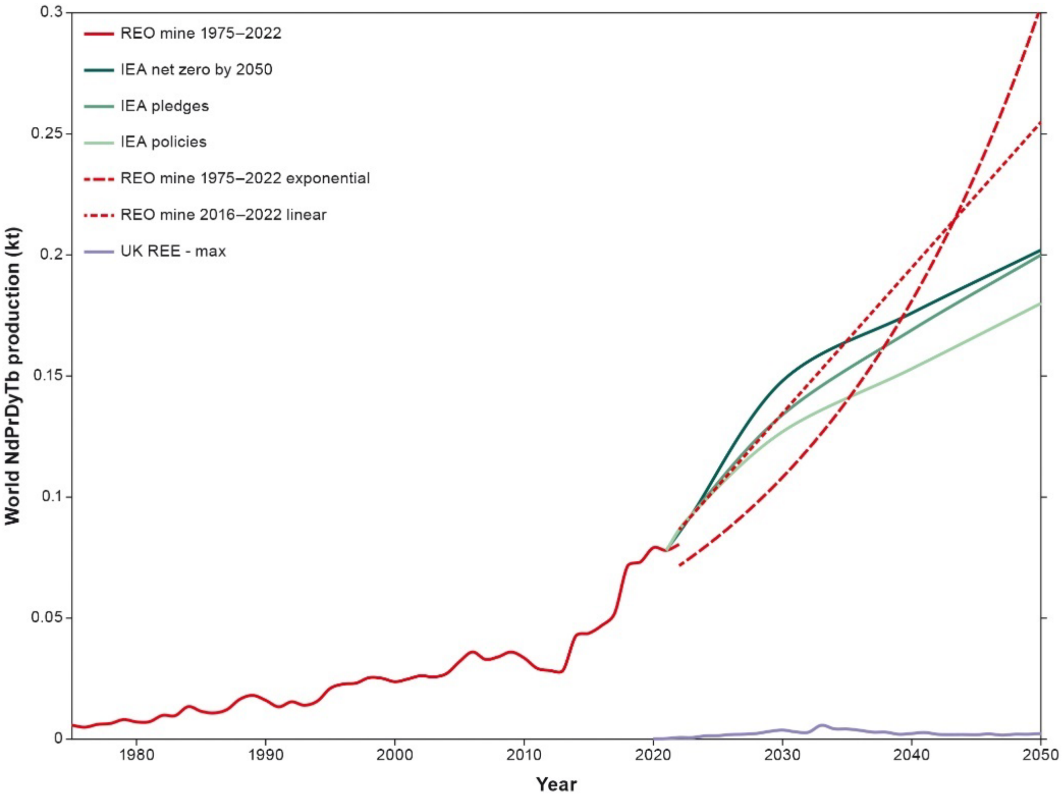


Figure 9 Approximate world historical Nd+Pr+Dy+Tb production (red line) (data updated from Weng et al. (2015)) and estimated future supply based on past production growth rates (exponential regression of data from 1975 to 2022 (dashed red line), coefficient of correlation of R^2 0.92) and future demand based on three IEA scenarios: stated policies (light green line); announced pledges (middle green line), and net zero (dark green line) (International Energy Agency, 2024d). The estimated UK annual demand over time (light purple) is also illustrated as the maximum demand of the four National Grid future energy scenarios (National Grid, 2023a). BGS © UKRI.

From this graph, the projected production of Nd+Pr+Dy+Tb is likely to meet all three IEA scenarios. Whilst this appears to be a positive outcome, it should be noted that most of this production is from China, which has enacted strict trade measures on REE exports in recent years (Section 4.5.3). Furthermore, the REEs have amongst the highest global supply risk of all candidate materials in this assessment. This means that, for the REEs in the UK, the focus needs to be on securing supply rather than scaling up supply. Continual monitoring and detailed assessment of global demand and supply of the REEs is required to ensure that future UK requirements are met.

4.4 Decarbonisation effects on raw material demand

4.4.1 Decarbonisation and the energy transition

Given that numerous raw materials are fundamental to the production of technologies for the energy transition (for example, Li; REEs) (Wang et al., 2024), there are intrinsic links between climate change, net zero ambitions and the extraction of these raw materials (Ali et al., 2017; Depraiter and Goutte, 2023). As such, the mineral demand for clean energy technologies is anticipated to double by 2030 in a scenario involving current stated policies, or almost triple by 2030 and quadruple by 2040 in scenarios that achieve net zero greenhouse gas emissions by 2050 (International Energy Agency, 2024d).

Clean energy technologies are the predominant force driving the growth in demand for many critical minerals. Electric cars are the main source of demand for batteries, with global electric car sales reaching nearly 14 million in 2023, an increase of 35 per cent from the previous year that is expected to continue to grow at a similar rate (International Energy Agency, 2024d).

The global shift towards renewable energy is also contributing to the expansion of the critical minerals market. The growth in demand for electricity is expected to accelerate in the future, as a result of increased requirements from sectors such as light industry, electric vehicles, cooling, data centres and artificial intelligence. In response, almost 200 trade measures affecting clean energy production have been introduced globally since 2020 (International Energy Agency, 2024a). In the UK, from 2009 to 2023, onshore wind capacity has grown from 3,471 MW to 15,418 MW, offshore wind capacity from 951 MW to 14,745 MW and solar photovoltaics from 27 MW to 16,238 MW, respectively (Department for Energy Security and Net Zero, 2024).

Li has seen the greatest rise in demand of all the critical minerals due to the expanding electric vehicle market. Global demand for Li is forecast to grow threefold by the end of the decade, 90 per cent of which is attributed to batteries for the electric car industry. Electric car sales are expected to increase battery requirements for Li fivefold by 2030 and fourteenfold by 2050 (International Energy Agency, 2024d).

Changes in battery chemistry will also have a profound effect on material demand. Li-ion batteries are already moving towards higher Mn chemistries and replacing Co with higher Ni concentrations, whilst demand for Na-ion batteries is expected to grow. These shifts are expected to cause a dramatic increase in demand for Ni and Mn, both of which are also used in the production of renewable energy, such as wind and geothermal. Demand for Co is still expected to grow but the trend towards low-Co and Co-free battery chemistries in both electric cars and storage batteries is slowing the speed of that growth. Global demand for graphite in batteries is expected to at least double by 2030 and, although Si is increasingly being used as a substitute, it is unlikely to affect this growth in demand in the near future (International Energy Agency, 2024d).

The global shift toward electric vehicles is expected to cause a drop in demand for some PGEs, such as Rh and Pd, due to the move away from internal combustion engines in which they are used in catalytic converters within exhaust pipes for control of noxious emissions. Pt demand related to decarbonisation is tied to the sale of H-fuel cell vehicles; however, fuel cells have not yet been widely adopted for use in light duty vehicles, therefore future Pt demand remains uncertain. The implications of this are that all applications that rely on associated by-products such as Ru and Ir, such as microelectronics, Li-ion batteries, and a variety of medical applications, will be at risk and need to find alternatives. Electric vehicles and wind turbines containing REE permanent magnets (Nd-Fe-B magnets) are much more energy efficient than alternative technologies and lower the requirements for other critical minerals such as Li, Ni and Co. Consequently, the REE permanent magnet global demand nearly doubled between 2015 and 2023 and is forecast to double again by 2050 (International Energy Agency, 2024d), although increased recycling of scrap magnets is likely to contribute a secondary supply of REEs.

The global transition to electric vehicles and renewable energy is also raising demand for Cu and Al. Cu is used in Li-ion batteries, in wiring in electric vehicles, and in electricity transmission and distribution networks that connect renewable energy sites to the centres of demand. Importantly, most of the increase in Cu consumption in the energy grid will come from upgrading the existing network to sustain higher voltage and transmission capacity rather than additional length of cabling due to creation of new network sections. Al is also used in cabling and as a light structural metal in electric vehicles and renewable energy production (International Energy Agency, 2024d).

4.4.2 The energy transition and industrial minerals

The decarbonisation and net zero transition will not only require metals for sustainable technologies to generate renewable energy, but also industrial minerals for the chemical and mineral products used in the UK's manufacturing sector. Secure supplies of construction minerals and aggregates will also be essential for housing, national-scale construction projects and the installation of energy infrastructure. This section describes the effects of decarbonisation on industrial minerals from three sectors, including the construction, oil and gas and fertiliser sectors, from forward-looking scenarios.

The closure of the UK's last coal-fired power station in September 2024 has meant the loss of synthetic gypsum supply and the supply of furnace bottom ash for lightweight aggregates and cement clinker uses (Section 4.1). Although there is an estimated 100 million tonnes of coal fly-ash stockpiled at former coal-fired power stations (United Kingdom Quality Ash Association), assessment (Alberici et al., 2017) has suggested that:

- not all coal fly-ash stockpiles in the UK can be utilised due to the tendency for stockpiled fly-ash to agglomerate and lose reactivity
- a decline in supply and production of coal fly-ash from the closure of coal-fired power stations will induce two scenarios for meeting fly-ash demand:
    - recover stockpiled fly-ash
    - import from other countries producing fly ash
- further research is required to assess the quality and end uses of different types of coal fly-ash for cement and concrete production, as well as to research alternatives to fly-ash and granulated blast furnace slag

Data collected in this CA from UK Trade Info (HM Revenue & Customs, 2024) has shown the UK has increased imports of alternative raw materials for construction, including pumice and roasted pyrite (Alp et al., 2009; Oliveira et al., 2012). Based on industry insights and trade data, it is also understood that the supply of synthetic gypsum has been replaced by imports, whilst roasted pyrite can be used as a cement iron additive (Alp et al., 2009) or pumice for lightweight aggregates (Harben, 2002; Presley, 2006). Further study is required to assess the role 'alternative' raw materials in construction supply chains in the UK.

The closure of the Ratcliffe-on-Soar coal-fired power station marked a significant step on the UK's transition to net zero. In the long term, the UK's and the world's transition to net zero will see substantial reductions in the refining of petroleum and natural gas and, therefore, the production of by-products such as sulphur (S). S is typically converted to sulphuric acid (H_2SO_4), which is used in numerous manufacturing processes including the production of phosphorus (P) fertilisers, non-ferrous ore leaching and pulp and paper production (SCRREEN, 2023a). However, as the supply of S is anticipated to decrease, the demand for it has been predicted to increase due to rapid growth in the green economy and intensive agriculture (Maslin et al., 2022), leading to possible competition between the extraction of metals required for the green economy and fertiliser production for intensive agriculture to feed an ever-increasing global population (Grady, 2024a; Maslin et al., 2022). This competition could be eased by researching economically viable alternatives for H_2SO_4 or adopting different reagents for fertiliser production and ore extraction (Grady, 2024b).

The decrease in oil and gas production will also reduce the amount of drilling fluids used and, consequently, the demand for industrial minerals, such as barite and bentonite, used by the oil and gas sector (SCRREEN, 2023c; SCRREEN, 2023b).

With a growing UK population and increasing competition for land use for housing, renewable energy infrastructure, transport and industry, the agricultural sector faces challenges in the provision of domestic food supply. Climate change effects, including unpredictable weather and seasonal patterns inducing regional flooding and national droughts, have further affected the agricultural industry.

Additional challenges faced by the fertiliser industry in the UK include fertiliser use efficiency and reducing environmental impacts (Barnett and Wentworth, 2024). The high cost of fertilisers and improvements in agricultural practice have seen a decline in the use of nitrogen (N), phosphate and potash fertilisers (Barnett and Wentworth, 2024). This CA lists P, typically derived from phosphate rock, as critical, but not potassium (K) based salts and fertilisers (noting that the UK has the operating Boulby and developing Woodsmith potash mines, both capable of providing potash and polyhalite fertilisers).

4.5 Trade regulations and global supply risks

Trade regulations are measures imposed to control the export or import of products, including critical minerals and associated technologies. Regulations can take various forms, including:

- export quotas
- tariffs
- licensing requirements
- complete prohibition

Typically, a government or trading bloc impose them to protect domestic industries, manage domestic supply and demand, or for geopolitical leverage. Trade regulations can disrupt global supply chains and trade, leading to uncertainty, price increases and reduced availability (Organisation for Economic Co-operation and Development, 2010). Several countries and trading blocs have imposed trade regulations on raw and processed materials in recent times. These include China (World Trade Organisation, 2022), the USA’s Inflation Reduction Act (The White House, 2022) and the European Union (European Union, 2024).

In this CA, we have adopted a case study approach to trade regulations rather than incorporating trade barriers into the estimation of UK economic vulnerability in a quantitative way. The available data is highly variable, making it difficult to implement an objective, quantitative approach to the inclusion of trade barriers (Section 2.13.1). It should be noted that trade regulations also have the potential to affect the 'global supply risk' factor.

As in Section 2.13.1, this section presents three case studies that demonstrate the effects of trade regulations on selected critical minerals. A brief outline of the implications of trade regulations for the UK is also given.

4.5.1 Antimony

In August 2024, China introduced export regulations on Sb. Most Sb is used in flame retardants, Pb-acid batteries and the production of solar photovoltaic (PV) glass (Bedder, 2024b; Home, 2024; Lv et al., 2024). It also has significant application in military ammunition (Home, 2024; Sadden, 2024) as well as in semiconductors (Baskaran and Schwartz, 2024). The new regulations, effective from September 2024 (Bedder, 2024b; Lv et al., 2024), do not limit export quantities but require exporters to apply for additional licences (Argus Media, 2024; Home, 2024). The regulations cover Sb ore, ingots and oxide. They also prohibit the export of Au-Sb smelting and separation technologies without permission (Baskaran and Schwartz, 2024; Bedder, 2024b; Lv et al., 2024).

Historically, China has long maintained a leading role in world Sb mine production, shown in Figure 10. China's antimony production is derived mainly from primary deposits (Schwarz-Schampera, 2014a), although China operates a large Sb smelting sector that is supplemented by imports, giving China an average share of 48 per cent of global mine production and about 63 per cent of Sb smelting-refining in recent years (see Appendix 3). China has also increased environmental requirements and inspections at smelters in recent years, leading to numerous sites being shut down and a sharp decline in mine and smelter production (Adnan et al. (2024); U.S. Geological Survey (2022c).

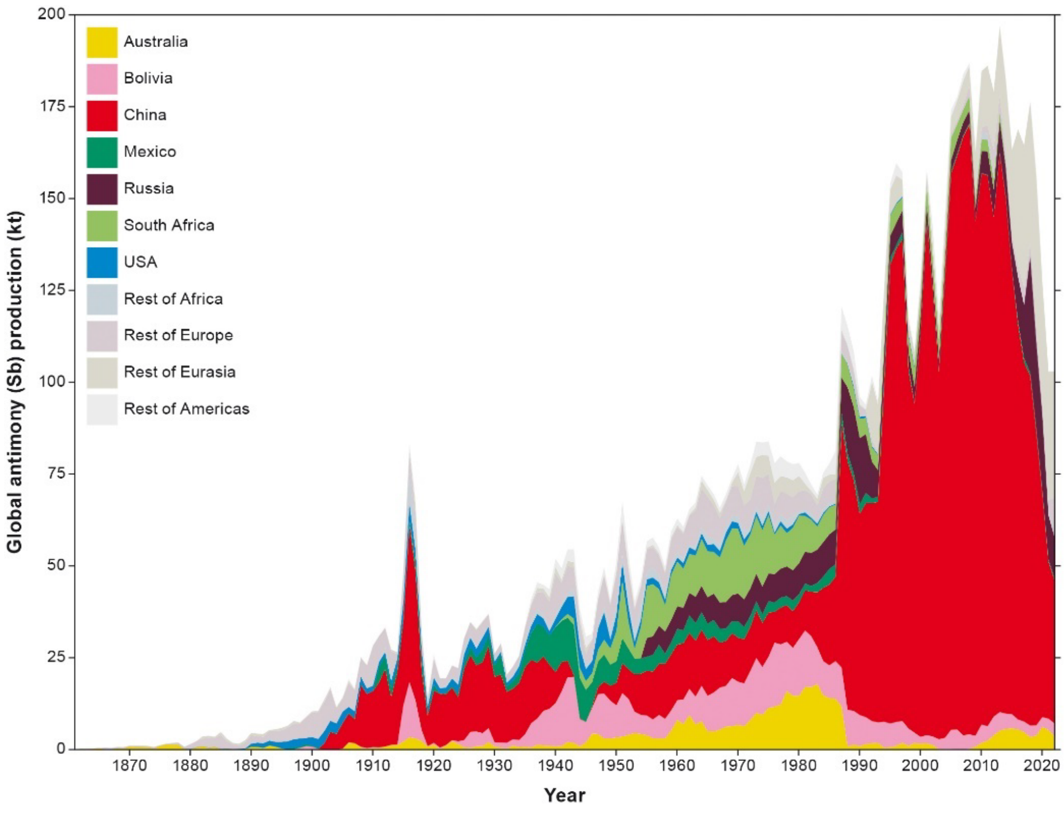


Figure 10 Historical world Sb mine production (Synthesis by G M Mudd, unpublished. Data sources combine BGS (Idoine et al., 2024), USGS (U.S. Geological Survey, 2024b; U.S. Geological Survey, 2024a) and (Anonymous, 1942b), including historical editions of these reports). BGS © UKRI.

The regulations target Sb oxides with a purity greater than 99.99 per cent and other high-purity Sb compounds (99.999 per cent). This threshold suggests they are aimed at high value-added products and advanced processing technologies (Zhang, 2024). Since China is now a net importer of Sb ore, the regulations are considered to be more significant for higher-value Sb products (Bedder, 2024b). However, the measures are still expected to further reduce China's Sb metal exports, which have been shrinking since 2022 due to tightening concentrate supplies and growing domestic demand. Increased metal supplies from Tajikistan, India and Thailand have, however, gone some way to providing alternative sources (Argus Media, 2024).

The Sb price reached record highs in 2024, rising from $23.5/kg before the August announcement to $31.25/kg in October (Argus Media, 2024). However, other supply chain events also contributed to trade disruption and price increases, including (Bedder, 2024a; Belda, 2024; Home, 2024):

- reduced Russian supply
- re-routing of shipments around the Red Sea
- conflict in Myanmar
- declining Chinese exports

With the Sb market forecast to have a shortfall of about 10 000 t before the regulations were announced (Home, 2024), it is thought to be very likely that global availability will be affected, with shortfalls possible (Bedder, 2024a; Sadden, 2024).

If all these events affecting Sb were taken into quantitative account, such trade issues would affect both global supply risk (for example, greater production concentration; less diverse global trade), UK economic vulnerability (for example, increased prices leading to increased AC), as well as the potentially increased difficulty of securing Sb materials.

4.5.2 Gallium and germanium

Ga and Ge are essential to numerous industries, most notably semiconductors, microprocessors, solar PVs and magnets used in renewable technologies (Bedder, 2024a; Liang and Marsh, 2023; Morris, 2023). Both also have important military applications, including in radar, high-power lasers and satellites. Ga is produced as a by-product of Al or Zn, while Ge can be recovered as a by-product from Zn or coal fly-ash. China accounts for about 95 per cent and 92 per cent of Ga and Ge production, respectively (Appendix 3). Historical world Ga and Ge production are shown in Figure 11**.**

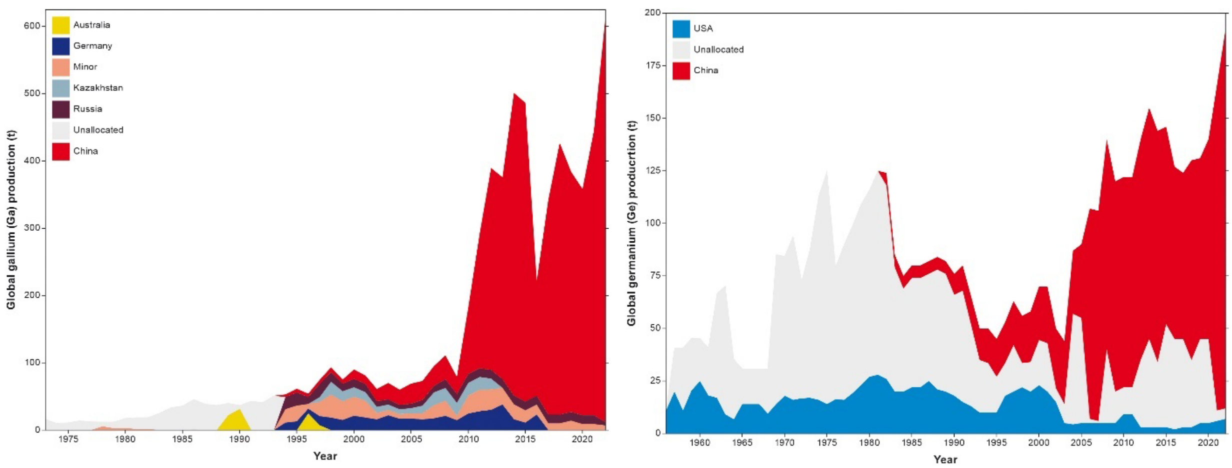


Figure 11 Historical world Ga (left) and Ge (right) production ('unallocated' is all other countries except those shown). Data sources combine BGS (Idoine et al., 2024) and USGS (U.S. Geological Survey, 2024b; U.S. Geological Survey, 2024a) data, including historical editions of these reports. BGS © UKRI.

In July 2023, China announced that, from August 2023, special licences were required to export eight Ga and six Ge products (International Energy Agency, 2024c; Liang and Marsh, 2023; Lv and Patton, 2023). Exporters are now required to obtain a licence for dual-use items and technologies (those with civilian and military applications) on a case-by-case basis (Morris, 2023). The regulations have impacted global supply, with exports falling in the months following the imposition of the regulations. Although they returned to ‘normal’ levels by December 2023, global 2024 exports are set to be lower than in 2022 and 2023 (Pronk, 2024).

Ga and Ge prices have risen since the imposition of the trade regulations, from around $250 to $265/kg Ga before the announcement, to around $550 to $600/kg in March 2024, stabilising thereafter (Argus Media, 2024; Pan et al., 2024). Ge metal exports have declined, with an average of 2216 kg per month between January and May 2024, less than half of that during the same period in 2023. Ge metal prices have risen from about $1350 to $1400/kg before the announcement to about $3000/kg in October 2024 (Argus Media, 2024; Pan et al., 2024), whilst germanium dioxide (GeO_2) prices rose from $915/kg to $2150/kg in the same timeframe (Argus Media, 2024). The imposition of these regulations by China has had a significant effect on the global availability and prices of Ga and Ge. However, the effect is expected to be more pronounced for Ga due to its limited production outside China compared to Ge (Asenov, 2023; Belda et al., 2023).

As with Sb, China’s trade restrictions affected both global supply risk (for example, greater production concentration; less diverse global trade), UK economic vulnerability (for example, increased prices leading to increased apparent consumption) as well as the potential increased difficulty of securing Ga and Ge materials. It should be noted that both Ga and Ge have amongst the highest scores for global supply risk in this study (beaten only by Ru), meaning these trade issues make the context even more difficult for these materials.

4.5.3 Rare earth elements

REEs are crucial components in a wide range of technologies, most notably in high-strength permanent magnets and catalysts used in renewable technologies. They also have significant military-related applications, such as in communications and weapon systems (Mancheri, 2015; Mancheri et al., 2019; Merriman, 2023a).

Historical world REE oxide production is given in Figure 12, showing the rise of China’s REE sector from the 1980s to become the leading global producer by 2000. China now accounts for 64 per cent of global REE production (Appendix 3).

China has placed export quotas and licensing requirements on REEs since 1999. From 2006, export quotas were reduced significantly, with a deep 70 per cent cut in 2010 (Mancheri, 2015; Wübbeke, 2013). In addition, a series of other controls were enacted in 2010, including tariffs of 15 to 20 per cent on REE exports and increased tax rates on some REEs, REE oxides (REOs) and associated products (Godek, 2023).

As a result of this restricted supply and combined with speculative buying, prices reached record levels, peaking in mid-2011 (Mancheri et al., 2019; Merriman, 2023b) (Figure 14). For example, neodymium oxide (Nd_2O_3) rose from $15 208/t in 2009, through $50 635/t in 2010 to peak at $250 574/t in 2011 before falling to $122 364/t in 2012 and eventually $71 833/t in 2013 (Stormcrow, 2015). In 2013, many short-term REE prices remained 1000 per cent higher than their 10-year lows (Tyrer and Sykes, 2013). Annual average prices for Dy and Nd indexed to 2005 are shown in Figure 13, showing the clear increase after the 2010 export restrictions.

The 2010 export quotas divided REEs into light, medium and heavy. This led to exporters favouring the higher-value heavy REEs (Mancheri et al., 2019), restricting the availability of light and medium REEs to the market. In 2014, the World Trade Organisation ruled against China’s system of export tariffs and quotas (Mancheri et al., 2019; Merriman, 2023b). Subsequently, it was replaced in 2015 by a licencing system for exporters, tariffs and a production quota system (Mancheri et al., 2019; Merriman, 2023b).

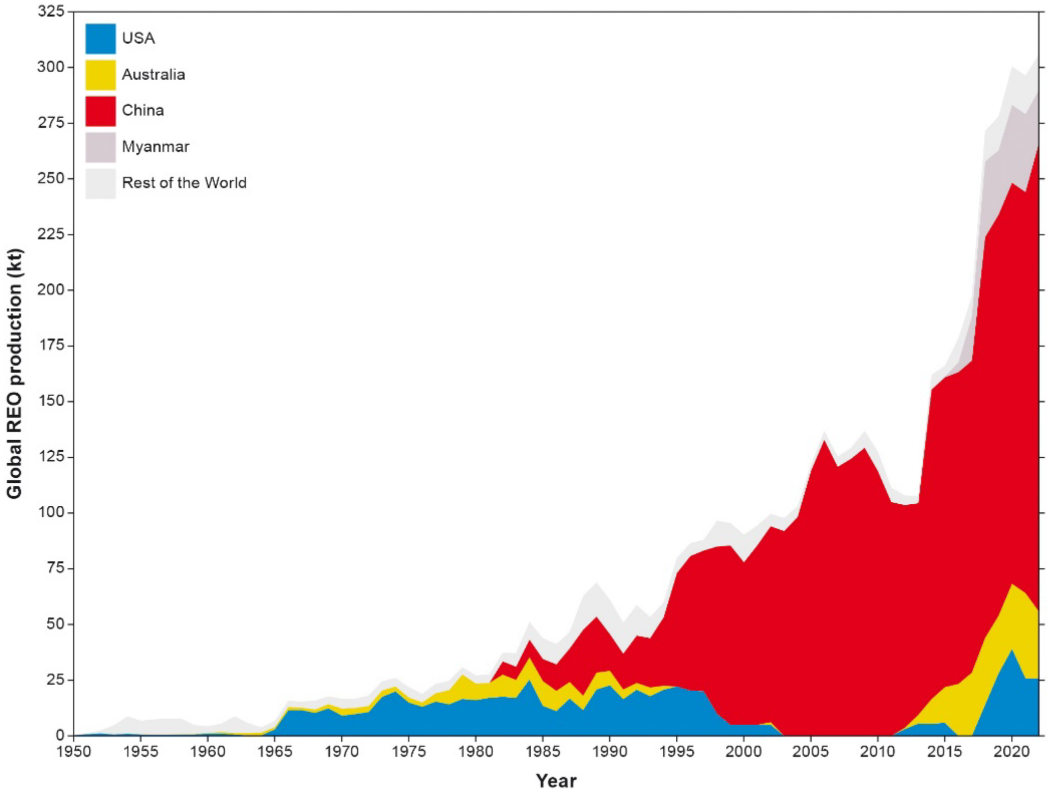


Figure 12 Historical world REE oxide production by country. Data updated by G M Mudd from Weng et al. (2015) using BGS (Idoine et al., 2024) and USGS (U.S. Geological Survey, 2024b; U.S. Geological Survey, 2024a) data, including historical editions of these reports, and (Anonymous, 1942a)). BGS © UKRI.

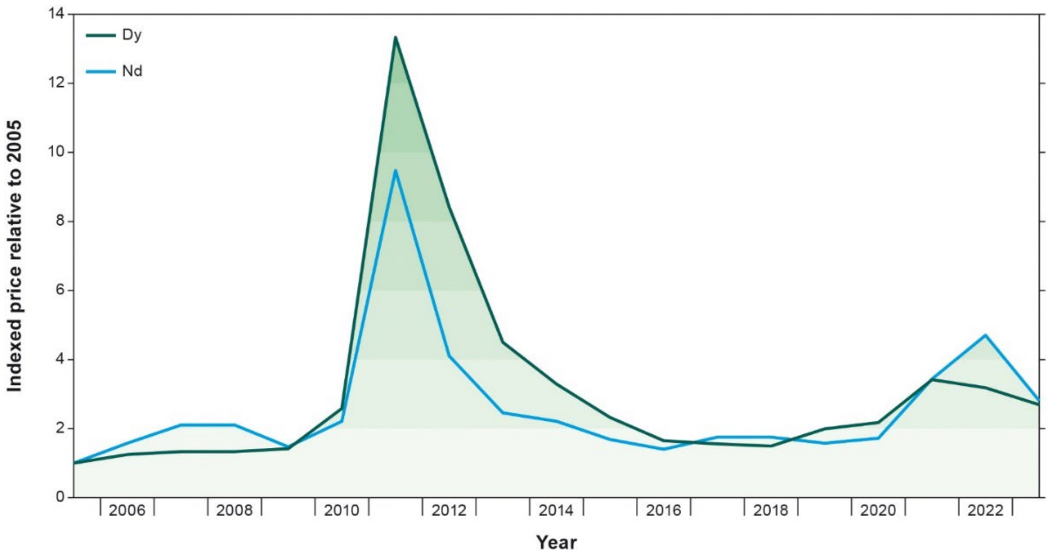


Figure 13 Average annual prices for Dy and Nd indexed to 2005. Data from USGS (U.S. Geological Survey, 2024b; U.S. Geological Survey, 2024a). Note: average annual prices do not show price changes at monthly or shorter time scales. BGS © UKRI.

More recently, China banned the export of REE refining and magnet manufacturing technologies in 2023, whilst new regulations on REE mining, smelting and trading came into effect in October 2024. Chinese REE resources became state-owned and REE mining, smelting and separation and export now need to use a system, developed and monitored by the government, to record the flow of REE products (Baskaran, 2024; Merriman, 2024; Woo, 2024).

4.5.4 Trade regulations and implications for the UK

Trade regulations can significantly disrupt global critical mineral supply chains and trade, potentially causing shortages and price volatility. The extent of disruption is highly variable. It is influenced by many factors, including the nature of the regulations, their timing and duration, and supply chain resilience (Organisation for Economic Co-operation and Development, 2010).

Trade disruption creates challenges for downstream operators and industries, which may struggle to secure sufficient supply or face economic challenges, affecting end-product or service delivery (Mancheri et al., 2019). Uncertainty may also deter investment and development. In turn, this can have knock-on effects on both national and international security, and on economic, development and environmental targets. Furthermore, imbalances in supply and capacity can shift competitive advantages between companies and nations (Organisation for Economic Co-operation and Development, 2010).

However, the challenges imposed by trade regulations can stimulate innovation, for example in the form of material efficiency or substitution, as well as the development of alternative sources (Mancheri et al., 2019). In the long term, such innovation can generate more resilient and diversified supply chains and trade mechanisms.

As the UK is reliant on imports of many raw and processed materials, its economy is vulnerable to the effects of global trade measures and regulations. Additionally, the UK's critical mineral refining and manufacturing capacity being in its nascent stages (platinum group elements being the exception) potentially heightens this vulnerability. It is noted that trade policy should seek to minimise the barriers to the flow of such materials across borders.

4.6 UK current and historical mine production and mineral resources

The UK has had extensive mining sectors in the past, as well as some key sectors maintaining production in the present day. For example:

- Sn, Cu and W were extensively mined in Cornwall and Devon
- Cu and Fe ore in Wales
- Fe ore in Oxfordshire and Northern Ireland
- Au in Scotland and Northern Ireland
- fluorspar, Pb and Zn across many areas in northern England and Scotland

The commodities being actively mined in the UK in recent years include:

- Au
- W
- kaolin clay
- K salts (as potash or polyhalite)
- halite
- barite
- industrial (silica) sand
- fluorspar
- gypsum
- a variety of other industrial and construction minerals

There are deposits with resource data adhering to modern industry standards, whilst for many commodities there are areas of known mineralisation based on historic mining and geological investigations (Bide et al., 2020b; Deady et al., 2023).

Examples of recent industry reported mineral resources include:

- South Crofty (Cornish Metals Inc), England: Sn; Cu; Zn

- Parys Mountain (Anglesey Mining Plc), Wales: Cu; Pb; Zn; Ag; Au
- Hemerdon (Tungsten West Plc), England: Sn; W
- Curraghinalt (Dalradian Gold), Northern Ireland: Au; Ag; Cu
- Cononish (previously Scotgold Resources Plc), Scotland: Au; Ag
- Trelavour (Cornish Lithium Plc), England: Li
- St Austell (Imerys British Lithium Ltd), England: Li
- Redmoor (Strategic Minerals Plc), England: Sn; W; Cu
- Cavanacaw (Galantas Gold Corporation), Northern Ireland: Au; Ag; Pb

Examples of historic reports of mineral resources for various deposits include:

- Arthrath, Littlemill, Muirtack and Rodburn in Scotland: Ni; Cu
- Yate in England: Sr
- Coed Y Brenin in Wales: Cu; Mo; Au

With respect to specific commodities, areas with historically assessed mineralisation are known for (Bide et al., 2020b):

- barite
- Cu
- feldspar
- fluorspar
- Au
- gypsum
- kaolin clay
- Pb
- Li
- Ni
- perlite
- phosphate rock
- Sr
- Ag
- Sn
- talc
- W
- Zn

Metals such as Cu, Pb, Sn and Zn are often hosts to a variety of companion metals, such as Cd, Sb, In, Te, Ge and others.

Recent reviews by CMIC have shown different areas of the UK are prospective for:

- Co (Gunn and Deady, 2022b)
- graphite (Lusty and Goodenough, 2022)
- Li (Shaw, 2022)
- Ni (Gunn and Deady, 2022a)
- Mn (Josso and Lusty, 2023)
- PGEs (Currie and Elliott, 2024a)
- REEs (Currie and Elliott, 2024b)

This brief review highlights that there are areas in the UK prospective for potential domestic mine supply (Deady et al., 2023), but a significant body of further work is required to assess this potential. Specifically, a range of modern geophysical and geochemical surveys would be needed, as these facilitate mineral exploration targeting and enhance the chances of exploration success. Furthermore, many of the regions with known deposits or mineralisation are located within areas statutorily protected for conservation values or heritage sites, meaning that mining projects would require detailed investigation and assessment before planning permissions could be awarded. Significant additional work is also needed to investigate and address social and community issues and ensure appropriate governance and regulatory settings.

Recent UK mine production over the period to 2018 to 2022, the status of mineral resources and historical UK mine production has been compiled in Appendix 8. During this specific period, the UK produced:

- K salts (potash; polyhalite)
- barite
- gypsum

- fluorspar
- industrial salt
- industrial (silica) sand
- kaolin clay
- minor amounts of
    - Au
    - Ag
    - Sn
    - W
    - talc

4.7 Recycling potential

The extent of recycling for the candidate materials assessed in this study is highly variable, ranging from zero to a maximum of 95 per cent (Au). The UK imports and exports waste and scrap flows for a range of materials, derived from related processing and manufacturing activities. The distinction between secondary material flows and primary production is not always clear in trade and economic data. Expert judgement has been applied here to ensure that the CA focused on raw material inputs to the UK economy.

Selected examples of the importance of these activities include:

- W: the UK is the third largest global exporter of W, which is derived from processing of secondary materials given there is no operating W mine at present in the UK
- PGEs: the UK is one of the world's largest refiners of PGEs, based entirely on imports and subsequent exports of processed products
- Cu: there is no secondary Cu smelter-refinery in the UK, meaning all Cu scrap is exported with refined Cu metal and subsequent products made from the scrap then imported
- Waste electrical and electronic equipment (WEEE) has high end-of-life collection rates, which are driven by policy, regulations and supportive consumer behaviour; however, most of this material is still mostly exported and not processed in the UK
- Waste and scrap exports: UK and global trade data shows significant quantities of waste and scrap derived from many materials are exported from the UK, suggesting that there are opportunities to process this material in the UK and retain the stocks here

Another major challenge with recycling, especially waste and scrap flows, is discerning the relevant metal contents. For example, imported waste and scrap containing PGEs increased from 3150 t in 2018 to 5772 t in 2022 (Bide et al., 2024), although the metal content of this flow is not publicly available. In addition, WEEE comprises 14 categories, each with a considerable variety of products, appliances and technologies. Assigning average metal contents to WEEE data is therefore extremely difficult.

Overall, the area of recycling needs a greater capacity to synthesise data, monitor material flows through the economy and explore opportunities to improve the circularity of the UK economy. Given the fact that recycling can be considered a midstream industry, further investment into recycling is well placed to support future supply needs for the UK.

5 Review of other risks and opportunities

Throughout the conduct of this study, including consultation with stakeholders, a range of risks and opportunities has come to light, which is worthy of consideration. The examples given are not exhaustive but provide some illustration of previously unaccounted-for risks and opportunities for the UK.

5.1 Climate change risks to global supply

Climate change presents significant risks to the supply of critical minerals as well as opportunities for new technologies driving demand growth for a wide variety of critical minerals. The dominant focus in research and policy, however, has typically been on the latter: growing demand for critical minerals has been driven by mitigation technologies. There remains very sparse research on the impacts of climate change on the areas where critical minerals are being or could be mined.

The issue of water resource risks due to climate change has been explored by Northey et al. (2017), highlighting that up to 32 per cent of Cu, Ni and Pb-Zn mineral resources globally are in areas subject to shifting climates and worsening water balances.

Further research, based on the most recent climate change modelling and assessments, needs to explore risks such as:

- flooding: this can potentially affect mine production, for example, Hurricane Helene-induced flooding in North Carolina, USA, impacted high-purity silica mines supplying the semiconductor industry (Hsu, 2024)
- water stress: many countries producing critical minerals are already facing high levels of water stress, for example Chile or Spain, and countries producing non-critical minerals such as Cu, for example Chile, suffer water stress that could cause significant supply constraints and disruptions (Kuzma et al., 2023)
- extreme heat: this can lead to loss of production capacity due to the effect on labour productivity, especially safe working conditions
- extreme storms, including wind: storms can damage infrastructure and lead to loss of production

A recent study by PwC (2024) explored the impacts of climate change on key commodities, including metals, minerals and food, from a low-emissions scenario only. They found that 62 per cent of each Fe and bauxite (Al ore) and 26 per cent of Zn production are exposed to significant, high or extreme heat stress, while 74 per cent of each Li and Co and 54 per cent of Cu production are exposed to significant, high or extreme drought risks. They also note that some of the countries producing these materials are subject to significant climate change risks, but that 81 per cent of the world's Li, 50 per cent of bauxite and 44 per cent of Fe were each sourced from no more than ten mines within these countries.

The IEA recently included risk assessment of critical minerals in their Global Critical Minerals Outlook 2024 report, including supply risks (market factors), geopolitical risks, disruption response potential and climate change risks combined environmental, social and governance (ESG) risks (International Energy Agency, 2024d). The IEA's analyses are summarised in Table 14 below, highlighting the broad range of risks faced by key materials but especially the high climate-related risks.

The area of present and future climate change risks to the supply of raw materials, both critical and non-critical, needs substantial research to assess supply disruption potential.

Table 14 Risks facing key commodities for renewable energy and electric vehicle batteries (from (International Energy Agency, 2024d), where risks are rated on a 7 point scale with 1 being low, 4 medium and 7 high.

Material	Supply risk	Geopolitical risk	Disruption response potential	ESG and climate risk
Copper (Cu)	5 / 7 31% shortfall in project pipeline for APS scenario	3 / 7 Relatively diversified supply	2 / 7 Mature markets, sizeable secondary supply	5 / 7 52% of mines in high water stress areas
Lithium (Li)	6 / 7 High price volatility	5 / 7 85% refining by top 3 countries in 2030	6 / 7 3% secondary supply only	5 / 7 50% of mines in high water stress areas
Nickel (Ni)	2 / 7 Only 6% of battery pack cost in 2023	6 / 7 61% of mining in single country by 2030	5 / 7 1% secondary supply only	6 / 7 High carbon intensity during refining
Cobalt (Co)	4 / 7 16% shortfall in project pipeline for APS scenario	6 / 7 84% of mining in single country by 2030	3 / 7 Growing adoption of low cobalt battery chemistries	6 / 7 Low social and environmental performance in mining
Graphite (natural)	2 / 7 High demand growth above historical rates	7 / 7 10x demand outside top producer in 2030	6 / 7 Limited potential for substitution	6 / 7 Low social and environmental performance in mining
Rare earth elements (REEs)	3 / 7 High price volatility	6 / 7 77% refining by one country in 2030	6 / 7 Poor market price transparency	5 / 7 High carbon intensity during refining

5.2 Other risks and opportunities for the UK

There are numerous risks that could affect the supply of critical and non-critical minerals to the UK, which require continual monitoring and associated research. These include:

- Ukraine-Russia war: this could lead to rapid changes in materials required for military equipment and technologies (for example, W; specialty alloys; munitions)
- decarbonisation: this is already leading to significant changes in the markets for some materials (for example, gypsum) and can be expected to affect the future supply of others (especially S)
- trade barriers and tariffs: these both remain a fundamental risk to reliable raw material supply (critical and non-critical) meaning that, given rising geopolitical tensions globally, a more dynamic approach to critical minerals may be required
- fluorspar: as the UK has not produced fluorspar since 2023, it is likely that the criticality of F for the UK will soon change significantly. (It is worth noting that fluorspar, the source mineral containing F, is listed as critical by the EU, USA, Canada and Australia, with only the EU producing minor quantities of fluorspar.)

At present, a range of opportunities relating to both critical and non-critical minerals are evident for the UK:

- potassium (K) salts: although not listed as critical in this study, the UK is a growing producer of K salts, especially of polyhailte, and therefore could meet the some of the needs of its trading partners for these materials.
- Iron (Fe): The changes currently taking place in the UK Fe and steel sector provide opportunities to explore greater circularity, which should specifically address specialty steels and alloys and incorporate the need for detailed and accurate material flow data to ensure success. This will require substantial efforts to achieve. Future CAs could explore the ways that different grades or alloys of steel might be incorporated (for example, the US Department of Energy lists electrical-grade steel as critical (U.S. Department of Energy, 2023)).
- domestic production: the UK has known mineral deposits of Li, Sn, W, Sr and Ni-Co and significant potential for the discovery of Cu, Pb, Zn and other deposits. Many by-products are potentially associated with these metals, such as Cd, In, Ge and Te. If they prove to be economic and meet regulatory and community requirements, these projects could help the UK achieve resilient material supply chains as well as potentially provide for exports in excess of UK requirements. It is important that planning processes safeguard known areas of mineralisation (for example, UK Sr deposits are no longer being safeguarded in planning provisions) as well as linking mining to smelting and refining stages.
- midstream processing: the UK imports a range of materials, including waste and scrap, and re-processes them into higher-value materials or products (for example, PGEs). This is too complex to evaluate in a CA, but further research to explore specific opportunities is justified.

6 Recommendations for future UK criticality assessments and related research needs

This study has highlighted a number of areas where methodological improvements in CA are required. It has also identified a wide range of topics that require further study to understand material supply chains and thus to contribute to maintaining secure and sustainable material supplies to the UK. We have identified a set of recommendations relating to this and future criticality assessments, specifically:

6.1 Midstream manufacturing and material flows

The UK has a variety of midstream processing capabilities for some materials (for example, PGEs; W) but full supply chain analyses are complex and rarely available for the UK context. We recommend focussing future efforts on investigating and documenting in detail specific materials, such as REEs, PGEs and W, and their flows through the UK economy. Data gathering needs should be assessed with respect to adequacy for use in material flows along supply chains.

Future work is recommended that develops methods to distinguish and quantify primary and secondary flows in the UK economy, as some economic data does not currently allow for this. Secondary flows present a substantial opportunity for the UK to capture and retain value, improving resilience and the circularity of the UK economy. Further work is required to identify and capture the best opportunities where the UK has existing strengths and can build new strengths (for example, recycling REE magnets).

The UK requires midstream activities essential to decarbonisation. For example, there is no secondary Cu smelter-refinery and no production of battery materials, such as cathodes, or permanent magnets. All opportunities to develop these missing capacities should be explored, especially to support a modern industrial strategy for the UK.

6.2 Trade barriers and partnerships

There is a requirement for developing a reliable and holistic approach that incorporates trade barriers and partnerships into the CA for the UK. Whilst various approaches have been adopted in other CAs (U.S. Geological Survey, 2022b; European Commission, 2023), they do not incorporate to incorporate all aspects considered necessary for a robust criticality assessment.

6.3 Deep-dive studies

There is a clear requirement for deep-dive studies on particular commodities, especially those relevant to the UK's domestic production potential, midstream manufacturing or international interests (industry and trade). Such studies are essential for developing detailed datasets and a quantitative understanding of mineral resources, mining, refining, uses by sector or application, the extent of and opportunities for recycling, ESG issues and other constraints affecting that commodity as well as for potentially developing global supply scenarios. Given UK strengths and concerns, we recommend that Cu, Fe, Ta and W be given high priority for such studies. Other material such as Li, V and Sr should also be considered for similar detailed analyses.

Given the rapid development of quantum computing and the increasing pace of digital transformation, information and communications technology (ICT) will continue to increase in importance. As demonstrated in this report, this brings a growing reliance on a wide range of materials. We hence recommend prioritising deep-dive studies on ICT generally, or for specific technologies such as quantum computing in the near future.

As the proportion of electricity derived from renewable energy sources increases in the UK, there will be a growing need for energy storage systems. We hence recommend a deep-dive study on the potential growth of energy storage systems, perhaps with a particular focus on grid-scale batteries.

All deep-dive studies should include a foresight analysis to project future scenarios of UK material demand in a global context.

6.4 Domestic production opportunities

Increasing UK domestic production for various raw materials will require better pre-competitive data that supports the process of mineral exploration through to mine development. Such data has been shown to lead to significant discoveries as well as economic benefits (for example, Australia (Deloitte, 2023); Spain (Herrero de Egaña et al., 2020), and Ontario, Canada (Rainsford, 2019)) yet are currently not widely available in the UK. We recommend undertaking modern geophysical surveys of the most prospective parts of the UK to improve data availability, mineral exploration targeting and the chances for new deposit discovery.

6.5 Future methodological issues

Our study has identified the need for developing a methodology that enables a rapid response in the interim between consecutive criticality assessments; for example, in response to trade-related or other events that affect the global, regional or local supply of particular materials. We hence recommend development of a new approach that allows need to extend and complement this CA until a new, full assessment is completed. Alternatively, it might be possible to simply update the data for a material and compare any changes to this study (for example, if material X has trade restrictions placed on it by the leading producer in mid-2025, all data could be updated to 2024 and compared against the data in this study).

It is also important that further work be completed to investigate the ambiguity found during this study where secondary processing appears as primary production in economic data. For future work in this area, clear methods or guidelines must be developed to facilitate accurate interpretation of trade and economic data for syntheses such as CAs, deep dives, foresights or related studies.

Future CAs should investigate the treatment of the REEs ideally as individual elements, or at least as the light vs. heavy distinction, as this is important for key technologies, especially permanent magnets.

Many candidate materials that have not been deemed critical in this assessment merit continued close attention, especially those located close to the criticality threshold or with concerns for future supply reliability, such as Cu, Pd and U. Many factors can affect the future criticality designation of these materials, whether it be climate change impacts, social issues or governance challenges. Therefore, continued monitoring of the full 82 candidate materials is recommended, including their use in the next CA. We recommend that the materials plotting below the criticality threshold are maintained on a watch list, which maintains close monitoring and assessment. Further research on additional potential indicators and sensitivity analyses should be done. This could include ways of dealing with trade barriers, price volatility, production concentration at the scale of companies, and improvements for the GVA.

6.6 Future criticality assessments and related research

It is recommended that CAs continue to be performed at regular intervals, combining short-term analyses to respond to urgent issues with long-term strategic thinking. Short-term responses could assess dynamic changes to a specific material, whilst long-term approaches would assess trends in supply and demand and technological evolution. The next full CA for the UK should be delivered no later than 2027.

It is noted that, to address the risks identified in CAs, there needs to be a mix of primary supply, secondary capacity, planning a strong industrial strategy built on a strong critical minerals foundation and maintaining the expertise to analyse and assess the numerous material supply chains, technologies and their links to the UK economy. We conclude by highlighting that this requires ongoing support for criticality-related research, associated data needs (mining and refining; trade data; economic data; material stocks and flows; etc.) and increasing the amount of international collaboration.

Appendix 1 Datasets used for the ESG score

World Bank: World Governance Index (WGI) (World Bank, 2024)

- WGI raw values are a score from -2.5 to 2.5 across 6 individual aspects (where 2.5 represents great governance, -2.5 worst governance), each of these are normalised to a 1 to 10 scale, the geometric mean of all 6 aspects then calculated and this value inverted so that 1 represents great governance and 10 the worst governance.

United Nations Development Program: Human Development Index (HDI) (United Nations Development Programme, 2024)

- HDI raw values are a score out of 1 (where 1 represents the highest state of development, 0 means lowest), these are normalised to a 1 to 10 scale and then inverted so that 1 represents the highest state of development and 10 the lowest;

Yale University: Environmental Performance Index (EPI) (Block et al., 2024)

- EPI raw values are a score out of 100 (where 100 represents the best environmental outcomes, 0 means lowest), these are normalised to a 1 to 10 scale and then inverted so that 1 represents the best environmental outcomes and 10 the lowest;

Equation 1 $ESG(i) = \sqrt[3]{(EPI(i) * HDI(i) * WGI(i))}$

Country/territory	Inverted rescaled WGI	Inverted rescaled HDI	Inverted rescaled EPI	ESG score
Afghanistan	8.7	-	6.1	7.3
Albania	5.5	2.9	5.8	4.5
Algeria	7.0	3.3	7.3	5.5
American Samoa	3.8	-	-	3.8
Andorra	3.0	2.0	-	2.5
Angola	6.9	4.7	7.3	6.2
Anguilla	3.7	-	-	3.7
Antigua and Barbuda	4.8	2.6	5.3	4.0
Argentina	6.0	2.4	6.3	4.5
Armenia	5.9	2.9	5.7	4.6
Aruba	3.5	-	-	3.5

Country/territory	Inverted rescaled WGI	Inverted rescaled HDI	Inverted rescaled EPI	ESG score
Australia	2.8	1.5	4.6	2.7
Austria	3.2	1.7	4.0	2.8
Azerbaijan	6.9	3.2	6.5	5.2
Bahamas	4.5	2.6	4.9	3.9
Bahrain	5.6	2.0	6.2	4.1
Bangladesh	7.1	4.0	7.9	6.1
Barbados	4.1	2.7	5.2	3.9
Belarus	7.5	2.8	5.6	4.9
Belgium	3.4	1.5	4.8	2.9
Belize	5.8	3.7	5.5	4.9
Benin	6.1	5.5	7.3	6.2
Bermuda	3.6	-	-	3.6
Bhutan	4.6	3.9	6.2	4.8
Bolivia	6.9	3.7	6.4	5.5
Bosnia & Herzegovina	6.4	3.0	6.5	5.0
Botswana	4.4	3.6	5.1	4.3
Brazil	6.0	3.2	6.1	4.9
Brunei	4.2	2.6	5.9	4.0

Country / Territory	Inverted rescaled WGI	Inverted rescaled HDI	Inverted rescaled EPI	ESG Score
Burkina Faso	7.0	-	6.8	6.9
Burundi	7.8	-	7.3	7.5
Cabo Verde	-	4.1	6.2	5.0
Cambodia	6.9	4.6	7.3	6.1
Cameroon	7.4	4.7	7.3	6.3
Canada	2.9	1.6	5.5	2.9
Cape Verde	4.5	-	-	4.5
Cayman Islands	3.8	-	-	3.8
Central African Republic	8.4	-	6.0	7.1
Chad	8.0	-	7.5	7.7
Chile	4.2	2.3	5.8	3.8
China	6.3	2.9	7.4	5.1
Chinese Taipei	3.4	-	5.9	4.5
Colombia	5.9	3.2	6.2	4.9
Comoros	7.5	4.7	6.2	6.0
Congo	7.5	4.7	6.4	6.1
Congo, Democratic Republic of the	8.4	5.7	6.7	6.8
Cook Islands	5.1	-	-	5.1
Costa Rica	4.5	2.7	5.8	4.2
Côte d'Ivoire	6.2	5.2	7.0	6.1

Country/territory	Inverted rescaled WGI	Inverted rescaled HDI	Inverted rescaled EPI	ESG score
Croatia	4.7	2.1	4.6	3.6
Cuba	6.6	3.1	5.7	4.9
Cyprus	4.4	1.8	4.8	3.4
Czech Republic	3.7	1.9	4.6	3.2
Denmark	2.4	1.4	3.0	2.2
Djibouti	7.1	5.4	5.7	6.0
Dominica	4.5	3.3	5.4	4.3
Dominican Republic	5.5	3.1	6.2	4.7
East Timor	6.1	4.9	6.8	5.9
Ecuador	6.2	3.1	5.8	4.8
Egypt	6.9	3.4	6.8	5.5
El Salvador	6.3	3.9	6.3	5.4
Equatorial Guinea	7.9	4.2	6.0	5.8
Eritrea	8.6	5.6	7.1	7.0
Estonia	3.2	1.9	4.5	3.0
Eswatini	6.8	4.5	6.0	5.7
Ethiopia	7.4	5.6	7.1	6.7
Fiji	5.0	3.4	7.2	5.0
Finland	2.5	1.5	3.1	2.3
France	3.7	1.8	4.4	3.1
French Guiana	3.7	-	-	3.7

Country / Territory	Inverted rescaled WGI	Inverted rescaled HDI	Inverted rescaled EPI	ESG Score
Gabon	6.8	3.8	5.5	5.2
Gambia	6.2	5.5	6.7	6.1
Georgia	5.0	2.7	6.5	4.4
Germany	3.1	1.5	4.4	2.7
Ghana	5.5	4.6	7.5	5.7
Greece	4.8	2.0	4.9	3.6
Greenland	3.3	-	-	3.3
Grenada	4.6	2.9	5.7	4.2
Guam	3.8	-	-	3.8
Guinea	7.3	5.8	7.2	6.7
Guinea-Bissau	7.5	5.7	6.4	6.5
Guyana	5.9	3.3	6.5	5.0
Haiti	8.3	5.0	7.7	6.8
Honduras	6.8	4.4	6.7	5.9
Hong Kong SAR, China	3.8	1.4	-	2.3
Hungary	4.8	2.3	5.0	3.8
Iceland	2.9	1.4	4.3	2.6
India	5.7	4.2	8.3	5.8
Indonesia	5.6	3.6	7.5	5.3
Iran	7.8	3.0	6.9	5.4

Country / Territory	Inverted rescaled WGI	Inverted rescaled HDI	Inverted rescaled EPI	ESG Score
Iraq	8.4	3.9	7.5	6.3
Ireland	2.9	1.5	4.8	2.7
Israel	4.7	1.8	5.7	3.6
Italy	4.5	1.8	4.8	3.4
Jamaica	5.0	3.6	5.9	4.8
Japan	3.0	1.7	4.9	2.9
Jersey, Channel Islands	3.2	-	-	3.2
Jordan	5.7	3.4	6.1	4.9
Kazakhstan	6.1	2.8	6.3	4.8
Kenya	6.4	4.6	7.2	6.0
Kiribati	4.7	4.3	5.6	4.8
Korea, Democratic Peoples Republic of	8.6	-	5.8	7.0
Korea, Republic of	3.8	1.6	-	2.5
Kosovo	6.0	-	-	6.0
Kuwait	5.4	2.4	6.2	4.3
Kyrgyzstan	7.1	3.7	6.8	5.6
Laos	7.0	4.4	7.2	6.1
Latvia	4.0	2.1	4.5	3.4
Lebanon	7.6	3.5	7.1	5.7
Lesotho	6.3	5.3	7.1	6.2

Country / Territory	Inverted rescaled WGI	Inverted rescaled HDI	Inverted rescaled EPI	ESG Score
Liberia	7.0	5.6	7.8	6.7
Libya	8.8	3.3	-	5.4
Liechtenstein	2.6	1.5	-	2.0
Lithuania	3.8	2.1	5.0	3.4
Luxembourg	2.6	1.7	3.5	2.5
Macao SAR, China	4.1	-	-	4.1
Madagascar	6.9	5.6	7.5	6.6
Malawi	6.3	5.4	6.3	6.0
Malaysia	4.8	2.7	6.9	4.5
Maldives	5.8	3.1	6.6	4.9
Mali	7.9	-	7.4	7.7
Malta	4.2	1.8	3.2	2.9
Marshall Islands	4.6	3.4	6.7	4.7
Martinique	4.1	-	-	4.1
Mauritania	6.8	5.1	7.5	6.4
Mauritius	4.1	2.8	6.0	4.1
Mexico	6.5	3.0	5.9	4.8
Micronesia, Federated States of	4.6	4.3	6.6	5.1

Country / Territory	Inverted rescaled WGI	Inverted rescaled HDI	Inverted rescaled EPI	ESG Score
Monaco	3.1	-	-	3.1
Mongolia	5.7	3.3	7.3	5.2
Montenegro	5.4	2.4	5.8	4.2
Morocco	6.0	3.7	7.4	5.5
Mozambique	7.1	-	7.1	7.1
Myanmar	8.5	4.5	8.3	6.8
Namibia	5.0	4.5	5.4	5.0
Nauru	4.8	3.7	-	4.3
Nepal	6.4	4.6	7.5	6.0
Netherlands	2.8	1.5	4.4	2.6
New Zealand	2.5	1.5	4.9	2.7
Nicaragua	7.4	4.0	6.6	5.8
Niger	6.8	-	6.6	6.7
Nigeria	7.5	5.1	7.5	6.6
Niue	4.7	-	-	4.7
North Macedonia	5.4	3.1	5.1	4.4
Norway	2.6	1.3	4.7	2.5
Oman	5.5	2.6	7.2	4.7
Pakistan	7.3	5.1	7.8	6.6
Palau	4.1	2.8	-	3.4
Palestine, State of	-	3.6	-	3.6

Country / Territory	Inverted rescaled WGI	Inverted rescaled HDI	Inverted rescaled EPI	ESG Score
Panama	5.6	2.6	5.5	4.3
Papua New Guinea	6.5	4.9	7.8	6.3
Paraguay	6.3	3.4	6.3	5.1
Peru	6.1	3.1	6.4	5.0
Philippines	6.0	3.6	7.4	5.4
Poland	4.6	2.1	5.4	3.7
Portugal	3.8	2.1	5.5	3.5
Puerto Rico	5.0	-	-	5.0
Qatar	4.6	2.1	7.0	4.1
Réunion	4.3	-	-	4.3
Romania	5.0	2.6	5.0	4.0
Russia	7.4	2.6	6.6	5.0
Rwanda	5.5	5.1	7.0	5.8
Samoa	4.5	3.7	6.7	4.8
San Marino	3.2	2.2	-	2.7
São Tomé and Principe	6.0	4.5	5.2	5.2
Saudi Arabia	5.8	2.1	6.6	4.3
Senegal	5.7	5.3	6.9	6.0
Serbia	5.7	2.8	6.0	4.6
Seychelles	4.2	2.8	5.0	3.9
Sierra Leone	6.7	-	7.1	6.9

Country / Territory	Inverted rescaled WGI	Inverted rescaled HDI	Inverted rescaled EPI	ESG Score
Singapore	2.8	1.5	5.4	2.8
Slovakia	4.5	2.3	4.6	3.6
Slovenia	3.9	1.7	3.9	3.0
Solomon Islands	5.9	4.9	6.9	5.8
Somalia	9.2	-	-	9.2
South Africa	5.7	3.5	6.7	5.1
South Sudan	9.2	-	-	9.2
Spain	4.2	1.8	4.9	3.3
St. Kitts and Nevis	4.4	2.5	-	3.3
St. Lucia	4.5	3.5	5.6	4.4
St. Vincent and the Grenadines	4.3	3.1	5.2	4.1
Sudan	8.4	5.4	7.5	7.0
Suriname	6.0	3.8	5.9	5.1
Sweden	2.7	1.4	3.5	2.4
Switzerland	2.5	1.3	4.1	2.3
Syria	9.1	5.0	-	6.7
Tajikistan	7.7	3.9	6.7	5.8
Tanzania	6.3	5.2	6.9	6.1
Thailand	5.9	2.8	6.6	4.7
Togo	6.7	5.1	6.9	6.2

Country / Territory	Inverted rescaled WGI	Inverted rescaled HDI	Inverted rescaled EPI	ESG Score
Trinidad & Tobago	5.4	2.7	5.7	4.4
Tunisia	6.1	3.4	6.3	5.1
Turkey	6.5	2.3	7.6	4.9
Turkmenistan	8.2	3.3	6.7	5.6
Tuvalu	4.6	4.1	-	4.3
Uganda	6.8	5.1	6.8	6.1
Ukraine	7.0	3.4	5.5	5.1
United Arab Emirates	4.6	1.6	5.3	3.4
United Kingdom	3.3	1.5	3.0	2.5
United States of America	3.8	1.7	5.4	3.2
Uruguay	3.6	2.5	6.6	3.9
Uzbekistan	6.8	3.5	6.6	5.4
Vanuatu	5.2	4.5	6.7	5.4
Venezuela	8.7	3.7	5.8	5.7
Vietnam	6.2	3.5	8.2	5.6
Virgin Islands (U.S.)	4.3	-	-	4.3
West Bank and Gaza	7.2	-	-	7.2
Yemen, Republic of	9.1	-	-	9.1
Zambia	6.2	4.9	6.5	5.8
Zimbabwe	7.7	5.1	5.8	6.1

Appendix 2 Data quality

- Green: complete, up-to-date, reliable (for example, all five years of data; data consistent and certain)
- Amber: partially useable (for example, data for a single year only; some inconsistencies or uncertainties in data or metal contents)
- Red: unreliable or not available (for example, no data; high uncertainty)

Commodity	Mine production concentration	Refined production concentration	Global trade concentration	Companion ality	Recycling rates	UK apparent consumption	UK net import reliance	Gross value added
Aluminium (Al)	Green	Green	Green	Green	Green	Green	Green	Green
Antimony (Sb)	Green	Amber	Green	Amber	Amber	Green	Green	Green
Arsenic (As)	Green	Green	Amber	Amber	Amber	Amber	Amber	Green
Beryllium (Be)	Green	Amber	Green	Green	Amber	Green	Green	Amber
Bismuth (Bi)	Green	Green	Green	Amber	Amber	Amber	Amber	Amber
Cadmium (Cd)	Not relevant	Green	Green	Green	Green	Green	Green	Amber
Caesium (CS)	Red	Red	Amber	Amber	Amber	Red	Red	Amber
Graphite (natural)	Green	Not relevant	Green	Green	Amber	Green	Green	Green
Chromium (Cr)	Green	Green	Green	Green	Green	Green	Green	Green

Commodity	Mine production concentration	Refined production concentration	Global trade concentration	Companionality	Recycling rates	UK apparent consumption	UK net import reliance	Gross value added
Copper (Cu)								
Gallium (Ga)								
Germanium (Ge)	Not relevant							
Gold (Au)								
Hafnium (Hf)	Not relevant							
Helium (He)	Not relevant							
Hydrogen (H)					Not relevant			
Indium (In)	Not relevant							
Iridium (Ir)								
Iron (Fe)								
Lead (Pb)								
Lithium (Li)								

Commodity	Mine production concentration	Refined production concentration	Global trade concentration	Companionality	Recycling rates	UK apparent consumption	UK net import reliance	Gross value added
Manganese (Mn)								
Mercury (Hg)								
Molybdenum (Mo)								
Nickel (Ni)								
Niobium (Nb)								
Palladium (Pd)								
Phosphorus (P)								
Platinum (Pt)								
Potassium (K)		Not relevant						
Rare earth elements (REE)								
Rhenium (Re)								

Commodity	Mine production concentration	Refined production concentration	Global trade concentration	Companionality	Recycling rates	UK apparent consumption	UK net import reliance	Gross value added
Rhodium (Rh)								
Rubidium (Rb)								
Ruthenium (Ru)								
Selenium (Se)	Not relevant							
Silicon (Si)								
Silver (Ag)								
Sodium (Na)		Not relevant						
Strontium (Sr)		Not relevant						
Sulphur (S)		Not relevant						
Tantalum (Ta)								
Tellurium (Te)	Not relevant							
Thallium (Tl)								

Commodity	Mine production concentration	Refined production concentration	Global trade concentration	Companion ality	Recycling rates	UK apparent consumption	UK net import reliance	Gross value added
Thorium (Th)								
Tin (Sn)								
Titanium (Ti)								
Tungsten (W)								
Uranium (U)								
Vanadium (V)								
Zinc (Zn)								
Zirconium (Zr)								

Commodity	Mine production concentration	Refined production concentration	Global Trade concentration	Companionality	Recycling rates	UK apparent consumption	UK net import reliance	Gross value added
Barite		Not relevant						
Bentonite		Not relevant						
Borates								
Diamonds		Not relevant						
Diatomite		Not relevant						
Feldspar		Not relevant						
Fluorine		Not relevant						
Garnet		Not relevant						
Gypsum		Not relevant						
Kaolin clay		Not relevant						
Kyanite		Not relevant						
Industrial limestone		Not relevant						

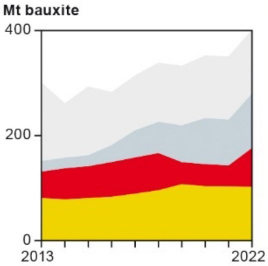
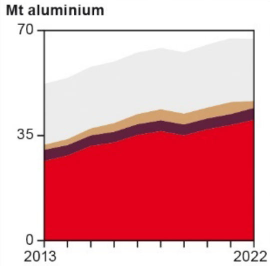
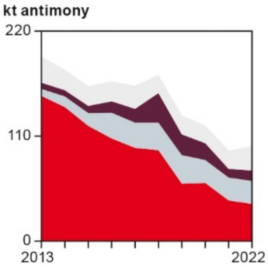
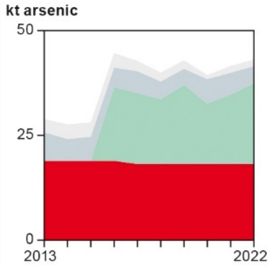
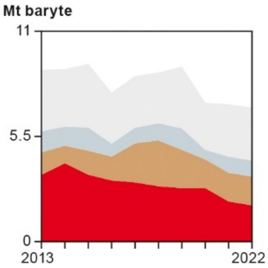
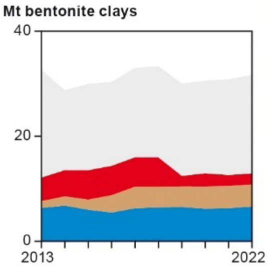
Commodity	Mine production concentration	Refined production concentration	Global trade concentration	Companionality	Recycling rates	UK apparent consumption	UK net import reliance	Gross value added
Perlite		Not relevant						
Pumice		Not relevant						
Pyrophyllite		Not relevant						
Industrial salt		Not relevant						
Industrial (silica) sand		Not relevant						
Talc		Not relevant						
Vermiculite		Not relevant						
Wollastonite		Not relevant						
Zeolite		Not relevant						

Appendix 3 Mining and refining production of each candidate material showing the top three producing countries, 2018 to 2022

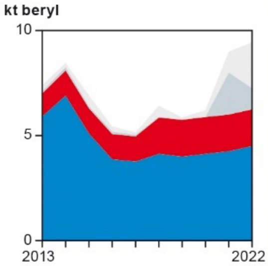
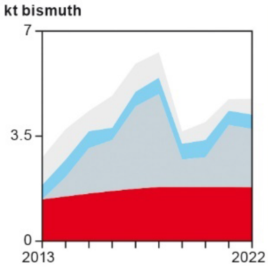
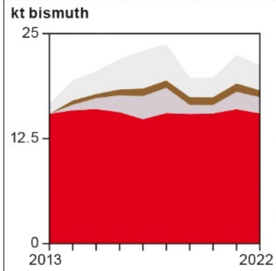
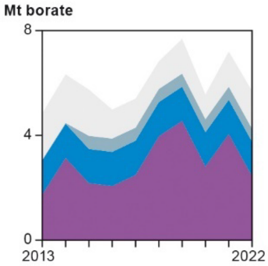
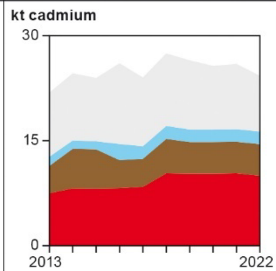
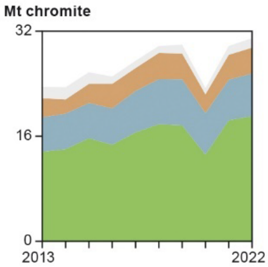
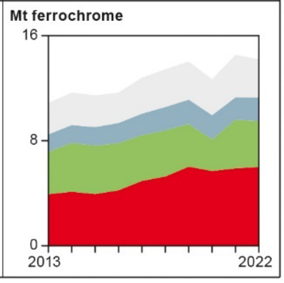
Data sources: BGS – World Mineral Production (Idoine et al., 2024; SCRREEN, 2023d; U.S. Geological Survey, 2024b)

Note: the use of 'Miscellaneous 1' (or 2 or 3) is where a country is not specifically given a colour and only appears rarely. For example, Tajikistan contributes 21.1 per cent of global Sb production but it has no colour specified, meaning for Sb, Tajikistan is represented by the colour for Miscellaneous 1. In cases where there is more than one country without a specified colour, Miscellaneous 1 is the largest producer, Miscellaneous 2 the second largest and Miscellaneous 3 the third largest.

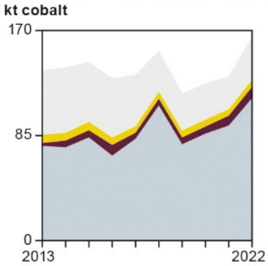
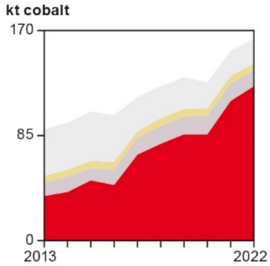
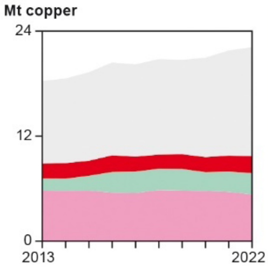
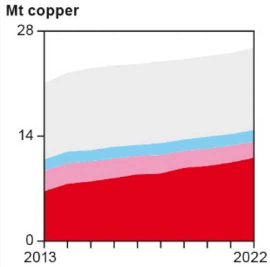
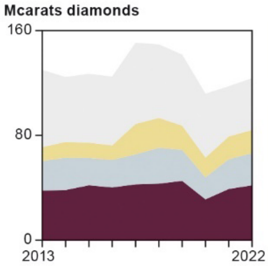
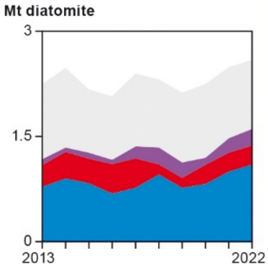
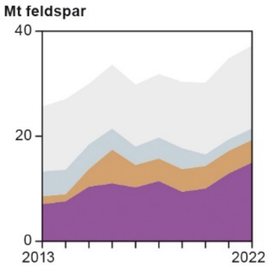
China	India	Republic of Korea	Canada	Chile	Miscellaneous 1
Russia	USA	Peru	South Africa	Rest of the World	Miscellaneous 2
Australia	Japan	Turkey	Kazakhstan		Miscellaneous 3

<table>
<tr><th></th><th colspan="3">Mining</th><th colspan="3">Refining</th></tr>
<tr><th>Material</th><th>Top three countries (2018–2022) [source]</th><th>Score</th><th>Graph</th><th>Top three countries (2018–2022) [source]</th><th>Score</th><th>Graph</th></tr>
<tr><td>Aluminium (Al)</td><td>Australia (28.9%),
Guinea (23.0%),
China (15.1%)
(data BGS)</td><td>6959</td><td>
</td><td>China (57.3%),
Russia (5.68%),
India (5.29%)
(data BGS)</td><td>17213</td><td>
</td></tr>
<tr><td>Antimony (Sb)</td><td>China (48.0%),
Tajikistan (21.1%),
Russia (14.5%)
(data BGS)</td><td>15512</td><td>
</td><td>China (63.4%),
Belgium (11.0%),
Vietnam (8.54%)
(data EU SCRREEN)</td><td>21429</td><td>(Time series not available, average 2016–2020 only)</td></tr>
<tr><td>Arsenic (As)</td><td>No data available</td><td></td><td></td><td>China (43.9%),
Peru (40.8%),
Morocco (11.2%)
(data BGS)</td><td>18916</td><td>
</td></tr>
<tr><td>Barium (Ba)</td><td>China (31.7%),
India (22.5%),
Morocco (10.7%)
(data BGS)</td><td>8747</td><td>
</td><td>Not relevant
(used in mineral form)</td><td></td><td></td></tr>
<tr><td>Bentonite clay</td><td>USA (27.9%),
India (17.9%),
China (12.4%)
(data BGS)</td><td>5163</td><td>
</td><td>Not relevant
(used in mineral form)</td><td></td><td></td></tr>
</table>

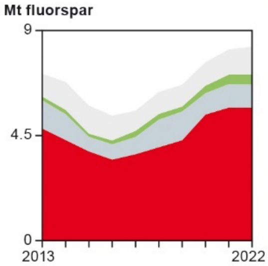
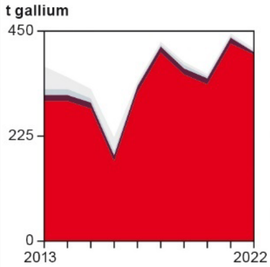
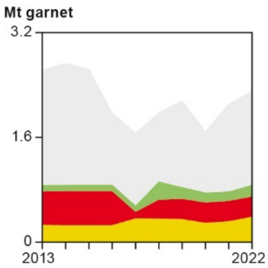
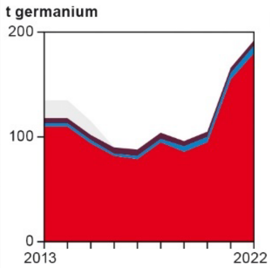
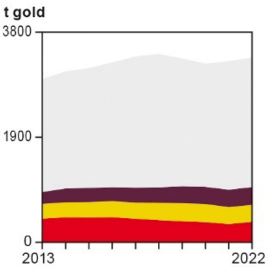
China	India	Republic of Korea	Canada	Chile	Miscellaneous 1
Russia	USA	Peru	South Africa	Rest of the World	Miscellaneous 2
Australia	Japan	Turkey	Kazakhstan		Miscellaneous 3

	Mining			**Refining**		
Material	**Top three countries (2018–2022) [source]**	**Score**	**Graph**	**Top three countries (2018–2022) [source]**	**Score**	**Graph**
Beryllium (Be)	USA (56.9%), China (23.6%), Brazil (8.29%) (data BGS, USGS)	13689		USA (47%), Kazakhstan (30%), China (23%) (data EU SCRREEN)	14285	(Time series not available, Average 2016–2020 only)
Bismuth (Bi)	China (38.6%), Vietnam (38.6%), Japan (11.1%) (data BGS)	16335		China (81.3%), Laos (9.45%), RO Korea (4.75%) (data USGS)	16335	
Borate (B_2O_3)	Turkey (54.2%), USA (19.7%), Kazakhstan (7.59%)	15820		Not relevant (used in mineral form)		
Cadmium (Cd)	Not relevant (smelter / refinery by-product only)			China (39.3%), RO Korea (9.06%), Japan (7.41%) (data BGS)	8877	
Chromium (Cr)	South Africa (47.6%), Kazakhstan (18.2%), India (10.2%) (data BGS)	13830		China (42.0%), South Africa (23.8%), Kazakhstan (13.0%) (data BGS, USGS)	12763	

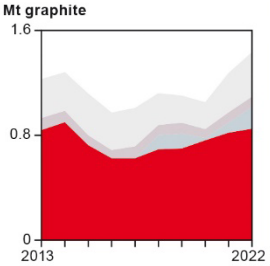
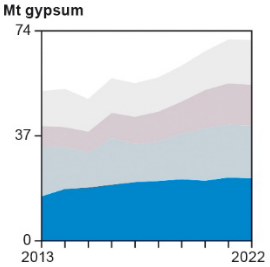
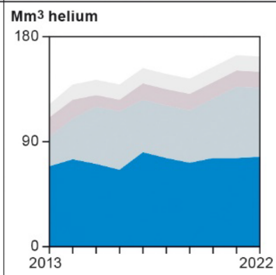
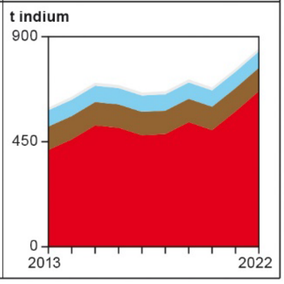
China | India | Republic of Korea | Canada | Chile | Miscellaneous 1
Russia | USA | Peru | South Africa | Rest of the World | Miscellaneous 2
Australia | Japan | Turkey | Kazakhstan | Miscellaneous 3

	Mining			Refining		
Material	**Top three countries (2018–2022) [source]**	**Score**	**Graph**	**Top three countries (2018–2022) [source]**	**Score**	**Graph**
Cobalt (Co)	DRC (69.1%), Russia (4.82%), Australia (4.01%) (data BGS)	32804		China (70.6%), Finland (10.2%), Canada (4.32%) (data BGS)	25887	
Copper	Chile (26.6%), Peru (11.1%), China (8.25%) (data BGS)	3666		China (40.8%), Chile (9.28%), Japan (6.26%) (data BGS)	8986	
Diamonds	Russia (31.2%), Botswana (17.9%), Canada (14.2%) (data BGS)	6870		Not relevant (no refining involved)		
Diatomite	USA (39.5%), China (9.35%), Turkey (8.58%) (data BGS)	5851		Not relevant (used in mineral form)		
Feldspar	Turkey (35.8%), India (13.1%), Italy (8.88%) (data BGS)	7509		Not relevant (used in mineral form)		

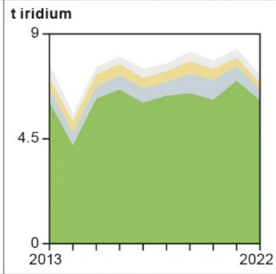
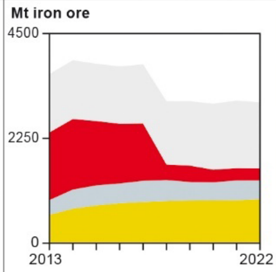
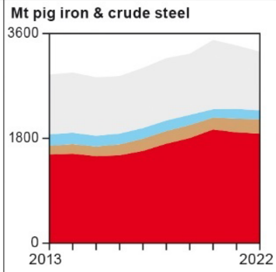
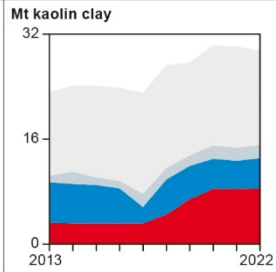
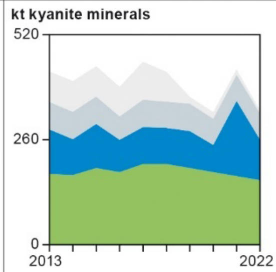
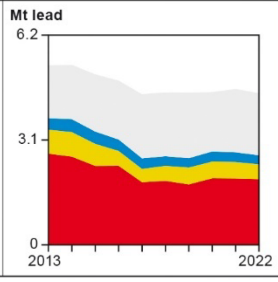
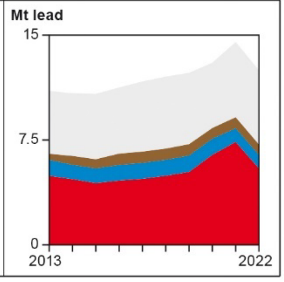
China | India | Republic of Korea | Canada | Chile | Miscellaneous 1
Russia | USA | Peru | South Africa | Rest of the World | Miscellaneous 2
Australia | Japan | Turkey | Kazakhstan | Miscellaneous 3

	Mining			Refining		
Material	**Top three countries (2018–2022) [source]**	**Score**	**Graph**	**Top three countries (2018–2022) [source]**	**Score**	**Graph**
Fluorine (F)	China (67.5%), Mexico (14.3%), South Africa (4.29%) (data BGS)	24528		Not relevant (processed into hydrofluoric acid)		
Gallium (Ga)	Not relevant (smelter / refinery by-product only)			China (94.8%), Russia (2.81%), Ukraine (1.09%) (data BGS)	46209	
Garnet	Australia (35.2%), China (31.3%), South Africa (19.1%) (data USGS)	10237		Not relevant (used in mineral form)		
Germanium (Ge)	Not relevant (smelter / refinery by-product only)			China (92.2%), USA (3.92%), Russia (3.92%) (data BGS)	43782	
Gold (Au)	China (11.1%), Australia (9.54%), Russia (9.21%) (data BGS)	1310		No data available		

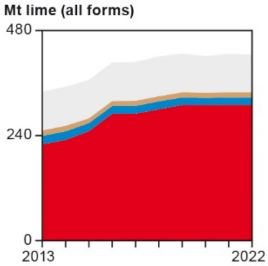
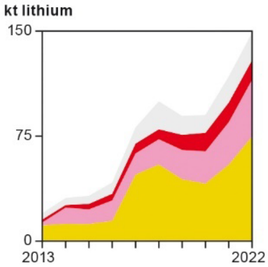
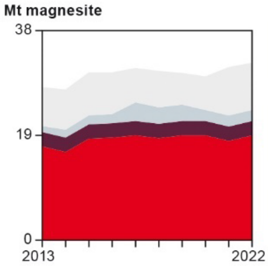
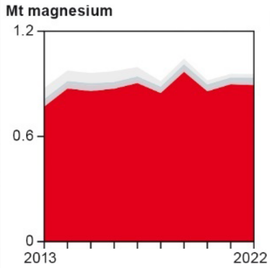
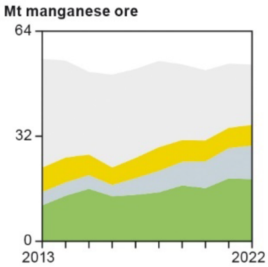
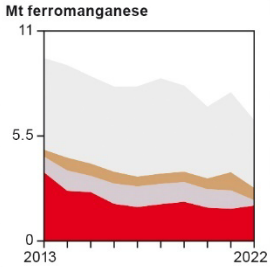
China
Russia
Australia
India
USA
Japan
Republic of Korea
Peru
Turkey
Canada
South Africa
Kazakhstan
Chile
Rest of the World
Miscellaneous 1
Miscellaneous 2
Miscellaneous 3

	Mining			Refining		
Material	**Top three countries (2018–2022) [source]**	**Score**	**Graph**	**Top three countries (2018–2022) [source]**	**Score**	**Graph**
Graphite (natural)	China (63.9%), Mozambique (8.05%), Brazil (6.44%) (data BGS)	21640		Not relevant (used in mineral form)		
Gypsum ($CaSO_4$)	USA (13.2%), Iran (10.5%), Spain (7.85%) (data BGS)	1367		Not relevant (used in mineral form)		
Hafnium (Hf)	Not relevant (smelter / refinery by-product only)			France (50.0%), USA (45.7%), China (2.9%), Russia (1.4%) (data Alkane, etc)	14468	
Helium (He)	Not relevant (by-product of petroleum refining)			USA (48.8%), Qatar (33.8%), Algeria (9.06%) (data BGS)	12808	
Indium (In)	Not relevant (smelter / refinery by-product only)			China (64.4%), RO Korea (11.7%), Japan (8.16%) (data BGS)	21870	

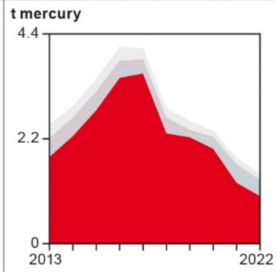
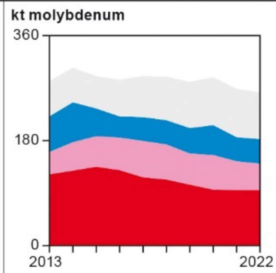
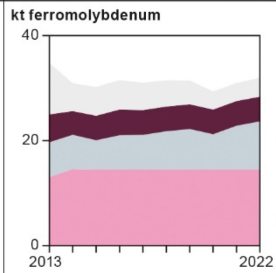
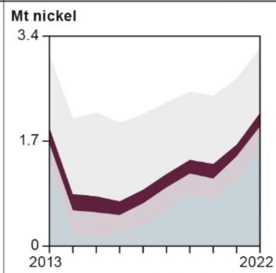
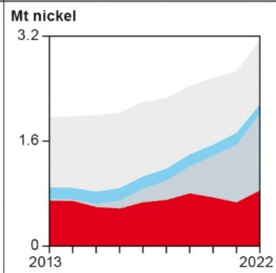
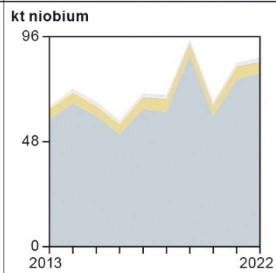
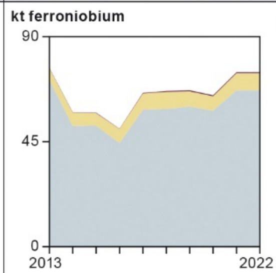
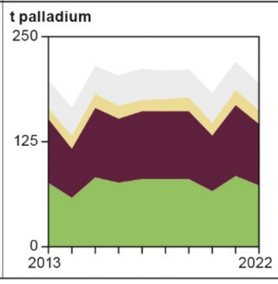
China	India	Republic of Korea	Canada	Chile	Miscellaneous 1
Russia	USA	Peru	South Africa	Rest of the World	Miscellaneous 2
Australia	Japan	Turkey	Kazakhstan		Miscellaneous 3

	Mining			Refining		
Material	**Top three countries (2018–2022) [source]**	**Score**	**Graph**	**Top three countries (2018–2022) [source]**	**Score**	**Graph**
Iridium (Ir)	South Africa (81.6%), Zimbabwe (8.49%), Canada (5.40%) (data BGS, USGS, JM)	34735		No data available		
Iron (Fe)	Australia (36.5%), Brazil (16.3%), China (11.7%) (data BGS)	5586		China (55.8%), India (6.76%), Japan (4.94%) (data BGS)	16315	
Kaolin clay	China (25.3%), USA (16.5%), Iran (6.51%) (data BGS)	4407		Not relevant (used in mineral form)		
Kyanite	South Africa (47.7%), USA (28.3%), France (17.4%) (data BGS)	15171		Not relevant (used in mineral form)		
Lead (Pb)	China (42.3%), Australia (10.5%), USA (6.19%) (data BGS)	9597		China (45.6%), USA (8.37%), RO Korea (6.11%) (data BGS)	11077	

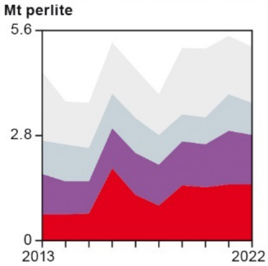
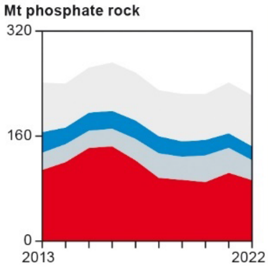
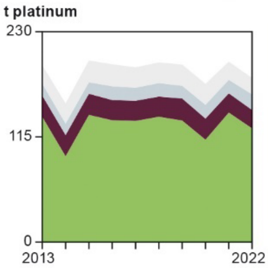
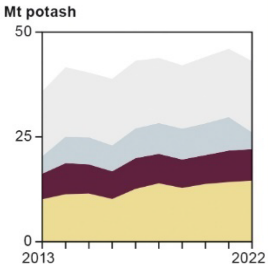
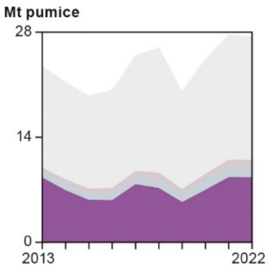
China	India	Republic of Korea	Canada	Chile	Miscellaneous 1
Russia	USA	Peru	South Africa	Rest of the World	Miscellaneous 2
Australia	Japan	Turkey	Kazakhstan		Miscellaneous 3

	Mining			**Refining**		
Material	**Top three countries (2018–2022) [source]**	**Score**	**Graph**	**Top three countries (2018–2022) [source]**	**Score**	**Graph**
Industrial limestone (lime)	China (72.0%), USA (3.95%), India (3.69%) (data USGS)	26757		Not relevant (used in mineral form)		
Lithium (Li)	Australia (49.4%), Chile (24.3%), China (10.9%) (data BGS)	9416		China (56.6%), Chile (32.3%), Argentina (11.1%) (data EU SCRREEN)	20985	(Time series not available, average 2016–2020 only)
Magnesite	China (60.6%), Russia (8.43%), Brazil (7.74%) (data BGS)	19545		Not relevant (used in mineral form)		
Magnesium (Mg)	(Extracted directly from dolomite or magnesite; specific data not available)			China (93.3%), Israel (2.10%), Brazil (2.03%)	44750	
Manganese (Mn)	South Africa (32.1%), Gabon (15.4%), Australia (12.2%) (data BGS)	6917		China (24.6%), Ukraine (11.4%), India (8.58%) (data BGS, USGS)	4193	

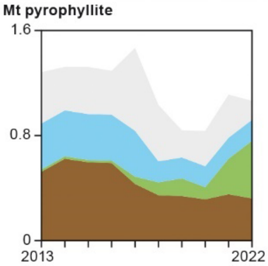
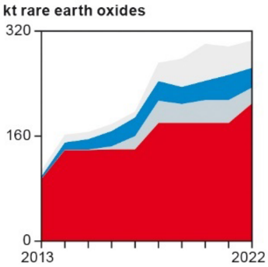
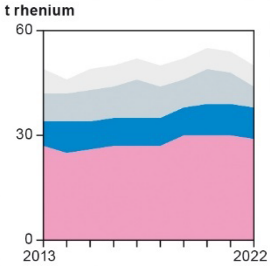
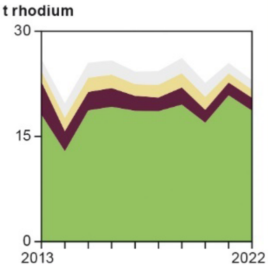
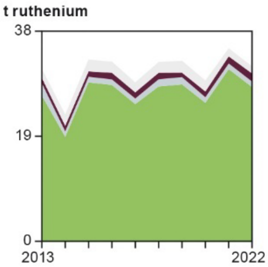
China | India | Republic of Korea | Canada | Chile | Miscellaneous 1
Russia | USA | Peru | South Africa | Rest of the World | Miscellaneous 2
Australia | Japan | Turkey | Kazakhstan | | Miscellaneous 3

	Mining			Refining		
Material	**Top three countries (2018–2022) [source]**	**Score**	**Graph**	**Top three countries (2018–2022) [source]**	**Score**	**Graph**
Mercury (Hg)	China (79.9%), Tajikistan (9.49%), Mexico (3.80%) (data BGS, USGS)	33386		Not relevant (used in chemical form)		
Molybdenum (Mo)	China (36.3%), Chile (19.3%), USA (15.8%) (data BGS)	8986		Chile (46.7%), Armenia (25.3%), Russia (15.1%) (data BGS)	12420	
Nickel (Ni)	Indonesia (37.0%), Philippines (13.2%), Russia (8.27%) (data BGS)	8582		China (28.9%), Indonesia (25.8%), Japan (6.65%) (data BGS)	7975	
Niobium (Nb)	Brazil (90.9%), Canada (6.11%), Nigeria (0.78%) (data BGS)	40402		Brazil (89.4%), Canada (10.1%), Russia (0.51%) (data BGS, USGS)	39322	
Palladium (Pd)	Russia (41.7%), South Africa (35.4%), Canada (7.35%) (data BGS, USGS, JM)	35368		No data available		

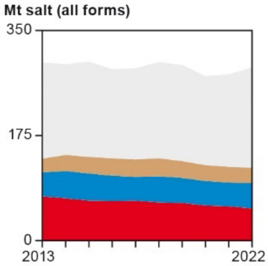
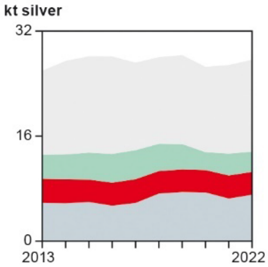
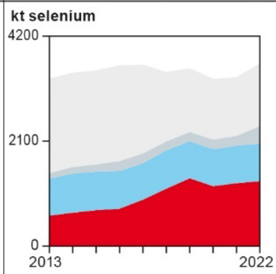
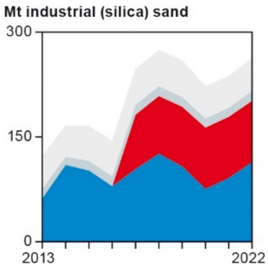
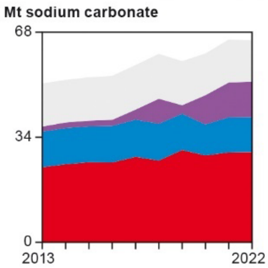
China · Russia · Australia · India · USA · Japan · Republic of Korea · Peru · Turkey · Canada · South Africa · Kazakhstan · Chile · Rest of the World · Miscellaneous 1 · Miscellaneous 2 · Miscellaneous 3

	Mining			Refining		
Material	**Top three countries (2018–2022) [source]**	**Score**	**Graph**	**Top three countries (2018–2022) [source]**	**Score**	**Graph**
Perlite	China (27.6%), Turkey (24.9%), Greece (16.4%) (data BGS)	7885		Not relevant (used in mineral form)		
Phosphorous (P)	China (41.8%), Morocco (16.0%), USA (10.1%) (data BGS)	25506		China (78%), USA (11%), Kazakhstan (6%) (data EU SCRREEN)	31835	(Time series not available, average 2016–2020 only)
Platinum (Pt)	South Africa (69.0%), Russia (11.7%), Zimbabwe (8.02%) (data BGS, USGS, JM)	25506		No data available		
Potassium (K)	Canada (31.7%), Russia (16.3%), Belarus (15.6%) (data BGS)	5489		Not relevant (used in mineral form)		
Pumice	Turkey (42.8%), Uganda (6.69%), Greece (5.44%) (data USGS)	9296		Not relevant (used in mineral form)		

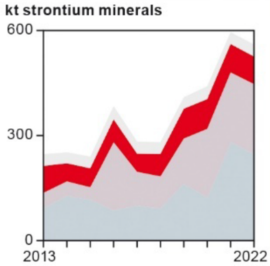
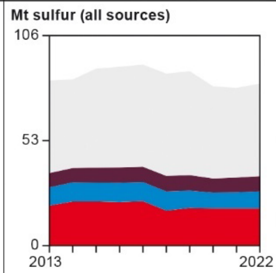
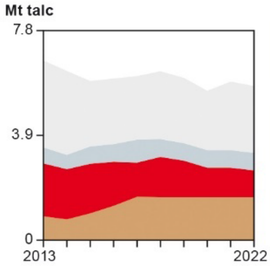
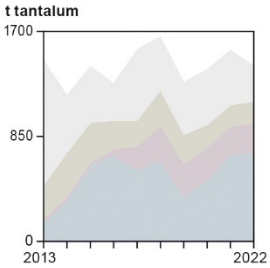
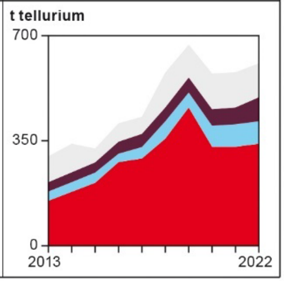
China | India | Republic of Korea | Canada | Chile | Miscellaneous 1
Russia | USA | Peru | South Africa | Rest of the World | Miscellaneous 2
Australia | Japan | Turkey | Kazakhstan | | Miscellaneous 3

	Mining			Refining		
Material	**Top three countries (2018–2022) [source]**	**Score**	**Graph**	**Top three countries (2018–2022) [source]**	**Score**	**Graph**
Pyrophyllite	RO Korea (34.3%), South Africa (21.2%), Japan (16.4%) (data BGS)	6010		Not relevant (used in mineral form)		
Rare Earth Elements (REE)	China (64.0%), Myanmar (10.8%), USA (9.13%) (data BGS, USGS)	22177		China (86.8%), Malaysia (12.1%), Estonia, India (2.2%) (IEA, 2021)	39385	2021 data only
Rhenium (Re)	Not relevant (smelter / refinery by-product only)			Chile (55.9%), USA (16.9%), Poland (16.1%) (data BGS)	13784	
Rhodium (Rh)	South Africa (78.8%), Russia (8.19%), Canada (6.84%) (data BGS, USGS, JM)	42250		No data available		
Ruthenium (Ru)	South Africa (90.5%), Zimbabwe (3.67%), Russia (3.66%) (data BGS, USGS, JM)	34735		No data available		

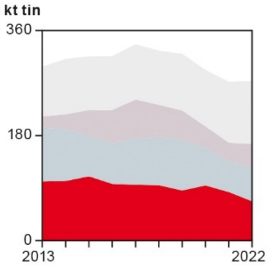
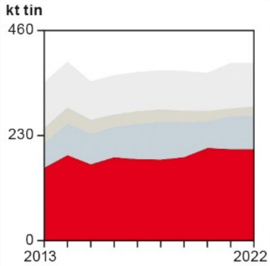
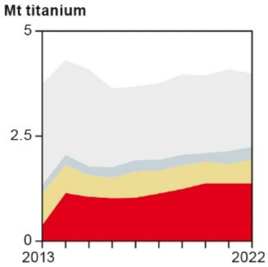
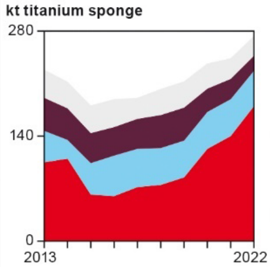
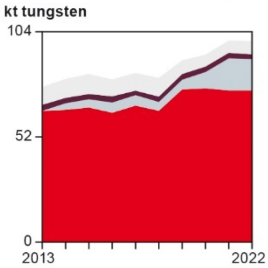
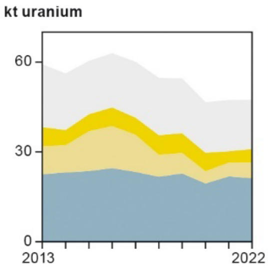
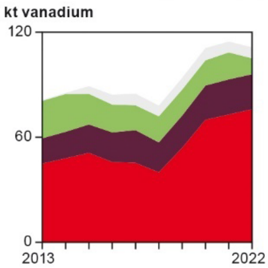
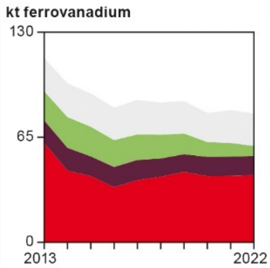
China, India, Republic of Korea, Canada, Chile, Miscellaneous 1
Russia, USA, Peru, South Africa, Rest of the World, Miscellaneous 2
Australia, Japan, Turkey, Kazakhstan, Miscellaneous 3

	Mining			Refining		
Material	**Top three countries (2018–2022) [source]**	**Score**	**Graph**	**Top three countries (2018–2022) [source]**	**Score**	**Graph**
Salt	China (20.7%), USA (14.5%), India (9.57%) (data BGS)	3411		Not relevant (used in mineral form)		
Silver (Ag)	Mexico (26.0%), China (12.6%), Peru (12.5%) (data BGS)	4867		No data available		
Selenium (Se)	Not relevant (smelter / refinery by-product only)			China (36.0%), Japan (21.5%), Germany (7.47%) (data BGS)	8170	
Industrial (silica) sand	USA (30.3%), China (25.4%), Italy (4.01%) (data BGS)	6346		Not relevant (used in mineral form)		
Sodium (Na)	China (45.8%), USA (18.0%), Turkey (13.9%) (data USGS)	12774		Not relevant (used in mineral form)		

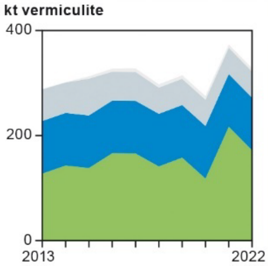
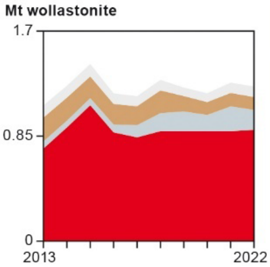
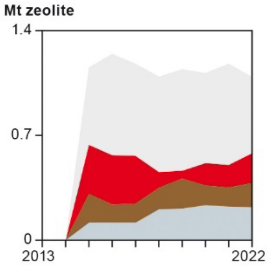
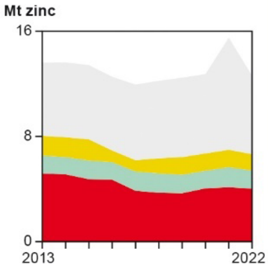
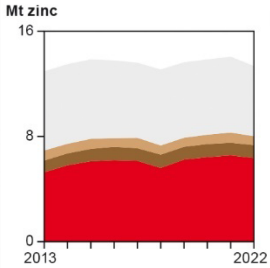
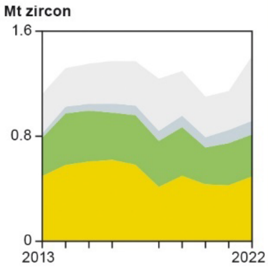
China | India | Republic of Korea | Canada | Chile | Miscellaneous 1
Russia | USA | Peru | South Africa | Rest of the World | Miscellaneous 2
Australia | Japan | Turkey | Kazakhstan | | Miscellaneous 3

	Mining			Refining		
Material	**Top three countries (2018–2022) [source]**	**Score**	**Graph**	**Top three countries (2018–2022) [source]**	**Score**	**Graph**
Strontium (Sr)	Spain (38.4%), Iran (35.0%), China (16.5%) (data BGS)	12989		Not relevant (used in mineral form)		
Sulfur (S)	Not relevant (almost entirely smelter / refinery by-product only)			China (22.4%), USA (10.3%), Russia (9.09%) (data BGS)	3336	
Talc	India (27.1%), China (20.5%), Brazil (11.0%) (data BGS)	7038		Not relevant (used in mineral form)		
Tantalum (Ta)	DRC (39.8%), Nigeria (17.6%), Rwanda (14.4%) (data BGS)	14043		China (45.5%), USA (11.4%), Japan (9.1%) (TIC, 2020)		Data for 2018 only
Tellurium (Te)	Not relevant (smelter / refinery by-product only)			China (60.5%), Japan (10.9%), Russia (9.54%) (data BGS)	19597	

China · India · Republic of Korea · Canada · Chile · Miscellaneous 1
Russia · USA · Peru · South Africa · Rest of the World · Miscellaneous 2
Australia · Japan · Turkey · Kazakhstan · Miscellaneous 3

	Mining			Refining		
Material	**Top three countries (2018–2022) [source]**	**Score**	**Graph**	**Top three countries (2018–2022) [source]**	**Score**	**Graph**
Tin (Sn)	China (28.7%), Indonesia (23.3%), Myanmar (14.4%) (data BGS)	8524		China (51.0%), Indonesia (19.3%), Malaysia (5.88%) (data BGS)	15514	
Titanium (Ti)	China (33.0%), Canada (13.4%), Mozambique (6.70%) (data BGS)	6441		China (51.6%), Japan (20.8%), Russia (14.2%) (data USGS)	15956	
Tungsten (W)	China (79.2%), Vietnam (10.5%), Russia (2.85%) (data BGS)	32923		No data available		
Uranium (U)	Kazakhstan (42.7%), Canada (11.2%), Australia (11.0%) (data BGS)	9379		No data available		
Vanadium (V)	China (61.5%), Russia (18.7%), South Africa (13.5%) (data BGS)	22146		China (50.0%), Russia (14.0%), South Africa (12.0%) (data BGS, USGS)	14318	

China · India · Republic of Korea · Canada · Chile · Miscellaneous 1
Russia · USA · Peru · South Africa · Rest of the World · Miscellaneous 2
Australia · Japan · Turkey · Kazakhstan · Miscellaneous 3

	Mining			Refining		
Material	**Top three countries (2018–2022) [source]**	**Score**	**Graph**	**Top three countries (2018–2022) [source]**	**Score**	**Graph**
Vermiculite	South Africa (36.5%), USA (22.6%), Brazil (11.3%) (data BGS)	9119		Not relevant (used in mineral form)		
Wollastonite	China (71.1%), Mexico (12.7%), India (9.96%) (data BGS)	27329		Not relevant (used in mineral form)		
Zeolite	Slovakia (19.5%), RO Korea (13.6%), China (11.7%) (data USGS)	2545		Not relevant (used in mineral form)		
Zinc	China (30.0%), Peru (10.9%), Australia (9.70%) (data BGS)	5457		China (45.9%), RO Korea (7.23%), India (5.23%) (data BGS)	11102	
Zirconium (Zr)	Australia (36.7%), South Africa (26.5%), Mozambique (7.20%) (data BGS)	7583		USA (47.5%), China (20.5%), France (20.2%) (data EU SCRREEN)	10705	(Time series not available, average 2016–2020 only)

Appendix 4 Global trade concentration

Data sources: BGS – World Mineral Production; UN Comtrade

Material	Country	Trade share (%)	Modified HHI
Aluminium (Al)	China	61.0	3725
	USA	4.7	22
	United Arab Emirates	4.1	17
			3764
Antimony (Sb)	USA	22.9	524
	Netherlands	10.0	99
	Japan	9.0	82
			705
Arsenic (As)	India	26.9	722
	USA	20.4	415
	New Zealand	5.9	35
			1171
Barite	USA	41.7	1738
	Saudi Arabia	12.2	150
	Guyana	5.0	25
			1912

Material	Country	Trade share (%)	Modified HHI
Bentonite clay	Canada	12.8	163
	Germany	11.4	129
	Indonesia	7.9	62
			354
Beryllium (Be)	China	21.9	480
	India	15.6	243
	Poland	12.1	147
			870
Bismuth (Bi)	USA	26.2	687
	Germany	23.0	530
	Netherlands	8.8	78
			1295
Borates	China	47.1	2223
	Germany	4.9	24
	Korea, Republic of	4.1	17
			2264
Cadmium (Cd)	India	59.1	3494
	China	15.5	239
	Belgium	11.9	143
			3876

Material	Country	Trade share (%)	Modified HHI
Chromium (Cr)	China	76.3	5821
	Indonesia	7.0	49
	Japan	4.0	16
			5886
Cobalt (Co)	China	80.1	6409
	Korea, Republic of	5.3	28
	USA	2.5	6
			6443
Copper (Cu)	China	64.5	4154
	Japan	5.5	30
	Germany	4.6	21
			4206
Diatomite	Ukraine	19.5	379
	Korea, Republic of	9.9	98
	Thailand	9.9	98
			575
Feldspars	Spain	37.1	1378
	Italy	23.6	558
	Russian Federation	7.1	50
			1986

Material	Country	Trade share (%)	Modified HHI
Fluorine (F)	Mozambique	17.8	318
	USA	17.7	313
	India	10.1	102
			733
Gallium (Ga)	USA	19.8	392
	Malaysia	9.9	97
	Japan	8.8	77
			566
Germanium (Ge)	Malaysia	37.7	1420
	USA	13.8	192
	China	4.9	24
			1636
Gold (Au)	India	21.4	457
	China	21.2	450
	Switzerland	19.6	386
			1293
Gypsum	USA	19.6	386
	India	17.0	290
	Japan	7.8	61
			737

Material	Country	Trade share (%)	Modified HHI
Hafnium (Hf)	Malaysia	23.0	530
	Japan	14.2	200
	Saudi Arabia	9.7	94
			824
Helium (He)	Philippines	46.7	2181
	South Africa	29.3	860
	Indonesia	11.6	134
			3176
Indium (In)	Malaysia	18.9	358
	India	15.4	236
	Japan	14.0	197
			791
Iridium (Ir)	Japan	33.5	1121
	USA	24.2	587
	China	23.2	540
			2248
Iron (Fe)	Japan	32.0	1025
	Korea, Republic of	20.5	420
	Germany	10.6	113
			1558

Material	Country	Trade share (%)	Modified HHI
Kaolin clay	Spain	22.1	488
	Italy	10.3	107
	Japan	6.4	41
			635
Kyanite	Germany	20.8	431
	China	15.0	225
	Spain	10.1	102
			757
Lead (Pb)	China	31.5	990
	USA	17.6	310
	Vietnam	8.6	74
			1375
Industrial limestone	India	42.1	1769
	Germany	8.8	77
	China	7.5	56
			1901
Lithium (Li)	Korea, Republic of	47.2	2231
	Japan	33.7	1135
	USA	3.4	12
			3378

Material	Country	Trade share (%)	Modified HHI
Magnesite	Indonesia	24.1	582
	Japan	18.3	336
	India	8.7	76
			994
Magnesium (Mg)	Canada	11.9	142
	Malaysia	7.4	54
	France	5.8	34
			230
Manganese (Mn)	China	66.9	4478
	USA	4.4	19
	Japan	3.7	13
			4511
Molybdenum (Mo)	Japan	19.9	397
	China	12.8	164
	Korea, Republic of	11.1	123
			683
Natural diamonds	Thailand	49.2	2423
	Spain	12.4	155
	India	12.3	152
			2730

Material	Country	Trade share (%)	Modified HHI
Natural graphite	Dominican Republic	29.6	874
	Japan	11.5	133
	India	8.8	77
			1084
Nickel (Ni)	China	71.6	5126
	Japan	7.0	49
	USA	4.0	16
			5191
Niobium (Nb)	China	32.1	1033
	Thailand	10.6	112
	USA	8.4	71
			1215
Palladium (Pd)	China	25.6	656
	Germany	15.4	237
	Japan	11.2	125
			1018
Perlite	USA	14.2	202
	Korea, Republic of	12.7	163
	Zimbabwe	9.1	83
			448

Material	Country	Trade share (%)	Modified HHI
Phosphorus (P)	India	34.3	1176
	Brazil	14.9	221
	Pakistan	4.2	18
			1416
Platinum (Pt)	Belgium	50.9	2591
	Japan	20.2	409
	USA	7.3	53
			3053
Potassium (K)	Brazil	22.5	508
	USA	21.0	440
	China	19.5	381
			1330
Pumice	China	22.8	520
	United Kingdom	20.9	437
	USA	17.2	295
			1252
Pyrophyllite	Italy	36.7	1350
	Belgium	18.4	339
	United Arab Emirates	5.2	27
			1716

Material	Country	Trade share (%)	Modified HHI
Rare earth elements (REEs)	Japan	24.5	603
	France	10.5	111
	Italy	7.8	62
			775
Rhenium (Re)	Netherlands	19.9	397
	USA	18.5	341
	Malaysia	12.2	149
			886
Rhodium (Rh)	USA	27.0	731
	China	23.1	532
	Japan	21.6	467
			1730
Ruthenium (Ru)	Japan	34.9	1217
	USA	25.3	638
	China	20.0	400
			2255
Industrial salt	USA	33.4	1117
	Japan	11.7	137
	China	10.9	120
			1374

Material	Country	Trade share (%)	Modified HHI
Selenium (Se)	China	26.3	690
	India	13.8	190
	Belgium	9.1	83
			964
Industrial (silica) sand	Canada	19.9	396
	United Arab Emirates	18.6	345
	China	10.9	119
			860
Silicon (Si)	Japan	19.2	370
	Germany	12.9	168
	USA	11.3	129
			666
Silver (Ag)	China	24.8	614
	India	21.2	450
	USA	13.8	191
			1256
Sodium (Na) compounds	Mexico	16.6	276
	Brazil	10.1	101
	Vietnam	6.5	43
			419

Material	Country	Trade share (%)	Modified HHI
Strontium (Sr)	China	26.4	696
	Japan	17.6	308
	USA	12.5	157
			1161
Sulphur (S)	China	29.9	892
	Morocco	23.4	546
	Brazil	5.8	33
			1471
Talc	Germany	16.7	278
	Japan	13.4	181
	Korea, Republic of	9.0	82
			540
Tantalum (Ta)	Thailand	58.6	3432
	China	9.5	90
	Japan	7.3	54
			3576
Tin (Sn)	China	45.3	2048
	USA	10.9	119
	Japan	8.2	67
			2234

Material	Country	Trade share (%)	Modified HHI
Titanium (Ti)	China	38.7	1497
	USA	13.9	192
	Germany	9.3	87
			1776
Tungsten (W)	USA	31.5	993
	Japan	15.8	249
	Germany	14.6	212
			1455
Uranium (U)	China	29.4	864
	Russian Federation	28.3	799
	USA	11.3	128
			1791
Vanadium (V)	USA	13.1	172
	Thailand	11.8	138
	Germany	10.0	100
			410
Vermiculite	USA	14.2	202
	Korea, Republic of	12.7	163
	Zimbabwe	9.1	83
			448

Material	Country	Trade share (%)	Modified HHI
Zinc (Zn)	China	39.7	1574
	Korea, Republic of	8.5	73
	Germany	8.1	65
			1712
Zirconium (Zr)	China	71.4	5100
	Spain	7.4	54
	India	6.3	39
			5194

Appendix 5 Companionality and companion metal fraction estimates for all candidate materials

[EK] Expert commodity knowledge (for example, based on unpublished data and internal reports; industry knowledge and experience; company discussions, etc.)

P: companion metal fraction calculated by using production data and assigning each country as primary or co-/by-product status.

MR: companion metal fraction calculated by using global mineral resources studies (reference cited) to assign primary or co-/by-product status.

Commodity (references, method)	Primary Production		Co-/By-Production		
	Deposit Type	Fraction (%)	Host Commodity	Deposit Type	Fraction (%)
Aluminium (Al) [1,EK] **P**	Karstic bauxite Lateritic bauxite	12 88	-	-	-
Antimony (Sb) [2] **MR**	Carbonate Replacement	60	Au Pb	Au-Sb vein-type Polymetallic base metal vein Reduced magmatic Hot springs	20 8 10 2
Arsenic (As) [3,4] **MR**	Primary Arsenic	8	Cu / Cu-Au	Various types	92
Barytes ($BaSO_4$) [3,4,5,EK] **MR**	Bedded sedimentary, Bedded volcanic, Vein / cavity, Residual	98	-	Miscellaneous	2
Bentonite Clay [5,EK] **P**	Primary	100	-	-	-
Beryllium (Be) [6,7,EK] **MR**	Volcanogenic, Carbonate-hosted epithermal	80	Li / Ta	LCT pegmatites	20
Bismuth (Bi) [3,4,8,EK] **MR**	Primary Bismuth	10	Cu, Pb	Skarn Epithermal Sediment-hosted	80 5 5
Borates (B_2O_3) [3,4,5,EK] **MR**	Primary Boron	99.7	K-Na	Potash, salt	0.3
Cadmium (Cd) [3,4,5,EK] **P**	-	-	Zn, Pb, Cu	Sediment-hosted, volcanic massive sulfide, others	100
Caesium [4,EK] **MR**	LCT pegmatites	2	Li, Ta	LCT pegmatites	98
Chromium (Cr) [3,4,5,EK] **MR**	Stratiform	88.78	PGEs Ni-Co	Stratiform PGE Ni-Co Laterites	10.91 0.31
Cobalt (Co) [3,4,5,EK] **MR**	Co-Ni-As (-Au-Ag) mineralisation	1.45	Cu Ni Ni-Cu	Stratiform sed-hosted Cu-Co Ni-Co laterites Magmatic Ni-Cu (Co-PGE)	69.42 17.55 11.58

Commodity (references, method)	Primary Production		Co-/By-Production		
	Deposit Type	Fraction (%)	Host Commodity	Deposit Type	Fraction (%)
Copper (Cu) [9,EK] **MR**	Porphyry Sediment-hosted Iron Oxide Cu-Au	75.08 10.17 4.68	Zn-Pb-Cu Ni Zn-Pb-Cu Zn-Pb-Cu Pb-Zn Au	Volcanogenic massive sulfide Magmatic Sulfide Skarn Epithermal Sediment-hosted Pb-Zn Orogenic Au	3.07 3.35 1.90 1.12 0.52 0.11
Diamonds [5,EK] **P**	Kimberlite / Lamproite pipes, Placer	100	-	-	-
Diatomite [5,EK] **P**	Primary	100	-	-	-
Feldspar [5,EK] **P**	Primary	100	-	-	-
Fluorine [5,EK] **P**	Primary Fluorspar	100	-	-	-
Gallium (Ga) [3,4,5,EK] **MR**	-	-	Al Zn	Bauxite / red muds Refinery residues	95 5
Garnet [4,EK] **MR**	Primary	90	Ti-Zr	Heavy mineral sands	10
Germanium (Ge) [3,4,5,EK] **MR**	-	-	Zn Coal	Zn-containing deposits Coal ash	60 40
Gold (Au) [3,4,5,10,EK] **MR**	Orogenic, Porphyry, Placer (>70% Au value)	64.4	Cu-Pb-Zn-Ni	Porphyry, VMS, Epithermal, IOCG, miscellaneous: 20-70% Au value <20% Au value	 24.1 11.5
Graphite (C, natural) [6,EK] **P**	Primary	100	-	-	-
Gypsum ($CaSO_4$) [6,EK] **P**	Primary	100	-	-	-
Hafnium (Hf) [3,4,5,EK] **MR**	-	-	Zr	Heavy mineral sands	100
Helium (He) [5,EK] **MR**	-	-	Gas	Petroleum hydrocarbons	100
Hydrogen (natural) [EK] **MR**	*no data*	*no data*	*no data*	*no data*	*no data*
Indium (In) [3,4,5,11,12,EK] **MR**	-	-	Zn Sn / Cu	Sulfide-based Zn Sulfide-based Sn / Cu	90 10
Industrial Limestone [5,EK] **P**	Primary	100	-	-	-
Industrial salt [5,EK] **P**	Primary	100	-	-	-
Industrial (silica) sand [5,EK] **P**	Primary	100	-	-	-
Iridium (Ir) [5,12,13,EK] **MR**	-	-	PGEs Ni-Cu Pt	Stratiform-hosted PGE Magmatic sulfide-based Ni-Cu Placer Pt	90.11 1.33 8.56
Iron (Fe) [3,4,5,EK] **P**	Primary Fe	100	-	-	-
Kaolin Clay [5,EK] **P**	Primary	100	-	-	-
Kyanite [5,EK] **P**	Primary	100	-	-	-
Lead (Pb) [3,4,5,15,EK] **MR**	Sediment-hosted Epithermal Volcanic-related Skarn Mesothermal vein Miscellaneous	61.78 9.31 6.68 6.13 1.53 1.52	Cu -Zn-Au Cu -Zn-Au Cu -Zn-Au Cu -Zn-Au Cu -Zn-Au Cu -Zn-Au	Volcanic-related Porphyry Skarn Epithermal Sediment-hosted Miscellaneous	4.66 2.82 2.24 1.27 1.58 0.50

Commodity (references, method)	Primary Production		Co-/By-Production		
	Deposit Type	Fraction (%)	Host Commodity	Deposit Type	Fraction (%)
Lithium [3,4,5,EK] **MR**	LCT pegmatites	55.8	K-Li	Continental brine	44.2
Magnesite [5,EK] **P**	Primary	100	-	-	-
Magnesium (Mg) [5,EK] **MR**	Primary	97	Various	Miscellaneous	3
Manganese (Mn) [5,EK] **P**	Stratiform	100	Various	Miscellaneous	3
Mercury (Hg) [3,4,5,16,EK] **MR**	Primary	65	Zn Au Ag Sb non-Fe Gas	-	13 9 4 4 3 2
Molybdenum (Mo) [3,4,5,EK] **MR**	Porphyry Mo	34	Cu	Porphyry Cu	66
Nickel (Ni) [3,4,5,17,EK] **MR**	Ni laterites Archaean komatiite Proterozoic komatiite Miscellaneous Fe-Ni alloy Impact-related	54.32 6.52 1.63 1.44 0.80 0.70	PGEs Ni-PGEs Mn Cu various	Layered intrusive M-UM intrusion Seafloor Mn nodules Sediment-hosted Miscellaneous	12.93 12.22 6.76 1.34 1.34
Niobium (Nb) [2,3,5,EK] **MR**	Pyrochlore / Carbonatite	97.14	Sn	Artisanal, by-product	2.86
Palladium (Pd) [5,13,14,EK] **MR**	Stratiform-hosted Placer Pt	50.57 0.05	Ni-Cu Ni-Cu	Magmatic sulfide-based Ni-Cu Refinery residues	47.27 2.11
Perlite [5,EK] **P**	Primary	100	-	-	-
Phosphate Rock [5,EK] **P**	Primary	100	-	-	-
Phosphorous [4,5,EK] **P**	Primary	100	-	-	-
Platinum (Pt) [5,13,14,EK] **MR**	Stratiform-hosted Placer Pt	79.26 2.55	Ni-Cu Ni-Cu	Magmatic sulfide-based Ni-Cu Refinery residues	17.55 0.64
Potassium (K) [3,4,5,EK] **P**	Primary	100	-	-	-
Pumice [5,EK] **P**	Primary	100	-	-	-
Pyrites [5,EK] **MR**	-		various	Base metals (Cu-Pb-Zn-Ni), Au	100
Pyrophyllite [5,EK] **P**	Primary	100	-	-	-
Rare Earth Elements (REEs) [3,4,5,EK] **MR**	Carbonatite Ionic clays	14.08 18.84	Fe Ti-Zr	Carbonatite Heavy mineral sands	63.99 3.09
Rhenium (Re) [3,4,5,18,EK] **MR**	-	-	Cu-Mo Cu	Porphyry Cu-Mo Sed-hosted Stratabound Cu	78.2 21.8
Rhodium (Rh) [5,13,14,EK] **MR**	-	-	PGEs Ni-Cu Pt	Stratiform-hosted PGE Magmatic sulfide-based Ni-Cu Placer Pt	84.95 14.98 0.07
Rubidium (Rb) [EK] **MR**	-	-	Li-Cs-Ta	LCT pegmatites	100

Commodity (references, method)	Primary Production		Co-/By-Production		
	Deposit Type	Fraction (%)	Host Commodity	Deposit Type	Fraction (%)
Ruthenium (Ru) [5,13,14,EK] **MR**	-	-	PGEs Ni-Cu Pt	Stratiform-hosted PGE Magmatic sulfide-based Ni-Cu Placer Pt	94.18 5.75 0.07
Selenium (Se) [5,19,EK] **MR**	-	-	Cu Cu Cu Cu Cu Cu Cu Various	Porphyry Sediment-hosted Cu Skarn Volcanic massive sulfide Iron oxide Cu-Au Magmatic Ni-Cu Vein-hosted Minor miscellaneous	84.54 11.32 1.20 1.17 0.72 0.72 0.25 0.08%
Silicon (Si) [5,EK] **P**	Primary	100	-	-	-
Silver (Ag) [5,20,EK] **MR**	Primary Ag	27.46	Pb-Zn Cu Au Various	Pb-Zn mines Cu mines Au mines Miscellaneous mines	32.53 24.51 14.95 0.55
Sodium (Na) [5,21,EK] **P**	Primary	100	-	-	-
Strontium (Sr) [3,4,5,EK] **P**	Primary	100	-	-	-
Sulfur (S) [5,EK] **MR**	Frasch process Sulfur ore	0.61 0.08	Petroleum Pyrite	Refining of hydrocarbons Pyrite roasting	92.35 6.96
Talc [5,EK] **P**	Primary	100	-	-	-
Tantalum (Ta) [3,4,5,22,EK] **MR**	Pegmatites	78	REE	Granite Alkaline granite-syenite Tin slag	5 12 5
Tellurium (Te) [3,4,5,23,EK] **MR**	-	-	NiCu Cu-Pb-Zn Cu various Pb	Magmatic Ni-Cu sulfides Volcanic massive sulfides Porphyry Cu Unknown Pb smelters	21.35 14.83 24.69 29.14 10.00
Thallium (Tl) [EK] **MR**	-	-	Zn	Zinc refining	100
Thorium (Th) [EK] **MR**	-	-	REEs	Possible by-product from REE refining	100
Tin (Sn) [3,4,5,EK] **P**	Primary	100	-	-	-
Titanium (Ti) [3,4,5,EK] **MR**	Primary ilmenite	47.47	Ti-Zr	Heavy mineral sands	52.53
Tungsten (W) [3,4,5,EK] **MR**	Skarn Vein / breccia stockwork Porphyry Disseminated Stratabound	36 35 16 5 3	Sn	Miscellaneous	5
Uranium (U) [3,4,5,EK] **MR**	Sandstone-hosted Unconformity-related Metasomatite Volcanic-related Granite Metamorphite Carbonatite Remediation Intrusive	63.22 13.15 1.21 3.69 0.41 0.77 0.41 0.01 10.47	Cu U-V Au	Iron-oxide related (IOCG) Surficial (calcrete) Au-U Conglomerate	6.63 0.31 0.32

Commodity (references, method)	Primary Production		Co-/By-Production		
	Deposit Type	Fraction (%)	Host Commodity	Deposit Type	Fraction (%)
Vanadium (V) [3,4,5,EK] **MR**	Shale-hosted V / Vanadate	12	Fe-Ti	Titanomagnetite slags	88
Vermiculite [5,EK] **P**	Primary	100	-	-	-
Wollastonite [5,EK] **P**	Primary	100	-	-	-
Zeolite [5,EK] **P**	Primary	100	-	-	-
Zinc (Zn) [3,4,5,15,EK] **MR**	Sediment-hosted Epithermal Skarn Volcanic-related Porphyry Miscellaneous	55.85 6.04 5.92 5.43 0.72 1.33	Cu -Zn-Au Cu -Zn-Au Cu -Zn-Au Cu -Zn-Au Cu -Zn-Au Cu -Zn-Au	Volcanic-related Skarn Sediment-hosted Porphyry Epithermal Miscellaneous	12.08 5.24 3.02 2.31 1.50 0.55
Zirconium (Zr) [3,4,5,EK] **MR**	-	-	Ti Ti	Heavy mineral sands Magmatic	94 6

References

[1] (Binnemans et al., 2015). [2] (Schwarz-Schampera, 2014b). [3] (Nassar et al., 2015). [4] (Graedel et al., 2022). [5] (Idoine et al., 2024). [6] (Trueman and Sabey, 2014). [7] (Lederer et al., 2016). [8] (Deady et al., 2022). [9] (Mudd and Jowitt, 2018a). [10] (Mudd and Jowitt, 2018b). [11] (Lokanc et al., 2015a). [12] (Werner et al., 2017). [13] (Mudd, 2023). [14] (Cowley, 2024). [15] (Mudd et al., 2017). [16] (United Nations Environment Programme, 2017). [17] (Mudd and Jowitt, 2022). [18] (Werner et al., 2023). [19] (Stiftner et al., 2024). [20] (The Silver Institute, various). [21] (U.S. Geological Survey, 2024a) (including historical editions). [22] (Bundesanstalt für Geowissenschaften und Rohstoffe, 2021). [23] (McNulty et al., 2022).

Appendix 6 Recycling rates

All recycling information has been compiled from a wide variety of sources. As per the methodology adopted, the data below represents global end-of-life recycling collection rates (EoLRR), unless otherwise noted. The process used and conceptualisation is explained in Section 2.2.4.

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Aluminium (Al)	Construction	25	95	(Norsk Hydro, 2021)	EoLRR values for most of the sectors are based on the BGS in-house estimates and from (Aluminium Federation, 2020)
	Transportation	23	95		
	Electrical	12	12		
	Machinery & Equipment	11	75		
	Foil stock	9	42		
	Packaging	8	42		
	Consumer durables	6	75		
	Other uses	6	75		
	Total		71.4		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Antimony (Sb)	Flame retardants	50	0	(International Antimony Association, 2024)	EoLRR for Antimony is manually entered due to the absence of openly accessible data for different sectors. (Dupont et al., 2016)
	Lead-acid batteries	35	0		
	Plastics (catalysts and stabilizers)	7	0		
	Other metallurgical	6	0		
	Glass and ceramics	1	0		
	Other	1	0		
	Total		20		
Arsenic (As)	Wood preservation, pesticides	80	0	(U.S. Geological Survey, 2024b)	For new production, closed-loop recycling of GaAs waste generated during semiconductor fabrication may be feasible. However, we are maintaining it at zero because there are no reliable sources to back up any figures.
	Semiconductor devices (GaAs)	6	0		
	Metallurgical	3	0		
	Batteries	1	0		
	Others	10	0		
	Total		0		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Barite	Oil industry	69	10	(The Barytes association, 2024; Graedel et al., 2022)	EoLRR values are based on BGS in-house estimates and from (Bleiwas and Miller, 2015)
	Chemical - electronics, TV screen, glass, ceramics and medical applications (barium meals)	16	0		
	Fillers - car, rubber and paint industry, radiation shielding	15	0		
	Total		6.9		
Bentonite	Metal casting	30	83	(SRP Minerals, 2024)	(Foundary Management & Technology, 2020)
	Iron ore palletisation	20	0		
	Cat litter	15	0		
	Drilling mud	10	10		Like barite EoLRR as both minerals applied together
	Civil engineering	10	0		
	Refining	4	0		
	Others	11	0		
	Total		25.9		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Beryllium (Be)	Industrial components	25	0	(U.S. Geological Survey, 2024b)	
	Aerospace & defence	17	30		EoLRR value is adopted from (Graedel et al., 2022)
	Automotive electronics	14	0		
	Telecomm. infrastructure	10	0		
	Consumer electronics	7	0		
	Energy applications	7	0		
	Semiconductor applications	1	0		
	Other	19	0		
	Total		5.1		
Bismuth (Bi)	Chemicals	62	0	(VERAM, 2017)	CRM Alliance reported Bismuth RR <1%. Bismuth is difficult to recycle since it is commonly used in dissipative applications like pigments and medicines.
	Fusible alloys	28	0		
	Metallurgical additives and others	10	0		
	Total		0		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Borate	Insulation	19	80	(Helvacı, 2017)	EoLRR is based on BGS in-house estimates
	Frit-Glazed ceramics	16	0		
	Agriculture	13	0		
	Specialized glass	11	43		EoLRR value is based on (Smulian, 2022)
	Industrial/Chemical application	11	0		
	TFG Fiberglass Fibers	10	0		
	TFT Liquid crystal displays	3	0		
	Other	17	0		
	Total		19.93		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Cadmium (Cd)	Jewellery (this application is not authorised in the EU)	57	0	(International Cadmium Association, 2024b)	
	NiCd batteries	23	75		(International Cadmium Association, 2024b)
	PVC stabilizers (This application is not authorised in the EU)	8	0		
	Cd Plating	4	0		
	Technical alloys	4	0		
	Pigment manufacturing	3	0		
	Other (presumably including Photovoltaics)	1	90		(International Cadmium Association, 2024b)
	Total		18.15		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Caesium (Cs)	Oil and gas drilling	90	80	BGS in-house estimates	Caesium formate is leased to oil and gas corporations for use as drilling fluid at a loss of 15% to 20%. Therefore, we assumed that 80% are reused or recycled.
	Atomic clocks	2	0		
	Infrared optics	2	0		
	Photoelectric cells	2	0		
	Chemical Uses	2	0		
	Isotope Applications	1	0		
	Other	1	0		
	Total		72		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Chromium (Cr)	Ferrochrome (stainless steel products)	80	85	(International Chromium Development Association, 2024)	EoLRR value refers to an average of European recycling rate based on (Worldstainless, 2023)
	Superalloys	15	62		(Curwick et al., 1980)
	Tanning (leather)	2	0		
	Chemicals	2	0		
	Refractory bricks and mortars	1	0		
	Total		77.3		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Cobalt (Co)	EV batteries	40	65	(Cobalt Institute, 2023)	EoLRR value is based on (Cobalt Institute, 2024)
	Portable batteries	30	65		
	Superalloys	9	11		
	Hard metals	5	24		
	Catalysts	3	11		
	Ceramics	3	0		
	Others	10	0		
	Total		48.02		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Copper (Cu)	Power generation, distribution, and transmission	44	90	(International Copper Association, 2022)	(EuRIC AISBL, 2020)
	Construction	20	90		(EuRIC AISBL, 2020)
	Electric appliances	14	60		(Baldé et al., 2024)
	Transport	12	90		(EuRIC AISBL, 2020)
	Others	10	0		
	Total		76.8		
Diatomite	Filtration products	55	4	(U.S. Geological Survey, 2023b)	(SCRREEN, 2023d)
	Absorbents, fillers, lightweight aggregates	44	4		(SCRREEN, 2023d)
	Specialized pharmaceutical and biomedical purposes	1	0		
	Total		3.96		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Feldspar	Construction, bricks and tiles	46	10	(IMA Europe, 2023)	BGS in-house estimate based on various readings and interaction with stakeholders
	Ceramics	45	0		
	Glass	6	43		(Smulian, 2022)
	other	3	0		
	Total		7.18		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Fluorine (F)	Steel and iron making	36	0	(SCRREEN, 2023d)	
	Aluminium making and other metallurgy	15	0		
	Solid fluoropolymers (cookware coating and cable insulation)	11	0		
	Fluorochemicals	11	0		
	Refrigeration and air conditioning	9	0		
	HF in alkylation process for oil refining	4	0		
	UF6 in nuclear fuel	7	0		
	Others (cement, ceramics, glass, melting rods, glazes)	7	0		
	Total		0		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Gallium (Ga)	Semiconductors, Integrated circuits, field effect transistors and(GaAs, GaN, GaP wafers)	50	0	(Cui et al., 2016)	EoLRR for Gallium is manually entered due to the absence of openly accessible data for different sectors. (Jia et al., 2022)
	LEDs	38	0		
	Photodetector/solar cell	4	0		
	Magnets	3	0		
	Others	5	0		
	Total		17		
Garnet	Waterjet cutting	35	0	(U.S. Geological Survey, 2012)	
	Abrasive blasting media	30	0		
	Water filtration	20	0		
	Abrasive powders	10	0		
	Other	5	0		
	Total		0		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Germanium (Ge)	Infrared systems	30	60	(Patel and Karamalidis, 2021)	EoLRR value is from (U.S. Geological Survey, 2023a)
	Fiber optics	20	60		(U.S. Geological Survey, 2023a)
	Polymer catalysts	20	0		
	Electronics and solar panels	15	0		
	Others	15	0		
	Total		30		
Gold (Au)	Jewellery	46	99	(U.S. Geological Survey, 2024b)	(Recyclinginside, 2020)
	Central banks and other institutions	23	99		
	Physical bars	16	99		
	Official coins and medals and imitation coins	9	99		
	electrical and electronics	5	20		(Baldé et al., 2024)
	Others	1	50		BGS in-house estimate
	Total		94.56		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Gypsum	Plasterboard	52	45.9	(Highley, 2006)	(SPECFINISH, 2016)
	Cement manufacturing	32	0		
	Specialist uses	16	0		
	Total		23.87		
Hafnium (Hf)	Superalloys	45	62	(Stanford Advanced Materials, 2024)	(Curwick et al., 1980)
	Nuclear control rods	13	0		
	Plasma cutting tips	13	0		
	Optical coatings	11	0		
	Catalysts	7	0		
	CVD/targets	7	0		
	Special steels	3	0		
	Electronics	1	0		
	Total		27.9		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Helium (He)	MRI scanners	30	90	(4He resources, 2024)	(Simionescu, 2024)
	Science and cryogenic	14	0		
	Welding	12	0		
	Balloons	8	0		
	Fiber Optics	6	0		
	Pressurization and purging	6	0		
	Electronics	4	0		
	Other	20	0		
	Total		27		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Indium (In)	Flat panel displays	56	20.3	(Lokanc et al., 2015b)	(Baldé et al., 2024)
	Solders	10	0		
	PV cells	8	0		
	Thermal interface material	6	0		
	Batteries	5	0		
	Alloys/compounds	4	0		
	Semiconductors and LEDs	3	0		
	Other	8	0		
	Total		11.37		
Iridium (Ir)	Electrochemical	46	0	(Johnson Matthey plc, 2024a)	
	Electrical & electronics	16	0		
	Chemical	13	0		
	Other	25	0		
	Total		0		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Iron (Fe)	Steel production	98	85	(U.S. Geological Survey, 2024b)	(Worldstainless, 2023)
	Pure iron and other uses	2	0		
	Total		83.3		
Kaolin clay	Paper	50	76.6	(Bloodworth et al., 2009)	(Department for Environment Food & Rural Affairs, 2024)
	Ceramic	30	0		
	Fillers in paint, rubber, plastics, adhesives and sealants, and pharmaceuticals	10	0		
	Others includes of animal feed, white cement and glass fibre.	10	0		
	Total		38.3		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Kyanite	Refractories (iron and steel industries)	70	0	(U.S. Geological Survey, 2024b)	
	Refractories (cement, chemicals, glass, nonferrous metals, and other materials)	20	0		
	Other	10	0		
	Total		0		
Lead (Pb)	Batteries	80	95	(International Lead & Zinc Study Group, 2023b)	(International Lead Association, 2024)
	Rolled & Extruded products	6	60		(International Lead Association, 2024)
	Pigments and other compounds	5	0		
	Shot & Ammunition	3	0		
	Alloys	2	60		(International Lead Association, 2024)
	Others	4	0		
	Total		80.8		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Limestone	Construction uses	78	74	(Harrison et al., 2006)	(IMA Europe, 2023)
	Cement making	13	10		BGS in-house estimate
	Industrial uses	8	0		
	Agriculture uses	1	0		
	Total		59.02		
Lithium (Li)	Batteries	65	5	(Bae and Kim, 2021)	(CAS Science Team, 2022)
	Ceramic and glass	18	0		
	Grease	5	0		
	Polymer	3	0		
	Casting	3	0		
	Others	6	0		
	Total		3.25		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Magnesite	Steel making	57	76	(SCRREEN, 2023d)	BGS in-house estimate
	Agriculture	14	0		
	Paper	12	70.6		(Department for Environment Food & Rural Affairs, 2024)
	Cement	9	0		
	Ceramics	5	0		
	Other	3	0		
	Total		51.79		
Magnesium (Mg)	Aluminium alloys	38	76	(European Aluminium, 2021)	(International Aluminium, 2024)
	Die castings	36	50		(International Magnesium Association, 2024)
	Iron & Steel	12	0		
	Metal reduction	8	0		
	Other	6	0		
	Total		46.88		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Manganese (Mn)	Steel-all forms	88	85	(Sun et al., 2020)	(Worldstainless, 2023)
	Batteries (cathodes)	2	8		(European Parliament Briefing, 2024)
	Other	10	0		
	Total		74.96		
Molybdenum (Mo)	Molybdenum grade alloy steels & irons (constructional steel, tool and high-speed steel and cast iron)	54	50	(International Molybdenum Association, 2024)	(International Molybdenum Association, 2015)
	Stainless Steels	25	50		(International Molybdenum Association, 2015)
	Chemicals	13	0		
	Metallic form	5	50		(International Molybdenum Association, 2015)
	Superalloys	3	62		(Curwick et al., 1980)
	Total		43.86		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Natural diamonds	Industrial use (used to create utensils for cutting and/or abrasive ones)	80	0	(Real Diamond Invest, 2024)	
	Commercial use (Jewel)	18	0		
	Investment	2	0		
	Total		0		
Natural graphite	Batteries	52	8	(ECGA, 2022)	(Ciacci et al., 2022)
	Refractories	24	50		(O'Driscoll, 2024)
	Recarburizing	2	0		
	Lubricants	3	0		
	Castings	8	0		
	Graphite shapes	1	0		
	Friction products	3	0		
	Other	7	0		
	Total		16.16		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Natural Hydrogen	Ammonia production	55	0	(WHA International Inc, 2023)	Data reported here represent Hydrogen alone, it doesn't distinguish between natural and artificial
	Petroleum refining	25	0		
	Methanol production	10	0		
	Other (like renewable energy)	10	0		
	Total		0		
Nickel (Ni)	Stainless steel	65	85	(Nickel Institute, 2021)	(Griswold, 2019)
	Batteries	17	16		(European Parliament Briefing, 2024)
	Non-ferrous alloys	5	33		EoLRR value is based on aluminium figures as it is the key element used with nickel for non-ferrous application. (Bureau of International Recycling, 2024)
	Plating	5	0		
	Alloy steels	3	0		
	Foundry	2	0		
	Others	3	0		
	Total		59.62		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Niobium (Nb)	Ferro-niobium: high strength low alloy steel (structural, automobile, pipelines, etc.)	83	5	(MSP-REFRAM, 2021)	(MSP-REFRAM, 2021)
	Superalloys	8	62		(Curwick et al., 1980)
	Chemicals	3	0		
	Others (superconductors, magnets, etc.)	6	0		
	Total		9.11		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Palladium (Pd)	Automotive	84	30	(Johnson Matthey plc, 2024a)	Note: Sector breakdowns of recycling data is referred to only for secondary supply and excludes the closed-looped recycling. Johnson Matthey plc will be releasing the detailed recycling data in the forthcoming whitepaper “Reclaiming the future: PGM insights for a circular economy” to be published in December. It will be hosted on the website here PGM recent publications | Johnson Matthey.
	Chemical	5	0		Note: IEA has reported 60% EoLRR for Palladium. (International Energy Agency, 2021)
	Electrical	5	88		
	Dental	2	0		
	Jewellery	1	11		
	Investment	1	0		
	Other	2	0		
	Total		29.71		
	Note: Johnson Matthey will be publishing new data to estimate palladium recycling rates after this CA.				

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Perlite	Construction products	47	1	(U.S. Geological Survey, 2024b)	BGS in-house estimate
	Horticultural aggregate	16	0		
	Filler	15	0		
	Filter acids	14	0		
	Other	8	0		
	Total		0.47		
Phosphorus (P)	Fertilizer	82	0	(Marjolein de Ridder, 2012)	
	Industrial	8	0		
	Animal feed	7	0		
	White Phosphorus derivatives	3	0		
	Total		0		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Platinum (Pt)	Automotive	43	32	(Johnson Matthey plc, 2024a)	Note: IEA has reported 60% EoLRR for Platinum. (International Energy Agency, 2021)
	Jewellery	18	17		
	Glass	9	0		
	Chemical	8	0		
	Dental & biomedical	4	0		
	pollution control	4	18		
	Electrical	3	17		
	Petroleum	2	0		
	Other	9	0		
	Total		18.05		
	Note: Johnson Matthey will be publishing new data to estimate platinum recycling rates after this CA.				

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Potassium (K)	Fertilizers	85	0	(Graedel et al., 2022)	
	Chemical and industrial applications	15	0		
	Total		0		
Pumice	Building blocks	38	1	(U.S. Geological Survey, 2022a)	BGS in-house estimate
	Horticulture & landscaping	38	0		
	Concrete aggregate	15	1		BGS in-house estimate
	Abrasives & cleaning	8	0		
	Other	1	0		
	Total		0.53		
Pyrophyllite	Refractory Industry	75	10	(Ali et al., 2021)	BGS in-house estimate
	Pesticides	10	0		
	Paints	5	0		
	Others	10	0		
	Total		7.5		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Rare earth elements (REE)	Magnets	44.3	0	(Natural Resources Canada, 2023)	
	Catalysts	17.1	0		
	Polishing powders	11.1	0		
	Metallurgical additives and others	6.6	0		
	Glass	6.3	0		
	Batteries	2.6	0		
	Ceramics	3.1	0		
	Phosphors	0.5	0		
	Pigments	0.3	0		
	Others	8.1	0		
	Total		0		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Rhenium (Re)	Superalloys (Aerospace)	70	62	(Lunk, 2015)	(Curwick et al., 1980)
	Catalysts	14	0		
	Other alloys (industrial gas turbines, thermocouples, etc.)	13	0		
	Electrical contacts	2	0		
	Others	1	0		
	Total		43.4		
Rhodium (Rh)	Automotive	88	32	(Johnson Matthey plc, 2024a)	
	Chemical	9	0		
	Glass	1	0		
	Electrical	1	0		
	Others	1	0		
	Total		28.16		
	Note: Johnson Matthey will be publishing new data to estimate rhodium recycling rates after this CA.				

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Rubidium (Rb)	Atomic clocks that are especially used only when high-precision time keeping is required.	20	0	BGS in-house estimates	
	Photocells that are used to convert light energy to electrical energy.	20	0		
	Medical equipment that are ideal for monitoring ischemia, a condition where blood flow is obstructed through the main coronary arteries	10	0		
	Vacuum tubes	10	0		
	Special glasses	10	0		
	Fireworks	10	0		
	Ion Engines	5	0		
	Thermoelectric generators	5	0		
	Others	10	0		
	Total		0		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Ruthenium (Ru)	Chemical	46	0	(Johnson Matthey plc, 2024a)	
	Electrical	29	0		
	Electrochemical	12	0		
	Other	13	0		
	Total		0		
	Note: Johnson Matthey will be publishing new data to estimate palladium recycling rates after this CA.				

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Salt (NaCl)	Chlorine/sodium hydroxide	39	0	(S&P Global, 2023) (The data from the figure were extracted with the help of PlotDigitizer tool)	
	Sodium Carbonate	20	0		
	De-icing	12	0		
	Food	12	0		
	General Industrial	4	0		
	Agriculture	3	0		
	Water softening systems	3	0		
	Sodium Chlorate	1	0		
	Others	6	0		
	Total		0		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Selenium (Se)	Metallurgy (including manganese production)	40	0	(U.S. Geological Survey, 2017)	EoLRR for Selenium is manually entered due to the absence of openly accessible data for different sectors. (Kavlak and Graedel, 2013)
	Glass manufacturing	25	0		
	Agriculture	10	0		
	chemicals and pigments	10	0		
	Electronics	10	0		
	Others	5	0		
	Total		10		
Industrial (silica) sand	Industrial uses	68	0	(Bide et al., 2020a)	
	Glass	27	43		(Smulian, 2022)
	Foundry and moulding	5	79		(IMA Europe, 2023)
	Total		15.56		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Silicon (Si)	Aluminium alloys; including foundry, ceramics	41	33	(BRGM, 2020)	EoLRR value is based on aluminium figures as it is the key element used with silicon for alloys application. (Bureau of International Recycling, 2024)
	Silicones, silanes	35	0		
	Solar applications	18	10		(Lunardi et al., 2018)
	others	6	0		
	Total		15.33		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Silver (Ag)	Electrical & electronics	37	15	(The Silver Institute, 2024)	All the breakdown values for EolRR are adopted from (Graedel et al., 2022)
	Bar & coin investment	20	80		Note: IEA has reported 49.70% EoLRR for silver (International Energy Agency, 2021)
	Jewellery	17	80		
	Other industrial use	13	55		
	Silverware	5	5		
	Brazing alloys	4	80		
	Photography	2	5		
	Other	2	5		
	Total		45.95		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Sodium (compounds) (Na)	Chemical Synthesis	72	0	(Persistence Market Research, 2017; Rajagopal, 2021)	
	Metal manufacturing & refining	10	0		
	Pharmaceuticals	5	0		
	Other (Nuclear, rubber, and Battery)	13	0		
	Total		0		
Strontium (Sr)	Drilling fluids	23	10	(U.S. Geological Survey, 2024b)	BGS in-house estimate
	Ceramic ferrite magnets	29	0		
	Pyrotechnics and signals	29	0		
	Electrolytic production of zinc	5	0		
	Master alloys	5	0		
	Pigments and fillers	5	0		
	Others	4	0		
	Total		2.3		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Sulfur (S)	Chemical applications (including fertilizers)	71	0	(SCRREEN, 2023d)	
	Petroleum refining	24	0		
	Metallurgy	4	0		
	Paper production	1	0		
	Total		0		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Talc	Polymer for cars	34	90	(SCRREEN, 2023d)	(IMA Europe, 2023)
	Paper	21	70.6		(Department for Environment Food & Rural Affairs, 2024)
	Paint and coatings	18	0		
	Feed	8	0		
	Building material	7	0		
	Fertilisers	4	0		
	Rubber	2	0		
	Cosmetics	1	0		
	Pharmaceuticals	1	0		
	Other	4	0		
	Total		45.43		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Tantalum (Ta)	Capacitors	33	0	(MSP-REFRAM, 2020)	
	Superalloys	22	62		(Curwick et al., 1980)
	Sputtering targets	17	0		
	Chemicals	11	0		
	Mill products	9	0		
	Carbides	8	0		
	Total		13.64		
Tellurium (Te)	Solar power	40	90	(U.S. Geological Survey, 2020)	(International Cadmium Association, 2024a)
	Thermo-electric devices	30	0		
	Metallurgy	15	0		
	Chemical manufacture	10	0		
	Rubber vulcanising	5	0		
	Total		36		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Thallium (Tl)	Electronics industry in photoelectric cells	65	0	BGS in-house estimate	
	Others (pharmaceuticals, alloys, glass)	35	0		
	Total		0		
Thorium (Th)	Nuclear reactor	50	0	BGS in-house estimate	
	Heat resistant ceramics	20	0		
	Refractory metal manufacturing	20	0		
	Electronics equipment coatings	2	0		
	Gas mantles	2	0		
	Others	6	0		
	Total		0		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Tin (Sn)	Solder	48	0	(International Tin Association, 2021)	EoLRR for Tin is manually entered due to the absence of openly accessible data for different sectors. (International Tin Association, 2020)
	Chemicals	17	0		
	Tinplate	12	0		
	Lead-acid batteries	7	0		
	Tin-Copper	7	0		
	Others	9	0		
	Total		33		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Titanium (Ti)	Paints	54	0	(Graedel et al., 2022)	(Graedel et al., 2022)
	Polymers	24	0		
	Aerospace	8	80		
	Medical equipment	6	30		
	Automotive	3	30		
	Alloys	2	30		
	Hand-held objects	2	30		
	Others	1	0		
	Total		10.3		
Tungsten (W)	Tungsten carbide products	65	40	(International Tungsten Industry Association, 2024)	(Zeiler et al., 2021)
	Steels & superalloys	14	15		
	Tungsten metallic products	12	22		
	Chemicals and others	9	5		
	Total		31.19		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Uranium (U)	Energy production	90	7.6	(World Nuclear Association, 2024a)	EoLRR is based on BGS in-house estimate
	Isotopes used for medical, industrial, and defence purposes	10	0		
	Total		6.84		
Vanadium (V)	Steels: HSLA, alloy steels, stainless steels (1-6 percent vanadium)	91	91	(Graedel et al., 2022)	(Worldstainless, 2023)
	Superalloys: Titanium-Aluminium-Vanadium alloys and V–Cr–Ti alloy (90 wt%)	3	62		(Curwick et al., 1980)
	Cost iron	2	0		
	Chemicals	3	0		
	Energy storage	1	0		
	Total		84.67		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Vermiculite	Agriculture	30	0	(U.S. Geological Survey, 2024b)	
	Lightweight aggregate	21	1		BGS in-house estimate
	Insulation	14	0		
	Other	35	0		
	Total		0.21		
Wollastonite	Ceramics	35	0	(Nair and Sairam, 2021)	
	Polymers	33	17		(Brooking, 2024)
	Paints and coatings	12	0		
	Other	20	0		
	Total		5.61		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Zeolite	Drying	62.5	0	(El Bojaddayni et al., 2023)	
	Separation	18.7	0		
	Adsorption	11.4	0		
	Detergent	3.1	0		
	Others	4.3	0		
	Total		0		
Zinc (Zn)	Steel products galvanizing	60	0	(International Lead & Zinc Study Group, 2023a)	EoLRR for Zinc is manually entered due to the absence of openly accessible data for different sectors. (International Energy Agency, 2021)
	Die-Casting alloys	13	0		
	Brass & Casting	11	0		
	Oxides & Chemicals	9	0		
	Semi-Manufactures	5	0		
	Others	2	0		
	Total		33		

Symbol/name	Application/end use	Share of end use (%)	EoLRR (%)	Source(s)	Comment(s)
Zirconium (Zr)	Advance ceramics	38	0	(ZIRCOMET, 2019)	
	Ceramics pigments	18	0		
	Cubic zirconia	14	0		
	Catalyst	15	0		
	TiO2 pigment coating	5	0		
	Paper coating	3	0		
	Others	7	0		
	Total		0		

These are the synthesized end-of-life recycling collection rates (EoLRR).

Commodity	EoLRR (%)	Commodity	EoLRR (%)
Aluminium (Al)	71	Rhodium (Rh)	28
Antimony (Sb)	20	Ruthenium (Ru)	0
Arsenic (As)	0	Selenium (Se)	10
Beryllium (Be)	5	Silicon (Si)	15
Bismuth (Bi)	0	Silver (Ag)	46
Cadmium (Cd)	18	Sodium (Na)	0
Natural Graphite	16	Strontium (Sr)	2
Chromium (Cr)	77	Sulphur (S)	0
Cobalt (Co)	48	Tantalum (Ta)	14
Copper (Cu)	77	Tellurium (Te)	36
Gallium (Ga)	17	Tin (Sn)	33
Germanium (Ge)	30	Titanium (Ti)	10
Gold (Au)	95	Tungsten (W)	31
Hafnium (Hf)	28	Uranium (U)	7
Helium (He)	27	Vanadium (V)	85
Indium (In)	11	Zinc (Zn)	33
Iridium (Ir)	0	Zirconium (Zr)	0
Iron (Fe)	83	Barite	7
Lead (Pb)	81	Bentonite	26
Lithium (Li)	3	Borates	20

Commodity	EoLRR (%)	Commodity	EoLRR (%)
Magnesium (Mg)	47	Diamonds	0
Manganese (Mn)	75	Diatomite	4
Molybdenum (Mo)	44	Feldspar	7
Nickel (Ni)	60	Fluorine	1
Niobium (Nb)	9	Garnet	0
Palladium (Pd)	30	Gypsum	24
Phosphorus (P)	0	Kaolin clay	38
Platinum (Pt)	18	Kyanite	0
Potassium (K)	0	Industrial limestone	59
Rare earth elements (REE)	0	Magnesite	52
Rhenium (Re)	43	Perlite	0
Pumice	1	Industrial (silica) sand	16
Pyrophyllite	8	Talc	45
Industrial salt	0	Vermiculite	0

Appendix 7 Gross value added

UK GVA is a way to measure the financial value of goods and services in the UK economy, allowing assessment at national and regional levels and across different industries or sectors of the economy. It is calculated from an annual business survey, leading to a comprehensive set of statistics covering all sectors of the UK economy. The allocation of business activity is based on ‘Standard industrial classification’ (SIC) codes (Office for National Statistics, 2007). These are similar to HS codes in trade data and map business activity to subsections of major industrial sectors. For example, two-digit SIC codes map major industrial sectors (for example, 07 is metal mining; 26 is electronics manufacturing), whilst four-digit SIC codes map to specific parts of each industrial sector (or example, 07.29 is mining of non-ferrous metal ores; 26.51 is manufacture of instruments and appliances for measuring, testing and navigation). Anything <10% and ‘other’ have been excluded from mapping. These are predominantly EU and world application use.

Candidate material	Application end use	Share of application for CM (%)	Reference for application use and share (%)	SIC07 code(s)	avgGVA total (£ million)	Notes
				(Office for National Statistics, 2024)		
Aluminium (Al)	Mobility - transport	42	(SCRREEN, 2023d)	29.2 Manufacture of bodies (coachwork) for motor vehicles; manufacture of trailers and semi-trailers	991	
	Construction	23		25.12 Manufacture of doors and windows of metal	1,045	
	Packaging	17		25.92 Manufacture of light metal packaging	579	

	High-tech engineering	12				Excluded as 'high-tech engineering' is too vague
	Consumer durables	6				
Antimony (Sb)	Flame retardants	43	(SCRREEN, 2023d)	20.13 Manufacture of other inorganic basic chemicals - based on this being ATO (Sb2O3)	1,074	
	Lead acid batteries	32		27.2 Manufacture of batteries and accumulators	136	
	Lead alloys	14		24.43 Lead, zinc, and tin production	65	
	Plastics	6				
	Glass and Ceramics	5				
Arsenic (As)	Zinc production	70	(SCRREEN, 2023d)	24.43 Lead, zinc, and tin production	65	
	Glassmaking	18		23.1 Manufacture of glass and glass products	1,428	
	Chemicals	7				

	Alloys	5				
Beryllium (Be)	Electronic and telecommunications equipment	30	(European Commission, 2024)	26.1 Manufacture of computer, electronic and optical products	1,314	
	Industrial components	20		28.12 Manufacture of fluid power equipment 28.13 Manufacture of other pumps and compressors 28.14 Manufacture of other taps and valves 28.15 Manufacture of bearings, gears, gearing and driving elements	499 1,134 572 485	
	Auto electronics	17		29.31 Manufacture of electrical and electronic equipment for motor vehicles	237	
	Aerospace and defence	6				
	Other	27				

Bismuth (Bi)	Chemicals	80	(SCRREEN, 2023d)	20.13 Manufacture of other inorganic basic chemicals	1,074	
	Fusible alloys	10		24.45 Other non-ferrous metal production	158	
	Metallurgy	10		24.45 Other non-ferrous metal production	158	
Cadmium (Cd)	NiCd batteries	91	(SCRREEN, 2023d)	27.2 Manufacture of batteries and accumulators	136	
	Alloys	5				
	Solar	1				
	Coating	3				
Chromium (Cr)	Products made of steel	74	(SCRREEN, 2023d)	24.1 Manufacture of basic iron and steel and of ferro-alloys	1,152	
	Products made of alloy steel	19		24.1 Manufacture of basic iron and steel and of ferro-alloys	1,152	
	Casting moulds	3				

	Products made of chromium chemicals	3				
	Refractory bricks & mortars	1				
Cobalt (Co)	Super alloys	30	(SCRREEN, 2023d)	24.45 Other non-ferrous metal production	158	
	Magnets	18		23.44 Manufacture of other technical ceramic products	29	Includes manufacture of ceramic and ferrite magnets
	Internationally dissipative uses					Excluded as 'Internationally dissipative uses' is too vague
	Hard metals	13		24.45 Other non-ferrous metal production	158	
	Batteries	13		27.2 Manufacture of batteries and accumulators	136	
	Catalysts	9				
Copper (Cu)	Electrical power (20.9%) + power utility (6.5%)	27.4	(SCRREEN, 2023d)	24.44 Copper production	94	Includes manufacturing of copper wire

	Telecommunications	2.7				
	Industry (electrical) (6.5%) + (non-electrical) (9.7%)	16.2		24.44 Copper production	94	Includes manufacturing of copper wire
	Automotive (electrical) (9.7%) + other transport (4.2%)	13.9			237	
	Automotive (non-electrical)	0.7				
	Consumer & general products (7.9%) + electronics (2.1%)	10		26.11 Manufacture of electronic components	879	Includes semiconductors and wafers (PVs)
	Cooling	3				
	Diverse	12.7				Excluded as 'diverse' is too vague
	Plumbing	10.2		24.44 Copper production	94	Includes semi-manufacturing of copper (e.g. pipes)
	Building plant	0.4				
	Architecture	1.6				
	Communications	1.2				

Gallium (Ga)	Integrated circuits	40	(SCRREEN, 2023d)	26.12 Manufacture of loaded electronic boards	434	
	Optoelectronics	20		26.11 Manufacture of electronic components and boards	879	Includes LEDs (main use of Ga in optics)
	Sensors	18		26.51 Manufacture of instruments and appliances for measuring, testing and navigation	4,966	Includes different types of sensors (e.g. radiation, temperature)
	Magnets	14		23.44 Manufacture of other technical ceramic products	29	Includes manufacture of ceramic and ferrite magnets
	GaAs modules (PV)	3				
	Other	5				
Germanium (Ge)	Infrared optics	52	(SCRREEN, 2023d)	26.7 Manufacture of optical instruments and photographic equipment	371	
	Optical fibres	23		27.31 Manufacture of fibre optic cables	101	

	Satellite solar cells	12		26.11 Manufacture of electronic components	879	Includes semiconductors and wafers (PVs)
	Other	13				Excluded as 'other' is too vague
Gold (Au)	Investment	41	(SCRREEN, 2023d)			Excluded as investment falls under a very broad set of SIC07 codes (e.g. financial services)
	Electronics	41		26.1 Manufacture of electronic components and boards	1,314	
	Jewellery	9				
	Dentistry	2				
	Other	7				
Hafnium (Hf)	Superalloys (aircraft)	43	(SCRREEN, 2023d)	24.45 Other non-ferrous metal production	158	
	Superalloys (turbines)	18		24.45 Other non-ferrous metal production	158	

	Plasma cutting tips	15		24.44 Copper production	94	Includes copper alloys that are used to manufacture plasma cutting tips
	Nuclear control rods	11		25.3 Manufacture of steam generators, except central heating hot water boilers	282	Includes nuclear reactors
	Catalyst precursors	7				
	Other	6				
Helium (He)	Cryogenics	22	(SCRREEN, 2023d)	26.6 Manufacture of irradiation, electromedical and electrotherapeutic equipment	585	Assuming main use is in medical imaging kit
	Controlled atmospheres (23%) + welding (8%)	31		20.11 Manufacture of industrial gases	644	
	Pressurisation and purging (9%) + leak detection (7%)	16		20.11 Manufacture of industrial gases	644	
	Semiconductors, optic fibres	8				
	Balloons	14		20.11 Manufacture of industrial gases	644	

	Analysis	9				
Indium (In)	Flat panel displays	60	(SCRREEN, 2023d)	26.4 Manufacture of consumer electronics	281	Includes TVs and displays
	Solders	11		20.59 Manufacture of other chemical products n.e.c.	1,999	Includes powders and pastes used in soldering, brazing or welding
	PV cells	9				
	Thermal interface material (7%) + semiconductors and LEDs (3%)	10		26.11 Manufacture of electronic components and boards	879	
	Batteries	6				
	Alloys/compounds	4				
Iron (Fe)	Construction	38	(SCRREEN, 2023d)	25.11 Manufacture of metal structures and parts of structures	3,374	
	Automotive	16		29.2 Manufacture of bodies (coachwork) for motor vehicles; manufacture of	991	

				trailers and semi-trailers		
	Mechanical engineering	15				Excluded as 'Mechanical engineering' is too vague
	Metalware	14		25.11 Manufacture of metal structures and parts of structures	3,374	
	Tubes	10		25.11 Casting of iron	155	Includes pipes and hollow sections
	Domestic appliances	2				
	Transport	2				
	Other	3				
Lead (Pb)	Batteries	84	(SCRREEN, 2023d)	27.2 Manufacture of batteries and accumulators	136	
	Rolled and extruded products	6				
	Compounds and pigments	4				
	Shots and ammunition	4				

	Cable sheathing	1				
	Alloys and solders	1				
Lithium (Li)	Batteries	71	(SCRREEN, 2023d)	27.2 Manufacture of batteries and accumulators	136	
	Ceramics and glass	14		23.4 Manufacture of other porcelain and ceramic products 23.1 Manufacture of glass and glass products	341 1,428	
	Lubricating greases	4				
	Polymer production	2				
	Continuous casting mould flux powders	2				
	Air treatment	1				
	Other	6				
Magnesium (Mg)	Transportation (automotive)	50	(SCRREEN, 2023d)	29.2 Manufacture of bodies (coachwork) for motor vehicles; manufacture of	991	

				trailers and semi-trailers		
	Packaging	21		25.92 Manufacture of light metal packaging	579	
	Construction	13		23.52 Manufacture of lime and plaster 23.51 Manufacture of cement	101 148	
	Delsuphurisation agent	12		24.1 Manufacture of basic iron and steel and of ferro-alloys - use here is to desulphurise steel	1,152	
	Transportation (air, marine etc)	4				
Manganese (Mn)	Building and construction	43	(SCRREEN, 2023d)	25.11 Manufacture of metal structures and parts of structures	3,374	
	Metalware	14		25.11 Manufacture of metal structures and parts of structures	3,374	
	Transportation (motor vehicles)	10		29.2 Manufacture of bodies (coachwork)	991	

				for motor vehicles; manufacture of trailers and semi-trailers		
	Transportation (other transport equipment)	10		29.2 Manufacture of bodies (coachwork) for motor vehicles; manufacture of trailers and semi-trailers	991	
	Engineering (industrial)	9				
	Engineering (machinery & equipment)	8				
	Domestic appliances	2				
	Batteries	2				
	Other	2				
Molybdenum (Mo)	Engineering steels	40	(SCRREEN, 2023d)	24.1 Manufacture of basic iron and steel and of ferro-alloys	1,152	
	Stainless steel (23%) + tool steels (8%)	31		24.1 Manufacture of basic iron and steel and of ferro-alloys	1,152	

	Chemicals	13				Excluded as 'chemicals' is too vague, this could include catalysts, pigments, lubricants, etc.
	Foundries	8				
	Mo-metals	6				
	Nickel alloys	2				
Nickel (Ni)	Stainless steel	49	(SCRREEN, 2023d)	24.1 Manufacture of basic iron and steel and of ferro-alloys	1,152	
	Ni-based & Cu-based alloys	23		24.45 Other non-ferrous metal production	158	
	Alloy steel & casting	18		24.52 Casting of steel	64	
	Plating	4				
	Batteries	2				
	Other	4				
Niobium (Nb)	Construction (steel)	47	(SCRREEN, 2023d)	25.11 Manufacture of metal structures	3,374	

				and parts of structures		
	Automative (steel)	24		29.2 Manufacture of bodies (coachwork) for motor vehicles; manufacture of trailers and semi-trailers	991	
	Oil & gas	17		24.52 Casting of steel - assume here main use is pipework	64	
	Stainless steel	10		24.1 Manufacture of basic iron and steel and of ferro-alloys	1,152	
	Special steel	2				
Phosphorus (P)	Plastics	30	(SCRREEN, 2023d)	20.16 Manufacture of plastics in primary forms	1,475	
	Food industry	21		20.13 Manufacture of other inorganic basic chemicals	1,074	Added to food in chemical form e.g. phosphoric acid or P-salts.
	Water treatment	17		20.13 Manufacture of other inorganic basic chemicals	1,074	Zn-phosphate used to inhibit corrosion in water distribution systems

	Metal treatment	15		25.61 Treatment and coating of metals	942	
	Pharmaceuticals	7				
	Other	10				
Potassium (K)	Fertilisers	92	(Graedel et al., 2022)	20.15 Manufacture of fertilisers and nitrogen compounds	453	Includes ammonia
	Chemicals	8				
Rare earth elements	Magnets	53	(SCRREEN, 2023d)	25.99 Manufacture of other fabricated metal products n.e.c.		Includes permanent magnets
	Catalysts	25		20.59 Manufacture of other chemical products n.e.c.		Includes catalysts
	Metallurgical	9				
	Polishing powders	3				
	Ceramics (3%) + other (7%)	10		23.4 Manufacture of other porcelain and ceramic products 23.1 Manufacture of		The assumption here is that 'other' is glass

				glass and glass products		
Rhenium (Re)	Aerospace	83	(SCRREEN, 2023d)	30.30 Manufacture of air and spacecraft and related machinery	6,733	Includes parts for jet engines
	Catalysts in petroleum industry	17		20.59 Manufacture of other chemical products n.e.c.	1,999	Includes catalysts
Selenium (Se)	Glass manufacturing	30	(SCRREEN, 2023d)	23.1 Manufacture of glass and glass products	1,428	
	Metallurgy	15		24.1 Manufacture of basic iron and steel and of ferro-alloys	1,152	A small amount of Se added to iron and steel improves ductility
	Electronics	15		26.11 Manufacture of electronic components	879	Includes semiconductors and wafers (PVs)
	Pigments	15		20.12 Manufacture of dyes and pigments	348	
	Agriculture/biological	15		20.15 Manufacture of fertilisers and nitrogen compounds	453	A small amount of Se added to fertilisers aids plant/crop growth

	Other	10				
Silicon (Si)	Chemical applications	54	(SCRREEN, 2023d)	20.13 Manufacture of other inorganic basic chemicals	1,074	
	Aluminium alloys	38		24.42 Aluminium production	221	
	Solar applications	6				
	Electronic applications	2				
Silver (Ag)	Electrical/electronics	21	(SCRREEN, 2023d)	26.1 Manufacture of electronic components and boards	1,314	
	Jewellery	17		32.12 Manufacture of jewellery and related articles	340	
	Investment (coins and medals)	15		32.11 Striking of coins	-	
	Investment (bars)	12		24.41 Precious metals production	59	
	PV	11		26.11 Manufacture of electronic components	879	Includessemiconductors and wafers (PVs)

	Other	24				
Sodium (Na)	Chemicals	86	Personal estimates based on BGS knowledge	20.13 Manufacture of other inorganic basic chemicals	1,074	
	Other	14				
Strontium (Sr)	Magnets	40	(SCRREEN, 2023d)	23.44 Manufacture of other technical ceramic products	29	Includes manufacture of ceramic and ferrite magnets
	Pyrotechnics & signals	40		20.51 Manufacture of explosives	54	
	Master alloys	5				
	Pigements & fillers	5				
	Zinc production	5				
	Glass	5				
	Drilling fluids	0				
Sulphur (S)	Chemical applications	71	(SCRREEN, 2023d)	20.13 Manufacture of other inorganic basic chemicals	1,074	

	Petroleum refining	24		20.59 Manufacture of other chemical products n.e.c.	1,999	Includes catalysts
	Metallurgy	4				
	Paper production	1				
Tantalum (Ta)	Capacitors	36	(SCRREEN, 2023d)	27.9 Manufacture of other electrical equipment	748	Includes capacitors
	Superalloys	24		24.45 Other non-ferrous metal production	158	
	Sputtering targets	11		25.61 Treatment and coating of metals	942	
	Mill products	12		24.45 Other non-ferrous metal production	158	
	Carbides	9				
	Chemicals	8				
Tellurium (Te)	Solar power	40	(SCRREEN, 2023d)	26.11 Manufacture of electronic components	879	Includes semiconductors and wafers (PVs)

	Thermo electrical devices	30		26.11 Manufacture of electronic components	879	Includes semiconductors i.e. thermo-electric devices
	Metallurgy	15		24.1 Manufacture of basic iron and steel and of ferro-alloys	1,152	A small amount of Te added to iron and steel improves ductility
	Chemical manufacturing	10		20.59 Manufacture of other chemical products n.e.c.	1,999	Te is used in the manufacture of catalysts
	Rubber vulcanising	5				
Tin (Sn)	Solders	48	(SCRREEN, 2023d)	20.59 Manufacture of other chemical products n.e.c.	1,999	Includes powders and pastes used in soldering, brazing or welding
	Chemicals	17		20.13 Manufacture of other inorganic basic chemicals	1,074	
	Tinplate	12		25.61 Treatment and coating of metals	942	
	Lead acid batteries	7				
	Copper alloys	7				
	Other	9				

Titanium (Ti)	Pigments	78	(Graedel et al., 2022)	20.12 Manufacture of dyes and pigments	348	
	Aerospace	8				
	Medical equipment	6				
	Automotive	3				
	Alloys	2				
	Hand-held objects	2				
	Other	1				
Tungsten (W)	Tungsten carbide	64	(SCRREEN, 2023d)	28.49 Manufacture of other machine tools	169	Includes manufacture of parts and accessories for machine tools (assume cutting heads and drill bits)
	Tungsten metal	17		24.45 Other non-ferrous metal production	158	
	Steels and superalloys	11		24.45 Other non-ferrous metal production	158	
	Chemicals	8				

Uranium (U)	Energy production	90	(World Nuclear Association, 2024b)	24.46 Processing of nuclear fuel	-	
	Isotopes used for medical, industrial, and defence purposes	10				Excluded as isotopes were not included in the assessment
Vanadium (V)	HSLA Steel	50	(SCRREEN, 2023d)	29.2 Manufacture of bodies (coachwork) for motor vehicles; manufacture of trailers and semi-trailers	991	Specifies HSLA which is mainly used in car bodies, therefore assign to 29.2
	Special steels	38		24.1 Manufacture of basic iron and steel and of ferro-alloys	1,152	
	Superalloys	5				
	Chemcials	3				
	Cast iron	2				
	Other	2				
Zinc (Zn)	Galvanising	51	(SCRREEN, 2023d)	25.61 Treatment and coating of metals	942	

	Zn alloys	17		24.43 Lead, zinc and tin production	65	Includes alloys of Zn
	Brass and bronze	15		24.43 Lead, zinc and tin production	65	Includes alloys of Zn
	Zn compounds	10		20.13 Manufacture of other inorganic basic chemicals	1,074	
	Zn mill products	6				
	Other	1				
Zirconium (Zr)	Ceramics	50	(SCRREEN, 2023d)	23.4 Manufacture of other porcelain and ceramic products	341	
	Refactories	13		23.2 Manufacture of refractory products	149	
	Foundry	13		23.2 Manufacture of refractory products	149	
	Chemicals	11		20.13 Manufacture of other inorganic basic chemicals	1,074	
	Pigments	3				

	Superalloys, nuclear	3				
	Others	7				
Platinum (Pt)	Autocatalyst	90	(SCRREEN, 2023d)	29.32 Manufacture of other parts and accessories for motor vehicles	2,718	Includes catalytic converters
	Electrical	4				
	Chemcial	3				
	Dental	1				
	Jewellery	1				
	Other	1				
Rhodium (Rh)	Autocatalyst	91	(SCRREEN, 2023d)	29.32 Manufacture of other parts and accessories for motor vehicles	2,718	Includes catalytic converters
	Chemical	5				
	Glass	2				
	Other	2				

Iridium (Ir)	Electronics/electrical	30	(SCRREEN, 2023d)	26.11 Manufacture of electronic components		Includes LEDs and manufacture of display components (i.e. plasma, polymer, LCD)
	Electrochemical	26		27.9 Manufacture of other electrical equipment		Includes fuel cells - assume most of the use here is in fuel cells
	Chemical	9				
	Medical	9				
	Automotive	6				
	Other	20				
Palladium (Pd)	Autocatalysts	88	(SCRREEN, 2023d)	29.32 Manufacture of other parts and accessories for motor vehicles	2,718	Includes catalytic converters
	Electrical/electronics	4				
	Chemical	3				
	Dental and biomedical	2				
	Jewellery	2				

	Other	1				
Ruthenium (Ru)	Electrical/electronics	42	(SCRREEN, 2023d)	26.11 Manufacture of electronic components	879	Includes LEDs and manufacture of display components (i.e. plasma, polymer, LCD)
	Chemical	32		20.59 Manufacture of other chemical products n.e.c.	1,999	Includes catalysts
	Electrochemical	13		27.9 Manufacture of other electrical equipment	748	Includes fuel cells - assume most of the use here is in fuel cells
	Others	13				
Barite	Oil industry	69	Personal estimates based on Bleiwas and Miller (2014), and BGS knowledge.	23.99 Manufacture of other non-metallic mineral products not elsewhere classified	377	
	Chemical - electronics, TV screen, glass, ceramics and medical applications (barium meals)	16		21.1 Manufacture of basic pharmaceutical products 23.1 Manufacture of glass and glass products 26.4 Manufacture of consumer electronics	789 1,428 281	

	Fillers - car, rubber and paint industry, radiation shielding	15		22.1 Manufacture of rubber products 20.3 Manufacture of paints, varnishes and similar coatings, printing ink and mastics	1,024 1,448	
Bentonite	Pet litter	31	(SCRREEN, 2023d)	23.99 Manufacture of other non-metallic mineral products not elsewhere classified.	377	
	Foundry moulding	28		23.2 Manufacture of refractory products	149	
	Civil engineering	12				Excluded as 'civil engineering' is too vague
	Pelletising of iron	8				
	Bleaching earths	7				
	Paper	4				
	Specialities & drilling fluids	4				
	Feed production	3				
	Food & wine	0				

	Oil absorbents	0				
	Other	3				
Borates	Glass	49	(European Commission et al., 2020b)	23.1 Manufacture of glass and glass products	1,428	
	Ceramics	15		23.1 Manufacture of clay building materials	341	Mostly household ceramics where borates are used in glazes
	Fertilisers	13		20.15 Manufacture of fertilisers and nitrogen compounds	453	
Diamonds	Jewellery	95	(Real Diamond Invest, 2024)	32.12 Manufacture of jewellery and related articles	340	
	Abrasives	5				
Diatomite	Food industry	48	(SCRREEN, 2023d)	23.99 Manufacture of other non-metallic mineral products n.e.c.	377	The assumption is this is largely used for filtration
	Pellettising iron ore	23		7.1 Mining of iron ores inc. beneficiation and	-	

				agglomeration of iron ores		
	Activated raw granules	13		23.99 Manufacture of other non-metallic mineral products n.e.c.	377	The assumption is this is largely used for filtration
	Pet litter	7				
	Civil engineering	6				
	Drilling fluids	2				
	Foundry moulding sands	1				
Feldspar	Bricks and tiles	46	(SCRREEN, 2023d)	23.32 Manufacture of bricks, tiles and construction products, in baked clay	635	
	Ceramics	45		23.4 Manufacture of other porcelain and ceramic products	341	
	Glass	6				
	Other	3				

Fluorine (F)	Steel and iron making	36	(SCRREEN, 2023d)	24.1 Manufacture of basic iron and steel and of ferro-alloys	1,152	
	Aluminium making and other metallurgy	15		24.42 Aluminium production	221	
	Solid fluoropolymers (cookware coating and cable insulation)	11		20.16 Manufacture of plastics in primary forms	1,475	Includes polymers
	Fluorochemicals	11		20.13 Manufacture of other inorganic basic chemicals	1,074	
	Refrigeration and air conditioning	9				
	HF in alkylation process for oil refining	4				
	UF6 in nuclear fuel	7				
	Other (cement, ceramics, glass, melting rods, glazes)	7				
Garnet	Abrasives	65	Based on Harben (1999), and BGS knowledge	23.91 Production of abrasive products	47	
	Other	35				

Graphite (natural)	Refractories for steel making (32%) + foundries (9%)	41	(SCRREEN, 2023d)	23.2 Manufacture of refractory products	149	The association with steel making here is the production of furnace linings
	Lithium-ion batteries	25		27.2 Manufacture of batteries and accumulators	136	
	Lubricants (13%) + friction products (9%)	13		20.59 Manufacture of other chemical products n.e.c.	1,999	
	Steel recarburising	3				
	Other	9				
Gypsum	Plasterboard & wallboard	51	(SCRREEN, 2023d)	23.52 Manufacture of lime and plaster	101	
	Building plaster	26		23.52 Manufacture of lime and plaster	101	
	Cement production	17		23.51 Manufacture of cement	148	
	Agriculture	6				
Kaolin clay	Paper making	44	(European Commission, 2024)	17.2 Manufacture of articles of paper and paperboard	3,060	

	Ceramics	28		23.4 Manufacture of other porcelain and ceramic products	341	
	Fiberglass	9				
	Paints and construction	6				
	Refractories	5				
	Other	8				
Kyanite	Refractories	70	Based on Sweet Sweet et al. (2006) and BGS knowledge	23.2 Manufacture of refractory products	149	
	Ceramics	30		23.4 Manufacture of other porcelain and ceramic products	341	
Industrial limestone	Construction	31	(SCRREEN, 2023d)	23.51 Manufacture of cement	101	
	Paper, rubber & plastic	31		17.2 Manufacture of articles of paper and paperboard 20.16 Manufacture of plastics in primary forms 22.1 Manufacture of rubber products	3,060 1,475 1,024	

	Flue gas desulphurisation	9				
	Manufacture of basic metals	8				
	Paint, coating, adhesives	6				
	Agriculture	5				
	Feed	4				
	Other	6				
Magnesite	Steel making	57	(SCRREEN, 2023d)	23.2 Manufacture of refractory products - steel making here is furnace linings	149	
	Agriculture	14		10.91 Manufacture of prepared feeds for farm animals	842	
	Paper	12		17.2 Manufacture of articles of paper and paperboard	3,060	
	Cement	9				
	Ceramics	5				

	Glass	3				
Perlite	Construction	59	(SCRREEN, 2023d)	23.99 Manufacture of other non-metallic mineral products n.e.c.	377	The assumption is this is largely used for light weight aggregate
	Filtration	24		23.99 Manufacture of other non-metallic mineral products n.e.c.	377	The assumption is this is largely used for light weight aggregate
	Horticulutre	11		23.99 Manufacture of other non-metallic mineral products n.e.c.	377	The assumption is this is largely used for light weight aggregate
	Filler	6				
Pumice	Building blocks	38	(SCRREEN, 2023d)	23.99 Manufacture of other non-metallic mineral products n.e.c.	377	The assumption is this is largely used for light weight aggregate
	Horticulture & landscaping	38		23.99 Manufacture of other non-metallic mineral products n.e.c.	377	The assumption is this is largely used for light weight aggregate
	Concrete aggregate	15		23.61 Manufacture of concrete products	1,480	

				for construction purposes		
	Abrasives & cleaning	8				
	Other	1				
Pyrophyllite	Cement	56	Based on Hida and Kitagawa (2006) and BGS knowledge	23.51 Manufacture of cement	148	
	Ceramics and refractories	12		23.2 Manufacture of refractory products 23.4 Manufacture of other porcelain and ceramic products	149 341	
	Glass (fibres)	18		23.14 Manufacture of glass fibres	199	
Industrial salt	Chloralkali production	28	(SCRREEN, 2023d)	20.13 Manufacture of other inorganic basic chemical	1,074	
	Soda-ash production	25		20.13 Manufacture of other inorganic basic chemicals	1,074	
	De-icing	15		08.93 Extraction of salt	93	Mapped to this to capture the production of salt not the sector

	Food/feed	12		20.13 Manufacture of other inorganic basic chemicals	1,074	Added to food in chemical form e.g. salt
	Water softening	5				
	Other	15				
Industrial (silica) sand	Construction and soil	37	(European Commission, 2024)	23.32 Manufacture of bricks, tiles and construction products, in baked clay 23.4 Manufacture of other porcelain and ceramic products	635 341	
	Glass making	31		23.1 Manufacture of glass and glass products	1,428	
	Foundry casting	10		23.2 Manufacture of refractory products	149	
	Si metal and FeSi	3				
	Chemicals	3				
	Other	16				

Talc	Polymer for cars	34	(SCRREEN, 2023d)	20.16 Manufacture of plastics in primary forms	1,475	
	Paper	21		17.2 Manufacture of articles of paper and paperboard	3,060	
	Paint and coatings	18		20.3 Manufacture of paints, varnishes and similar coatings, printing ink and mastics	1,448	
	Feed	8				
	Building material	7				
	Fetilisers	4				
	Rubber	2				
	Cosmetics	1				
	Pharmaceuticals	1				
	Other	4				

Vermiculite	Agriculture	32	(SCRREEN, 2023d)	23.99 Manufacture of other non-metallic mineral products n.e.c.	377	The assumption is that this is largely used to improve soil water retention
	Lightweight aggregate	25		23.99 Manufacture of other non-metallic mineral products n.e.c.	377	The assumption is that this is largely used for light weight aggregate
	Insulation	13		23.99 Manufacture of other non-metallic mineral products n.e.c.	377	
	Other	30				

Appendix 8 UK mine production, mineral resources status and past production

This table is a synthesis of relevant UK mining data and information, namely:

- recent UK mineral production, averaged over 2018 to 2022, including 2022 specifically to indicate current production rate (Bide et al., 2024)
- mineral resources status: current (formal code-based resources), historic (old, non-code compliant estimates of mineral resources), unknown (not known if there is UK mineralisation) ((Bide et al., 2020b; Bide et al., 2022); BGS expert knowledge)
- historical production: yes or no (no comment or note on scale as this is contextual to the period in which that production occurred. For example, UK Fe ore production peaked at 20 million tonnes in 1942, compared to world production of 235 million tonnes in the same year, yet world production is now 2500 million tonnes. As such, the cumulative amount of Fe ore was historically very significant for the UK, although in comparison to other countries it would now appear more modest. All data from (Bide et al., 2024; Idoine et al., 2024; U.S. Geological Survey, 2024b; U.S. Geological Survey, 2024a), and earlier editions of these reports.

Material	Average annual production 2018 to 2022	Production in 2022	Mineral resources status	Historical UK production
Aluminium (bauxite)	-	-	Unknown	Yes
Antimony (Sb)	-	-	Unknown	Yes
Arsenic (As)	-	-	Unknown	Yes
Beryllium (Be)	-	-	Unknown	No
Bismuth (Bi)	-	-	Unknown	Yes
Cadmium (Cd)			Unknown	No
Chromium (Cr)	-	-	Unknown	Yes
Cobalt (Co)	-	-	Historic	Yes
Copper (Cu)	-	-	Current	Yes
Gallium (Ga)	-	-	Unknown	No
Germanium (Ge)	-	-	Unknown	No
Gold (Au)	0.085	0.27	Current	Yes
Hafnium (Hf)	-	-	Unknown	No
Helium (He)	-	-	Unknown	No
Indium (In)	-	-	Unknown	No
Iridium (Ir)	-	-	Unknown	No
Iron (Fe) (as Fe ore)	-	-	Historic	Yes
Lead (Pb)	-	-	Current	Yes
Lithium (Li)	-	-	Current	No
Magnesium (Mg)	-	-	Unknown	Yes

Material	Average annual production 2018-2022	Production in 2022	Mineral resources status	Historical UK production
Manganese (Mn)	-	-	Unknown	Yes
Molybdenum (Mo)	-	-	Unknown	No
Nickel (Ni)	-	-	Current	Yes
Niobium (Nb)	-	-	Unknown	No
Palladium (Pd)	-	-	Unknown	No
Phosphorus (P)	-	-	Historic	Yes
Platinum (Pt)	-	-	Unknown	No
Potassium (K salts)	739,200	953,000	Current	Yes
Rare earth elements	-	-	Unknown	No
Rhenium (Re)	-	-	Unknown	No
Rhodium (Rh)	-	-	Unknown	No
Ruthenium (Ru)	-	-	Unknown	No
Selenium (Se)	-	-	Unknown	No
Silicon (Si metal)	-	-	Unknown	No
Silver (Ag)	0.4	1.34	Current	Yes
Sodium (Na)	-	-	Unknown	Yes
Strontium (Sr)	-	-	Historic	Yes
Sulphur (S)			Unknown	Yes
Tantalum (Ta)	-	-	Unknown	No
Tellurium (Te)	-	-	Unknown	No

Tin (Sn)	40[A]	0	Current	Yes
Titanium (Ti)	-	-	Unknown	No
Tungsten (W)	240[A]	0	Current	Yes
Uranium (U)	-	-	Unknown	Yes
Vanadium (V)	-	-	Unknown	No
Zinc (Zn)	-	-	Current	Yes
Zirconium (Zr)	-	-	Unknown	No
Barite	39,800	30,000	Current	Yes
Bentonite clay	-	-	Unknown	No
Borates	-	-	Unknown	No
Clay and shale	4,020,000	4,004,000	Current	Yes
Diamonds (natural)	-	-	Unknown	No
Diatomite	-	-	Unknown	Yes
Feldspar	-	-	Unknown	Yes

Material	Average annual production 2018-2022	Production in 2022	Mineral resources status	Historical UK production
Fluorspar[B]	13,540[B]	12,700[B]	Historic	Yes
Garnet	-	-	Unknown	No
Gypsum (natural)	1,820,000	2,400,000	Current	Yes
Graphite (natural)	-	-	Unknown	Yes
Industrial limestone	no data[C]	no data[C]	Historic	Yes

Industrial salt	2,679,000	2,588,000	Historic	Yes
Industrial (silica) sand	5,033,000	4,931,000	Historic	Yes
Kaolin (china) clay	757,900	709,000	Current	Yes
Kyanite	-	-	Unknown	No
Magnesite	-	-	Unknown	No
Perlite	-	-	Historic	Yes
Pumice	-	-	Unknown	No
Pyrite	-	-	Unknown	Yes
Pyrophyllite	-	-	Unknown	No
Talc	2,000	3,000	Historic	Yes
Vermiculite	-	-	Unknown	No
Wollastonite	-	-	Unknown	No
Zeolite	-	-	Unknown	No

[A]Production was in 2018 only (none from 2019 to 2022). [B]Fluorspar mining ceased in the UK in mid-2023. [C]Production data is only reported for total construction aggregates, including chalk, igneous rock, limestone, dolomite and sandstone.

Glossary

AC	Apparent consumption
AI	Artificial intelligence
BGS	British Geological Survey
CA	Criticality assessment
CMF	Companion metal fraction
CMIC	Critical Minerals Intelligence Centre
DBT	Department for Business and Trade
EoL	End-of-life
EoLRIR	End-of-life recycling input rate
EoLRR	End-of-life recycling rate
EPI	Environmental performance index
ESG	Environmental, social and governance [indicator]
GTC	Global trade concentration
GVA	Gross value added
HDI	Human development index
HHI	Hirschman-Herfindahl index
HS	Harmonised system [codes]
kg	Kilograms
NIR	Net import reliance
PCI	Production concentration indicator
PGEs	Platinum group elements: ruthenium, rhodium, palladium, osmium, iridium and platinum
PV	Photovoltaic
REEs	Rare earth elements: the 15 lanthanoids plus scandium and yttrium
REOs	REE oxides
RIR	See EoLRIR
S	Global supply risk (when not sulphur)
SIC	Standard industrial classification [codes]

t	Metric tonnes
UKRI	UK Research and Innovation
USGS	US Geological Survey
V	UK economic vulnerability (when not vanadium)
WEEE	Waste electrical and electronic equipment
WGI	World governance index

References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://of-ukrinerc.olib.oclc.org/folio/.

4He resources. 2024. *The helium supply problem*. (UK: *Helium resources limited*.) Available: https://www.4he-resources.com/Helium%20supply.php [Accessed: 21 November 2024].

Adnan, M, Xiao, B, Ali, M U, Xiao, P, Zhao, P, Wang, H & Bibi, S 2024. Heavy metals pollution from smelting activities: A threat to soil and groundwater. *Ecotoxicology and Environmental Safety.* 274**,** 116189. Available: https://doi.org/10.1016/j.ecoenv.2024.116189.

Alberici, S, de Beer, J, van der Hoorn, I & Staats, M. 2017. Fly ash and blast furnance slag for cement manufacturing. *Department for Business, Energy and Industrial Strategy* Research paper number 19. (Online: Available: https://www.gov.uk/government/publications/cement-manufacturing-use-of-fly-ash-and-blast-furnace-slag [Accessed: 22 November 2024].

Ali, M A, Ahmed, H A, Ahmed, H M & Hefni, M 2021. Pyrophyllite: an economic mineral for different industrial applications. *Applied Sciences.* 11**,** 11357.

Ali, S H, Giurco, D, Arndt, N, Nickless, E, Brown, G, Demetriades, A, Durrheim, R, Enriquez, M A, Kinnaird, J, Littleboy, A, Meinert, L D, Oberhänsli, R, Salem, J, Schodde, R, Schneider, G, Vidal, O & Yakovleva, N 2017. Mineral supply for sustainable development requires resource governance. *Nature.* 543**,** 367-372. Available: 10.1038/nature21359.

Alp, İ, Deveci, H, Yazıcı, E Y, Türk, T & Süngün, Y H 2009. Potential use of pyrite cinders as raw material in cement production: Results of industrial scale trial operations. *Journal of Hazardous Materials.* 166**,** 144-149. Available: https://doi.org/10.1016/j.jhazmat.2008.10.129.

Aluminium Federation. 2020. UK Aluminium Industry Fact Sheet 5. Aluminium Recycling. Available: https://www.alfed.org.uk/files/Fact%20sheets/5-aluminium-recycling.pdf [Accessed: 21 November 2024].

Anonymous. 1942a. The Mineral Industry: Its Statistics, Technology and Trade 1940. *McGraw-Hill Book Company* Years 1892 to 1940 (see also the Internet Archive: www.archive.org). (New York, USA:

Anonymous. 1942b. *The Mineral Industry: Its Statistics, Technology and Trade 1940.* (New York, USA: *McGraw-Hill Book Company.*) ISBN: 1258681471. Years 1892 to 1940 (see also the Internet Archive: www.archive.org).

Argus Media. 2024. *Argus Metals*. Available: https://metals.argusmedia.com/

Asenov, G. 19 July 2023. China restrictions on gallium and germanium 'harmful' to US chipmakers. Available: https://www.fastmarkets.com/insights/china-restrictions-on-gallium-germanium-harmful-us-chipmakers [Accessed: 11 October 2024].

Australian Government. 2024. Australia's Critical Minerals List and Strategic Materials List. 20 June 2023; updated 20 Febrary 2024. (Online: *Critical Minerals Office, Department of Industry, Science and Resources.*) Available:

https://www.industry.gov.au/publications/australias-critical-minerals-list-and-strategic-materials-list [Accessed: 4 November 2024].

Bae, H & Kim, Y 2021. Technologies of lithium recycling from waste lithium ion batteries: a review. *Materials Advances.* 2**,** 3234-3250. Available: https://doi.org/10.1039/D1MA00216C [Accessed: 28 September 2024].

Baldé, C P, Kuehr, R, Yamamoto, T, McDonald, R, D'Angelo, E & Althaf, S, Bel, G, Deubzer, O, Fernandez-Cubillo, E, Forti, V, Heart, S, Honda, S, Iattoni, G, Khetriwal, D S, Luda di Cortemiglia, V, Lobuntsova, Y, Nnorom, I, Pralat, N & Wagner, M. 2024. Global E-Waste Monitor 2024. *International Telecommunication Union (ITU) and United Nations Institute for Training and Research (UNITAR),* (Geneva, Switzerland / Bonn, Germany,: *UNITAR.*) Available: https://api.globalewaste.org/publications/file/297/Global-E-waste-Monitor-2024.pdf [Accessed: 27 October 2024].

Barnett, S & Wentworth, J. 2024. The future of fertiliser use. *UNITED KINGDOM PARLIMENTARY OFFICE OF SCIENCE AND TECHNOLOGY.* (Online: *United Kingdom Parliment.*) Available: https://post.parliament.uk/research-briefings/post-pn-0710/ [Accessed: 22 November 2024].

Baskaran, G. 2024. What China's Ban on Rare Earths Processing Technology Exports Means. *Center for Strategic and International Studies (CSIS)*. 8 January 2024. (Online: *CSIS.*) Available: https://www.csis.org/analysis/what-chinas-ban-rare-earths-processing-technology-exports-means [Accessed: 1 August 2024].

Baskaran, G & Schwartz, M. 2024. China's Antimony Export Restrictions: The Impact on U.S. National Security. *Center for Strategic and International Studies (CSIS)*. 20 August 2024. (Online: *CSIS.*) Available: https://www.csis.org/analysis/chinas-antimony-export-restrictions-impact-us-national-security [Accessed: 1 October 2024].

Bedder, J. 2024a. Chip wars: China restricts exports of gallium and germanium. (Online: *Project Blue.*) Available: https://projectblue.com/blue/news-analysis/503/chip-wars:-china-restricts-exports-of-gallium-and-germanium [Accessed: 2024].

Bedder, J. 2024b. What will China's antimony export restrictions mean for the market? (Online: *Project Blue.*) Available: https://projectblue.com/blue/opinion-pieces/989/what-will-china%E2%80%99s-antimony-export-restrictions-mean-for-the-market [Accessed: 15 August].

Belda, C. 2024. Western antimony trade faces mounting difficulties. *Argus Metals*. 21 August 2024. (Online: *Argus News & analysis.*) Available: https://metals.argusmedia.com/newsandanalysis/article/2600305 [Accessed: 2024].

Belda, C, Morris, S & Saklatvala, E. 2023. China's Ga, Ge export controls may deter EU trade. *Argus Media*. 12 September 2023. (Online: *Argus Metals.*) Available: https://metals.argusmedia.com/newsandanalysis/article/2488372?keywords=china%e2%80%99s%20ga%2c%20ge%20export%20controls%20may%20deter%20eu%20trade&returnparams= [Accessed: 4 November 2024].

Bide, T, Bloodworth, A & Kendall, R. 2021. Mineral Planning Factsheet: Coal. *British Geological Survey* OR/21/028. (Nottingham, United Kingdom: *BRITISH GEOLOGICAL SURVEY.*) [Accessed: 22 November 2024].

Bide, T, Brown, T, Idoine, N & Mankelow, J. 2020a. Mineral planning factsheet: silica sand. *British Geological Survey* Available: https://nora.nerc.ac.uk/id/eprint/527215/ [Accessed: 22 November 2024].

Bide, T, Brown, T J, Gunn, A G & Mankelow, J 2020b. Utilisation of multiple current and legacy datasets to create a national minerals inventory: A UK case study. *Resources Policy.* 66**,** 10 pages. Available: 10.1016/j.resourpol.2020.101654.

Bide, T, Horn, S, Gunn, A, Price, F, Mitchell, C & Patton, M. 2022. Securing sustainable supply of critical raw materials for the UK, current issues and recommendations for improvement. *British Geological Survey* OR/22/034. (Keyworth: *BRITISH GEOLOGICAL SURVEY*.) Available: https://nora.nerc.ac.uk/id/eprint/533871/

Bide, T, Idoine, N E, Evans, E, Raycraft, E R & Mankelow, J. 2024. United Kingdom Minerals Yearbook 2023. *British Geological Survey* OR/24/025. (Keyworth, UK: *BRITISH GEOLOGICAL SURVEY*.) Available: https://nora.nerc.ac.uk/id/eprint/537480/ [Accessed: 1 October 2024].

Binnemans, K, Jones, P T, Blanpain, B, Van Gerven, T & Pontikes, Y 2015. Towards Zero-Waste Valorisation of Rare-Earth-Containing Industrial Process Residues: A Critical Review. *Journal of Cleaner Production.* 99**,** pp 17-38.

Bleiwas, D I & Miller, M M. 2014. Barite—A Case Study of Import Reliance on an Essential Material for Oil and Gas Exploration and Development Drilling. *U.S. Geological Survey* (Online: *U.S. GEOLOGICAL SURVEY*.) Available: https://pubs.usgs.gov/sir/2014/5230/pdf/sir2014-5230.pdf [Accessed: 4 November 2024].

Bleiwas, D I & Miller, M M. 2015. Barite: a case study of import reliance on an essential material for oil and gas exploration and development drilling. *US Geological Survey* 2328-0328. [Accessed: 22 November 2024].

Block, S, Emerson, J W, Esty, D C, de Sherbinin, A, Wendling, Z A & et al. 2024. 2024 Environmental Performance Index. *Yale Center for Environmental Law & Policy,* (New Haven, CT: *YALE CENTER FOR ENVIRONMENTAL LAW & POLICY*.) Available: https://epi.yale.edu/ [Accessed: 24 April 2024].

Bloodworth, A, Wrighton, C, Highley, D & Bate, R. 2009. Mineral planning factsheet: kaolin. *British Geological Survey* (Mineral planning factsheet) (Unpublished): Available: https://nora.nerc.ac.uk/id/eprint/534429/ [Accessed: 21 November 2024].

BRGM. 2020. Criticality assessment - Silicon metal. (Online: *French Geological Survey (BRGM).*), https://www.mineralinfo.fr/sites/default/files/documents/2020-12/materialcriticalitysiliconmetal-public20191030.pdf [Accessed: 25 May 2023].

Brooking, F. 2024. *Recycling Statistics: The UK Recycling Rate Of Plastic Is Just 17%*. *Pebble Magazine*.) Available: https://pebblemag.com/recycling-statistics-uk/ [Accessed: 22 November, 2024].

Brunning, A. 2014. The Chemical Elements of a Smartphone. 19 February 2014. (Online: *Compound Interest.*) Available: https://www.compoundchem.com/2014/02/19/the-chemical-elements-of-a-smartphone/ [Accessed: 4 November 2024].

Bundesanstalt für Geowissenschaften und Rohstoffe. 2021. Tantalum – Sustainability Information. *Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)* (Hannover, Germany: Available: www.bgr.bund.de/EN/Themen/Min_rohstoffe/Produkte/Informationen_zur_Nachhaltigkeit/tantalum_verzeichnis_en.html

Bureau of International Recycling. 2024. *Non-ferrous metals*. Available: https://archive.bir.org/industry/non-ferrous-metals [Accessed: 22 November, 2024].

CAS Science Team. 2022. A Review of the Current Methods and Global Developments. *American Chemical Society*.) Available: https://www.cas.org/resources/cas-insights/lithium-ion-battery-recycling [Accessed: 21 November, 2024].

Ciacci, L, de Matos, C T, Reck, B K, Wittmer, D, Bernardi, E, Mathieux, F & Passarini, F 2022. Material system analysis: Characterization of flows, stocks, and performance indicators of manganese, nickel, and natural graphite in the EU, 2012–2016. *Journal of Industrial Ecology.* 26, 1247-1260.

Cobalt Institute. 2023. Cobalt Market Report 2022. *Cobalt Institute, data from Benchmark Mineral Intelligence* (Online: *COBALT INSTITUTE*.) Available: https://www.cobaltinstitute.org/wp-content/uploads/2023/05/Cobalt-Market-Report-2022_final.pdf [Accessed: 1 October 2024].

Cobalt Institute. 2024. Cobalt Value Chain Mapping. Available: https://www.cobaltinstitute.org/cobalt-sourcing-responsability/cobalt-value-chain/ [Accessed: 21 November 2024].

Conceição, P, Calderón, C, Pavez Esbry, F G, Moumita, Hsu, Y-C, Ismail, G, Lengfelder, C L, Brian , Mirza, T, Mohammed, R P, Josefin , Kumar Shrestha, S, Tapia, H, Rivera Vázquez, C, Yokoi, Y & Zhang, Y. 2022. Human Development Report 2021/2022. *United Nations Development Programme* (New York, USA: *UNITED NATIONS DEVELOPMENT PROGRAMME*.) Available: https://hdr.undp.org/system/files/documents/global-report-document/hdr2021-22pdf_1.pdf [Accessed: 18 April 2023].

Cowley, A 2024. PGM Market Report May 2024. matthey.com/en/products-and-markets/pgms-and-circularity/pgm-markets/pgm-market-reports.

Cui, R, Guo, J, Yin, L, Huy, D & Liedtke, M. 2016. Supply and demand of lithium and gallium. (China and Germany: *Information Center of Ministry of Land and Resources, China. Federal Institute for Geosciences and Natural Resources, Germany.*), https://www.bgr.bund.de/EN/Themen/Min_rohstoffe/Downloads/studie_Li_Ga.pdf [Accessed: 21 November 2024].

Currie, D & Elliott, H. 2024a. The potential for platinum group elements in the UK. Available: https://nora.nerc.ac.uk/id/eprint/534415/

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

Curwick, L, Petersen, W, DeBarbadillo, J, Forest, S & Suffern, N. 1980. Superalloy scrap-generation and recycling. 21-30 in*: Superalloys 1980.* (United States: *ASM Metals Park.*)

Deady, E, Moon, C, Moore, K, Goodenough, K & Shail, R K 2022. Bismuth: economic geology and value chains. *Ore Geology Reviews.* 143, 104722. Available: https://doi.org/10.1016/j.oregeorev.2022.104722.

Deady, E A, Goodenough, K M, Currie, D, Lacinska, A, Grant, H, Patton, M, Cooper, M, Josso, P, Shaw, R, Everett, P & Bide, T. 2023. Potential for Critical Raw Material Prospectivity in the UK. *British Geological Survey* (Keyworth: *BRITISH GEOLOGICAL SURVEY*.)

Available: https://ukcmic.org/reports/ukcmic-potential-for-critical-raw-material-prospectivity-in-the-uk-cr23024.pdf

Deloitte. 2023. The economic value of government precompetitive geoscience data and analysis for Australia's resources industry. *Prepared by Deloitte Access Economics for Geoscience Australia* (Canberra, Australia: *GEOSCIENCE AUSTRALIA*.) Available: https://d28rz98at9flks.cloudfront.net/148640/148640_00_0.PDF

Department for Energy Security and Net Zero. 2024. Energy Trends: UK renewables. *GOV.UK* (Online: *UK GOVERNMENT*.) Available: https://www.gov.uk/government/statistics/energy-trends-section-6-renewables [Accessed: 16 October 2024].

Department for Environment Food & Rural Affairs. 2024. *UK statistics on waste*. Available: https://www.gov.uk/government/statistics/uk-waste-data/uk-statistics-on-waste [Accessed: 21 November 2024].

Department for Transport, The Rt Hon Richard Holden MP & The Rt Hon Jesse Norman MP. 2023. Government invests £200 million to drive innovation and get more zero emission trucks on our roads. 19 October 2023. (Online: *GOV.UK*.) Available: https://www.gov.uk/government/news/government-invests-200-million-to-drive-innovation-and-get-more-zero-emission-trucks-on-our-roads [Accessed: 16 October 2024].

Depraiter, L & Goutte, S 2023. The role and challenges of rare earths in the energy transition. *Resources Policy.* 86**,** 104137. Available: https://doi.org/10.1016/j.resourpol.2023.104137.

Drexhage, J, La Porta, D, Hund, K, McCormick, M & Ningthoujam, J. 2017. The Growing Role of Minerals and Metals for a Low Carbon Future. *World Bank* (Washington DC, USA: *WORLD BANK*.) Available: https://documents1.worldbank.org/curated/ar/207371500386458722/pdf/117581-WP-P159838-PUBLIC-ClimateSmartMiningJuly.pdf [Accessed: 1 October 2024].

Dupont, D, Arnout, S, Jones, P T & Binnemans, K 2016. Antimony recovery from end-of-life products and industrial process residues: a critical review. *Journal of Sustainable Metallurgy.* 2**,** 79-103.

ECGA. 2022. *Main uses of Carbon and Graphite*. (Online: *European Carbon and Graphite Association (ECGA) data from Wood MacKenzie*.) Available: https://ecga.net/main-uses-of-graphite/ [Accessed: 25 May 2023].

El Bojaddayni, I, Küçük, M E, El Ouardi, Y, Jilal, I, El Barkany, S, Moradi, K, Repo, E, Laatikainen, K & Ouammou, A 2023. A review on synthesis of zeolites from natural clay resources and waste ash: Recent approaches and progress. *Minerals Engineering.* 198**,** 108086.

EuRIC AISBL. 2020. Metal Recycling Factsheet. *EuRIC AISBL – Recycling: Bridging Circular Economy & Climate Policy. Brussels* Available: https://circulareconomy.europa.eu/platform/sites/default/files/euric_metal_recycling_factsheet.pdf [Accessed: 23 July 2024].

EuRIC AISBL. Undated. Metal Recycling Factsheet. *EuRIC AISBL,* (Online: *EURIC AISBL*.) Available: https://circulareconomy.europa.eu/platform/sites/default/files/euric_metal_recycling_factsheet.pdf [Accessed: 23 July 2024].

European Aluminium. 2021. *Risk of Europe-wide shutdowns due to Chinese magnesium supply shortage*. Available: https://european-aluminium.eu/wp-content/uploads/2022/08/2021-09-27-position-paper_impact-of-imminent-short-1.pdf [Accessed: 21 November 2024].

European Commission. 2023. Study on the Critical Raw Materials for the EU 2023 - Final Report. *Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, European Commission* 978-92-68-00414-2. (Brussels, Belgium: *EUROPEAN UNION*.) Available: https://data.europa.eu/doi/10.2873/725585 [Accessed: 14 April 2023].

European Commission. 2024. *Raw Materials Profiles*. (Online: *Raw Materials Information System*.) Available: https://rmis.jrc.ec.europa.eu/rmp/ [Accessed: 4 Novemeber 2024].

European Commission, Directorate-General for Internal Market, I, Entrepreneurship, SMEs, Blengini, G, El Latunussa, C, Eynard, U, Torres De Matos, C, Wittmer, D, Georgitzikis, K, Pavel, C, Carrara, S, Mancini, L, Unguru, M, Blagoeva, D, Mathieux, F & Pennington, D. 2020a. Study on the EU's list of critical raw materials (2020) : final report. *European Commission* (Luxembourg: *EUROPEAN UNION*.) Available: https://data.europa.eu/doi/10.2873/11619 [Accessed: 6 April 2023].

European Commission, Directorate-General for Internal Market, I, Entrepreneurship, SMEs, Blengini, G, El Latunussa, C, Eynard, U, Torres De Matos, C, Wittmer, D, Georgitzikis, K, Pavel, C, Carrara, S, Mancini, L, Unguru, M, Grohol, M, Mathieux, F & Pennington, D. 2020b. Study on the EU's list of critical raw materials (2020): critical raw materials factsheets. *European Commission* (Luxembourg: *EUROPEAN UNION*.) Available: https://doi.org/10.2873/92480 [Accessed: 28 September 2023].

European Commission, C, S.,, Bobba, S, Blagoeva, D, Alves Dias, P, Cavalli, A, Georgitzikis, K, Grohol, M, Itul, A, Kuzov, T, Latunussa, C, Lyons, L, Malano, G, Maury, T, Prior Arce, A, Somers, J, Telsnig, T, Veeh, C, Wittmer, D, Black, C, Pennington, D & Christou, M. 2023. Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study. *European Commission* (Luxembourg: *EUROPEAN UNION*.) Available: https://data.europa.eu/doi/10.2760/386650 [Accessed: 17 August 2023].

European Parliament Briefing. 2024. New EU regulatory framework for batteries: Setting sustainability requirements. *European Parliamentary Research Service* Available: https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/689337/EPRS_BRI(2021)689337_EN.pdf [Accessed: 22 November 2024].

European Union. 2024. Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020 (Text with EEA relevance). *UNION, O J O T E.* (Online: *Official Journal of the European Union.*) Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202401252 [Accessed: 4 November 2024].

Foundary Management & Technology. 2020. *A New Look at Recycling Green Sand Wastes*. (Ohio, United States: *Foundry Management & Technology*.) Available: https://www.foundrymag.com/molds-cores/article/21125856/new-look-at-recycling-green-sand-imerys-high-temperature-solutions?cid=eml-web [Accessed: 21 November 2024].

Godek, S. 2023. Why China's Export Controls on Germanium and Gallium May Not Be Effective. 19 July. (Online: *Stimson Center.*) Available: https://www.stimson.org/2023/why-chinas-export-controls-on-germanium-and-gallium-may-not-be-effective/ [Accessed: 3 October 2024].

Grady, B P 2024a. Sulfur: Long-term outlook for a critical element for surfactant production. *Journal of Surfactants and Detergents.* n/a**,** Available: https://doi.org/10.1002/jsde.12741 [Accessed: 2024/10/22].

Grady, B P 2024b. Sulfur: Long-term outlook for a critical element for surfactant production. *Journal of Surfactants and Detergents.* 27**,** 857-862. Available: https://doi.org/10.1002/jsde.12741 [Accessed: 22 October 2024].

Graedel, T E, Reck, B K & Miatto, A 2022. Alloy information helps prioritize material criticality lists. *Nature Communications.* 13**,** 150. Available: https://doi.org/10.1038/s41467-021-27829-w [Accessed: 29 September 2023].

Griswold, M. 2019. *Driving nickel recovery*. *Recycling Today*.) Available: https://www.recyclingtoday.com/article/driving-nickel-scrap-recovery/#:~:text=Stainless%20steel%20serves%20as%20a,percent%20of%20nickel%20is%20recycled [Accessed: 22 November, 2024].

Gunn, A & Deady, E. 2022a. The potential for nickel in the UK. Available: https://nora.nerc.ac.uk/id/eprint/535662/

Gunn, A & Deady, E. 2022b. The potential for cobalt in the UK. Available: https://nora.nerc.ac.uk/id/eprint/535247/

Harben, P W. 1999. *The industrial minerals handybook : a guide to markets, specifications, & prices.* Edition: 3rd. (London, UK: *Metal Bulletin PLC.*) ISBN: 1900663511; 9781900663519.

Harben, P W. 2002. Pumice and Scoria. 274-276 in*: The Industrial Minerals HandyBook.* Edition: 4th. (London, United Kingdom: *Industrial Minerals Information.*) ISBN: 1-904333-04-4.

Harrison, D, Highley, D, Bloodworth, A & Bate, R. 2006. Mineral planning factsheet: limestone. *British Geological Survey. (Mineral Planning Factsheet) (Unpublished)* Available: https://nora.nerc.ac.uk/id/eprint/534436/ [Accessed: 22 November 2024].

Helvacı, C 2017. Borate deposits: An overview and future forecast with regard to mineral deposits. *Journal of Boron.* 2**,** 59-70.

Herrero de Egaña, A, Vivancos, J & García-Cortés, Á 2020. Impact analysis and update to 2018 of the economic and social value of the MAGNA Plan (geological mapping at 1:50,000 scale). *Boletín Geológico y Minero.* 131**,** 817-829. https://bgm.revistas.csic.es/index.php/bgm/article/view/106 [Accessed: 1 October 2024].

Hida, T & Kitagawa, R. 2006. Pyrophyllite. 755-767 in*: Industrial Minerals and Rocks: Commodities, Markets and Uses.* Edition: 7th. (USA: *Society for Mining, Metallurgy, and Exploration, Inc.*) ISBN: 0873352491.

Highley, D B, Andrew; Bate, Richard 2006. Mineral planning factsheet : gypsum. *British Geological Survey.* 7. https://nora.nerc.ac.uk/id/eprint/534434 [Accessed: 22 November 2024].

HM Goverment. 2024. Invest 2035: the UK's modern industrial strategy. (London, United Kingdom: Available: https://www.gov.uk/government/consultations/invest-2035-the-uks-modern-industrial-strategy

HM Revenue & Customs. 2024. Overseas trade data. (Online: *UK Trade Info.*) Available: https://www.uktradeinfo.com/trade-data/ots-custom-table/ [Accessed: 1 April 2024].

Home, A. 2024. China fires latest warning signal with antimony controls. *Reuters*. Commodities. Available: https://www.reuters.com/markets/commodities/china-fires-latest-warning-signal-with-antimony-controls-2024-08-28 [Accessed: 2024-08-28T23:01:00Z].

Hsu, J. 2024. Will semiconductor production be derailed by Hurricane Helene? *New Scientist*. Available: https://www.newscientist.com/article/2450715-will-semiconductor-production-be-derailed-by-hurricane-helene/ [Accessed: 4 October 2024].

Idoine, N, Raycraft, E, Hobbs, S, Everett, P, Evans, E, Mills, A, Currie, D, Horn, S & Shaw, R. 2024. World mineral production 2018-2022. *British Geological Survey* (Keyworth: *BRITISH GEOLOGICAL SURVEY.*) Available: https://nora.nerc.ac.uk/id/eprint/537241/

IMA Europe. 2023. Recycling of industrial mineral applications Contribution to circular economy. *IMA-Europe AISBL, Twin Gardens, Belgium* Available: https://ima-europe.eu/wp-content/uploads/2023/08/IMA-Europe-Recycling-IM-2023-08-30-a-FINAL.pdf [Accessed: 21 November 2024].

International Aluminium. 2024. *International Aluminium Institute publishes global recycling data*. (London, UK: *International Aluminium Institute (IAI)*.) Available: https://international-aluminium.org/international-aluminium-institute-publishes-global-recycling-data/ [Accessed: 21 November 2024].

International Antimony Association. 2024. *Antimony*. (Brussels, Belgium: *International Antimony Association*.) Available: https://www.antimony.com/antimony-2/ [Accessed: 21 July 2024].

International Cadmium Association. 2024a. *Nickel-cadmium batteries are virtually 100% recyclable once they have been collected.* (Brussels: *The International Cadmium Association*.) Available: https://cadmium.ionainteractive.com/recycling/ [Accessed: 21 November 2024].

International Cadmium Association. 2024b. *Application. World cadmium applications (2019)*. (Brussels: *The International Cadmium Association*.) Available: https://www.cadmium.org/ [Accessed: 21 November 2024].

International Chromium Development Association. 2024. *Applications. Chrome: a critical ingredient.* (Paris, France: *International Chromium Development Association*.) Available: https://www.icdacr.com/applications [Accessed: 21 November 2024].

International Copper Association. 2022. Copper Recycling. *International Copper Association,* (Online: *INTERNATIONAL COPPER ASSOCIATION*.) Available: https://internationalcopper.org/wp-content/uploads/2022/02/ICA-RecyclingBrief-202201-A4-R2.pdf [Accessed: 23 July 2024].

International Energy Agency. 2018. Global EV Outlook 2018 - Towards cross-modal electrification. *International Energy Agency (IEA)* (Online: *IEA*.) Available: https://www.iea.org/reports/global-ev-outlook-2018 [Accessed: 17 January 2023].

International Energy Agency. 2021. *End-of-life recycling rates for selected metals*. (Paris, France: *International Energy Agency*.) Available: https://www.iea.org/data-and-statistics/charts/end-of-life-recycling-rates-for-selected-metals [Accessed: 22 November 2024].

International Energy Agency. 2022. Global Battery Supply Chains of EV batteries. *International Energy Agency (IEA)* (Online: *IEA*.) Available: https://iea.blob.core.windows.net/assets/4eb8c252-76b1-4710-8f5e-867e751c8dda/GlobalSupplyChainsofEVBatteries.pdf [Accessed: 25 January 2024].

International Energy Agency. 2024a. World Energy Outlook 2024. *International Energy Agency (IEA)* (Paris: *IEA*.) Available: https://www.iea.org/reports/world-energy-outlook-2024 [Accessed: 16 October 2024].

International Energy Agency. 2024b. Global EV Outlook 2024 - Moving towards increased affordability. *International Energy Agency (IEA)* (Paris: *IEA*.) Available: https://www.iea.org/reports/global-ev-outlook-2024 [Accessed: 16 October 2024].

International Energy Agency. 2024c. *Announcement on the Implementation of Export Control of Items Related to Gallium and Germanium*. Available: https://www.iea.org/policies/17893-announcement-on-the-implementation-of-export-control-of-items-related-to-gallium-and-germanium

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

International Lead & Zinc Study Group. 2023a. *What Is Zinc*. (Lisbon, Portugal: *International Lead & Zinc Study Group*.) Available: https://www.ilzsg.org/what-is-zinc/ [Accessed: 22 November 2024].

International Lead & Zinc Study Group. 2023b. *What Is Lead*. (Lisbon, Portugal: *International Lead and Zinc Study Group*.) Available: https://www.ilzsg.org/what-is-lead/ [Accessed: 21 November 2024].

International Lead Association. 2024. *Using lead responsibly is critical to achieving a sustainable and low carbon future*. (London, UK: *International Lead Association*.) Available: https://ila-lead.org/sustainability/ [Accessed: 21 November 2024].

International Magnesium Association. 2024. *Recycling Magnesium*. (Minneapolis, USA: *International Magnesium Association (IMA)*.) Available: https://www.intlmag.org/page/sustain_recycle_ima

International Molybdenum Association. 2015. A sustainable world with Molybdenum. *International Molybdenum Association (IMOA), London, UK* Available: https://www.imoa.info/download_files/sustainability/Sustainability-brochure-2015.pdf [Accessed: 22 November 2024].

International Molybdenum Association. 2024. *Uses of new Molybdenum*. (London, UK: *International Molybdenum Association*.) Available: https://www.imoa.info/molybdenum-uses/molybdenum-uses.php [Accessed: 22 November 2024].

International Tin Association. 2020. *Tin Recycling*. (Unit 3, Curo Park, Frogmore, St. Albans, Hertfordshire, AL2 2DD, UK: *International Tin Association*.) Available: https://www.internationaltin.org/recycling/ [Accessed: 22 November, 2024].

International Tin Association. 2021. *ITA Study – Tin surfed the pandemic wave*. (Unit 3, Curo Park, Frogmore, St. Albans, Hertfordshire, AL2 2DD, UK: *International Tin Association*.) Available: https://www.internationaltin.org/ita-study-tin-surfed-the-pandemic-wave/ [Accessed: 22 November, 2024].

International Trade Centre. 2024. Trade Map. (Online: *International Trade Centre*.) Available: https://www.trademap.org/Index.aspx [Accessed: 1 April 2024].

International Tungsten Industry Association. 2024. *Applications & Markets*. *The International Tungsten Industry Association (ITIA)*.) Available: https://www.itia.info/applications-markets/ [Accessed: 22 November, 2024].

Jackson, R, Kemp, D, Rahman, A, Turner, T, Cave, S & Wildblood, R. 2024a. Study on future material requirements of the national grid infrastructures to reach Net-Zero. *British Geological Survey via Decision Analysis Services Ltd* (Keyworth, UK: *BRITISH GEOLOGICAL SURVEY*.)

Jackson, R, Kemp, D, Rahman, A, Wilcox, M, Cave, S & Wildblood, R. 2024b. A UK foresight study of materials in decarbonisation technologies: the case of nuclear. *British Geological Survey via Decision Analysis Services Ltd* (Keyworth, UK: *BRITISH GEOLOGICAL SURVEY*.)

Jia, H, Zhou, Y, Wang, A, Wang, G, Li, T, Wang, C, Xing, W, Ma, Z & Li, P 2022. Evolution of the anthropogenic gallium cycle in China from 2005 to 2020. *Frontiers in Energy Research.* 10**,** 944617.

Johnson Matthey plc. 2024a. PGM Market report May 2024 (Excel file). (London, UK: *Johnson Matthey*.), https://matthey.com/en/products-and-markets/pgms-and-circularity/pgm-markets/pgm-market-reports [Accessed: 21 November 2024].

Johnson Matthey Plc. 2024b. *PGMs and circularity*. (Online: *Johnson Matthey Plc*.) Available: https://matthey.com/products-and-markets/pgms-and-circularity [Accessed: 28 October 2024].

Josso, P & Lusty, P. 2023. The potential for manganese in the UK. Available: https://nora.nerc.ac.uk/id/eprint/536560/

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

Kavlak, G & Graedel, T 2013. Global anthropogenic selenium cycles for 1940–2010. *Resources, Conservation and Recycling.* 73**,** 17-22.

Kumar, A, Thorbole, A & Gupta, R K 2025. Sustaining the future: Semiconductor materials and their recovery. *Materials Science in Semiconductor Processing.* 185**,** 108943. Available: https://doi.org/10.1016/j.mssp.2024.108943.

Kuzma, S, Saccoccia, L & Chertock, M. 2023. 25 Countries, Housing One-Quarter of the Population, Face Extremely High Water Stress. 16 August 2023. *World Resources Institute*.) Available: https://www.wri.org/insights/highest-water-stressed-countries

Leblanc, M & Billaud, P 1982. Cobalt Arsenide Orebodies Related to an Upper Proterozoic Ophiolite: Bou Azzer (Morocco). *Economic Geology.* 77**,** 162–175. Available: 10.2113/gsecongeo.77.1.162.

Lederer, G W, Foley, N K, Jaskula, B W & Ayuso, R A. 2016. Beryllium – A Critical Mineral Commodity – Resources, Production, and Supply Chain (Fact Sheet). *Mineral Resources Program, U.S. Geological Survey* (Reston, VA, USA:

Liang, A & Marsh, N. 2023. Gallium and germanium: What China's new move in microchip war means for world. *BBC News*. Business. (Online: *British Broadcasting Corporation (BBC).*) Available: https://www.bbc.co.uk/news/business-66118831 [Accessed: 2 August].

Lokanc, M, Eggert, R & M, R. 2015a. The availability of indium: the present, medium term, and long term. *National Renewable Energy Laboratory (NREL)* (Colorado, United States: *NREL*.) Available: https://www.nrel.gov/docs/fy16osti/62409.pdf [Accessed: 25/05/2023].

Lokanc, M, Eggert, R & Redlinger, M. 2015b. The availability of indium: the present, medium term, and long term. *National Renewable Energy Lab (NREL)* (Colorado, USA: *COLORADO SCHOOL OF MINES*.) Available: https://www.nrel.gov/docs/fy16osti/62409.pdf [Accessed: 1 October 2024].

Lunardi, M M, Alvarez-Gaitan, J P, Bilbao, J I & Corkish, R 2018. A review of recycling processes for photovoltaic modules. *Solar Panels and Photovoltaic Materials.* 30.

Lunk, H-J 2015. Discovery, properties and applications of chromium and its compounds. *ChemTexts.* 1**,** 6.

Lusty, P & Goodenough, K M. 2022. The potential for graphite in the UK. Available: https://nora.nerc.ac.uk/id/eprint/535252/

Lusty, P A J, Shaw, R A, Gunn, A G & Idoine, N E. 2021. UK criticality assessment of technology critical minerals and metals. *British Geological Survey,* CR/21/120. (Keyworth, UK: *BRITISH GEOLOGICAL SURVEY*.) Available: https://www.bgs.ac.uk/download/uk-criticality-assessment-of-technology-critical-minerals-and-metals/ [Accessed: 15 March 2023].

Lv, A, Liu, S, Nguyen, M, Devitt, P, Munroe, T & Lewis, B. 2024. Explainer: What is antimony and why is China curbing its exports? *Reuters*. 16 August 2024. (Online: *Reuters.*) Available: https://www.reuters.com/markets/commodities/what-is-antimony-why-is-china-curbing-its-exports-2024-08-16/ [Accessed: 1 October 2024].

Lv, A & Patton, D. 2023. China export curbs choke off shipments of gallium, germanium for second month. *Reuters*. 20 October 2023. (Online: *Reuters.*) Available: https://www.reuters.com/world/china/china-export-curbs-choke-off-shipments-gallium-germanium-second-month-2023-10-20 [Accessed: 1 October 2024].

Mancheri, N A 2015. World trade in rare earths, Chinese export restrictions, and implications. *Resources Policy.* 46**,** 262-271. Available: 10.1016/j.resourpol.2015.10.009 [Accessed: 2024-10-01 08:50:54].

Mancheri, N A, Sprecher, B, Bailey, G, Ge, J & Tukker, A 2019. Effect of Chinese policies on rare earth supply chain resilience. *Resources, Conservation and Recycling.* 142**,** 101-112. Available: 10.1016/j.resconrec.2018.11.017 [Accessed: 1 October 2024].

Marjolein de Ridder, S d J, Joshua Polchar, and Stephanie Lingemann,. 2012. Risks and Opportunities in the Global Phosphate Rock Market. *The Hague Centre for Strategic Studies (HCSS)* Available:

https://www.phosphorusplatform.eu/images/download/HCSS_17_12_12_Phosphate.pdf [Accessed: 22 November 2024].

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

Maslin, M, Van Heerde, L & Day, S 2022. Sulfur: A potential resource crisis that could stifle green technology and threaten food security as the world decarbonises. *The Geographical Journal.* 188**,** 498-505. Available: https://doi.org/10.1111/geoj.12475 [Accessed: 01 November 2024].

McNulty, B A, Jowitt, S M & Belousov, I 2022. The importance of geology in assessing by- and coproduct metal supply potential; a case study of antimony, bismuth, selenium, and tellurium within the copper production stream. *Economic Geology.* 117**,** 1367-1385. Available: https://doi.org/10.5382/econgeo.4919 [Accessed: 19 September 2023].

Merriman, D. 2023a. *Rare Earths: Explaining historical volatility and remaining uncertainty in the market*.

Merriman, D. 2023b. *Rare Earths: Explaining historical volatility and remaining uncertainty in the market*. Available: https://projectblue.com/blue/news-analysis/439/rare-earth:-explaining-historical-volatility-and-remaining-uncertainty-in-the-market- [Accessed: 1 October 2024].

Merriman, D. 2024. China announces new controls on rare earth resources and traceability. 2 July 2024. (Online: *Project Blue.*) Available: https://projectblue.com/blue/news-analysis/937/china-announces-new-controls-on-rare-earth-resources-and-traceability- [Accessed: 1 October 2024].

Millensifer, T A, Sinclair, D, Jonasson, I & Lipmann, A. 2014. Rhenium. 340-360 in*: Critical metals handbook.* (UK: *John Wiley & Sons, Ltd.*) ISBN: 9780470671719.

Morris, S. 2023. Viewpoint: Full impact of Ga, Ge controls yet to come. *Argus Media*. 20 December 2023. (Online: *Argus Metals.*) Available: https://metals.argusmedia.com/newsandanalysis/article/2521021?keywords=Viewpoint%3A%20Full%20impact%20of%20Ga%2C%20Ge%20controls%20yet%20to%20come&returnParams= [Accessed: 2 October 2024].

MSP-REFRAM. 2020. Towards a strong and sustainable european refractory metals supply-chain. *Multi-Stakeholder Platform for a Secure Supply of Refractory Metals in Europe* (Online: *PROMETIA*.) Available: https://prometia.eu/wp-content/uploads/2021/01/MSP-REFRAM-FINAL-REPORT-WEB.pdf [Accessed: 29 September 2023].

MSP-REFRAM. 2021. Niobium and Tantalum. *Multi-Stakeholder Platform for a Secure Supply of Refractory Metals in Europe* (Online: *PROMETIA*.) Available: https://prometia.eu/wp-content/uploads/2021/01/NIOBIUM-TANTALUM-v02.pdf [Accessed: 25 May 2023].

Mudd, G M. 2023. Platinum Group Elements: Critical Resources for Sustainable Technology. Chapter 5, pages 68-86 in*: Critical Minerals and Sustainability Transition.* (Boca Raton, Florida, USA: *CRC Press, Taylor & Francis Group.*)

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

Mudd, G M & Jowitt, S M 2018b. Global Resource Assessments of Primary Metals: An Optimistic Reality Check. *Natural Resources Research.* 27, pp 229-240. Available: doi: 10.1007/s11053-017-9349-0.

Mudd, G M & Jowitt, S M 2022. The New Century for Nickel Resources, Reserves, and Mining: Reassessing the Sustainability of the Devil's Metal. *Economic Geology.* 117, 1961-1983. Available: https://doi.org/10.5382/econgeo.4950 [Accessed: 22 August 2023].

Mudd, G M, Jowitt, S M & Werner, T T 2017. The world's lead-zinc mineral resources: scarcity, data, issues and opportunities. *Ore Geology Reviews.* 80, 1160-1190. Available: https://doi.org/10.1016/j.oregeorev.2016.08.010.

Mudd, G M, Weng, Z, Jowitt, S M, Turnbull, I D & Graedel, T E 2013. Quantifying the recoverable resources of by-product metals: The case of cobalt. *Ore Geology Reviews.* 55, 87-98. Available: https://doi.org/10.1016/j.oregeorev.2013.04.010.

Nair, N A & Sairam, V 2021. Research initiatives on the influence of wollastonite in cement-based construction material-A review. *Journal of Cleaner Production.* 283, 124665.

Nassar, N T, Graedel, T E & Harper, E M 2015. By-product metals are technologically essential but have problematic supply. *Science Advances.* 1, e1400180. Available: https://doi.org/10.1126/sciadv.1400180 [Accessed: 5 April 2023].

National Grid. 2023a. Future Energy Scenarios 2023 - July 2023. *National Grid* (Online: *NATIONAL GRID*.) Available: www.nationalgrideso.com/future-energy/future-energy-scenarios [Accessed: 17 October 2024].

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

Natural Resources Canada. 2022. The Canadian critical minerals strategy - from exploration to recycling: powering the green and digital economy for Canada and the world. (Ottawa, Canada:

Natural Resources Canada. 2023. *Rare earth elements facts*. (Online: *Natural Resources Canada*.) Available: https://natural-resources.canada.ca/our-natural-resources/minerals-mining/minerals-metals-facts/rare-earth-elements-facts/20522 [Accessed: 14 February 2023].

Nickel Institute. 2021. *About Nickel*. (Online: *Nickel Institute, data from Wood MacKenzie*.) Available: https://nickelinstitute.org/en/about-nickel-and-its-applications/ [Accessed: 25 May 2023].

Norsk Hydro. 2021. Annual report 2020. *Norsk Hydro ASA. Oslo, Norway* Available: https://www.hydro.com/globalassets/download-center/investor-downloads/ar20/annual-report-2020-new.pdf [Accessed: 18 July 2024].

Northey, S A, Mudd, G M, Werner, T T, Jowitt, S M, Haque, N, Yellishetty, M & Weng, Z 2017. The Exposure of Global Base Metal Resources to Water Criticality, Scarcity and Climate Change. *Global Environmental Change.* 44, pp 109-124.

Nuclear Energy Agency, Organisation for Economic Co-operation and Development & International Atomic Energy Agency. 2022. Uranium 2022: Resources, Production and Demand. *Nuclear Energy Agency, Organisation for Economic Co-operation and Development (NEA) and International Atomic Energy Agency (IAEA)* (Paris, France: *MEA AND IAEA*.) Available: www.nea.fr

O'Driscoll, M. 2024. *Squaring the Circle: Challenges & opportunities in recycling refractory minerals*. *IMFORMED Industrial Mineral Forums & Research Ltd*.) Available: https://imformed.com/squaring-the-circle-challenges-opportunities-in-recycling-refractory-minerals/#:~:text=About%20250%2C000%20tpa%20of%20spent,over%20the%20next%202%20years [Accessed: 22 November, 2024].

Office for National Statistics. 2007. *UK Standard Industrial Classification of Economic Activities 2007 (SIC 2007) - Structure and explanatory notes.* (Houndmills: *Palgrave Macmillan*.) ISBN: 978-0-230-21012-7.

Office for National Statistics. 2023. *UK Manufacturers' Sales by Product (PRODCOM) UK Statistics Authority*. (Online: *Office for National Statistics (ONS)*.) Available: https://www.ons.gov.uk/surveys/informationforbusinesses/businesssurveys/ukmanufacturerssalesbyproductprodcom [Accessed: 6 April 2024].

Office for National Statistics. 2024. Annual Business Survey, 2022 results. (On request: *Office for National Statistics*.)

Oliveira, M L S, Ward, C R, Izquierdo, M, Sampaio, C H, de Brum, I A S, Kautzmann, R M, Sabedot, S, Querol, X & Silva, L F O 2012. Chemical composition and minerals in pyrite ash of an abandoned sulphuric acid production plant. *Science of The Total Environment.* 430**,** 34-47. Available: https://doi.org/10.1016/j.scitotenv.2012.04.046.

Organisation for Economic Co-operation and Development. 2010. The Economic Impact of Export Restrictions on Raw Materials. *Organisation for Economic Co-operation and Development (OECD)* (Paris: *OECD PUBLICATIONS*.) Available: https://www.oecd.org/content/dam/oecd/en/publications/reports/2010/11/the-economic-impact-of-export-restrictions-on-raw-materials_g1g11e10/9789264096448-en.pdf [Accessed: 29 October 2024].

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

Pan, S, Cefai, S & Zhang, N. 22 July 2024. Markets largely adjusted to China's germanium, gallium, graphite export controls one year on. Available: https://www.fastmarkets.com/insights/markets-largely-adjusted-to-chinas-germanium-gallium-graphite-export-controls-one-year-on/ [Accessed: 11 October 2024].

Patel, M & Karamalidis, A K 2021. Germanium: A review of its US demand, uses, resources, chemistry, and separation technologies. *Separation and Purification Technology.* 275**,** 118981.

Persistence Market Research. 2017. *Sodium Metal Market*. *Persistence Market Research*.) Available: https://www.persistencemarketresearch.com/market-research/sodium-metal-market.asp [Accessed: 22 November, 2024].

Petavratzi, E, Horn, S, Shaw, R & Josso, P. 2024a. A UK foresight study of materials in decarbonisation technologies. *British Geological Survey* OR/24/005. (Keyworth, UK: *BRITISH GEOLOGICAL SURVEY*.)

Petavratzi, E, Josso, P, Shaw, R, Horn, S, Hsu, W-T & Singh, N. 2024b. A UK foresight study of materials in decarbonisation technologies: the case of traction motors. *British Geological Survey* CR/24/008N. (Keyworth, UK: *BRITISH GEOLOGICAL SURVEY*.)

Petavratzi, E, Josso, P, Shaw, R, Horn, S, Hsu, W-T & Singh, N. 2024c. A UK foresight study of materials in decarbonisation technologies: the case of wind turbines. *British Geological Survey* CR/24/009N. (Keyworth, UK: *BRITISH GEOLOGICAL SURVEY*.)

Petavratzi, E, Josso, P, Shaw, R, Horn, S & Singh, N. 2024d. A UK foresight study of materials in decarbonisation technologies: the case of batteries. *British Geological Survey* CR/24/007N. (Keyworth, UK: *BRITISH GEOLOGICAL SURVEY*.)

Petavratzi, E, Josso, P, Shaw, R, Horn, S & Singh, N. 2024e. A UK foresight study of materials in decarbonisation technologies: the case of photovoltaic cells. *British Geological Survey* CR/24/006N. (Keyworth, UK: *BRITISH GEOLOGICAL SURVEY*.)

Presley, G C. 2006. Pumice, Pumicite, and Volcanic Cinder. 743-753 in*: Industrial Minerals & Rocks: commodities, markets, and uses.* Edition: 7th. (Littleton, Colorado, United States of America: *Society for Mining, Metallurgy, and Exploration Incorporated.*) ISBN: 0-87335-233-5.

Pronk, K. 2024. Germanium prices shoot for the moon. 8 October 2024. (Online: *Project Blue.*) Available: https://projectblue.com/blue/news-analysis/1038/germanium-prices-shoot-for-the-moon [Accessed: 14 October 2024].

PwC. 2024. Climate risks to nine key commodities: protecting people and prosperity. *PwC* (London, UK: *PWC*.) Available: https://www.pwc.com/gx/en/issues/esg/how-does-climate-change-affect-natural-resources.html [Accessed: 14 October 2024].

Rainsford, D R B 2019. Pre-competitive geophysics in Ontario – attracting investment with data. *CSEG Recorder*. June 2019**,** 14 pages. https://cseg.ca/wp-content/uploads/2019-06-RECORDER-Pre-competitive_geophysics_in_Ontario.pdf.

Rajagopal, U. 2021. *Research ReportsGlobal Consumption of Sodium Metal is Projected to Surpass 127,400 Metric Tonnes by 2024-End*. *Global Banking & Finance Review*.) Available: https://www.globalbankingandfinance.com/global-consumption-of-sodium-metal-is-projected-to-surpass-127400-metric-tonnes-by-2024-end/ [Accessed: 22 November, 2024].

Real Diamond Invest. 2024. *The diamond market*. (Online: *Real Diamond Invest*.) Available: https://www.realdiamondinvest.it/en/the-diamond-market/ [Accessed: 4 November 2024].

Recyclinginside. 2020. *Gold Refining*. (Istanbul, Turkey: *PROSES MAKİNA*.) Available: https://recyclinginside.com/e-waste-recycling/gold-refining/ [Accessed: 21 November 2024].

Reuters. 2024a. CMOC to double copper output at Congo mines to 1 million tonnes by 2028. 10 July 2024. (Online: *Mining.com.*) Available: https://www.mining.com/web/cmoc-to-double-copper-output-at-congo-mines-to-1-million-tons-by-2028/

Reuters. 2024b. Zambia's copper output may rise to 1 mln tons by 2026 as mines expand. 5 April 2024. (Lusaka: *Reuters.*) Available: https://www.reuters.com/world/africa/zambiascopper-output-may-rise-1-mln-tons-by-2026-mines-expand-2024-04-05/ [Accessed: 05 November 2024].

Rodby, K E, Jaffe, R L, Olivetti, E A & Brushett, F R 2023. Materials availability and supply chain considerations for vanadium in grid-scale redox flow batteries. *Journal of Power Sources.* 560**,** 232605. Available: https://doi.org/10.1016/j.jpowsour.2022.232605.

S&P Global. 2023. *Sodium Chloride*. *S&P Global Inc.*) Available: https://www.spglobal.com/commodityinsights/en/ci/products/sodium-chloride-chemical-economics-handbook.html [Accessed: 22 November, 2024].

Sadden, E. 2024. *INTERVIEW: China antimony export restrictions exacerbate global supply fears: USAC*.

Schrijvers, D, Hool, A, Blengini, G A, Chen, W-Q, Dewulf, J, Eggert, R, van Ellen, L, Gauss, R, Goddin, J & Habib, K 2020. A review of methods and data to determine raw material criticality. *Resources, conservation and recycling.* 155**,** 104617. Available: https://doi.org/10.1016/j.resconrec.2019.104617 [Accessed: 5 April 2023].

Schwarz-Schampera, U. 2014a. Indium. 204-229 in*: Critical Metals Handbook.* Edition: 1st. (UK: *John Wiley & Sons, Ltd.*) ISBN: 9781118755341.

Schwarz-Schampera, U. 2014b. Antimony. pp 70-98 in*: Critical Metals Handbook. John Wiley & Sons.*)

SCRREEN. 2023a. SCRREEN2 - Sulphur. *European Union Horizon 2020 Programme* (Online: *EUROPEAN UNION HORIZON 2020 PROGRAMME*.) Available: https://scrreen.eu/crms-2023/ [Accessed: 22 November 2024].

SCRREEN. 2023b. SCRREEN2 - Baryte. *European Union Horizon 2020 Programme* (Online: *EUROPEAN UNION HORIZON 2020 PROGRAMME*.) Available: https://scrreen.eu/crms-2023/ [Accessed: 22 November 2024].

SCRREEN. 2023c. SCRREEN2 - Bentonite. *European Union Horizon 2020 Programme* (Online: *EUROPEAN UNION HORIZON 2020 PROGRAMME*.) Available: https://scrreen.eu/crms-2023/ [Accessed: 22 November 2024].

SCRREEN. 2023d. *CRMS 2023*. (Online: *SCRREEN*.) Available: https://scrreen.eu/crms-2023/ [Accessed: 6 April 2023].

Shaw, R. 2022. The potential for lithium in the UK. Available: https://nora.nerc.ac.uk/id/eprint/535661/

Simionescu, R. 2024. *New Liquid Helium Recycling System Offers Sustainable Research*. (Canada: *Brock University*.) Available: https://brocku.ca/mathematics-science/chemistry/2024/01/26/new-liquid-helium-recycling-system-offers-sustainable-research/ [Accessed: 21 November 2024].

Singh, N, Lusty, P & Josso, P. 2023. Scoping study on metals used in specailist alloys in the aerospace industry. *British Geological Survey* OR/23/016. (Keyworth, UK: *BRITISH GEOLOGICAL SURVEY*.) [Accessed: 4 November 2024].

Smulian, M. 2022. *UK labelled Europe's glass recycling 'laggard'*. (London, UK: *Materials recycling World*.) Available: https://www.mrw.co.uk/news/uk-labelled-europes-glass-recycling-laggard-01-09-2022/ [Accessed: 21 November 2024].

SPECFINISH. 2016. *Plasterboard recycling reaches 45.9%*. (Solihull, UK: *Finishes and Interiors Sector Ltd.*) Available: https://www.specfinish.co.uk/8924-2/ [Accessed: 21 November 2024].

SRP Minerals. 2024. *Bentonite*. (Gujarat, India: *SRP Minerals*.) Available: https://srpminerals.com/service/bentonite-powder/ [Accessed: 21 November 2024].

Stanford Advanced Materials. 2024. *The Performance and Application of Hafnium*. (United States: *Stanford Advanced Materials*.) Available: https://www.samaterials.com/content/the-performance-and-application-of-hafnium.html [Accessed: 21 November 2024].

Stiftner, R, Weber, L & Rechberger, H 2024. Methodology for a Better Estimation of the Reserves and Resources of Minor Metals Exemplified by Selenium in Different Copper Deposit Types. *Mineral Economics.* 37**,** 413-432. Available: 10.1007/s13563-023-00384-0.

Stormcrow. 2015. Rare earth oxides base prices 2009-2013. Price data (Online: *Statista*.) Available: https://www.statista.com/statistics/449834/average-rare-earth-oxide-prices-globally/ [Accessed: 21 October 2024].

Sun, X, Hao, H, Liu, Z & Zhao, F 2020. Insights into the global flow pattern of manganese. *Resources Policy*. 65**,** 101578. Available: https://doi.org/10.1016/j.resourpol.2019.101578 [Accessed: 10 July 2023].

Sweet, P C, Dixon, G B & Snoddy, J R. 2006. Kayanite, Andalusite, Sillimanite, and Mullite. 553-560 in*: Industrial Minerals and Rocks: Commodities, Markets and Uses.* Edition: 7th edititition. *Society for Mining, Metallurgy, and Exploration, Inc.*)

The Barytes association. 2024. *What is Barytes? - Uses of Barytes*. (Brussels, Belgium: *The Barytes association*.) Available: https://www.barytes.org/uses [Accessed: 21 November 2024].

The Observatory of Economic Complexity. 2024. *The Observatory of Economic Complexity*. (Online: *The Observatory of Economic Complexity*.) Available: https://oec.world/en [Accessed: 1 April 2024].

The Silver Institute. 2024. *Silver supply & demand*. (Washington, USA: *Silver Institute's World Silver Survey 2024.*) Available: https://silverinstitute.org/silver-supply-demand/ [Accessed: 22 November 2024].

The Silver Institute. various. World Silver Survey, Years 2014 to 2024. *The Silver Institute (TSI)* (Washington DC, USA: Available: www.silverinstitute.org/all-world-silver-surveys/

The White House. 2022. Inflation Reduction Act Guidebook | Clean Energy. *THE WHITE HOUSE.* Available: https://www.whitehouse.gov/cleanenergy/inflation-reduction-act-guidebook/ [Accessed: 30 October 2024].

Trueman, D L & Sabey, P. 2014. Beryllium. 99-121 in*: Critical Metals Handbook.* (Oxford: *John Wiley & Sons.*)

Tyrer, M & Sykes, J P 2013. The statistics of the rare earths industry. *Significance.* 10**,** 12-16. Available: 10.1111/j.1740-9713.2013.00645.x [Accessed: 21 October 2024].

U.S. Department of Energy. 2023. Notice of Final Determination on 2023 DOE Critical Materials List. *U.S. Department of Energy (USDoE)* (Washington D.C., USA: Available:

https://www.federalregister.gov/documents/2023/08/04/2023-16611/notice-of-final-determination-on-2023-doe-critical-materials-list [Accessed: 23 November 2024].

U.S. Geological Survey. 2012. Mineral commodity summaries 2012. *U.S. Geological Survey, Reston, Virginia* Available: https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/mineral-pubs/mcs/mcs2012.pdf [Accessed: 21 November 2024].

U.S. Geological Survey. 2017. Mineral commodity summaries 2017. *U.S. Geological Survey, Reston, Virginia: 2017* Available: https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/mineral-pubs/mcs/mcs2017.pdf [Accessed: 22 November 2024].

U.S. Geological Survey. 2020. Mineral commodity summaries 2020. *U.S. Geological Survey (USGS)* (Reston, USA: *USGS*.) Available: https://doi.org/10.3133/mcs2020 [Accessed: 26 May 2023].

U.S. Geological Survey. 2022a. Mineral Commodity Summaries 2022 - Pumice and Pumicite. *U.S. Geological Survey 2020 Reston, USA: USGS* Available: https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-pumice.pdf [Accessed: 22 November 2024].

U.S. Geological Survey. 22 February 2022b. U.S. Geological Survey Releases 2022 List of Critical Minerals. Available: https://www.usgs.gov/news/national-news-release/us-geological-survey-releases-2022-list-critical-minerals [Accessed: 17 April 2023].

U.S. Geological Survey. 2022c. Antimony. *United States Geological Survey (USGS)* (Reston, USA: *USGS*.) Available: https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-antimony.pdf [Accessed: 05 June 2023].

U.S. Geological Survey. 2023a. Germanium. *United States Geological Survey Reston, USA: USGS* Available: https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-germanium.pdf [Accessed: 21 November 2024].

U.S. Geological Survey. 2023b. Diatomite. *U.S. Geological Survey Reston, USA: USGS* Available: https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-diatomite.pdf [Accessed: 21 November 2024].

U.S. Geological Survey. 2024a. Minerals Yearbook - Metals and Minerals. *National Minerals Information Center* 2024. (Reston, VA: *U. S. GEOLOGICAL SURVEY*.) Available: https://www.usgs.gov/centers/national-minerals-information-center/minerals-yearbook-metals-and-minerals

U.S. Geological Survey. 2024b. Mineral commodity summaries 2024. *U. S. Geological Survey (USGS)* 2024. (Reston, VA: *USGS*.) Available: https://pubs.usgs.gov/publication/mcs2024

UK Government. 2024. Policy statement on onshore wind. (Online: *GOV.UK*.) Available: https://www.gov.uk/government/publications/policy-statement-on-onshore-wind/policy-statement-on-onshore-wind [Accessed: 21 October 2024].

UK Steel. 2024. Key statistics guide may 2024. *UK Steel* (Online: *UK STEEL*.) Available: https://www.uksteel.org/reports-and-publications [Accessed: 28 October 2024].

United Kingdom Quality Ash Association. 2024. *UK Quality Ash Association - About Us*. (Online: *United Kingdom Quality Ash Association*.) Available: https://www.ukqaa.org.uk/about/ [Accessed: 22 October 2024].

United Nations Department of Economic and Social Affairs. 2024. UN Comtrade Database. (Online: *United Nations,*.) Available: https://comtradeplus.un.org/ [Accessed: 1 April 2024].

United Nations Development Programme. 2024. Human Development Index (HDI). (Online: *United Nations*.), https://hdr.undp.org/data-center/human-development-index#/indicies/HDI [Accessed: 15 April 2024].

United Nations Environment Programme. 2017. Global Mercury Supply, Trade and Demand. *Chemicals and Health Branch,United Nations Environment Programme* (Geneva, Switzerland: Available: www.unep.org/resources/report/global-mercury-supply-trade-and-demand

United Nations Environment Programme. 2019. Global Mercury Assessment 2018. *UN Environment Programme (UNEP) Chemicals and Health Branch,* (Geneva, Switzerland: *UNEP*.) Available: https://www.unep.org/resources/publication/global-mercury-assessment-2018 [Accessed: 24 October 2024].

United Nations Environment Programme, Markus Reuter, Outotec Oyj, Christian Hudson, Antoinette van Schaik, Kari Heiskanen, Christina Meskers & Christian Hagelüken. 2013. Metal Recycling: Opportunities, Limits, Infrastructure. *United Nations Environment Programme (UNEP)* (Online: *UNEP*.) Available: https://www.resourcepanel.org/sites/default/files/documents/document/media/e-book_metals_report2b_recyclingopportunities_130919.pdf [Accessed: 1 April 2024].

UNSGPCETM. 2024. Resourcing the energy transition: principles to guide critical energy transition minerals towards equity and justice. *Report prepared by the United Nations Secretary-General's Panel on Critical Energy Transition Metals (UNSGPCETM)* Available: https://www.un.org/en/climatechange/critical-minerals

VERAM. 2017. *VERAM is a project funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 690388.* Available: http://veram2050.eu/nine-new-critical-materials/ [Accessed: 21 July 2024].

Wang, P, Yang, Y-Y, Heidrich, O, Chen, L-Y, Chen, L-H, Fishman, T & Chen, W-Q 2024. Regional rare-earth element supply and demand balanced with circular economy strategies. *Nature Geoscience.* 17, 94-102. Available: 10.1038/s41561-023-01350-9.

Weng, Z, Jowitt, S M, Mudd, G M & Haque, N 2015. A detailed assessment of global rare earth element resources: opportunities and challenges. *Economic Geology.* 110, 1925-1952.

Werner, T T, Mudd, G M & Jowitt, S M 2017. The world's by-product and critical metal resources part III: indium. *Ore Geology Reviews.* 86, 939-956.

Werner, T T, Mudd, G M, Jowitt, S M & Huston, D 2023. Rhenium mineral resources: A global assessment. *Resources Policy.* 82, 103441.

WHA International Inc. 2023. *Top Industrial Uses of Hydrogen, and the Need for Industrial Hydrogen Safety*. (5605 Dona Ana Road Las Cruces, NM 88007: Available: https://wha-international.com/hydrogen-in-industry/#_edn1%20;%20https://www.fchea.org/hydrogen-in-industrial-applications#:~:text=Hydrogen%20is%20primarily%20used%20as,of%20uses%20for%20hydrogen%20production. [Accessed: 22 November, 2024].

Wolf, M J, Emerson, J W, Esty, D C, de Sherbinin, A & Wendling, Z A. 2022. 2022 Environmental Performance Index (EPI). (New Haven, CT: *Yale Center for Environmental Law & Policy*.), https://epi.yale.edu/ [Accessed: 18 April 2023].

Woo, R. 2024. China issues rare earth regulations to further protect domestic supply. *Reuters*. 29 June 2024. (Online: *Reuters.*) Available: https://www.reuters.com/markets/commodities/china-issues-rare-earth-regulations-further-protect-domestic-supply-2024-06-29/ [Accessed: 1 October 2024].

World Bank. 2024. Worldwide Governance Indicators (WGI). (Online: *World Bank*.) Available: https://www.worldbank.org/en/publication/worldwide-governance-indicators [Accessed: 24 June 2024].

World Nuclear Association. 2024a. *World uranium mining production*. (London, UK: Available: https://world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/world-uranium-mining-production [Accessed: 10 November 2024].

World Nuclear Association. 2024b. *Uranium Markets*. (Online: *World Nuclear Association*.) Available: https://world-nuclear.org/information-library/nuclear-fuel-cycle/uranium-resources/uranium-markets [Accessed: 4 November 2024].

World Trade Organisation. 2022. Regional Trade Agreements Database. (Online: *World Trade Organisation*.), https://rtais.wto.org/UI/PublicMaintainRTAHome.aspx [Accessed: 24 August 2023].

Worldstainless. 2023. *Global Life Cycle of Stainless Steel*. (Brussels, Belgium: *Worldstainless*.) Available: https://www.worldstainless.org/news/global-life-cycle-of-stainless-steel/ [Accessed: 21 November 2024].

Wübbeke, J 2013. Rare earth elements in China: Policies and narratives of reinventing an industry. *Resources Policy.* 38**,** 384-394. Available: 10.1016/j.resourpol.2013.05.005 [Accessed: 1 October 2024].

Yan, W, Wang, Z, Cao, H, Zhang, Y & Sun, Z 2021. Criticality assessment of metal resources in China. *iScience.* 24**,** 102524. Available: https://doi.org/10.1016/j.isci.2021.102524 [Accessed: 4 April 2023].

Zeiler, B, Bartl, A & Schubert, W-D 2021. Recycling of tungsten: Current share, economic limitations, technologies and future potential. *International Journal of Refractory Metals and Hard Materials.* 98**,** 105546. Available: https://doi.org/10.1016/j.ijrmhm.2021.105546 [Accessed: 4 July 2023].

Zhang, M Y. 2024. Antimony: The hidden metal fuelling global competition. (Online: *Lowy Institute.*) Available: https://www.lowyinstitute.org/the-interpreter/antimony-hidden-metal-fuelling-global-competition [Accessed: 2024].

Zils, M, Einarsson, S, Hopkinson, P 2024a. A UK foresight study of materials in decarbonisation technologies: the case of heat pumps. *British Geological Survey via University of Exeter Business School* (Keyworth, UK: *BRITISH GEOLOGICAL SURVEY.*)

Zils, M, Einarsson, S, Hopkinson, P 2024b. A UK foresight study of materials in decarbonisation technologies: the case of electrolysers. *British Geological Survey via University of Exeter Business School* (Keyworth, UK: *BRITISH GEOLOGICAL SURVEY.*)

Zils, M, Einarsson, S, Hopkinson, P 2024c. A UK foresight study of materials in decarbonisation technologies: the case of fuel cells. *British Geological Survey via University of Exeter Business School* (Keyworth, UK: *BRITISH GEOLOGICAL SURVEY*.)

ZIRCOMET. 2019. *Zirconium Chemical and Fused Zirconium Oxide*. *ZIRCOMET LIMITED*.) Available: http://www.zircomet.com/sec/11189/Zirconium-Market-Update [Accessed: 22 November, 2024].