UK criticality assessment of technology critical minerals and metals

Decarbonisation & Resource Management

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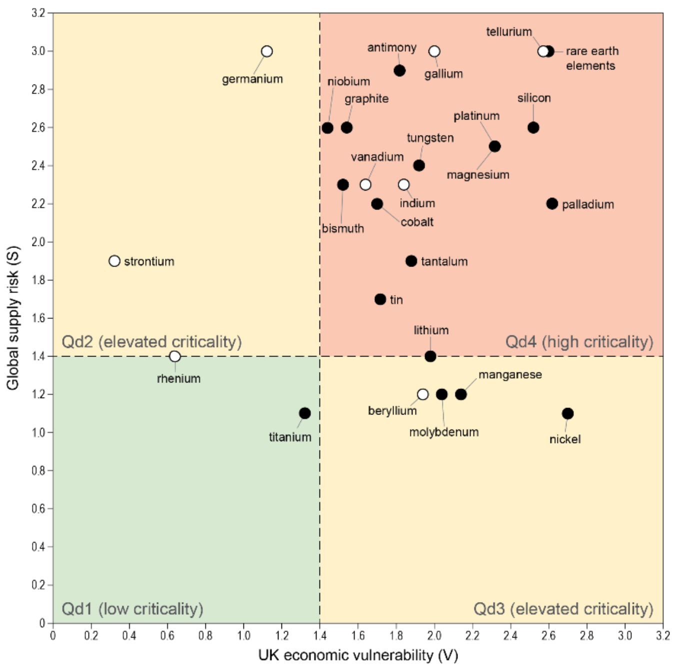

BRITISH GEOLOGICAL SURVEY

DECARBONISATION & RESOURCE MANAGEMENT

COMMISSIONED REPORT CR/21/120

UK criticality assessment of technology critical minerals and metals

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Foreword

This report is by the British Geological Survey (BGS) and was commissioned by the Department for Business, Energy and Industrial Strategy (BEIS), following a competitive tender exercise to produce a 'Criticality Assessment of Technology-Critical Minerals and Metals' (Order Number: PS21185).

Acknowledgements

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Summary

The current imperative to decarbonise means that the global economy will require a wide variety of mineral raw materials in ever-increasing quantities. It is therefore essential to know which materials are needed, in what quantities and to understand the impact of any supply disruption on the UK economy. 'Criticality assessment' aims to identify those minerals[1] which might be at risk of supply disruption and to use that information to inform the development of mitigation strategies. Criticality is generally assessed in terms of two dimensions, the likelihood of supply disruption, often termed supply risk, and the economic vulnerability of the consumer to potential supply disruption. Numerous criticality assessments have been published in the past decade employing a wide range of indicators to estimate the magnitude of supply risk and economic vulnerability. No two approaches are the same, and results differ according to who is asking the question and for what purpose. The governments of the United States (US) and the European Union (EU) are prominent in this field, having published broad criticality assessments focussed on their national needs and periodically updated since 2008.

In this study, 26 candidate materials (CMs) were assessed for their potential criticality to the UK economy in terms of their global supply risk (***S***) and the UK economic vulnerability (***V***) to such a disruption. Supply security is not related to physical availability, but instead is dependent on a host of non-geological factors that may constrain access to supplies at any point in the complex and dynamic international supply chains from which they are sourced. A change in any one of these economic, environmental, technical, social and political aspects can seriously compromise supply security. Three indicators were used in this study to estimate ***S*** for each CM: production concentration, companion metal fraction and recycling rate. ***V*** was calculated from six indicators: production evolution, price volatility, substitutability, global trade concentration, UK import reliance and UK gross value added contribution. A wide range of metrics, derived from publicly accessible databases and from the scientific literature, was used to quantify each indicator for each CM. The derived scores for each indicator, were weighted according to their importance to ***S*** and ***V***, and aggregated to produce overall estimates of ***S*** and ***V*** for each CM. Thresholds assigned to ***S*** and ***V*** were used to distinguish CM of differing levels of potential criticality. Eighteen of the 26 CMs have a 'high' potential criticality rating based on their values of both ***S*** and ***V***. These constitute the UK Critical Minerals List 2021.

UK Critical Minerals List 2021		
antimony	lithium	silicon
bismuth	magnesium	tantalum
cobalt	niobium	tellurium
gallium	palladium	tin
graphite	platinum	tungsten
indium	rare earth elements	vanadium

These results are broadly comparable with those published for the US, the EU and elsewhere. Any quantitative assessment of criticality fundamentally depends on the data used for the metrics that contribute to ranking the chosen indicators. In this study the data was derived from publicly accessible databases and from the scientific literature. For indicators relying on global mineral production data, the BGS World Mineral Production database provides up-to-data high quality data directly relevant to the objectives of this study. However, although reliable data on trade partners and traded volumes are held in global and UK databases, the data for several CMs (mostly minor metals) is commonly aggregated with other commodities and thus lacks the granularity needed for this assessment. For some indicators, such as recycling rates, companion metal fraction and substitutability, there are few up-to-date compilations of the

[1] 'minerals' refers to minerals, metals and their derivatives

appropriate metrics. These indicators are generally dependent on more assumptions, so data quality is inevitably poorer.

This preliminary assessment has highlighted the potential UK criticality of many minerals. The reliability of the findings can be improved by refinement of the methodology, including the specific indicators selected, and by assessing the availability of higher quality and UK-focussed data from a range of sources. It can also be improved by consultation with experts across the entire value chain of each CM. The most critical minerals should be prioritised for detailed studies of their entire value chains in order to determine appropriate interventions to ensure security of supply. Given the dynamic and complex nature of mineral supply chains and inherent data shortcomings, it is inevitable that such criticality assessments may fail to identify potential problems. They may also suggest that certain materials are at risk when, in fact, market forces may be able to resolve supply bottlenecks in the short or medium term. Given the continual evolution of global demand and supply patterns, certain minerals not included in this study should be considered for inclusion in future assessments. It is also important to stress that criticality assessment is based on existing data and understanding. It cannot, therefore, be used to predict future security of supply problems or trajectories of mineral demand.

1 Introduction and background

This study (Order Number: PS21185) to produce a 'Criticality Assessment of Technology-Critical Minerals and Metals', hereinafter referred to as an 'assessment of minerals critical to the UK' was commissioned by the Department for Business, Energy and Industrial Strategy (BEIS). BEIS is seeking to improve understanding of the minerals and metals currently considered most critical to the UK, potential changes in future demand for minerals and metals and their drivers and the impact of shifts in demand on the UK economy and security of mineral raw material supply.

The project was undertaken over a 6-week period, commencing on 1 November 2021 and ending on 15 December 2021.

1.1 AIMS AND OBJECTIVES

- To develop a robust and reproducible method of assessment to enable the production of a list of the most critical minerals and metals. This includes identifying those factors / metrics that are necessary in determining criticality of minerals and metals.
- To identify a means of determining which elements are of most 'strategic' importance to the UK, to include an approach to scoring, or categorising elements, to enable policy decisions to be considered based on subsets of the full list.
- Apply the methodology developed to produce a list of minerals and metals most critical to the UK.
- Identify the underlying rationale / justification for inclusion and positioning of each element on the list.

1.2 STUDY REQUIREMENTS

- The methodology should enable the list to be easily updated.
- The methodology whilst grounded in best practice and having reference to international comparators, should be specific to the UK and employ the best available UK-relevant information and understanding.
- The methodology should recognise and consider the environment, social and governance (ESG) issues associated with mining, extraction and processing of minerals.
- The methodology should be documented in a readily accessible format, and key supporting documentation should be provided in a format that enables them to be used by BEIS.

1.3 MINERAL CRITICALITY

Minerals and metals perform a myriad of functions, including enabling the technologies needed to combat the effects of climate change and to decarbonise the global economy, such as low carbon energy generation, zero emission transport and digital systems (Bloodworth *et al.,* 2019). Minerals are likely to assume greater importance in contributing to the UK's economic growth and high standard of living over the coming decades. This will be driven by requirements for the UK to bring all greenhouse gas emissions to net zero by 2050, and strategies to grow the advanced manufacturing sector (HM Government, 2020a,b). The policy of phasing out internal combustion engine vehicles in the UK by 2030 and plans to build a competitive integrated electric vehicle manufacture and battery industry at pace and scale will require resilient raw material supply chains (Department for Transport, 2021). Transforming the UK's energy system, including plans to quadruple UK offshore wind capacity by 2030 and drive growth in hydrogen, will also require major raw material inputs (HM Government, 2020a,b). However, the UK is not alone in these aspirations with many countries now pledged to achieve net-zero emissions. Some of these, in addition to having significant domestic production of critical raw materials, have established strategies to secure their supply for domestic industry (Prime Minister of Australia, 2021; Schmidt, 2021; United States Department of Energy, 2021). Recent studies by the International Energy Agency and the World Bank indicate there are global supply challenges for commodities such as cobalt, lithium and graphite, for which increases in demand of about 500 per cent are projected (World Bank Group, 2020; International Energy Agency, 2021). The House of Lords Science and Technology Select Committee has warned that UK net-zero targets are at risk if it does not address potential issues with future supplies of critical raw materials (CRMs) (House of Lords, 2021). Understanding UK vulnerabilities via a 'criticality assessment' is an important step in developing a critical minerals strategy for the UK, a commitment the Government has made in its 'Net Zero Strategy: Building Back Greener' (HM Government, 2021).

Although CRMs are defined in various ways according to who is asking the question and for what purpose, CRMs may be broadly classified as those at risk of supply disruption and which are of economic importance to the entity posing the question. Assessments of criticality by governments also commonly take account of the importance of materials to national defence and security. Monitoring of supply risks and the potential impacts of CRM supply disruption can help to ensure the availability of adequate and sustainable material supplies through policy intervention underpinned by research.

UK supply of most minerals and metals required for advanced manufacturing, and for reducing emissions across the economy via a clean energy system, is derived almost entirely from overseas through complex, dynamic international supply chains that often have poor end-to-end visibility.

As a consequence, the UK is vulnerable to supply disruption arising from numerous potential causes of geopolitical, economic, environmental and social nature. It is, therefore, important to understand what materials are at risk of supply disruption, to determine the severity of impacts resulting from such disruption and to identify appropriate mitigation. This can help to ensure that UK supply chains are robust, secure and sustainable and meet the needs of UK government and business. A UK-focussed criticality assessment is the first stage in this process, serving to identify those minerals potentially critical to the UK economy.

2 Criticality and criticality assessment

2.1 SECURITY OF SUPPLY OF MINERALS

For more than 200 years, there has been periodic concern over ability to provide the goods and services required to support a growing global population. Such concerns tend to be most prominent at times of rapid economic growth, such as in the mid-19th Century during the first industrial revolution, and the period of economic renewal following the end of World War II. In 1972 the Club of Rome predicted that the world would run out of mineral and other resources sooner rather than later (Meadow *et al.,* 1972). During the 'Cold War' of the mid to late 20th Century, it was argued that the then Soviet Union was engaged in a 'resource war' designed to cut off the West from its supplies of essential raw materials. At the same time, apartheid South Africa dominated the western world's supply of many minerals and metals, notably chromium, vanadium and the platinum-group metals (PGMs). Simultaneously, much of the West's cobalt was sourced from Zaire (now the Democratic Republic of Congo, DRC) then ruled by the corrupt and unstable regime of Mobutu Sese Seko. As a consequence, various governments became concerned about the security of supply of what were then generally referred to as 'strategic' raw materials. Considerable effort was devoted to diversifying the supply base of these materials and to the establishment of stockpiles of some.

In the early 2000s, growing geopolitical instability, increased resource nationalism and growing awareness of the links between supply of some minerals with conflict and human rights abuses, led to renewed concern regarding short- and medium-term availability of mineral commodities. Among countries heavily-reliant on imported materials, there was also increased concern, regarding China's dominance of both supply and consumption of a large number of mineral commodities including rare earth elements (REEs), tungsten, antimony, fluorspar and many more. Additional factors also raised the level of concern in western economies, notably the high concentration of global supply of some raw materials, including niobium, PGMs, cobalt, beryllium, rhenium, etc. These materials came to be designated as 'critical' on account of the potential vulnerability of consuming nations to disruption of their supply.

2.2 CRITICALITY ASSESSMENT

A report in 2008 by the United States (US) National Research Council (National Research Council, 2008) was the first serious attempt to define metal criticality and to suggest how it might be measured. It was based on approximations and expert judgement for 11 metals and groups of metals and used two parameters to determine criticality: the supply risk (or likelihood of supply disruption) and the impact of supply disruption (or vulnerability). A second major assessment, carried out for the European Union (EU) (European Commission, 2010), adopted a broadly similar approach, applying it to much wider range of materials and employing quantitative data to estimate the two dimensions of criticality.

In the following decade, interest in CRMs and their assessment increased greatly, accompanied by a proliferation of literature (Hofmann *et al.,* 2018). These studies vary greatly in scope, purpose and methodology, depending on who is asking the question, for what purpose and over what timescale. They have been undertaken by governments, non-governmental organizations, academics and commercial companies. Some have assessed large numbers of materials, others only those related to a particular industry or sector. Some have been global in scope while others have focussed on particular countries or regions. As a result many lists of CRMs have been produced, although none should be considered as fixed or correct. All assessments rely on the availability of data to allow quantification of the two key dimensions. Where data are lacking or unreliable, expert judgement is often elicited to provide qualitative estimates for the relevant metrics. Another serious limitation of criticality assessment is that it attempts to identify problems in the future based on the analysis of data from the past. Forecasts and scenarios of future demand are now increasingly being utilised in tandem with criticality assessments to anticipate future challenges.

Despite these shortcomings criticality assessment has a potentially important role to play in decision-making by governments and industry. They are widely used in the development of policy and research aimed at underpinning security of supply, encompassing entire mineral supply chains from deposit formation to exploration, mining, processing, manufacturing and recycling. They also elucidate other possible supply barriers such as trade restrictions, social licence to operate and environmental constraints related to land, water and energy use. They highlight those materials where further in-depth analysis is required, where data availability and quality are inadequate and where insight into future supply and demand scenarios is required.

The most comprehensive assessments have been undertaken by the EU and the USA, both starting in 2008, followed by occasional methodological changes and periodic updating of the CRM lists. These updates are carried out to reflect current policy priorities and data on supply, demand, concentration of production and other factors that might constrain access to raw materials, such as ESG imperatives. Other recent notable assessments have been undertaken by the governments of Australia, Canada and Japan (Australian Trade and Investment Commission, 2020; Malala and Adachi, 2021; Natural Resources Canada, 2021). A thorough review of the methods and data used in criticality assessments was published in 2020 (Schrijvers *et al.,* 2020). It provides useful discussion on the nature of the risk being evaluated, the materials that are considered and the indicators that are assessed. The aggregation and weighting of the selected indicators are also reviewed, together with the application of a threshold to separate critical and non-critical materials. A subsequent review considered the frequency with which minerals and elements have been included in 25 different criticality assessments from 2005 to 2020 and related data availability and uncertainty issues (McNulty and Jowitt, 2021). An overarching requirement for any criticality assessment is that it should be based on a transparent and robust methodology clearly communicated to all users and underpinned by reliable data. If data are absent or of poor quality, if assumptions and generalisations are not made explicit and if the applied methodology is opaque, then the value of the derived results may be seriously undermined.

3 Methodology for the assessment of minerals critical to the UK

3.1 PRINCIPLES

The methodology for identifying the minerals (refers to minerals, metals and their derivatives) potentially most critical to the UK is based on the assessment of two commonly-used dimensions of criticality, the likelihood of supply disruption (termed global supply risk) and the economic vulnerability of the UK to potential supply disruption. The method is reproducible and transparent in so far as it relies on several accessible, public domain data sources. However, it is important to note that the data which underpin this assessment are not always available, or of sufficient quality, for all materials considered (referred to as candidate materials, CMs). In such cases expert judgement has been used, where justifiable, to provide appropriate values. In a few cases where this has not been possible the data values for that particular metric are left blank and are not included in the determination of the criticality score for that CM.

The assessment of criticality involves the extraction of many datasets from databases and technical publications on a broad range of subjects including global production of minerals and metals, world and UK trade in minerals and metals, UK economic indicators, material supply chains, end-use applications and national governance indicators. These data are subsequently manipulated in various ways to derive the overall ratings of supply risk (***S***) and UK economic vulnerability (***V***) for each CM. Although the concept behind the methodology is relatively simple, it requires decisions to be made at several points in the assessment. Such decisions depend fundamentally on a clear understanding of the datasets being utilised, especially the inherent (and not always explicit) uncertainties, assumptions and aggregations they contain.

The key steps in the criticality assessment are:

1. Selection of candidate materials (CMs)
2. Selection of indicators of global supply risk (***S***)
3. Selection of indicators of UK economic vulnerability (***V***)
4. Selection of metrics for assessment of ***S*** and ***V*** indicators
5. Acquisition of data for all metrics for each CM
6. Analysis of data, resolution of quality issues and identification of gaps
7. Calculation of weighted scores for each indicator for each CM
8. Aggregation of scores to derive an overall rating for ***S*** and ***V*** for each CM
9. Detailed examination of the results and selection of criticality thresholds for ***S*** and ***V***
10. Identification of potentially critical minerals for the UK and presentation of the results

3.2 SELECTION OF CANDIDATE MATERIALS AND BOUNDARIES OF THE ASSESSMENT

As is common practice in this field, we have excluded energy minerals, construction raw materials, biotic materials, gases and most industrial minerals. We have included minerals that have been identified as 'critical' in many published criticality assessments (see analysis by Schrijvers *et al.*, 2020 and McNulty and Jowitt, 2021). Owing to the time constraints imposed on this study, we have excluded those minerals that have seldom, if ever, been classified as critical in the numerous assessments published in the past decade. Consequently, we have not assessed the criticality of a number of major industrial metals, such as iron, copper, lead and zinc, which have well established and diversified supply chains and relatively stable and transparent markets. The industrial minerals graphite and silicon have been included on account of their importance to advanced economies, especially in high-value manufacturing and clean energy technologies and because they have been classified as 'critical' in major published assessments (e.g. European Commission, 2020a; Nassar and Fortier, 2021). The 26 CMs assessed in this study are shown in Table 1. It is important to stress that raw materials not included in this study should be considered for inclusion in future assessments as the global raw materials supply landscape changes and technology trajectories evolve.

Candidate material	Element symbol
antimony	Sb
beryllium	Be
bismuth	Bi
cobalt	Co
gallium	Ga
germanium	Ge
graphite	C
indium	In
lithium	Li
magnesium	Mg
manganese	Mn
molybdenum	Mo
nickel	Ni
niobium	Nb
palladium (a platinum-group metal, PGM)	Pd
platinum (a platinum-group metal, PGM)	Pt
rare earth elements (a group of 17 elements, REE)	n/a
rhenium	Re
silicon	Si
strontium	Sr
tantalum	Ta
tellurium	Te
tin	Sn
titanium	Ti
tungsten	W
vanadium	V

Table 1 Candidate materials considered in the assessment of minerals critical to the UK.

Certain raw materials that occur together in nature are mined as a group of co-products or by-products of mainly base metal mining. These comprise the six platinum-group metals (PGMs) and the 17 rare earth elements (REEs). Given the resource constraints on this project, the lack of public data on many aspects of the value chains of individual REEs, and because they generally occur together geologically, we have treated the REEs as a single entity and have not attempted to resolve the criticality of each separately. In the case of the PGMs, some metrics are available for the most important individual metals, platinum and palladium, which allow them to be treated independently.

Our assessment does not extend across the complete supply chains of the CMs. Global supply risk (***S***) is assessed on the basis of three indicators, one of which considers either ores and concentrates or refined metal, a second which is based on ores and concentrates, and a third for which the material form is not applicable (Appendix 1). For three CMs (cobalt, nickel and tin) global production data are available for both ore and concentrates and refined metal thus allowing both forms to be evaluated (Appendix 1). Six indicators have been used to estimate the UK economic vulnerability (***V***) dimension of criticality in the context of global supply, market factors and trade patterns. Global trade competition and UK import reliance / sourcing are determined, where possible, on the basis of the material form considered to be most important to the UK economy. It has not been possible in this study to take account of all traded forms of individual CMs. This is because data availability precludes the integrated and consistent assessment of all variants for all CMs.

3.3 SELECTION OF INDICATORS

Published assessments vary greatly in their choice of indicators for the likelihood of supply disruption and the vulnerability to supply disruption (Schrijvers *et al*., 2020; McNulty and Jowitt, 2021). Those used in this study have been selected on the basis of a combination of best practice and judgement of their importance to the assessment of potential criticality to the UK. Three indicators have been used in the estimation of the global supply risk, while six have been employed for evaluating the UK economic vulnerability to a supply disruption. For each CM the scores for the ***S*** and ***V*** indicators were calculated in separate Microsoft Excel-based templates (Appendix 2 and Appendix 3).

3.4 GLOBAL SUPPLY RISK

3.4.1 Production concentration

Over the past three decades, production of many minerals and metals production has concentrated into a few countries. In the past geological availability was a key determinant of the location of processing and refining activities. However, the drivers behind this concentration are now more strongly related, to the policies of individual countries such as China, to secure raw material supplies. This production concentration poses a higher risk of supply disruption compared to raw materials sourced from a broader and diversified supply base (Brown, 2018). The potential for supply disruption caused by changes in government policy and regulation, trade relations, and a wealth of environmental, social and economic factors is likely to be more serious if the production is highly concentrated.

In this study, production concentration was quantified on the basis of a Production Concentration Index (PCI). Initially, five-years (2015–2019) of mineral production data was extracted from the BGS World Mineral Statistics Database (British Geological Survey, 2021) for each CM. An average of the five years' mineral production was calculated for each country. The five-year production averages for each country were summed to generate an average world total production for the CM. This was used to calculate the per cent share of global production for each country.

Average Worldwide Governance Indicator (WGI) (World Bank Group, 2021) values were determined for all countries and were used in the calculation of PCI. The WGI project reports aggregate and individual governance indicators each year for over 200 countries and territories. Six dimensions of governance are quantified on the basis of the views of numerous diverse stakeholder groups in industrial and developing countries: voice and accountability; political stability and absence of violence and terrorism; government effectiveness; regulatory quality; rule of law; and control of corruption. The average of these six dimensions for all producing countries was calculated for the five-year period 2015–2019.

The PCI was calculated by squaring the per cent share of global production for each country and then multiplying that value by the respective average WGI value. In this way the quality and stability of governance in the producing countries is included within this indicator. The PCI values for the top three producing countries were summed to give a total PCI value. The PCI values for the CMs were ranked: 1 (low), <10,000; 2 (medium), >10,000–20,000; and 3 (high), >20,000, to reflect the increasing supply risk associated with production concentration (Appendix 2).

Individual PCI values are calculated as follows:

$$PCI = \%\ of\ global\ production\verb|^|2*average\ WGI$$

3.4.2 Companion metal fraction

Many metals used in modern technology to deliver a particular function are not extracted from ores composed of their own minerals. Rather they are extracted from the ores of more common and widely used 'parent' metals such as aluminium, copper, lead and zinc, in which they occur as trace constituents or 'daughter' elements (Graedel *et al.*, 2014; Nassar *et al.,* 2015). Their concentration in the parent ores is so low that they are seldom economic to mine in their own right. Instead they may be recovered during the processing, smelting and refining of these ores if market conditions are favourable and the extraction technology is available. Consequently the extraction of these by-product metals does not respond in the usual manner to increased demand because its production is directly linked to that of its parent. If production of the parent metal is curtailed for any reason or if demand for the by-product increases significantly over a short period the ability of the market to supply secure and sustainable supplies of the by-product cannot be guaranteed. Consequently, the amount of a particular metal that is derived as a by-product, termed the 'companion metal fraction', is commonly used as an indicator of supply risk in criticality assessments (Schrjivers *et al.*, 2020; McNulty and Jowitt, 2021).

There are few published studies that report the companion metal fraction for a wide range of raw materials. In this study we have used the estimates given by an authoritative source (Nassar *et al.,* 2015) to derive a score for each CM. Although this dataset is not as recent as some used in this study, it is considered to be a reasonably accurate representation of the current situation, especially as installation of additional extraction capacity for a by-product metal is typically expensive and can take several years to implement. Companion metal fraction values for the CMs were ranked: 1 (low), <33 per cent; 2 (medium), >33–66 per cent; and 3 (high), >66 per cent, to reflect the of dependency of the CM on the production of another commodity.

3.4.3 Recycling rates

The recycling of metals from end-of-life products is a potentially important source of material supply complementary to that derived from mineral ores (primary supply). Secondary supply effectively diversifies the supply base thus reducing the associated supply risk. The production of metal from recycled stocks also provides substantial energy saving in comparison with production from primary ores (Bloodworth *et al.*, 2019).

In accordance with common practice in published criticality assessments (Schrijvers *et al.*, 2020), the end-of-life recycling input rate (EOL-RIR) of each CM has been used in this study as an indicator that contributes to the global supply risk dimension. The EOL-RIR is the ratio of recycling of old scrap to the supply of raw material. In other words, it is the production of secondary material from post-consumer functional recycling (old scrap) that replaces primary material input.

While recycling rates for some major industrial metals, such as steel, aluminium and copper, are relatively high and may exceed 50 per cent, rates for most 'low volume' technology metals are generally much lower and fall below 1 per cent. The reasons for this are complex, but relate essentially to the fact that these metals are commonly used in small amounts in complex products from which it is technically difficult to recover valuable metals. The low collection rates of EOL consumer goods is also a major factor in the low recycling rate for these metals.

The availability of up-to-date and relevant recycling rates for the CMs is problematic because there are few recent studies that cover the CMs considered here. It is also important to note that the EOL-RIR for any material varies according to its end-use application and the geographical location of recycling infrastructure. As a result, defining a single value to EOL-RIR for an individual CM relevant to the UK is inevitably subjective. The uncertainty is further compounded when a group of elements (e.g. REEs or PGMs) is treated as a single entity and is represented by a single value when it is likely that they have differing EOL-RIR. In this study we have used recycling rates from the fourth EU study on CRMs from 2020 (European Commission, 2020a), which provides data for all the CMs, albeit for some several years old. However, the rates for some CRMs have been updated by material-specific studies using Material System Analysis carried out by the EC (Talens Peiro *et al.,* 2018). For the REEs we have used an EOL-RIR of 5.5 per cent, which is the average of the two values reported separately by the EU for the light rare earth elements (LREE) and the heavy rare earth elements (HREE). The EOL-RIR for the CMs were ranked: 1 (high), >30 per cent; 2 (medium), >10–30 per cent; and 3 (low), <10 per cent, to reflect the role that recycling could potentially have in mitigating supply disruption. A summary of the three global supply risk indicators is provided in **Table 2**.

Indicator	Rationale	Description	Main data sources	Year of data publication
Production concentration	***S*** increases with greater concentration of mineral production and is also influenced by governance factors in the producing countries	Country share of total production of a CM was weighted using Worldwide Governance Indicators	BGS World Mineral Statistics database; Worldwide Governance Indicators (World Bank Group, 2021)	2015–2019
Companion metal fraction	***S*** increases with greater dependency on the production of another metal	Proportion of a CM that is produced as a by-product of the extraction (mining or refining) of another raw material	Nassar *et al.*, (2015): companionality estimates	2015
Recycling rate	Recycling is an additional source of metal supply that may alleviate ***S***	End-of-life recycling input rate of each CM	Study on the EU's list of Critical Raw Materials (European Commission, 2020a)	2020

Table 2 Summary of global supply risk indicators used in the assessment of minerals critical to the UK.

3.4.4 Other supply risk indicators that may be considered

Many other indicators have been used in the estimation of global supply risk (Schrijvers *et al.,* 2020). One that is often employed is the global distribution of reserves and associated depletion times for the reserves of CMs. However, we consider the use of this indicator to be fundamentally flawed because it is based on incorrect understanding of what mineral reserves actually represent (Crowson, 2011). In fact, reserves are a dynamic entity that measures what is available to exploit today under present conditions and with current technology. They are just a small part of a mineral resource, which is a natural concentration of minerals that is of potential economic interest for the future extraction of those minerals. Reserves are neither static nor well known on a global scale and are never actually depleted. As a result, they are not reliable indicators of future mineral availability and the concept of reserve depletion times is wholly invalid (Lusty *et al.*, 2020).

3.4.5 Aggregation and weighting and of global supply risk indicators

The calculated scores for each indicator for each CM range from 1–3. Aggregation of the three global supply risk indicator scores gives the global supply risk (***S***) for each CM (minimum = 3 and maximum = 9). The scores for the three ***S*** indicators were weighted according to their relative importance to potential criticality. 70 per cent of the total has been assigned to production concentration, with 20 per cent to the companion metal fraction and 10 per cent to the recycling rate. The latter is based on the current very low EOL-RIR values that are prevalent for most of the CMs such that their present contribution to alleviating supply risk is small.

Aggregation of the weighted ***S*** indicator scores gives the final ***S*** indicator value (Table 3), which defines the position of the CM in the ***S*** dimension (vertical axis) on the criticality matrix.

	Global supply risk (S) indicator scores			Global supply risk (S)	Weighted PC (70%)	Weighted CMF (20%)	Weighted RR (10%)	Sum of weighted S indicators
Candidate material	Production concentration (PC)	Companion metal fraction (CMF)	Recycling rate (RR)					
antimony	3	3	2	8	2.1	0.6	0.2	**2.9**
beryllium	1	1	3	5	0.7	0.2	0.3	**1.2**
bismuth	2	3	3	8	1.4	0.6	0.3	**2.3**
cobalt	2	3	2	7	1.4	0.6	0.2	**2.2**
gallium	3	3	3	9	2.1	0.6	0.3	**3.0**
germanium	3	3	3	9	2.1	0.6	0.3	**3.0**
graphite	3	1	3	7	2.1	0.2	0.3	**2.6**
indium	2	3	3	8	1.4	0.6	0.3	**2.3**
lithium	1	2	3	6	0.7	0.4	0.3	**1.4**
magnesium	3	1	2	6	2.1	0.2	0.2	**2.5**
manganese	1	1	3	5	0.7	0.2	0.3	**1.2**
molybdenum	1	2	1	4	0.7	0.4	0.1	**1.2**
nickel	1	1	2	4	0.7	0.2	0.2	**1.1**
niobium	3	1	3	7	2.1	0.2	0.3	**2.6**
palladium	2	3	2	7	1.4	0.6	0.2	**2.2**
platinum	3	1	2	6	2.1	0.2	0.2	**2.5**
rare earth elements	3	3	3	9	2.1	0.6	0.3	**3.0**
rhenium	1	3	1	5	0.7	0.6	0.1	**1.4**
silicon	3	1	3	7	2.1	0.2	0.3	**2.6**
strontium	2	1	3	6	1.4	0.2	0.3	**1.9**
tantalum	2	1	3	6	1.4	0.2	0.3	**1.9**
tellurium	3	3	3	9	2.1	0.6	0.3	**3.0**
tin	2	1	1	4	1.4	0.2	0.1	**1.7**
titanium	1	1	2	4	0.7	0.2	0.2	**1.1**
tungsten	3	1	1	5	2.1	0.2	0.1	**2.4**
vanadium	2	3	3	8	1.4	0.6	0.3	**2.3**

Rank

1. Low	2. Medium	3. High

Table 3 Global supply risk (***S***) indicator scores for 26 candidate materials. Global supply risk is based on calculated scores for three indicators. The scores for each indicator range from 1–3. Addition of the scores for each of the three global supply risk indicators gives the 'Global supply risk (S)' for each candidate material (min. = 3 and max. = 9). The scores for the three ***S*** indicators are weighted according to their relative importance to global supply risk. Addition of the scores for the three weighted indicators gives the ***S*** indicator value ('Sum of weighted S indicators'; min. = 1 and max. = 3), which defines the position of the candidate materials in the ***S*** dimension (vertical axis) on the criticality matrix.

3.5 UK ECONOMIC VULNERABILITY

3.5.1 Production evolution

This indicator aims to capture demand growth as a measure of a commodity's growing importance. In the absence of adequate global demand data across all CMs, production data are used as a proxy. In common with the approach taken by the United States Geological Survey (USGS) (McCullough and Nassar, 2017), a high value for this indicator is considered to increase ***V***. Although high growth rates have been achieved in the past as a result of increased mining and / or refining, it is uncertain if such growth rates can be maintained in the future, particularly when ESG performance is the foremost consideration (e.g. Eheliyagoda *et al.,* 2020). Not only is increasing supply dependent on the continual identification of new resources of these minerals and metals, but it is also necessary to overcome the many, varied barriers (environmental, social, economic, political, etc.) that determine whether these resources can be converted into reserves and actually mined. Given the forecasts of future rapid demand growth for many technology metals (e.g. Watari *et al.,* 2020; World Bank Group, 2020; International Energy Agency, 2021), it is recognised that past production changes should be evaluated alongside projections of future demand. However, while such forecasts are available for certain materials over various timescales, there is no single set of forecasts that cover many of the CMs evaluated in this study over the same time period. Available forecasts vary not only in the timescale and materials considered, but also in their geographical coverage and industrial sectors examined.

The changes in global production levels between 2010–2018 have been used to calculate a compound annual growth rate (CAGR) for that period for each CM. Data for 2019 were also inspected, but were excluded because of the apparent effect of the start of the COVID-19 pandemic in reducing production volumes in that year. The CAGR values for the CMs were ranked: 1 (low), <5 per cent; 2 (medium), >5–10 per cent; and 3 (high), >10 per cent, to reflect the growing demand for a CM and its potential impact on economic vulnerability.

3.5.2 Price volatility

The price of traded commodities is normally determined by a dynamic control cycle which operates to keep demand and supply in balance (Wellmer and Hagelüken, 2015). Under conditions of excess supply, a commodity price will normally fall and, when demand increases, the price generally rises. The price volatility is a measure of the day-to-day price fluctuations of a commodity. For many minor metals, especially those that are produced as by-products, price volatility has historically tended to be high (Renner and Wellmer, 2020). Where the size of the market is small and production highly concentrated, a disruption in supply resulting from an accident or strike or an abrupt change in government policy in a key producing country can lead to a price spike. In contrast, a rapid increase in demand for a particular commodity for use in a new technology can result in tightening of supplies and associated rapid price escalation. For example, the growth of the global market for electric vehicles in the past 3–4 years has led to serious concerns about the adequacy of existing production capacity to keep pace with growing demand for battery metals such as cobalt and lithium. This has led to significant price volatility for these metals (BGR, 2021). Such uncertainty over prices can have serious impacts on the economies of both producing and consuming countries. High price volatility is a serious deterrent to investment in new mining and processing capacity, while in consuming countries manufacturers that use these materials are affected by price uncertainties and thus on decision making for the future.

Price volatility data are available for a wide range of minerals and metals from the German Natural Resources Agency (DERA) in the Federal Institute for Geosciences and Natural Resources (BGR). They publish monthly price volatility averaged over a five-year or a one-year period. For this study, data for the period January 2016 to December 2020 have been used, although, where this was not available, data for the period October 2020 to September 2021 have been utilised for certain CMs. No price data are available in the public domain for two CMs, beryllium and strontium, so for these price volatility is not included in the estimation of ***V***. The price volatility of the CMs was ranked: 1 (low), <15 per cent; 2 (medium), >15–20 per cent;

and 3 (high), >20 per cent, to reflect the impact of potential price changes on economic vulnerability.

3.5.3 Substitutability

The possibility of achieving similar function and performance at the same or lower cost by using an alternative substitute material is often considered as an option for reducing the economic impact of supply disruption of a potential CRM. The degree to which it is feasible to utilise a substitute material to fulfil a particular function is termed the substitutability. It has been quantified by using a substitution index derived chiefly through expert elicitation in some published criticality assessments (European Commission, 2017a; 2020a; Blengini *et al.,* 2017 and references therein).

Inevitably, there is subjectivity incorporated into any estimation of a substitution index for individual CMs. This is exacerbated by the fact that most CMs have a multitude of end uses where the possibility of substitution is very variable. An example of substitution that is fairly common practice in the automotive sector is the replacement of platinum for palladium in autocatalysts. While the actual PGM loading in a catalyst is essentially determined by performance requirements for particular vehicle types, since the widespread introduction of emission control legislation starting in the 1990s there has been periodic substitution of platinum by palladium and vice-versa in response to sustained periods of price variation among the PGMs (World Platinum Investment Council, 2020).

In this study we have used the substitution indices from the EU 2020 criticality assessment which is the only publicly-available list which includes the CMs assessed in this study (European Commission, 2020a) (Appendix 4). This is derived on the basis of the cost and performance of the substitute material (European Commission, 2017a). The substitution index values for the CMs were ranked: 1 (low), <0.8 (substitutable); 2 (medium), >0.8–0.95 (potentially substitutable); and 3 (high), >0.95 (not substitutable), to reflect the increasing economic vulnerability associated with lower levels of substitutability.

3.5.4 Global trade concentration

An indicator of global trade concentration was used to identify those countries that import the greatest share of traded material for each CM. The countries that dominate the global imports of a particular form of material are subsequently in a position to control the production and trade of products further down the value chain. For example, China accounts for 77 per cent of the global total of net imports of cobalt (unwrought metal). It is therefore, in a position to exert significant control over trade in derived intermediate materials and products that use them.

Export and import data were extracted from the UN Comtrade database for the main traded forms of each CM for all countries that trade in these materials. Average import and export values for the five-year period 2015–2019 were calculated. These allowed the determination of the total global export, import and net import tonnages for each traded form of a CM. The global trade concentration indicator was based on the material form assessed to be most important to the UK in terms of total volumes imported. For example, antimony oxides were used to assess global trade concentration as they are the dominant form in which the UK receives antimony, far exceeding UK imports of antimony metal. For each CM, the percentage share of global net imports taken by the top three importing countries was aggregated. The global trade concentration was ranked: 1 (low), <33 per cent; 2 (medium), >33–66 per cent; and 3 (high), >66 per cent, to reflect the higher economic vulnerability associated with CMs that have more concentrated net imports.

3.5.5 UK import reliance

The UK is heavily reliant on the import of many raw materials and intermediate products (refined metals, chemicals, etc.). In order to assess the UK economic vulnerability to disruption of imported supplies, it is important to understand the amount of material imported and its origin.

In order to calculate UK import reliance, the volume of UK imports and exports for each CM were extracted from the UK Trade Info dataset for the five years 2015–2019 (HM Revenue and Customs, 2021). Production data were derived from the BGS World Mineral Statistics database

(British Geological Survey, 2021) and PRODCOM (Office for National Statistics, 2020) for the same period. The contained metal content of these traded forms were then calculated based on well-established metal content estimates. The average tonnage of contained metal in the imports, exports and production for this period were used to calculate both the UK's apparent consumption and its net import reliance (NIR) for each CM. The equations used to derive these quantities are:

Apparent consumption = Imports + Production – Exports

Net Import Reliance = Imports – Exports / Apparent Consumption

For most CMs, this assessment was carried out for multiple forms of traded materials, including ores/concentrates, metal, compounds, waste/scrap, etc. The net import reliance values used in the calculation were based on the single material form in which the UK has the largest trade. Given the generally low level of UK production of the CMs, the calculated NIR values are mostly 100 per cent, or approaching 100 per cent. This equates to a ranking score of 3.

The UK import reliance indicator also considers import dependence (i.e. where the UK imports are sourced), as well as the existence of any trade barriers and the standards of governance in the supplier countries. This was carried out by modifying the NIR scores in two ways.For each CM, the proportion of imports originating in each of the top five trading countries was calculated. A trade concentration index (TCI) was calculated for the top three UK trading partners by squaring the percentage share of imports associated with each country and multiplying this by their respective average WGI values. A combined TCI was calculated by summing the TCI value for the top three countries. The combined TCI values were ranked: 1, <=1000; 2, >1000–2500; 3, >2500–5000; 4, >5000–7500; and 5, >7500. Finally, the existence of any trade restrictions (e.g. quotas, tariffs, embargoes) between the UK and its chief sources of imports were examined (OECD, 2020). Where no restrictions were evident a score of 1 was given, whilst where restrictions were identified for a particular CM a score of 2 was allocated, to reflect the increased economic vulnerability. The total net import reliance was calculated by summing the ranked values for net import reliance, import dependence and trade barriers. The total net import reliance value for each CM was ranked: 1 (low), <6; 2 (medium), >6–8; and 3 (high), >8.

3.5.6 UK GVA contribution

This indicator is designed to estimate the importance of each CM to the UK economy, specifically the manufacturing sector. The calculation methodology is based on that first used in the criticality assessment carried out for the EU in 2017 and employed again in the 2020 assessment (European Commission, 2017b; European Commission, 2020a).

The first step in the calculation of this indicator is to identify the end-use applications of each CM and to define the proportion used in each. However, these data vary considerably in their timing and geographical scope, and are not available for all CMs. Consequently, they may depart significantly from the ideal, which would be to have up-to-date application share information for the UK for all CMs. In addition, in some instances published end-uses are not consistent across all sources for each CM. For example, there may be differences apparent in the nomenclature and in the aggregation or splitting of individual applications.

The next step is to allocate each end-use application to the corresponding manufacturing sector using the UK Standard Industrial Classification of Economic Activities 2007 (SIC 2007). SIC is used to classify business establishments and other statistical units by the type of economic activity in which they are engaged (Office for National Statistics, 2009). End-use applications were mapped to 2 digit level 'Manufacturing' SIC codes based on the explanatory notes provided in Office for National Statistics (2009). Gross value added (GVA) for each of the relevant SIC codes was extracted from the 'Regional gross value added (balanced) by industry: all International Territorial Level (ITL) regions' (Table 1b: ITL1 & UK chained volume measures in 2018 money value) published by the Office for National Statistics (Office for National Statistics, 2021a). However, for reasons which are unclear, SIC 19-20 are reported as a single entry in this dataset. In contrast, the United Kingdom National Accounts: The Blue Book 2021 (Table 2.3: 'Gross value added at basic priced by industry, chained volume indices') lists GVA data separately for: 'Coke and refined petroleum products' (19) and 'Chemicals and chemical products' (20). As a consequence, this source (Office for National Statistics, 2021b) was used for these SIC codes. 2018 GVA data was used in this part of the assessment as the 2019 data from the 'Regional gross value added (balanced) by industry' dataset is considered 'provisional'.

The potential contribution that a CM makes to UK GVA is based on the percentage that each of its end-use applications share as a proportion of the total GVA (in pounds) which is contributed by the relevant manufacturing sector. The GVA shares derived for each end-use application were aggregated to give the total GVA contribution for the relevant CM.

The estimated UK GVA contribution is associated with considerable uncertainty. This arises from the inability to unambiguously map end-use applications to particular SIC codes and because in some cases splitting end-use applications across more than one SIC code would more accurately reflect a CMs potential GVA contribution. However, because of time constraints in this study we have attempted to adhere consistently to the definitions of each SIC code provided in Office for National Statistics (2009). The total GVA contributions of the CMs were ranked: 1 (low), <£8 billion; 2 (medium), >£8–£13 billion; and 3 (high), >£13 billion, to reflect the potential impact of economic vulnerability on the UK economy. A summary of the six UK economic vulnerability indicators is provided in Table 4.

3.5.7 Aggregation and weighting of UK economic vulnerability indicators

The calculated scores for each indicator for each CM range from 1–3. Aggregation of the six UK economic vulnerability indicator scores gives the UK economic vulnerability (***V***) for each CM (minimum = 6 and maximum = 18, where all indicators are available). The scores for the six ***V*** indicators were weighted according to their relative importance to potential criticality. The following percentages were allocated to each indicator: production evolution (8%); price volatility (10%); substitutability (2%); global trade concentration (10%); UK import reliance (50%); and UK GVA contribution (20%). The latter two indicators are highly weighted because, in contrast to the others, they relate specifically to the UK. The low weighting for substitutability reflects the low level of substitutability of many of the CMs, as such its role in alleviating economic vulnerability is small. Aggregation of the weighted indicator scores gives the final ***V*** indicator value (Table 5), which defines the position of the CM in the ***V*** dimension (horizontal axis) on the criticality matrix.

3.5.8 Presentation of results, assignment of thresholds and rating of potential UK criticality

The scores for the three supply risk indicators and the six vulnerability indicators for each CM are shown in **Table 3** and Table 5. Weighted ***V*** indicator values were plotted against weighted ***S*** indicator values for each CM to produce a criticality matrix (Figure 1). Two thresholds were chosen (***V*** = 1.4 and ***S*** = 1.4) to distinguish four areas of differing potential UK criticality in the matrix (Figure 1; Table 6) and group the CMs into subsets. The location of some CMs on the criticality matrix (Figure 1) is affected by the absence of data in one or more of the ***V*** indicators. In these cases, those indicators have not been accounted for in the estimation of ***V***. Dummy values have not been introduced so as to avoid additional subjective influence on the aggregated scores.

3.5.9 Stakeholder consultation on the methodology and results

The emerging outputs from the study, including the results for individual CMs were presented to key stakeholders. The approximately one-hour consultation meetings typically took the form of BGS describing the scope and objectives of the assessment of minerals critical to the UK, ahead of presenting a worked example of the criticality assessment for a specific CM. The CM selected was generally based on the specific interest and expertise of the stakeholder. The stakeholders were specifically asked to comment on the criticality methodology, indicators and metrics used, the quality of the underlying data and data sources, the scoring of the indicators and the overall criticality results for the CM. Where time permitted the feedback and any new information and data received was used to refine the methodology and update the analysis. The stakeholder engagement broadly validated the methodology employed and the results. However, it also illustrated the power of a broad and more timely stakeholder engagement in any study, including the importance of having sufficient time to take on board the comments and address uncertainties and data gaps based on new information received.

Indicator	Rationale	Description	Main data sources	Age of data/ source
Production evolution	High growth rates in mineral demand (production is used as a proxy) increase vulnerability if supply cannot adequately respond	Compound annual growth rate of global production of the CM is calculated over 9 years	BGS World Mineral Statistics database	2010–2018
Price volatility	Uncertainty and fluctuating commodity prices can impact consuming countries	Price volatility over the period Jan. 2016–Dec. 2021, or when unavailable, for Oct. 2020–Sep. 2021.	DERA Volatilitätsmonitor (BGR, 2021): no data for Re, Be and Sr prices; Re from BRGM	2016–2020
Substitutability	Substitution may reduce the economic impact of supply disruption of certain materials	Index of substitutability of the CM in its major applications based on technical performance and material cost of the substitute	Study on the EU's list of Critical Raw Materials, Annex 4 (European Commission, 2020a)	2020
Global trade concentration	Countries that dominate global imports of a material are in a position to control the production and trade of products further down the value chain	Global trade concentration is calculated from the share of trade in a CM (based on the form of the CM that UK imports in greatest volumes) that is taken by the top three net importing countries	UN Comtrade Database	2015–2019
UK import reliance	The UK is heavily reliant on imports of raw materials and intermediate products. It is therefore vulnerable to disruption of these supplies, which will be influenced by where its imports are sourced	Net import reliance, calculated from trade data (based on the form of the CM that the UK imports in greatest volumes) is modified by the degree of concentration of UK trading partners, governance in these countries and any trade restrictions	UK Trade Info (HM Revenue and Customs, 2021); BGS World Mineral Statistics database; PRODCOM (Office for National Statistics, 2020); Worldwide Governance Indicators (World Bank Group, 2021); Inventory of Export Restrictions (OECD, 2020)	2015–2019 2020
UK GVA contribution	Raw materials and intermediate products are vital to UK manufacturing, which makes a significant contribution to the economy	UK GVA contribution from CM end-use applications in UK manufacturing. Applications are mapped to 2-digit level 'Manufacturing' codes, against which GVA is reported and the contribution of the CM to each code calculated according to level of use	Application shares (various); GVA data (Office for National Statistics, 2021a,b).	Various 2018

Table 4 Summary of UK economic vulnerability indicators used in the assessment of minerals critical to the UK.

Candidate material	UK economic vulnerability (V) indicator scores: Production evolution (PE)	Price volatility (PV)	Substitutability (SB)	Global trade concentration (GTC)	UK import reliance (IR)	UK GVA contribution (GVA)	UK economic vulnerability (V)	Weighted PE (8%)	Weighted PV (10%)	Weighted SB (2%)	Weighted GTC (10%)	Weighted IR (50%)	Weighted GVA (20%)	Sum of weighted V indicators
antimony	1	2	2	1	2	2	10	0.1	0.2	0.0	0.1	1.0	0.4	**1.8**
beryllium	1		3	2	2	3	11	0.1	0.0	0.1	0.2	1.0	0.6	**1.9**
bismuth	2	2	3	2	1	2	12	0.2	0.2	0.1	0.2	0.5	0.4	**1.5**
cobalt	2	3	2	3	1	2	13	0.2	0.3	0.0	0.3	0.5	0.4	**1.7**
gallium	3	3	3		2	2	13	0.2	0.3	0.1	0.0	1.0	0.4	**2.0**
germanium	1	1	2		1	2	7	0.1	0.1	0.0	0.0	0.5	0.4	**1.1**
graphite	1	1	3	1	2	1	9	0.1	0.1	0.1	0.1	1.0	0.2	**1.5**
indium	1	3	3		2	2	11	0.1	0.3	0.1	0.0	1.0	0.4	**1.8**
lithium	3	3	2	2	2	1	13	0.2	0.3	0.0	0.2	1.0	0.2	**2.0**
magnesium	1	2	2	1	3	2	11	0.1	0.2	0.0	0.1	1.5	0.4	**2.3**
manganese	1	3	3	1	2	3	13	0.1	0.3	0.1	0.1	1.0	0.6	**2.1**
molybdenum	1	1	3	2	2	3	12	0.1	0.1	0.1	0.2	1.0	0.6	**2.0**
nickel	2	3	2	3	3	2	15	0.2	0.3	0.0	0.3	1.5	0.4	**2.7**
niobium	1	1	3	1	1	3	10	0.1	0.1	0.1	0.1	0.5	0.6	**1.4**
palladium	1	3	2	1	3	3	13	0.1	0.3	0.0	0.1	1.5	0.6	**2.6**
platinum	1	2	2	1	3	2	11	0.1	0.2	0.0	0.1	1.5	0.4	**2.3**
rare earth elements	2	3	2	2	3	2	14	0.2	0.3	0.0	0.2	1.5	0.4	**2.6**
rhenium	1	1	3			2	7	0.1	0.1	0.1	0.0	0.0	0.4	**0.6**
silicon	2	2	3	2	3	2	14	0.2	0.2	0.1	0.2	1.5	0.4	**2.5**
strontium	1		2			1	4	0.1	0.0	0.0	0.0	0.0	0.2	**0.3**
tantalum	3	1	2	1	2	2	11	0.2	0.1	0.0	0.1	1.0	0.4	**1.9**
tellurium	3	2	2		3	3	13	0.2	0.2	0.0	0.0	1.5	0.6	**2.6**
tin	1	1	2	1	2	2	9	0.1	0.1	0.0	0.1	1.0	0.4	**1.7**
titanium	1	1	2	2	1	2	9	0.1	0.1	0.0	0.2	0.5	0.4	**1.3**
tungsten	1	1	2	1	2	3	10	0.1	0.1	0.0	0.1	1.0	0.6	**1.9**
vanadium	1	3	3		2	1	10	0.1	0.3	0.1	0.0	1.0	0.2	**1.6**

Rank

1. Low	2. Medium	3. High	No data

Table 5 UK economic vulnerability (***V***) indicator scores for 26 candidate materials. UK economic vulnerability is based on calculated scores for six indicators. The scores for each indicator range from 1–3. Addition of the scores for each of the six UK economic vulnerability indicators gives the 'UK economic vulnerability (V)' for each candidate material (min. = 6 and max. = 18, where all indicators are calculated). The scores for the six ***V*** indicators are weighted according to their relative importance to UK economic vulnerability. Addition of the scores for the six weighted indicators gives the ***V*** indicator value ('Sum of weighted V indicators'; min. = 1 and max. = 3, where all indicators are calculated; rows may not total due to rounding of weighted indicator scores), which defines the position of the candidate materials in the ***V*** dimension (horizontal axis) on the criticality matrix.

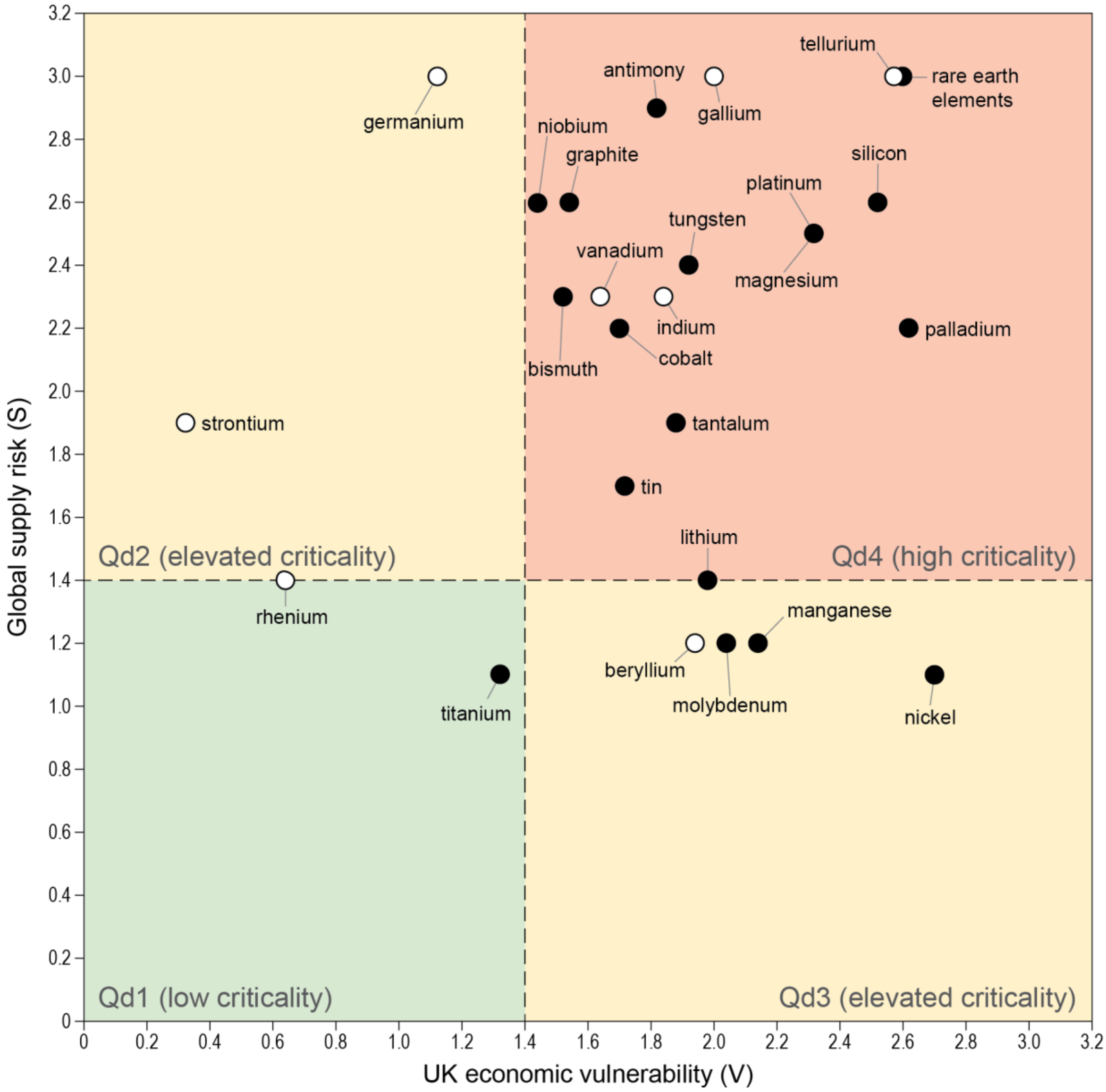

Figure 1 Assessment of 26 candidate materials potentially critical to the UK. The horizontal axis of the criticality matrix reflects the economic vulnerability of the UK (***V***) to a potential supply disruption and the vertical axis reflects the likelihood of supply disruption, termed global supply risk (***S***). Criticality thresholds (dashed lines) are set at 1.4 for ***V*** and ***S***, and define four quadrants of potential criticality: Quadrant 4 (Qd4), high potential criticality (high ***V*** and ***S***); Quadrant 3 (Qd3), elevated potential criticality (high ***V***, low ***S***); Quadrant 2 (Qd2), elevated potential criticality (low ***V***, high ***S***); and Quadrant 1 (Qd1), low potential criticality (low ***V*** and ***S***). Solid symbols indicate candidate materials that were scored on all 9 indicators. Open symbols represent those candidate materials for which one or more ***V*** indicators are absent due to no data. Therefore, for these candidate materials the aggregated ***V*** scores are not based on the full set of 6 ***V*** indicators.

Quadrant	***V***	***S***	**Potential criticality level**
Qd4	High	High	High
Qd3	High	Low	Elevated
Qd2	Low	High	Elevated
Qd1	Low	Low	Low

Table 6 Areas of differing levels of potential criticality defined on the criticality matrix (Figure 1).

4 Results and discussion

The results from the assessment of minerals critical to the UK are shown in the heat maps for global supply risk (***S***) and UK economic vulnerability (***V***) (Table 3 and Table 5), and in the CM Factsheets (Appendix 5). These tables show the weighted scores for each indicator and the sum of the weighted indicator scores, which define the position of each CM on the criticality matrix (Figure 1).

Of the 26 CMs evaluated, 18 are equal to or greater than the thresholds for both dimensions of criticality (***V*** and ***S*** ≥ 1.4), clustering in the top-right Quadrant 4 (Qd4). These are judged to have high potential criticality to the UK (Table 7). The CMs with the highest ***S*** rating are the REE, tellurium, gallium, germanium and antimony. China is the leading producer of 16 of the CMs evaluated (Table 8). Other leading producing countries are: South Africa for manganese, platinum and palladium; Chile for rhenium and lithium; Australia for lithium; Brazil for niobium; the US for beryllium; Russia for palladium; and the Democratic Republic of Congo for tantalum (Table 8).

Minerals of high potential criticality to the UK		
antimony	lithium	silicon
bismuth	magnesium	tantalum
cobalt	niobium	tellurium
gallium	palladium	tin
graphite	platinum	tungsten
indium	Rare earth elements	vanadium

Table 7 The 18 minerals assessed to have high potential criticality to the UK.

The CMs with the highest ***V*** rating are palladium, the REE, tellurium, silicon, platinum and magnesium. Given that the UK assessment was based on a selection of CMs considered critical or near-critical in several published studies (Schrjivers *et al.*, 2020), it is not surprising that 18 CMs fall within the top-right quadrant (Qd4). However, it is important to recognise that given the inherent complexities and the data shortcomings, it is inevitable that such criticality assessments will not deliver results of universal application, and also that they may fail to identify potential problems. They may suggest that certain materials are at risk when, in fact, market forces may be able to solve the problems in the short or medium term. They may also produce false negatives whereby supplies of some materials are incorrectly identified as secure (Graedel *et al.*, 2014). In this assessment, lithium, is located at the boundary of Qd4. Note that lithium was not considered critical in the 2017 EU study on CRMs (European Commission, 2017b), but does appear on the EU's 2020 list of CRMs (European Commission, 2020a). Its elevated criticality in the most recent EU assessment highlights that such studies provide only a ‘snapshot’ of a dynamic system and that a small shift in the position of a threshold or a minor change in ***S*** or ***V*** ratings can affect the criticality rating of a CM.

Two of the CMs falling within Qd4 (judged to have high potential criticality to the UK) do not appear on the EU list of CRMs 2020. Tin exceeds the EU threshold for economic importance, but is located marginally below the threshold defined for supply risk by the EU. Tellurium also exceeds the EU threshold for economic importance, but has a relatively low supply risk. In contrast, in this assessment tellurium scores consistently high for all three ***S*** indicators (***S*** = 3.0) and has elevated ***V***, plotting near the top right-hand corner of Qd4.

Beryllium, germanium, strontium and titanium appear on the EU’s list of CRMs 2020, but fall outside Qd4 in the UK assessment. Because it has high ***V*** but low ***S***, beryllium is located in Quadrant 3 (Qd3). Strontium and germanium are located in Quadrant 2 (Q2) respectively owing to their low ***V*** and elevated to high ***S***. Located in Quadrant 1 (Qd1), titanium is situated proximal to the ***V*** threshold but overall has low potential criticality. Other CMs outside Qd4 (high potential criticality) are located in Qd2 (rhenium) and Qd3 (manganese, molybdenum, nickel). Their slightly lower level of potential criticality is broadly consistent with the results of the 2020 EU study on CRMs in which they were not designated critical. In common with the EU 2020 study, in this assessment both manganese and molybdenum have elevated ***V*** and plot proximal to the ***S*** threshold. As in the 2020 EU study, this assessment shows nickel has elevated ***V*** but low ***S***. Rhenium had amongst the lowest economic importance and supply risk scores in the 2020 EU study. However, in this UK assessment rhenium falls on the boundary of Q2 and has elevated potential criticality.

Direct comparison with the results of the US draft Critical Minerals List of 2021 (Nassar and Fortier, 2021) are less straightforward as it assesses criticality in three dimensions and provides a quantitative ranking of 54 non-fuel mineral commodities. The US draft list takes a US perspective on criticality and uses a complex methodology that has been considerably refined and updated since it was first published (McCullough and Nassar, 2017). Another major contrast with the UK is in the scale and composition of the key industrial sectors in the US and the associated economic vulnerability related to specific commodities. Furthermore, the US has significant domestic production of some of the CMs which moderates the supply risk for the US This is most notable for beryllium (rank = 43) where the US accounts for about 70 per cent of global production; for molybdenum (c. 14% of world production; rank = 51); rhenium (c. 16% of world production; rank = 40); and palladium (c. 6% of world production).

Nevertheless, the results of this UK assessment are broadly consistent with the US list, with gallium, niobium, cobalt, selected REE and platinum ranking in the top ten commodities on the US draft Critical Minerals List, and bismuth, antimony, tantalum and tungsten ranking in the top 20 commodities evaluated. The other CMs that fall in Qd4 are ranked in the following order in the US draft Critical Minerals List: vanadium (21), tin (22), magnesium (23), palladium (25), graphite (28), indium (32), lithium (35), and tellurium (36). Silicon was not evaluated by the US study. The CMs that fall within Qd3 and have elevated criticality in the UK assessment mostly occur further down the US draft Critical Minerals List i.e. nickel (41), beryllium (43), molybdenum (51), owing to their relatively low supply risk. In contrast to the UK study, the US assessment considers manganese to have greater supply risk than these other commodities, ranking it at 34. The US assessment considers germanium (rank = 24) to have moderate supply risk, which is the dimension that gives germanium elevated criticality in the UK study. Strontium which also falls in Qd2 is assessed to have low economic vulnerability by the US study (rank = 39), which is consistent with the UK results. The US evaluated rhenium to have low supply risk and economic vulnerability, which is broadly consistent with its position in the UK study. Titanium, the only CM located in Qd1, is ranked 26 by the US assessment owing to its moderate supply risk and elevated economic vulnerability. The UK assessment places it proximal to the ***V*** threshold, therefore, a small change in its score for this dimension or a minor change in the position of the threshold would move it into a quadrant of elevated potential criticality.

Whilst absent from this assessment, the US draft Critical Minerals List awarded a high rank to various individual REEs and PGMs (that were evaluated separately), aluminium (8), fluorspar (9), hafnium (19), zinc (27) and chromium (29).

Candidate material	Leading producer	Global production (%)
antimony	China	60
beryllium	USA	71
bismuth	Vietnam	40
cobalt	China	56
gallium	China	90
germanium	China	89
graphite	China	63
indium	China	62
lithium	Australia	53
magnesium	China	90
manganese	South Africa	28
molybdenum	China	42
nickel	China	30
niobium	Brazil	88
palladium	Russia	39
platinum	South Africa	71
rare earth elements	China	78
rhenium	Chile	54
silicon	China	79
strontium	Spain	34
tantalum	Democratic Republic of Congo	35
tellurium	China	69
tin	China	49
titanium	China	34
tungsten	China	81
vanadium	China	53

Table 8 Leading producers of the candidate materials and their proportion of world production, based on 5-year average production data.

5 Data issues and limitations

Any quantitative assessment of criticality fundamentally depends on the data used for the metrics that contribute to ranking the chosen indicators. Where such data are absent or unreliable, the quality of the assessment are inevitably degraded. In this study, where data are absent it was decided not to include values based on our own judgement. It was considered that such gaps are best filled by experts who have appropriate and up-to-date knowledge of a particular metric, or in some cases by acquiring new data from commercial databases.

In order to determine their suitability for this study, the quality of all the datasets used to provide the metrics for each indicator was assessed in a qualitative manner. The factors evaluated for each metric were:

- Geographical coverage
- Data aggregation; ability to resolve the required level of detail; data gaps
- Reliability of data sources, assumptions, uncertainties and quality controls
- Suitability (relevance of the metric to its indicator)
- Age of dataset and frequency of updates
- Type of data source (public, commercial, free, subscription)

Using these indicators, a data quality rating was determined:

1. Poor quality data
2. Satisfactory quality data
3. Good quality data

The main sources of data used in this assessment are large, regularly-updated databases, such as those maintained by the United Nations, the European Commission, the UK government and BGS. Other data have been taken from government and company technical reports, and from peer-reviewed papers in the scientific literature. These sources vary considerably in terms of age and relevance, but were included because no suitable alternatives were available.

The data quality rankings of the main data types used in this assessment are summarised in Table 9.

5.1 WORLD MINERAL PRODUCTION DATA

Data for annual production of each CM was used in the global production concentration and production evolution indicators.

The annual production of numerous metals and minerals is reported by BGS and USGS using procedures established for many decades. In this study, we used BGS data because we are confident of its quality and few revisions are made to the data after publication. The BGS database compilers aim for integrity and accuracy in the data and, for quality control purposes, participate in international specialist groups, and maintain close links with other mineral statistics providers in Europe and North America. In this study, production data averaged over the five-year period 2015–2019 was used for the calculation of production concentration.

There is some inevitable uncertainty in reported global mineral production data because it is derived from hundreds of overseas sources, mainly government agencies, whose quality assurance procedures are not always well understood. In a few instances, there is also a lack of clarity over what material form is being reported, or what the contained metal content of that form actually is. For example, in reporting a global mine production figure for lithium in terms of tonnes of lithium metal, BGS acquires data reported for production from both hard-rock deposits and from brines. In some cases the mine production is reported as tonnes of ore produced, while in others it may be as tonnes of a mineral concentrate. Additional complexity arises because the lithium may be contained in different mineral species (e.g. spodumene or lepidolite) within the ore from which the lithium is extracted. This is further complicated because the minerals themselves may vary in composition within, or between individual orebodies. Consequently, it is necessary to make some generalised assumptions for these variables in order to define a reliable estimate of the lithium metal produced by each country. The aggregation of these national estimates allows the global total to be derived. Similar issues arise in the calculation of global production for tantalum and niobium.

Beyond a small community of expert practitioners, data uncertainties of this nature are not widely known. However, they have serious implications for sustainable resource management which inevitably depends on a sound understanding of the physical stocks and flows of materials that make up the physical economy. The EU MinFuture project examined many of these uncertainties for mineral production and trade data, and made many recommendations to assist with their resolution (MinFuture, 2018).

For several minor metals (mostly obtained as by-products industrial metal processing) such as indium, tellurium, gallium and germanium, production data may either be absent on grounds of commercial confidentiality, or infrequently reported by the refiners that extract them. Reported global totals are therefore poorly-constrained for these CMs, and are generally estimated on the basis of past data and/or expert knowledge (McNulty and Jowitt, 2020).

Data type	Associated indicators in this study	Data sources	Data quality (3, good; 2, satisfactory; 1, poor)
World mineral production	Production concentration; production evolution	BGS World Mineral Statistics database	3
Governance indicators	Production concentration; UK import reliance	World Bank Group WGI	3
Companion metal fraction	Companion metal fraction	Nassar *et al.*, (2015)	2
EOL-RIR (recycling rate)	Recycling rate	European Commission (2020a)	1
Price volatility	Price volatility	DERA/BGR	3
Substitution index	Substitutability	European Commission (2020a)	1
Global trade	Global trade concentration; UK import reliance	UN Comtrade	3
UK imports/exports	UK import reliance	UK Trade	2
UK trade restrictions	UK import reliance	OECD	1
End-use applications	UK GVA contribution	Numerous	2
UK GVA by SIC 2007	UK GVA contribution	Office for National Statistics (2021a,b)	3

Table 9 Summary of data types, data sources and data quality used in this study.

The ‘Production Evolution’ indicator uses BGS World Mineral Production data for the period 2010–2018. Data for 2019 have been omitted because of the apparent influence of the COVID-19 pandemic in disrupting typical production levels of some CMs. The ‘Compound Annual Growth Rate’ (CAGR) is calculated from the difference between global production in 2018 and in 2010.

This indicator would have greater value if the CAGR were compared with forecasts of future demand for the CMs. However, such forecasts that exist do not cover all CMs and have not been produced by a single organisation or author (e.g. European Commission, 2020b; JRC, 2020; Watari *et al.,* 2020; World Bank Group, 2020; Fraser *et al.,* 2021; IEA, 2021). Furthermore, these estimates also vary in the timescales they consider and the scope of their coverage, both geographically, and in terms of the application sectors considered.

5.2 GOVERNANCE QUALITY DATA

The Worldwide Governance Indicators (WGI) produced by the World Bank Group were used in the production concentration and UK import reliance indicators. The WGI was utilised to take account of the standards of governance in the main global producing countries and in those countries that are the main sources of the UK's imports of each CM.

These indicators are long established and are considered to be the most reliable and relevant for this study. However, other indices are available that also take account of a producing country's ability to supply raw materials. For example, the Policy Potential Index (PPI), published annually by the Fraser Institute, relates specifically to the attractiveness of a country for mining investment and the ability of that country to continue to carry out mining (Yunis and Aliakbari, 2020). The USGS used the PPI to derive an Ability to Supply Index (ASI), which takes account of many factors in producing countries including political stability, security, availability of labour, adequacy of infrastructure, trade barriers, regulations, taxation and land access (Nassar *et al.*, 2020). In the same publication, the USGS also developed a Willingness to Supply Index (WSI) in their evaluation of mineral commodity supply risk to the US manufacturing sector. The WSI assessed trade, ideological ('shared values') and defence issues between the US and its trading partners.

5.3 COMPANION METAL FRACTION

Nassar *et al.* (2015) published the only available systematic assessment of the proportions of metals/metalloids that are extracted as by-products of another, parent metal. These data, published for 63 metals/metalloids, are considered to be informed estimates for 2008 and were based on industry information, published literature and expert consultation. While mineral supply is inherently dynamic in nature, given the long lead times and expense involved in establishing new refining capacity, the published data are considered to be reasonably reliable (i.e. satisfactory quality). For some CMs, production will have increased significantly in recent years in response to changing demand patterns. However, given that the parent-daughter relationship is immutable, the by-product proportion is unlikely to have changed greatly and the companion metal fraction will be broadly similar to those reported by Nassar *et al.* (2015)

5.4 RECYCLING RATES

Data for the end-of-life recycling input rates for individual CMs are generally poor and outdated. In this study, we used the rates compiled for the EU 2020 criticality assessment (European Commission, 2020a) as it is the most complete, publicly accessible compilation for a wide range of materials. Some of these data have been estimated using a detailed Material Systems Analysis (MSA) methodology implemented by the EC (Talens Peiro *et al.*, 2018), although many are derived from a compilation published by the United Nations in 2011 (Graedel *et al.,* 2011). The quality of this dataset is therefore rated as 'poor'.

5.5 PRICE VOLATILITY DATA

The price data used in the calculation of price volatility for some CMs are published at frequent intervals (daily or more frequently) by various trade bodies, companies and metal exchanges, such as the London Metal Exchange (LME). For others, particularly those with very small markets (where annual production is a few tens or hundreds of tonnes, such as rhenium, indium and tellurium) and which are not traded on the open market, accurate and regular price data are difficult to obtain. In many cases, they are estimated by industry experts and are only available on a subscription basis.

In this study, we have used price volatility data which is published monthly by the Federal Institute for Geosciences and Natural Resources (BGR) and German Mineral Resources Agency (DERA). (BGR, 2021). This is calculated from daily price data sourced from the LME and other specialist providers of data on mineral commodities. The quality of this data are considered to be generally high, although for two CMs (beryllium and strontium) no price volatility data are available in the public domain. Rhenium data was obtained from BRGM, the

French geological survey. Its price volatility was calculated using the same method applied by BGR/DERA.

5.6 SUBSTITUTABILITY

The main challenge in estimating values for this indicator relate to the difficulty of encapsulating the degree of substitutability in a single number ('Substitution Index') for all applications of each CM. Since they are based solely on expert opinion, this index is entirely subjective. The quality of the dataset used in this study, obtained from the EU 2020 assessment (European Commission, 2020a), is therefore rated as 'poor'.

5.7 GLOBAL TRADE DATA

The trade data used in the calculation of the global trade concentration and the UK import reliance indicators was sourced from the UN Comtrade database (United Nations Statistics Division, 2021). This is a long-established database that is widely used in criticality assessments (e.g. European Commission, 2020a). However, the data availability for several individual CMs is constrained by the UN Comtrade coding system which aggregates data for multiple commodities under a single code. Consequently, for several CMs, including gallium, germanium, rhenium, strontium, tellurium and vanadium, no separate trade data are available for many of the different forms traded. For example, commodity code HS8112 includes beryllium, germanium, gallium, vanadium, indium and rhenium. According to UN Comtrade the UK reported imports of 1,965 tonnes in 2019 against this code. However, it is not possible to determine how many tonnes of each commodity (beryllium, gallium, etc.) were contained in that trade flow. In cases where trade data for a CMs are aggregated with others, it was not possible to calculate the global trade concentration. As a consequence this indicator was omitted from the calculation of vulnerability for such materials (shown as grey cells in Table 5).

5.8 UK TRADE DATA AND TRADE RESTRICTIONS

For the calculation of UK net import reliance, data were acquired from UK Trade Info (HM Revenue and Customs, 2021). UK import and export data were obtained for all traded material forms of each candidate material for the period 2015–2019. Average volumes for that period were calculated and these converted to contained metal using published or assumed metal content values for each form. This step introduces a degree of uncertainty to the derived trade volumes, but is essential for comparing the amount of metal contained in each traded form and allows comparison between CMs.

The importance of the calculation of the metal content can be illustrated by reviewing UK imports of three forms of titanium. The average import volume of titanium concentrates between 2015–2019 is c. 247 000 tonnes with an assumed average metal content of 33 per cent titanium. For unwrought and powder titanium the import volume is c. 11 000 tonnes with an average metal content of 95 per cent titanium, while for titanium oxides the volume is c. 5 000 tonnes with an average metal content of 58 per cent titanium.

For each candidate material, it was necessary to determine those countries from which the UK imports are sourced in greatest quantities. This trade partner information was extracted from the UK Trade Info (HM Revenue and Customs, 2021). This database contains trade information for most CMs, for the years 2015–2019, at a suitable resolution (i.e. individual trade codes for each candidate material). Therefore, the quality of this dataset is rated 'good'.

Information on trade restrictions potentially affecting exports of raw materials to the UK from specific countries is provided by the OECD. The OECD dataset covers the period 2015–2019, but does not include data for all countries or all CMs (e.g. Te, Ge, In). The resolution of the data are also poor since it does not distinguish between the existence of trade quotas, tariffs or embargoes, which can impact the economic vulnerability to differing degrees.

5.9 UK MATERIAL USAGE AND GVA DATA

The assessment of the UK GVA contribution requires data on two metrics, the material end-use applications, together with GVA data for key UK manufacturing sectors.

The contribution of each candidate material to the UK economy was based on elements of the EU methodology for the calculation of economic importance to the EU (European Commission, 2017b; 2020). As discussed in the UK Methodology section, the availability of reliable, complete and up-to-date compilations of candidate material end-uses is generally poor. Furthermore, the age and scope of the reported data vary considerably and sometimes differ in terms of whether they strictly refer to first-use or end-use. For example, tungsten first use is dominated by cemented carbides and steels and alloys, whilst important end-uses applications include the automotive, mining and construction and defence sectors. Some compilations are more than ten years old, while some provide a breakdown of uses across the globe, and other compilations are restricted to the EU only. There are no available data for current usage within the UK.

The age of the dataset for end-use applications is particularly significant for those CMs where the application shares have changed significantly in recent years. For example, in the EU 2020 assessment just 3 per cent of cobalt use in the EU was allocated to 'batteries' on the basis of 2015 data from the Cobalt Institute (European Commission, 2020c). In this study, the share of cobalt use allocated to 'batteries' was 57 per cent, based on 2020 global data from the Cobalt Institute (Cobalt Institute, 2021).

End-use application data for each candidate material was mapped to the corresponding UK manufacturing sectors, against which the ONS reports GVA data. The GVA of those sectors was then used to estimate the contributions of each candidate material to each sector. Although these UK-specific datasets are regularly updated and are of high quality, this assessment would benefit considerably from a more detailed breakdown of UK manufacturing activity and matching GVA data. This approach is also limited where components, products and manufacturing activities are allocated in the 2 digit level SIC codes defined by ONS (2009). For example, the 'Manufacture of batteries and accumulators' and 'Manufacture of wiring and wiring devices' fall within Division 27: 'Manufacture of electrical equipment'. However, this takes no account of the uses (and therefore, GVA contribution) of these components in other industrial sectors, for example, automotive and aerospace, which have their own Divisions, 'Manufacture of motor vehicles, trailers and semi-trailers' and 'Manufacture of other transport equipment', respectively.

The data used in this study for evaluation of the UK GVA indicator is therefore rated as being of 'satisfactory' quality.

6 Conclusions and lessons learnt

Minerals and metals are vitally important for the delivery of a decarbonised economy and to ensure the long term security and economic well-being of the UK. However, many other countries have similar goals and all, therefore, require adequate, secure and sustainable supplies of raw materials. Although the UK is a significant minerals producer, especially of construction materials, industrial minerals and fertilizer minerals, it lacks significant domestic production of most metals and many other mineral-derived products and is therefore, heavily reliant on imported supplies. Consequently the UK is potentially vulnerable to any disruption in the supply of these materials. Understanding UK vulnerability by carrying out a criticality assessment is the first stage in developing a domestic critical minerals strategy for securing technology-critical minerals and metals.

The criticality assessment methodology developed in this study broadly follows international best practice and employs the best publicly-available UK-relevant information and understanding. The methodology is reproducible and transparent, with all data sources explicitly identified and the underlying calculation forms provided.

This preliminary assessment provides an early warning of minerals potentially critical to the UK economy. It considers 26 CMs, which were selected chiefly on the basis of the results of previous criticality studies conducted elsewhere. These were assessed for their potential criticality to the UK economy in terms of their global supply risk (***S***) and the UK economic vulnerability (***V***) to such a disruption. Three indicators were used in this study to estimate ***S*** for each candidate material: production concentration, companion metal fraction and recycling rate.

V was calculated from six indicators: production evolution, price volatility, substitutability, global trade concentration, UK import reliance and UK gross value added (GVA) contribution. Thresholds assigned to ***S*** and ***V*** were used to distinguish CMs of differing levels of potential criticality. Eighteen of the 26 CMs have a 'high' potential criticality rating based on their values of both ***S*** and ***V***. These comprise: antimony, bismuth, cobalt, gallium, graphite, indium, lithium, magnesium, niobium, palladium, platinum, rare earth elements, silicon, tantalum, tellurium, tin, tungsten and vanadium. These results are broadly comparable with those published for other advanced economies.

Any quantitative assessment of criticality depends fundamentally on its scope and objectives. These factors determine the indicators selected to estimate ***S*** and ***V*** and the metrics chosen to provide quantitative measurements of each indicator. The availability, quality and representativeness of the datasets employed provide fundamental limits on the reliability of the scores calculated for each indicator. Additional variation is derived from the methods chosen for weighting and aggregation of the indicators and the selection of thresholds to separate CMs with differing levels of potential criticality.

It is also important to note that raw material supplies are sourced in diverse forms from highly complex, dynamic international supply chains. Disruption to supply can occur at any point in the supply chain resulting from diverse causes, typically of economic, geopolitical, environmental or social character. It has not been possible in this study to take account of all traded forms of individual CMs. This is because data availability precludes the integrated and consistent assessment of all variants (e.g. ores and concentrates, refined metals, metal compounds and alloys, and intermediate products) for all CMs.

The indicators selected for this assessment were based on those commonly used in criticality assessment studies conducted elsewhere. Two of the nine indicators are UK specific, namely, UK import reliance and UK GVA contribution. This limited UK specificity reflects the global nature of mineral markets and the many externalities that affect security of mineral supply. Although reliable data on trade partners and traded volumes are available, the data for several CMs, mostly minor metals, is commonly aggregated and thus lacks the detail needed for this assessment. High uncertainty is associated with the assessment of the contribution of a candidate material to UK GVA, owing to the way the indicator is derived and the lack of UK-specific data on end-use applications. There are few up-to-date compilations for some of the other indicators, such as recycling rate, companion metal fraction and substitutability. Consequently many assumptions and generalisations are required to define appropriate values for these.

The stakeholder engagement undertaken in this study demonstrates that UK consumers of critical minerals and allied industry associations are an important source of data and information, and have detailed knowledge of the global raw material supply chains that their businesses rely on. They are frequently best placed to assess risks in specific applications and industrial sectors, and proved willing to share information and data to enhance the assessment.

Most criticality assessment methodologies require data aggregation at various stages in the analysis. The number of aggregation stages and the aggregation methods employed will influence the results of the assessment. Aggregation results in loss of information and in this study both aggregated and disaggregated indicator data are presented (Table 3 and Table 5).

Application of thresholds to distinguish critical from non-critical minerals continues to be widely debated in the scientific literature. The thresholds selected for ***S*** and ***V*** in this study were chosen by the research team based on the objectives and scope of the assessment.

Whilst the systematic quantitative approach taken in this assessment promotes transparency and reproducibility, it cannot adequately reflect the complexities of global raw material supply chains for all CMs. Given the dynamic and complex nature of mineral supply chains and the inherent data shortcomings, it is inevitable that such criticality assessments may fail to identify potential problems. Significant change can occur at any time in response to altered global circumstances, be they political, economic, environmental or social in nature. They may also suggest that certain minerals are at risk when, in fact, market forces may be able to resolve supply bottlenecks in the short or medium term. It should be noted that both the EU and the US undertake regular review and revision of potentially critical raw materials. On each occasion the methodology is also refined, although, in order to facilitate comparison with previous assessments and to monitor trends, such revision should be kept at a minimum.

It is also vitally important to stress that any criticality assessment is based on existing data and understanding. It cannot, therefore, be used to predict future security of supply problems or trajectories of mineral demand.

7 Recommendations

1. **Methodology refinement:**
   - ***Indicator selection:*** the choice of indicators used to calculate ***S*** and ***V*** should be reviewed, considering their relevance to UK security of mineral supply, their representation of the factors under consideration, data availability and quality, and the objectives and scope of the study.
   - ***Data aggregation methods:*** various approaches should be explored, including how several metrics are combined to produce a composite single indicator score (e.g. UK import reliance); the way indicators can be aggregated to arrive at a score for a specific dimension (e.g. ***V***); and the validity of aggregating different indicator scores to derive a single candidate raw material-specific score. The influence of indicator selection and aggregation methods on the final results of the assessment could be evaluated via a sensitivity analysis. Increased understanding of the relevance of indicators for different purposes could help prioritise data collection efforts and improvements.
   - Uncertainty analysis: interpretation and communication of the results of critically assessment may benefit from calculating uncertainty ranges for the data sources used.
   - ***Definition of criticality thresholds:*** application of thresholds and the process for their selection requires further investigation, including stakeholder consultation.

2. **Data enhancement:** data used in criticality assessment should be up-to-date and, as far as possible, UK-specific.
   - In some instances, with more time, permitting detailed investigation and manipulation of data from public domain sources and through consultation with third party data holders (e.g. ONS, HMRC, HM Treasury) it may be possible to address certain data deficiencies for some metrics.
   - Assess the availability of higher quality and UK-focussed data from commercial sources.
   - In parallel with existing initiatives (e.g. National Materials Datahub; Interdisciplinary Circular Economy Centre for Technology Metals – Met4Tech Virtual Data Observatory), improving data (including quality, harmonisation via common standards, timeliness, access) on stocks and flows of critical minerals along their entire value chains should be considered as part of the National Data Strategy.

3. **Stakeholder engagement:** an important adjunct to the quantitative assessment of potential
   - UK criticality is consultation with a broad range of stakeholders who have in-depth knowledge of the global demand and supply of individual materials and of potential issues for the UK economy.
   - Expert knowledge of the complete value chain of each critical mineral should be used to complement the data used in this quantitative study, to test the emerging results and to assist in improving the quality of future assessments.
   - Best practice for future UK criticality assessments should involve using a combination of quantitative assessment and in-depth stakeholder consultation for all CMs.

4. **Expansion of scope and updates:**
   - ***Assessment of a wider range of CMs*****:** minerals omitted from this study should be considered for inclusion in future assessments as the global raw materials supply landscape changes and technology trajectories evolve.
   - ***Consideration of different mineral forms:*** future assessments should attempt to differentiate between the criticality of different traded forms (e.g. ores and concentrates, refined metals, specific compounds) of a candidate material that are important to the UK economy. However, it is important to recognise that this would still not account for UK reliance on critical minerals embedded in imported components and finished goods, such as tantalum in circuit boards, rare earth elements in magnets that are used electric motors or lithium and cobalt in lithium-ion batteries incorporated in electric vehicles.
   - ***Timely revision:*** regular review and re-assessment of potentially critical raw materials to the UK at intervals not exceeding 3 years.

5. **Further investigations:**
   - ***Detailed studies of specific CRMs:*** minerals with the greatest potential UK criticality should be prioritised for detailed studies of their entire value chains in order to determine appropriate interventions to ensure security of supply.
   - ***Foresight studies:*** although forecasting future demand for raw materials is fraught with uncertainty, it is essential to maintain a good understanding of future drivers of global CRM demand, how competition for CRMs may evolve and potential supply bottlenecks that might impact on the UK. Integral to this is the development of improved understanding of UK-specific demand for CRMs, with an emphasis on the strategic technologies and sectors that underpin the policy objectives of the government. This should be informed by close engagement with key stakeholders in UK manufacturing (e.g. electric mobility, aerospace and defence, renewable energy).

Appendix 1

SUMMARY OF THE MINERAL FORMS ANALYSED FOR EACH INDICATOR FOR EACH CANDIDATE MATERIAL AND THE DATA SOURCES USED IN THE IN THE ASSESSMENT OF MINERALS CRITICAL TO THE UK

	Global Supply Risk indicators			UK Economic Vulnerability indicators					
Main data source	World Mineral Statistics Database World Bank Group WGI	Nassar *et al.*	EU CRM Assessment	World Mineral Statistics Database	DERA Volatilitätsmonitor	EU CRM Assessment	UN Comtrade	UK Trade OECD World Bank Group WGI ONS (Prodcom) World Mineral Statistics Database	ONS
Age of data source	2015-2019 2015-2019	2015	2020	2010-2018	2016-2020	2020	2015-2019	2015-2019 2020 2015-2019 2015-2019 2015-2019	2018
Candidate material	Production concentration	Companion metal fraction	Recycling rate	Production evolution	Price volatility	Substitutability	Global trade concentration	Import reliance	UK GVA contribution
antimony	ores & concs (metal content)	ores & concs	N/A	ores & concs (metal content)	metal	N/A	antimony oxide	antimony oxide	multiple forms
beryllium	ores & concentrates	ores & concs	N/A	ores & concentrates	no data	N/A	beryllium metal	beryllium metal	multiple forms
bismuth	ores & concs (metal content)	ores & concs	N/A	ores & concs (metal content)	metal	N/A	bismuth metal	bismuth metal	multiple forms

cobalt	ores & concs (metal content) refined metal	ores & concs	N/A	ores & concs (metal content) refined metal	metal	N/A	cobalt metal	cobalt metal	multiple forms
gallium	refined metal	ores & concs	N/A	refined metal	metal	N/A	no data	gallium metal	multiple forms
germanium	refined metal	ores & concs	N/A	refined metal	germanium dioxide	N/A	no data	germanium metal	multiple forms
graphite	ores & concs	no data	N/A	ores & concs	flake graphite	N/A	natural graphite	natural graphite	multiple forms
indium	refined metal	ores & concs	N/A	refined metal	metal	N/A	no data	indium metal	multiple forms
lithium	ores & concs (metal content)	ores & concs	N/A	ores & concs (metal content)	lithium carbonate	N/A	lithium carbonate	lithium carbonate	multiple forms
magnesium	refined metal	ores & concs	N/A	refined metal	metal	N/A	magnesium metal	magnesium metal	multiple forms
manganese	ores & concs	ores & concs	N/A	ores & concs	metal	N/A	manganese oxide	manganese oxide	multiple forms
molybdenu m	ores & concs (metal content)	ores & concs	N/A	ores & concs (metal content)	metal	N/A	molybdenum ores & concs	molybdenu m ores & concs	multiple forms
nickel	ores & concs (metal content) refined metal	ores & concs	N/A	ores & concs (metal content) refined metal	metal	N/A	nickel mattes & sinters	nickel mattes & sinters	multiple forms
niobium	ores & concs (metal content)	ores & concs	N/A	ores & concs (metal content)	niobium pentoxide	N/A	niobium metal	niobium metal	multiple forms
palladium	ores & concs (metal content)	ores & concs	N/A	ores & concs (metal content)	metal	N/A	palladium metal	palladium metal	multiple forms

platinum	ores & concs (metal content)	ores & concs	N/A	ores & concs (metal content)	metal	N/A	platinum metal	platinum metal	multiple forms
rare earth elements	ores & concs (metal content)	ores & concs	N/A	ores & concs (metal content)	neodymium oxide	N/A	cerium compounds	cerium compounds	multiple forms
rhenium	refined metal	ores & concs	N/A	refined metal	ammonium perrhenate	N/A	no data	no data	multiple forms
silicon	refined metal	no data	N/A	refined metal	metal	N/A	silicon metal	silicon metal	multiple forms
strontium	ores & concs	ores & concs	N/A	ores & concs	no data	N/A	no data	no data	multiple forms
tantalum	ores & concs (metal content)	ores & concs	N/A	ores & concs (metal content)	tantalum pentoxide	N/A	tantalum metal	tantalum metal	multiple forms
tellurium	refined metal	ores & concs	N/A	refined metal	metal	N/A	no data	tellurium metal	multiple forms
tin	ores & concs (metal content) refined metal	ores & concs	N/A	ores & concs (metal content) refined metal	metal	N/A	tin metal	tin metal	multiple forms
titanium	ores & concs (metal content)	ores & concs	N/A	ores & concs (metal content)	titanium oxide	N/A	titanium ores & concs	titanium ores & concs	multiple forms
tungsten	ores & concs (metal content)	ores & concs	N/A	ores & concs (metal content)	ammonium paratungstate	N/A	tungsten carbide	tungsten carbide	multiple forms
vanadium	ores & concs (metal content)	ores & concs	N/A	ores & concs (metal content)	ferro-vanadium	N/A	no data	vanadium metal	multiple forms

Appendix 2

CRITICALITY ASSESSMENT CALCULATION TEMPLATE INSTRUCTIONS

Supply risk

Cells highlighted PINK require user input.

TAB – 'Calculated SR'

1. Select candidate material (CM) from the drop-down list in CELL B3
2. Select the form to be assessed from the drop-down list in CELL B4

TAB – 'A – Production concentration

1. Download global production data for a CM of interest, for a five-year period, from MineralsUK (https://www2.bgs.ac.uk/mineralsuk/statistics/wms.cfc?method=searchWMS)
2. Copy and paste raw production data into the 'RAW production data' tab in the Blank SR Template. Remove all columns except 'COUNTRY' and the data columns for the five-year period of interest. Columns ending 'FTNOTE' can also be deleted.
3. Empty rows in the raw production data (i.e. rows with blank cells or X) should be deleted.
4. Copy the country list into the 'Country' column (COLUMN A) of the 'Production concentration' tab.
5. Copy production data for the five-years of interest in to columns C-G. Amend the range of years in CELLS C1 to G1 as required.
6. Calculations in columns J-N are automated, if more rows are required simply copy the formulas down.
7. A combined Production Concentration Index (PCI) figure for the top three producers will be calculated automatically in CELL R5. A PCI rank (1-3) will automatically be given in CELL S5.
8. The result in CELL S5 will automatically copy through to the 'Calculated SR' tab.
9. Make a note of data sources used in COLUMNS H and O.

TAB – 'B – Companion metal fraction'

1. Select the candidate material of interest from the drop-down list in CELL A2 in the 'Companion metal fraction' tab.
2. The corresponding companion fraction figure will automatically populate in CELL B2.
3. A companion metal fraction rank (1-3) will automatically populate in CELL C2.
4. The result in CELL C2 will automatically copy through to the 'Calculated SR' tab.
5. Make a note of data sources used in COLUMN D.

TAB – 'C – Recycling rate'

1. Select the candidate material of interest from the drop-down list in CELL A2 in the 'Recycling rate' tab.
2. The corresponding recycling rate figure will automatically populate in CELL B2.
3. A recycling rate rank (1-3) will automatically populate in CELL C2.
4. The result in CELL C2 will automatically copy through to the 'Calculated SR' tab.
5. Make a note of data sources used in COLUMN D.

TAB – 'Data sources'

1. Record data sources used here along with information about data quality.

UK economic vulnerability

Cells highlighted PINK require user input.

TAB – 'Calculated VS'

1. Select candidate material (CM) from the drop-down list in CELL B3
2. Select the form to be assessed from the drop-down list in CELL B4

TAB – 'A – Production evolution'

1. Select the candidate material of interest from the drop-down list in CELL A2 in the 'Production evolution' tab.
2. The corresponding production evolution figure will automatically populate in CELL B2.
3. A production evolution rank (1-3) will automatically populate in CELL C2.
4. The result in CELL C2 will automatically copy through to the 'Calculated VS' tab.
5. Make a note of data sources used in COLUMN D.

TAB – 'B – Price volatility'

1. Select the candidate material of interest from the drop-down list in CELL A2 in the 'Price volatility' tab.
2. The corresponding price volatility figure will automatically populate in CELL B2.
3. A price volatility rank (1-3) will automatically populate in CELL C2.
4. The result in CELL C2 will automatically copy through to the 'Calculated VS' tab.
5. Make a note of data sources used in COLUMN D.

TAB – 'C – Substitution'

1. Select the candidate material of interest from the drop-down list in CELL A2 in the 'Substitution' tab.
2. The corresponding price volatility figure will automatically populate in CELL B2.
3. A substitution rank (1-3) will automatically populate in CELL C2.
4. The result in CELL C2 will automatically copy through to the 'Calculated VS' tab.
5. Make a note of data sources used in COLUMN D.

TAB – 'D – Global trade concentration'

1. Select the candidate material of interest from the drop-down list in CELL E1 in the 'Global trade concentration' tab.
2. The corresponding global trade concentration figures will automatically populate in CELLS D4 to F4 (CM, Country and Net import share).
3. The top three importers will automatically populate CELLS I2 to I4. Similarly, the corresponding global trade concentration will automatically populate CELLS J2 to J4. The global trade concentration figures will be ranked (1-3) automatically in CELLS K2 to K4. A total (combined) global trade concentration figure will be given in CELL J5 with a corresponding rank in CELL K5.
4. The result in CELL K5 will automatically copy through to the 'Calculated VS' tab.
5. Make a note of data sources used in COLUMN G.

TAB – 'E – Import reliance'

1. Select the candidate material of interest from the drop-down list in CELL A2 in the 'Import reliance' tab.
2. The corresponding total import reliance figure will automatically populate in CELL B2.
3. An import reliance rank (1-3) will automatically populate in CELL C2.
4. The result in CELL C2 will automatically copy through to the 'Calculated VS' tab.
5. Make a note of data sources used in COLUMN D.

TAB – 'F – UK GVA contribution'

1. Select the candidate material of interest from the drop-down list in CELL A2 in the 'UK GVA contribution' tab.
2. Copy and paste application information in to COLUMN B and the corresponding application share in COLUMN C.
3. Select the most appropriate SIC07 code description from the drop-down list in CELL D2.
4. GVA £ million will automatically populate in COLUMN E when an item is chosen from the drop-down list in COLUMN E. The UK GVA contribution calculation will automatically populate COLUNM F.
5. A total UK GVA contribution will automatically be calculated in CELL I2. This will be automatically ranked (1-3) in CELL J2.
6. The result in CELL J2 will automatically copy through to the 'Calculated VS' tab.
7. Make a note of data sources used in COLUMN G.

Appendix 3

EXAMPLE OF THE CALCULATION OF SUPPLY RISK AND UK ECONOMIC VULNERABILITY INDICATORS FOR A SINGLE CANDIDATE MATERIAL: THE RARE EARTH ELEMENTS

Supply risk

Production concentration					
Top three producers	PCI of top three producers	PCI rank		Ranking	
China	30,284	3		1	Low (<10,000)
Burma	486	1		2	Medium (>10,000 to 20,000)
Australia	32	1		3	High (>20,000)
TOTAL	30,803	3			

Companion metal fraction					
Candidate material	Companion metal fraction (%)	Companion metal fraction rank		Ranking	
rare earth elements	100	3		1	Low (<33%)
				2	Medium (>33 to 66%)
				3	High (>66%)

Recycling rate					
Candidate material	Recycling rate (%)	Recycling rate rank		Ranking	
rare earth elements	5.5	3		1	High (>30%)
				2	Medium (>10 to 30%)
				3	Low (<10%)

Global supply risk (S) indicator scores				
Candidate material	Production concertation	Companion metal fraction	Recycling rate	Global supply risk
rare earth elements	3	3	3	9

UK economic vulnerability

Production evolution					
Candidate material	9-year compound annual growth rate (%)	9-year compound annual growth rate rank		Ranking	
rare earth elements	10	2		1	Low (<5%)
				2	Medium (>5 to 10%)
				3	High (>10%)

Price volatility					
Candidate material	Price volatility (%)	Price volatility rank		Ranking	
rare earth elements	29.1	3		1	Low (<15%)
				2	Medium (>15 to 20%)
				3	High (>20%)

Substitutability						
Candidate material	Substitution index	Substitution index rank		Ranking		
rare earth elements	0.9	2		1	Low (<0.8)	*Substitutable*
				2	Medium (>0.8 to 0.95)	*Possibly substitutable*
				3	High (>0.95)	*Not substitutable*

Global trade concentration									
Candidate material	Country	Net import share		Top importers	Global trade concentration	Rank		Ranking	
cerium compounds	Japan	27%		Japan	27%	1		1	Low (<33%)
cerium compounds	USA	10%		USA	10%	1		2	Medium (>33 to 66%)
cerium compounds	Estonia	6%		Estonia	6%	1		3	High (>66%)
cerium compounds	Germany	4%		**TOTAL**	44%	2			
cerium compounds	Rep. of Korea	3%							

UK import reliance					
Candidate material	Total import reliance*	Total import reliance rank		Ranking	
cerium compounds	10	3		1	Low (<6)
				2	Medium (>6 to 8)
				3	High (>8)

UK GVA contribution								
Candidate material	Application	Application share (%)	SIC07 code description	GVA £ million (2018)	UK GVA contribution		Total UK GVA (£ million) contribution	UK GVA contribution
rare earth elements	Magnets	29	27 - electrical equipment	4,801	1,392		8,066	2
rare earth elements	Catalysts	21	20 - chemicals and chemical products	10,581	2,222			
rare earth elements	Polishing	13	26 - computer, electronic and optical products	13,564	1,763			
rare earth elements	Metallurgy	8	24 - basic metals	4,026	322		Ranking	
rare earth elements	Glass	8	23 - other non-metallic mineral products	5,712	457		1	Low (<£8 billion)
rare earth elements	Batteries	7	27 - electrical equipment	4,801	336		2	Medium (>£8 to £13 billion)
rare earth elements	Ceramics	4	23 - other non-metallic mineral products	5,712	228		3	High (>£13 billion)
rare earth elements	Phosphors	1	26 - computer, electronic and optical products	13,564	136			
rare earth elements	Pigments	0.4	20 - chemicals and chemical products	10,581	42			
rare earth elements	Other	8.6	26 - computer, electronic and optical products	13,564	1,167			

UK economic vulnerability (V) indicator scores							
Candidate material	Production evolution	Price volatility	Substitution	Global trade concentration	Import reliance	UK GVA contribution	UK economic vulnerability
rare earth elements	2	3	2	2	3	2	14

Appendix 4

SUBSTITUTION INDEX VALUES USED IN THE SUBSTITUTABILITY INDICATOR

Candidate material	Substitution Index (source: European Commission, 2020a)
antimony	0.92
beryllium	0.99
bismuth	0.96
cobalt	0.92
gallium	0.98
germanium	0.95
graphite	0.99
indium	0.97
lithium	0.93
magnesium	0.93
manganese	1
molybdenum	1
nickel	0.83
niobium	0.97
platinum group metals (group average)	0.9
rare earth elements	0.9
rhenium	0.98
silicon	0.99
strontium	0.93
tantalum	0.95
tellurium	0.86
tin	0.9
titanium	0.92
tungsten	0.95
vanadium	0.98

Appendix 5

CANDIDATE MATERIAL FACTSHEETS

Material name / element symbol / parent group	**Antimony, Sb**		
Potential UK Criticality	HIGH		
Global Supply Risk (1-3)	3.0		
UK Economic Vulnerability (1-3)	1.8		
Key Facts			
Major end uses (EU)	Flame retardants (43%); lead-acid batteries (32%); lead alloys (14%)		
World production (tonnes; average 2015-2019)	159,258		
Major world producers (% of average total 2015-2019)	China (60%), Tajikistan (16%), Russia (11%)		
By-product status	Antimony is generally a co-product with gold; it may also be a by-product of lead mining.		
End of Life Recycling Input Rate (global)	28%		
UK production / import reliance	0 / 100%		
Major global trading countries (average net imports 2015-2019)	USA (15%), Germany (8%), Other Asia (6%), Japan (5%), Italy (5%)		
UK trade – main forms traded; top three trading partners	Antimony oxide, antimony metal Belgium, France, Germany		
Current importance to UK manufacturing (GVA contribution of key applications)	£9,239 million GVA.		
Importance to UK policy objectives	Antimony is used as a fire retardant in construction and defence applications, and as an alloying agent in lead acid batteries and small arms munitions		
Global Supply Risk Indicators	**Material form assessed**	**Score***	**Data quality/ availability****
Production concentration and governance	ores & concs. (metal content)	2.1	3
Companion metal fraction	ores & concs.	0.6	2
End of life recycling input rate	multiple forms	0.2	1
Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	ores & concs. (metal content)	0.1	3
Price volatility	metal	0.2	3
Substitution index	multiple forms	0.0	1
Global trade concentration	antimony oxide	0.1	2
UK import reliance	antimony oxide	1.0	3
UK GVA contribution	multiple forms	0.4	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good.*

Material name / element symbol / parent group	Beryllium, Be		
Potential UK Criticality	ELEVATED (V)		
Global Supply Risk (1-3)	1.1		
UK Economic Vulnerability (1-3)	1.9		
Key Facts			
Major end uses (USA)	Aerospace/defence (24%), industrial components (23%), automotive electronics (12%)		
World production (tonnes; average 2015-2019)	5,967		
Major world producers (% of average total 2015-2019)	USA (71%), China (22%), Mozambique (5%)		
By-product status	Approximately 20% of global beryllium supply is sourced as a by-product of mining lithium-caesium-tantalum (LCT) pegmatites, in the form of beryl.		
End of Life Recycling Input Rate (global)	0%		
UK production / import reliance	0 / 100%		
Major global trading countries (average net imports 2015-2019)	Norway (44%), Netherlands (9%), Spain (6%), Malaysia (6%), Poland (4%)		
UK trade – main forms traded; top three trading partners	Beryllium metal France, Italy, USA		
Current importance to UK manufacturing (GVA contribution of key applications)	£13,878 million GVA.		
Importance to UK policy objectives	Beryllium is widely used in automotive, aerospace and electronics applications. It also has many applications in the defence sector.		
Global Supply Risk Indicators	**Material form assessed**	**Score***	**Data quality/ availability****
Production concentration and governance	ores & concs.	0.7	3
Companion metal fraction	ores & concs.	0.2	2
End of life recycling input rate	multiple forms	0.3	1
Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	ores & concs.	0.1	3
Price volatility	no data		1
Substitution index	multiple forms	0.1	1
Global trade concentration	beryllium metal	0.2	2
UK import reliance	beryllium metal	1.0	3
UK GVA contribution	multiple forms	0.6	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good.*

Material name / element symbol / parent group	**Bismuth, Bi**		
Potential UK Criticality	HIGH		
Global Supply Risk (1-3)	2.3		
UK Economic Vulnerability (1-3)	1.5		
Key Facts			
Major end uses (EU)	Chemicals (62%), low-melting alloys (28%), metallurgical additives (10%)		
World production (tonnes; average 2015-2019)	4,987		
Major world producers (% of average total 2015-2019)	Vietnam (40%), China (34%), Japan (10%)		
By-product status	Bismuth is generally a by-product of lead mining but can also be a by-product of copper and tin mining.		
End of Life Recycling Input Rate (global)	0%		
UK production / import reliance	0 / 100%		
Major global trading countries (average net imports 2015-2019)	USA (17%), Germany (17%), Netherlands (6%), Italy (3%), France (3%)		
UK trade – main forms traded; top three trading partners	Bismuth metal Italy, Germany, USA		
Current importance to UK manufacturing (GVA contribution of key applications)	£8,480 million GVA.		
Importance to UK policy objectives	Bismuth replaces lead and other potentially harmful metals in various applications		
Global Supply Risk Indicators	**Material form assessed**	**Score***	**Data quality/ availability****
Production concentration and governance	ores & concs. (metal content)	1.4	3
Companion metal fraction	ores & concs.	0.6	2
End of life recycling input rate	multiple forms	0.3	1
Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	ores & concs. (metal content)	0.2	3
Price volatility	metal	0.2	3
Substitution index	multiple forms	0.1	1
Global trade concentration	bismuth metal	0.2	2
UK import reliance	bismuth metal	0.5	3
UK GVA contribution	multiple forms	0.4	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good.*

Material name / element symbol / parent group	Cobalt, Co
Potential UK Criticality	HIGH
Global Supply Risk (1-3)	2.2 (rm) / 2.9 (o & c)
UK Economic Vulnerability (1-3)	1.6 (rm)
Key Facts	
Major end uses (Global)	Batteries (57%), Ni-based alloys (13%), tool-materials (8%)
World production (tonnes; average 2015-2019)	116,633 (rm) 139,149 (o & c)
Major world producers (% of average total 2015-2019)	China (56%), Finland (11%), Belgium (6%) (rm) Democratic Republic of Congo (61%), China (5%), Canada (5%) (o & c)
By-product status	Cobalt is largely extracted as a by-product of copper and nickel mining.
End of Life Recycling Input Rate (global)	22%
UK production / import reliance	0 / 96%
Major global trading countries (average net imports 2015-2019)	China (77%), Belgium (3%), USA (3%), Japan (2%), UK (1%)
UK trade – main forms traded; top three trading partners	Cobalt metal, cobalt oxide, cobalt scrap Netherlands (49%), Belgium (11%), New Caledonia (8%)
Current importance to UK manufacturing (GVA contribution of key applications)	£8,182 million GVA.
Importance to UK policy objectives	Cobalt is a key constituent of most Li-ion batteries used in electric vehicles, consumer goods and stationary energy storage

Global Supply Risk Indicators	**Material form assessed**		**Score***		**Data quality/ availability****
Production concentration and governance	o & c (mc)	rm	2.1	1.4	3
Companion metal fraction	o & c	o & c	0.6	0.6	2
End of life recycling input rate	m	m	0.2	0.2	1

Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	refined metal	0.2	3
Price volatility	metal	0.3	3
Substitution index	multiple forms	0.0	1
Global trade concentration	cobalt metal	0.3	2
UK import reliance	cobalt metal	0.5	3
UK GVA contribution	multiple forms	0.4	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good. o & c (mc) = ores & concs. (metal content). rm = refined metal. m = multiple forms*

Material name / element symbol / parent group	**Gallium, Ga**		
Potential UK Criticality	HIGH		
Global Supply Risk (1-3)	3.0		
UK Economic Vulnerability (1-3)	2.0		
Key Facts			
Major end uses (Global)	Integrated circuits (50%), lighting (38%), CIGS solar cells (4%)		
World production (tonnes; average 2015-2019)	339		
Major world producers (% of average total 2015-2019)	China (91%), Russia (4%), Germany (2%)		
By-product status	Gallium is almost exclusively a by-product of bauxite (aluminium) mining. However, it can also be a by-product of zinc mining.		
End of Life Recycling Input Rate (global)	0%		
UK production / import reliance	0 / 100%		
Major global trading countries (average net imports 2015-2019)	No global trade data		
UK trade – main forms traded; top three trading partners	Gallium metal Germany (46%), China (24%), South Korea (20%)		
Current importance to UK manufacturing (GVA contribution of key applications)	£9,708 million GVA.		
Importance to UK policy objectives	Widely used in electronic and optical systems for defence. Its use in photovoltaics may grow in the future		
Global Supply Risk Indicators	**Material form assessed**	**Score***	**Data quality/ availability****
Production concentration and governance	refined metal	2.1	3
Companion metal fraction	ores & concs.	0.6	2
End of life recycling input rate	multiple forms	0.3	1
Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	refined metal	0.2	3
Price volatility	metal	0.3	3
Substitution index	multiple forms	0.1	1
Global trade concentration	no data		1
UK import reliance	gallium metal	1.0	3
UK GVA contribution	multiple forms	0.4	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good*

Material name / element symbol / parent group	Germanium, Ge		
Potential UK Criticality	ELEVATED (S)		
Global Supply Risk (1-3)	3.0		
UK Economic Vulnerability (1-3)	1.1		
Key Facts			
Major end uses (EU)	Infrared optics (47%), optical fibres (40%), satellite solar cells (13%)		
World production (tonnes; average 2015-2019)	98		
Major world producers (% of average total 2015-2019)	China (89%), Russia (6%), USA (3%)		
By-product status	Germanium is almost exclusively a by-product of zinc mining.		
End of Life Recycling Input Rate (global)	2%		
UK production / import reliance	0 / 100%		
Major global trading countries (average net imports 2015-2019)	No global trade data		
UK trade – main forms traded; top three trading partners	Germanium metal Liechtenstein (68%), Switzerland (12%), USA (5%)		
Current importance to UK manufacturing (GVA contribution of key applications)	£10,059 million GVA.		
Importance to UK policy objectives	Widely used in electronic applications in defence; also in fibre optics vital to digital infrastructure		
Global Supply Risk Indicators	**Material form assessed**	**Score***	**Data quality/ availability****
Production concentration and governance	refined metal	2.1	3
Companion metal fraction	ores & concs.	0.6	2
End of life recycling input rate	multiple forms	0.3	1
Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	refined metal	0.1	3
Price volatility	germanium dioxide	0.1	3
Substitution index	multiple forms	0.0	1
Global trade concentration	no data		1
UK import reliance	germanium metal	0.5	3
UK GVA contribution	multiple forms	0.4	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good*

Material name / element symbol / parent group	**Graphite**		
Potential UK Criticality	HIGH		
Global Supply Risk (1-3)	2.6		
UK Economic Vulnerability (1-3)	1.5		
Key Facts			
Major end uses (Global)	Refractories for steelmaking (52%), refractories for foundries (14%), batteries (8%)		
World production (tonnes; average 2015-2019)	1,073,814		
Major world producers (% of average total 2015-2019)	China (63%), Brazil (8%), India (7%)		
By-product status	Graphite is not mined as a by-product		
End of Life Recycling Input Rate (global)	3%		
UK production / import reliance	0 / 100%		
Major global trading countries (average net imports 2015-2019)	Japan (11%), India (9%), South Korea (8%), Germany (7%), USA (7%)		
UK trade – main forms traded; top three trading partners	Natural graphite Austria (34%), China (23%), Netherlands (10%)		
Current importance to UK manufacturing (GVA contribution of key applications)	£5,042 million GVA.		
Importance to UK policy objectives	Graphite will become increasingly important in Li-ion batteries for use in electric vehicles		
Global Supply Risk Indicators	**Material form assessed**	**Score***	**Data quality/ availability****
Production concentration and governance	ores & concs.	2.1	3
Companion metal fraction	expert opinion	0.2	2
End of life recycling input rate	multiple forms	0.3	1
Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	ores & concs.	0.1	3
Price volatility	flake graphite	0.1	3
Substitution index	multiple forms	0.1	1
Global trade concentration	natural graphite	0.1	2
UK import reliance	natural graphite	1.0	3
UK GVA contribution	multiple forms	0.2	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good*

Material name / element symbol / parent group	Indium, In		
Potential UK Criticality	HIGH		
Global Supply Risk (1-3)	2.3		
UK Economic Vulnerability (1-3)	1.8		
Key Facts			
Major end uses (EU)	Flat panel displays (60%), solders (11%), photovoltaics (9%)		
World production (tonnes; average 2015-2019)	819		
Major world producers (% of average total 2015-2019)	China (62%), South Korea (12%), Japan (9%)		
By-product status	Indium is primarily extracted as a by-product of zinc mining. It can also be recovered as a by-product of tin and lead mining.		
End of Life Recycling Input Rate (global)	0%		
UK production / import reliance	0 / 100%		
Major global trading countries (average net imports 2015-2019)	No global trade data		
UK trade – main forms traded; top three trading partners	Indium metal Italy (83%), Canada (5%), South Korea (4%)		
Current importance to UK manufacturing (GVA contribution of key applications)	£12,657 million GVA.		
Importance to UK policy objectives	Diverse uses in electronic systems for defence. Growing importance in photovoltaics.		
Global Supply Risk Indicators	**Material form assessed**	**Score***	**Data quality/ availability****
Production concentration and governance	refined metal	1.4	3
Companion metal fraction	ores & concs.	0.6	2
End of life recycling input rate	multiple forms	0.3	1
Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	refined metal	0.1	3
Price volatility	metal	0.3	3
Substitution index	multiple forms	0.1	1
Global trade concentration	no data		1
UK import reliance	indium metal	1.0	3
UK GVA contribution	multiple forms	0.4	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good*

Material name / element symbol / parent group	**Lithium, Li**		
Potential UK Criticality	HIGH		
Global Supply Risk (1-3)	1.4		
UK Economic Vulnerability (1-3)	2.0		
Key Facts			
Major end uses (Global)	Batteries (71%), ceramics/glass (14%), lubricating greases (4%)		
World production (tonnes; average 2015-2019)	65,753		
Major world producers (% of average total 2015-2019)	Australia (53%), Chile (24%), China (9%)		
By-product status	Lithium is not extracted as a by-product of hard-rock mining. However, it is a by-product of potassium extraction from brines.		
End of Life Recycling Input Rate (global)	0%		
UK production / import reliance	0 / 100%		
Major global trading countries (average net imports 2015-2019)	South Korea (23%), China (17%), Japan (17%), USA (7%), Russia (5%)		
UK trade – main forms traded; top three trading partners	Lithium carbonate, lithium oxide Belgium (37%), Germany (30%), Argentina (12%)		
Current importance to UK manufacturing (GVA contribution of key applications)	£5,319 million GVA.		
Importance to UK policy objectives	A key constituent of Li-ion batteries used in electric vehicles, consumer devices and energy storage		
Global Supply Risk Indicators	**Material form assessed**	**Score***	**Data quality/ availability****
Production concentration and governance	ores & concs. (metal content)	0.7	3
Companion metal fraction	ores & concs.	0.4	2
End of life recycling input rate	multiple forms	0.3	1
Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	ores & concs. (metal content)	0.2	3
Price volatility	lithium carbonate	0.3	3
Substitution index	multiple forms	0.0	1
Global trade concentration	lithium carbonate	0.2	2
UK import reliance	lithium carbonate	1.0	3
UK GVA contribution	multiple forms	0.2	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good*

Material name / element symbol / parent group	**Magnesium, Mg**		
Potential UK Criticality	HIGH		
Global Supply Risk (1-3)	2.5		
UK Economic Vulnerability (1-3)	2.3		
Key Facts			
Major end uses (EU)	Transport automotive (44%), packaging (19%), construction (12%)		
World production (tonnes; average 2015-2019)	984,378		
Major world producers (% of average total 2015-2019)	China (91%), USA (4%), Israel (2%)		
By-product status	Magnesium is not generally extracted as a by-product.		
End of Life Recycling Input Rate (global)	13%		
UK production / import reliance	0 / 100%		
Major global trading countries (average net imports 2015-2019)	Japan (6%), India (5%), Germany (4%), United Arab Emirates (4%), Norway (4%)		
UK trade – main forms traded; top three trading partners	Magnesium metal China (61%), Israel (8%), Netherlands (6%)		
Current importance to UK manufacturing (GVA contribution of key applications)	£11,017 million GVA.		
Importance to UK policy objectives	Growing use in light-weighting, for road vehicles and military applications		
Global Supply Risk Indicators	**Material form assessed**	**Score***	**Data quality/ availability****
Production concentration and governance	refined metal	2.1	3
Companion metal fraction	ores & concs.	0.2	2
End of life recycling input rate	multiple forms	0.2	1
Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	refined metal	0.1	3
Price volatility	metal	0.2	3
Substitution index	multiple forms	0.0	1
Global trade concentration	magnesium metal	0.1	2
UK import reliance	magnesium metal	1.5	3
UK GVA contribution	multiple forms	0.4	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good*

Material name / element symbol / parent group	**Manganese, Mn**		
Potential UK Criticality	ELEVATED (V)		
Global Supply Risk (1-3)	1.2		
UK Economic Vulnerability (1-3)	2.1		
Key Facts			
Major end uses (EU)	Steel (construction) (24%), steel (automotive) (14%), steel (mechanical engineering) (13%)		
World production (tonnes; average 2015-2019)	53,211,014		
Major world producers (% of average total 2015-2019)	South Africa (29%), China (20%), Australia (12%)		
By-product status	Manganese is generally not mined as a by-product; however, it can be recovered as a by-product of iron mining.		
End of Life Recycling Input Rate (global)	8%		
UK production / import reliance	0 / 100%		
Major global trading countries (average net imports 2015-2019)	USA (11%), Russia (6%), Spain (4%), Poland (4%), Denmark (4%)		
UK trade – main forms traded; top three trading partners	Manganese oxide, manganese ores & concs., manganese metal South Africa (24%), Georgia (21%), Belgium (13%)		
Current importance to UK manufacturing (GVA contribution of key applications)	£13,614 million GVA.		
Importance to UK policy objectives	Although steel will remain the dominant use of manganese, it is a key constituent of Li-ion batteries for electric vehicles and a host of other purposes		
Global Supply Risk Indicators	**Material form assessed**	**Score***	**Data quality/ availability****
Production concentration and governance	ores & concs.	0.7	3
Companion metal fraction	ores & concs.	0.2	2
End of life recycling input rate	multiple forms	0.3	1
Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	ores & concs.	0.1	3
Price volatility	metal	0.3	3
Substitution index	multiple forms	0.1	1
Global trade concentration	manganese oxide	0.1	2
UK import reliance	manganese oxide	1.0	3
UK GVA contribution	multiple forms	0.6	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good*

Material name / element symbol / parent group	Molybdenum, Mo		
Potential UK Criticality	ELEVATED (V)		
Global Supply Risk (1-3)	1.2		
UK Economic Vulnerability (1-3)	2.0		
Key Facts			
Major end uses (EU)	Engineering steel (40%), stainless steel (23%), chemicals (13%)		
World production (tonnes; average 2015-2019)	287,081		
Major world producers (% of average total 2015-2019)	China (42%), Chile (20%), USA (15%)		
By-product status	Molybdenum is generally mined in its own right but can also be extracted as a by-product of copper mining.		
End of Life Recycling Input Rate (global)	30%		
UK production / import reliance	0 / 100%		
Major global trading countries (average net imports 2015-2019)	Japan (23%), South Korea (11%), UK (8%), Brazil (5%), India (5%)		
UK trade – main forms traded; top three trading partners	Molybdenum ores & concs., molybdenum metal, molybdenum waste/scrap, molybdenum oxide USA (63%), Netherlands (23%), Chile (9%)		
Current importance to UK manufacturing (GVA contribution of key applications)	£15,284 million GVA.		
Importance to UK policy objectives	Important in alloys and special steels for diverse military and civil applications		
Global Supply Risk Indicators	**Material form assessed**	**Score***	**Data quality/ availability****
Production concentration and governance	ores & concs. (metal content)	0.7	3
Companion metal fraction	ores & concs.	0.4	2
End of life recycling input rate	multiple forms	0.1	1
Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	ores & concs. (metal content)	0.1	3
Price volatility	metal	0.1	3
Substitution index	multiple forms	0.1	1
Global trade concentration	ores & concs.	0.2	2
UK import reliance	ores & concs.	1.0	3
UK GVA contribution	multiple forms	0.6	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good*

Material name / element symbol / parent group	**Nickel, Ni**				
Potential UK Criticality	ELEVATED (V)				
Global Supply Risk (1-3)	1.1 (rm) / 1.1 (o & c)				
UK Economic Vulnerability (1-3)	2.7 (rm)				
Key Facts					
Major end uses (Global)	Engineering (steel) (33%), metal-goods (steel) (23%), transport (steel) (16%)				
World production (tonnes; average 2015-2019)	2,206,417 (rm) 2,270,188 (o & c)				
Major world producers (% of average total 2015-2019)	China (305), Russia (10%), Indonesia (10%) (rm) Indonesia (21%), Philippines (15%), Russia (10%) (o & c)				
By-product status	Nickel is not generally mined as a by-product.				
End of Life Recycling Input Rate (global)	17%				
UK production / import reliance	0 / 100%				
Major global trading countries (average net imports 2015-2019)	Norway (38%), Japan (27%), Finland (10%), UK (9%), China (5%)				
UK trade – main forms traded; top three trading partners	Nickel metal, nickel mattes /sinters, nickel scrap Canada (69%), Indonesia (29%), USA (2%)				
Current importance to UK manufacturing (GVA contribution of key applications)	£11,389 million GVA.				
Importance to UK policy objectives	Most nickel is used in stainless steel, but its use in LI-ion batteries for electric vehicles is growing rapidly				
Global Supply Risk Indicators	**Material form assessed**		**Score***		**Data quality/ availability****
Production concentration and governance	o & c (mc)	rm	0.7	0.7	3
Companion metal fraction	o & c	o & c	0.2	0.2	2
End of life recycling input rate	m	m	0.2	0.2	1
Vulnerability Indicators	**Material form assessed**		**Score**		**Data quality/ availability**
Production evolution	refined metal		0.2		3
Price volatility	metal		0.3		3
Substitution index	multiple forms		0.0		1
Global trade concentration	nickel mattes & sinters		0.3		2
UK import reliance	nickel mattes & sinters		0.5		3
UK GVA contribution	multiple forms		0.4		2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good. o & c (mc) = ores & concs. (metal content). rm = refined metal. m = multiple forms*

Material name / element symbol / parent group	Niobium, Nb		
Potential UK Criticality	HIGH		
Global Supply Risk (1-3)	2.6		
UK Economic Vulnerability (1-3)	1.4		
Key Facts			
Major end uses (EU)	Construction steel (32%), automotive steel (28%), stainless steel (14%)		
World production (tonnes; average 2015-2019)	74,080		
Major world producers (% of average total 2015-2019)	Brazil (88%), Canada (9%), Russia (1%)		
By-product status	Niobium is generally mined as a commodity in its own right. However, niobium can be recovered as a by-product of tin mining.		
End of Life Recycling Input Rate (global)	0%		
UK production / import reliance	0 / 100%		
Major global trading countries (average net imports 2015-2019)	Saudi Arabia (3%), Malaysia (2%), Japan (2%), France (1%), Singapore (1%)		
UK trade – main forms traded; top three trading partners	Niobium metal Netherlands (38%), Germany (26%), Estonia (15%)		
Current importance to UK manufacturing (GVA contribution of key applications)	£13,511 million GVA.		
Importance to UK policy objectives	Increasing importance in HSLA steels for transport and construction use. Key constituent of superconducting magnets used in MRI scanners.		
Global Supply Risk Indicators	**Material form assessed**	**Score***	**Data quality/ availability****
Production concentration and governance	ores & concs. (metal content)	2.1	3
Companion metal fraction	ores & concs.	0.2	2
End of life recycling input rate	multiple forms	0.3	1
Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	ores & concs. (metal content)	0.1	3
Price volatility	niobium pentoxide	0.1	3
Substitution index	multiple forms	0.1	1
Global trade concentration	niobium metal	0.1	2
UK import reliance	niobium metal	0.5	3
UK GVA contribution	multiple forms	0.6	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good*

Material name / element symbol / parent group	**Palladium, Pd** One of 6 platinum-group metals (PGMs)		
Potential UK Criticality	HIGH		
Global Supply Risk (1-3)	2.2		
UK Economic Vulnerability (1-3)	2.6		
Key Facts			
Major end uses (Global)	Autocatalysts (85%), electronics (6%), chemicals (6%)		
World production (kilograms; average 2015-2019)	208,961		
Major world producers (% of average total 2015-2019)	Russia (39%), South Africa (38%), Canada (9%)		
By-product status	Palladium is co-product of platinum mining and a by-product of nickel mining		
End of Life Recycling Input Rate (global)	28%		
UK production / import reliance	0 / 100%		
Major global trading countries (average net imports 2015-2019)	China (8%), Japan (6%), Germany (6%), Malaysia (4%), UK (4%)		
UK trade – main forms traded; top three trading partners	Palladium metal, palladium in catalysts, palladium in waste/scrap Italy (50%), Russia (10%), Switzerland (15%)		
Current importance to UK manufacturing (GVA contribution of key applications)	£16,073 million GVA.		
Importance to UK policy objectives	Key constituent of autocatalysts used in emission control for petrol and hybrid vehicles		
Global Supply Risk Indicators	**Material form assessed**	**Score***	**Data quality/ availability****
Production concentration and governance	ores & concs. (metal content)	1.4	3
Companion metal fraction	ores & concs.	0.6	2
End of life recycling input rate	multiple forms	0.2	1
Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	ores & concs. (metal content)	0.1	3
Price volatility	metal	0.3	3
Substitution index	multiple forms	0.0	1
Global trade concentration	palladium metal	0.1	2
UK import reliance	palladium metal	1.5	3
UK GVA contribution	multiple forms	0.4	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good*

Material name / element symbol / parent group	**Platinum, Pt** One of 6 platinum-group metals (PGMs)		
Potential UK Criticality	HIGH		
Global Supply Risk (1-3)	2.5		
UK Economic Vulnerability (1-3)	2.3		
Key Facts			
Major end uses (Global)	Autocatalysts (71%); jewellery (9%); chemicals manufacture (6%)		
World production (kilograms; average 2015-2019)	188,923		
Major world producers (% of average total 2015-2019)	South Africa (71%); Russia (11%); Zimbabwe (8%)		
By-product status	Platinum is generally a co-product with palladium; it may also be a by-product of nickel mining, notably in Russia.		
End of Life Recycling Input Rate (global)	25%		
UK production / import reliance	0 / 100%		
Major global trading countries (average net imports 2015-2019)	China (12%), UK (7%), Germany (5%), North Macedonia (5%), USA (5%)		
UK trade – main forms traded; top three trading partners	Platinum metal, platinum in catalysts, platinum in waste/scrap; Italy, South Africa, Russia		
Current importance to UK manufacturing (GVA contribution of key applications)	£10,089 million GVA. UK is a major producer of: autocatalysts and materials for autocatalysts; platinum chemicals for industrial process catalysts; and platinum in equipment for glass making and in medical applications.		
Importance to UK policy objectives	Platinum will remain important in autocatalysts in ICE vehicles. After 2030 fuel cell vehicles and electrolysers for hydrogen production will need more platinum.		
Global Supply Risk Indicators	**Material form assessed**	**Score***	**Data quality/ availability****
Production concentration and governance	ores & concs. (metal content)	2.1	3
Companion metal fraction	ores & concs.	0.2	2
End of life recycling input rate	multiple forms	0.2	1
Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	ores & concs. (metal content)	0.1	3
Price volatility	metal	0.2	3
Substitution index	multiple forms	0.0	1
Global trade concentration	platinum metal	0.1	2
UK import reliance	platinum metal	1.5	3
UK GVA contribution	multiple forms	0.4	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good*

Material name / element symbol / parent group	Rare earth elements, REEs		
Potential UK Criticality	HIGH		
Global Supply Risk (1-3)	3.0		
UK Economic Vulnerability (1-3)	2.6		
Key Facts			
Major end uses (Global)	Magnets (29%), catalysts (21%), polishing compounds (13%)		
World production (tonnes; average 2015-2019)	200,914		
Major world producers (% of average total 2015-2019)	China (76%), Burma (9%), Australia (8%)		
By-product status	Rare earth elements are generally extracted as by-products of iron, tin and titanium mining.		
End of Life Recycling Input Rate (global)	5.5%		
UK production / import reliance	0 / 100%		
Major global trading countries (average net imports 2015-2019)	Japan (27%), USA (10%), Estonia (6%), Germany (4%), South Korea (3%)		
UK trade – main forms traded; top three trading partners	Cerium compound, other rare earth compounds Malaysia (32%), China (30%), Estonia (11%)		
Current importance to UK manufacturing (GVA contribution of key applications)	£8,066 million GVA.		
Importance to UK policy objectives	High strength magnets used in electric vehicles and offshore wind turbines. Numerous defence applications		
Global Supply Risk Indicators	**Material form assessed**	**Score***	**Data quality/ availability****
Production concentration and governance	ores & concs. (metal content)	2.1	3
Companion metal fraction	ores & concs.	0.6	2
End of life recycling input rate	multiple forms	0.3	1
Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	ores & concs. (metal content)	0.2	3
Price volatility	neodymium oxide	0.3	3
Substitution index	multiple forms	0.0	1
Global trade concentration	cerium compounds	0.2	2
UK import reliance	cerium compounds	1.5	3
UK GVA contribution	multiple forms	0.4	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good*

Material name / element symbol / parent group	**Rhenium, Re**		
Potential UK Criticality	ELEVATED (S)		
Global Supply Risk (1-3)	1.4		
UK Economic Vulnerability (1-3)	0.6		
Key Facts			
Major end uses (Global)	Aerospace (83%), catalysts (17%)		
World production (tonnes; average 2015-2019)	50		
Major world producers (% of average total 2015-2019)	Chile (54%), Poland (18%), USA (16%)		
By-product status	Rhenium is extracted as a by-product of copper and molybdenum mining.		
End of Life Recycling Input Rate (global)	50%		
UK production / import reliance	0 / 100%		
Major global trading countries (average net imports 2015-2019)	No global trade data		
UK trade – main forms traded; top three trading partners	No UK trade data		
Current importance to UK manufacturing (GVA contribution of key applications)	£10,692 million GVA.		
Importance to UK policy objectives	An important constituent of superalloys used in gas turbine blades and in jet engines for military use.		
Global Supply Risk Indicators	**Material form assessed**	**Score***	**Data quality/ availability****
Production concentration and governance	refined metal	0.7	3
Companion metal fraction	ores & concs.	0.6	2
End of life recycling input rate	multiple forms	0.1	1
Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	refined metal	0.1	3
Price volatility	ammonium perrhenate	0.1	3
Substitution index	multiple forms	0.1	1
Global trade concentration	no data		1
UK import reliance	no data		1
UK GVA contribution	multiple forms	0.4	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good*

Material name / element symbol / parent group	Silicon, Si		
Potential UK Criticality	HIGH		
Global Supply Risk (1-3)	2.6		
UK Economic Vulnerability (1-3)	2.5		
Key Facts			
Major end uses (EU)	Chemicals (54%), aluminium alloys (38%), solar panels (6%)		
World production (tonnes; average 2015-2019)	2,786,994		
Major world producers (% of average total 2015-2019)	China (79%), Brazil (5%), Norway (5%)		
By-product status	Silicon is not mined as a by-product		
End of Life Recycling Input Rate (global)	0%		
UK production / import reliance	0 / 94%		
Major global trading countries (average net imports 2015-2019)	China (43%), Bahrain (8%), Other Asia (5%), India (4%), Qatar (4%)		
UK trade – main forms traded; top three trading partners	Silicon metal Brazil (57%), China (12%), France (10%)		
Current importance to UK manufacturing (GVA contribution of key applications)	£8,480 million GVA.		
Importance to UK policy objectives	A key constituent of most solar photovoltaic cells. Widely used in semiconductors for numerous applications.		
Global Supply Risk Indicators	**Material form assessed**	**Score***	**Data quality/ availability****
Production concentration and governance	refined metal	2.1	3
Companion metal fraction	ores & concs.	0.2	2
End of life recycling input rate	multiple forms	0.3	1
Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	refined metal	0.2	3
Price volatility	metal	0.2	3
Substitution index	multiple forms	0.1	1
Global trade concentration	silicon metal	0.2	2
UK import reliance	silicon metal	1.5	3
UK GVA contribution	multiple forms	0.4	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good*

Material name / element symbol / parent group	Strontium, Sr		
Potential UK Criticality	ELEVATED (S)		
Global Supply Risk (1-3)	1.9		
UK Economic Vulnerability (1-3)	0.3		
Key Facts			
Major end uses (Global)	Drilling fluid (70%), pyrotechnics (9%), magnets (9%)		
World production (tonnes; average 2015-2019)	323,876		
Major world producers (% of average total 2015-2019)	Spain (34%), Iran (34%), China (17%)		
By-product status	Strontium is not mined as a by-product.		
End of Life Recycling Input Rate (global)	0%		
UK production / import reliance	0 / 100%		
Major global trading countries (average net imports 2015-2019)	No global trade data		
UK trade – main forms traded; top three trading partners	No UK trade data		
Current importance to UK manufacturing (GVA contribution of key applications)	£6,113 million GVA.		
Importance to UK policy objectives	-		
Global Supply Risk Indicators	**Material form assessed**	**Score***	**Data quality/ availability****
Production concentration and governance	ores & concs.	1.4	3
Companion metal fraction	ores & concs.	0.2	2
End of life recycling input rate	multiple forms	0.3	1
Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	ores & concs.	0.1	3
Price volatility	no data		1
Substitution index	multiple forms	0.0	1
Global trade concentration	no data		1
UK import reliance	no data		1
UK GVA contribution	multiple forms	0.2	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good*

Material name / element symbol / parent group	Tantalum, Ta		
Potential UK Criticality	HIGH		
Global Supply Risk (1-3)	1.9		
UK Economic Vulnerability (1-3)	1.9		
Key Facts			
Major end uses (EU)	Capacitors (40%), sputtering targets for electronics (20%) super-alloys (aerospace) (14%)		
World production (tonnes; average 2015-2019)	1,293		
Major world producers (% of average total 2015-2019)	Democratic Republic of Congo (35%), Rwanda (30%), Brazil (11%)		
By-product status	Tantalum is generally extracted in its own right but can also be a by-product of lithium and tin mining.		
End of Life Recycling Input Rate (global)	0%		
UK production / import reliance	0 / 100%		
Major global trading countries (average net imports 2015-2019)	USA (14%), Russia (5%), El Salvador (4%), Germany (4%), Czech Republic (3%)		
UK trade – main forms traded; top three trading partners	Tantalum metal USA (46%), Australia (14%), Ireland (12%)		
Current importance to UK manufacturing (GVA contribution of key applications)	£12,846 million GVA.		
Importance to UK policy objectives	Tantalum is widely used in electronic components and superalloys for defence applications.		
Global Supply Risk Indicators	**Material form assessed**	**Score***	**Data quality/ availability****
Production concentration and governance	ores & concs. (metal content)	1.4	3
Companion metal fraction	ores & concs.	0.2	2
End of life recycling input rate	multiple forms	0.3	1
Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	ores & concs. (metal content)	0.2	3
Price volatility	tantalum pentoxide	0.1	3
Substitution index	multiple forms	0.0	1
Global trade concentration	tantalum metal	0.1	3
UK import reliance	tantalum metal	1.0	3
UK GVA contribution	multiple forms	0.4	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good*

Material name / element symbol / parent group	**Tellurium, Te**		
Potential UK Criticality	HIGH		
Global Supply Risk (1-3)	3.0		
UK Economic Vulnerability (1-3)	2.6		
Key Facts			
Major end uses (EU)	Solar power (40%), thermo-electric devices (30%), metallurgy (15%)		
World production (tonnes; average 2015-2019)	461		
Major world producers (% of average total 2015-2019)	China (69%), Russia (9%), Japan (9%)		
By-product status	Most tellurium is a by-product of copper mining, but may also be recovered during the mining of lead.		
End of Life Recycling Input Rate (global)	1%		
UK production / import reliance	0 / 100%		
Major global trading countries (average net imports 2015-2019)	No global trade data		
UK trade – main forms traded; top three trading partners	Tellurium metal South Korea (62%), Japan (15%), France (15%)		
Current importance to UK manufacturing (GVA contribution of key applications)	£14,351 million GVA.		
Importance to UK policy objectives	Tellurium is a major part of cadmium telluride photovoltaics. This technology may become increasingly important.		
Global Supply Risk Indicators	**Material form assessed**	**Score***	**Data quality/ availability****
Production concentration and governance	refined metal	2.1	3
Companion metal fraction	ores & concs.	0.6	2
End of life recycling input rate	multiple forms	0.3	1
Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	refined metal	0.2	3
Price volatility	metal	0.2	3
Substitution index	multiple forms	0.0	1
Global trade concentration	no data		1
UK import reliance	tellurium metal	1.5	3
UK GVA contribution	multiple forms	0.6	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good*

Material name / element symbol / parent group	**Tin, Sn**
Potential UK Criticality	HIGH
Global Supply Risk (1-3)	1.7 (rm) / 1.0 (o & c)
UK Economic Vulnerability (1-3)	1.7 (rm)
Key Facts	
Major end uses (Global)	Solders (49%), chemicals (18%), tinplate (12%)
World production (tonnes; average 2015-2019)	364,893 (rm) 319,592 (o & c)
Major world producers (% of average total 2015-2019)	China (49%), Indonesia (20%), Malaysia (8%) (rm) China (30%), Indonesia (24%), Burma (17%) (o & c)
By-product status	Tin is not mined as a by-product.
End of Life Recycling Input Rate (global)	31%
UK production / import reliance	0 / 98%
Major global trading countries (average net imports 2015-2019)	USA (14%), Japan (11%), Germany (8%), South Korea (6%), India (4%)
UK trade – main forms traded; top three trading partners	Tin metal Peru (18%), Netherlands (18%), Indonesia (13%)
Current importance to UK manufacturing (GVA contribution of key applications)	£12,437 million GVA.
Importance to UK policy objectives	Tin use in solders for a wide range of new technologies is expected to grow as decarbonisation proceeds.

Global Supply Risk Indicators	**Material form assessed**		**Score***		**Data quality/ availability****
Production concentration and governance	o & c (mc)	rm	0.7	1.4	3
Companion metal fraction	o & c	o & c	0.2	0.2	2
End of life recycling input rate	m	m	0.1	0.1	1

Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	refined metal	0.1	3
Price volatility	metal	0.1	3
Substitution index	multiple forms	0.0	1
Global trade concentration	tin metal	0.1	2
UK import reliance	tin metal	1.0	3
UK GVA contribution	multiple forms	0.4	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good. o & c (mc) = ores & concs. (metal content). rm = refined metal. m = multiple forms.*

Material name / element symbol / parent group	Titanium, Ti		
Potential UK Criticality	LOW		
Global Supply Risk (1-3)	1.1		
UK Economic Vulnerability (1-3)	1.3		
Key Facts			
Major end uses (EU)	Paints (54%), polymers (24%), aerospace (8%)		
World production (tonnes; average 2015-2019)	5,817,596		
Major world producers (% of average total 2015-2019)	China (34%), Canada (12%), Australia (12%)		
By-product status	Titanium is generally not mined as a by-product.		
End of Life Recycling Input Rate (global)	19%		
UK production / import reliance	0 / 100%		
Major global trading countries (average net imports 2015-2019)	China (35%), USA (14%), Germany (10%), Japan (6%), Canada (3%)		
UK trade – main forms traded; top three trading partners	Titanium metal, titanium oxide, titanium ores & concs., titanium waste/scrap Australia (36%), Norway (22%), Canada (19%)		
Current importance to UK manufacturing (GVA contribution of key applications)	£10,599 million GVA.		
Importance to UK policy objectives	The role of titanium in light-weighting transport, especially aerospace, is expected to grow.		
Global Supply Risk Indicators	**Material form assessed**	**Score***	**Data quality/ availability****
Production concentration and governance	ores & concs. (metal content)	0.7	3
Companion metal fraction	ores & concs.	0.2	2
End of life recycling input rate	multiple forms	0.2	1
Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	ores & concs. (metal content)	0.1	3
Price volatility	titanium oxide	0.1	3
Substitution index	multiple forms	0.0	1
Global trade concentration	titanium ores & concs.	0.2	3
UK import reliance	titanium ores & concs.	0.5	3
UK GVA contribution	multiple forms	0.4	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good*

Material name / element symbol / parent group	Tungsten, W		
Potential UK Criticality	HIGH		
Global Supply Risk (1-3)	2.4		
UK Economic Vulnerability (1-3)	1.9		
Key Facts			
Major end uses (Global)	Milling/cutting tools (33%), construction/mining tools (23%), other wear tools (18%)		
World production (tonnes; average 2015-2019)	83,935		
Major world producers (% of average total 2015-2019)	China (81%), Vietnam (6%), Russia (3%)		
By-product status	Most tungsten is mined as a commodity in its own right. Some is a by-product of tin mining.		
End of Life Recycling Input Rate (global)	42%		
UK production / import reliance	0 / 100%		
Major global trading countries (average net imports 2015-2019)	Japan (12%), Germany (10%), USA (9%), Austria (6%), UK (6%)		
UK trade – main forms traded; top three trading partners	Tungsten carbide, tungsten metal, tungsten waste/scrap Austria (73%), Czech Republic (13%), Germany (10%)		
Current importance to UK manufacturing (GVA contribution of key applications)	£15,463 million GVA.		
Importance to UK policy objectives	Tungsten has numerous diverse applications in defence. It will remain crucial in 'wear tools' for many purposes.		
Global Supply Risk Indicators	**Material form assessed**	**Score***	**Data quality/ availability****
Production concentration and governance	ores & concs. (metal content)	2.1	3
Companion metal fraction	ores & concs.	0.2	2
End of life recycling input rate	multiple forms	0.1	1
Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	ores & concs. (metal content)	0.1	3
Price volatility	ammonium paratungstate	0.1	3
Substitution index	multiple forms	0.0	1
Global trade concentration	tungsten carbide	0.1	3
UK import reliance	tungsten carbide	1.0	3
UK GVA contribution	multiple forms	0.6	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good*

Material name / element symbol / parent group	**Vanadium, V**		
Potential UK Criticality	ELEVATED (S)		
Global Supply Risk (1-3)	2.3		
UK Economic Vulnerability (1-3)	1.6		
Key Facts			
Major end uses (EU)	HSLA steel (60%), special steel (30%), super-alloys (3%)		
World production (tonnes; average 2015-2019)	83,635		
Major world producers (% of average total 2015-2019)	China (53%), Russia (21%), South Africa (19%)		
By-product status	Most vanadium is mined as a commodity in its own right. Some is a by-product of iron and aluminium mining.		
End of Life Recycling Input Rate (global)	2%		
UK production / import reliance	0 / 100%		
Major global trading countries (average net imports 2015-2019)	No global trade data		
UK trade – main forms traded; top three trading partners	Vanadium metal Germany (70%), USA (15%), China (6%)		
Current importance to UK manufacturing (GVA contribution of key applications)	£7,928 million GVA.		
Importance to UK policy objectives	Vanadium redox flow batteries may become increasingly important for stationary energy storage.		
Global Supply Risk Indicators	**Material form assessed**	**Score***	**Data quality/ availability****
Production concentration and governance	ores & concs. (metal content)	1.4	3
Companion metal fraction	ores & concs.	0.6	2
End of life recycling input rate	multiple forms	0.3	1
Vulnerability Indicators	**Material form assessed**	**Score**	**Data quality/ availability**
Production evolution	ores & concs. (metal content)	0.1	3
Price volatility	ferro-vanadium	0.3	3
Substitution index	multiple forms	0.1	1
Global trade concentration	no data		1
UK import reliance	vanadium metal	1.0	3
UK GVA contribution	multiple forms	0.2	2

*Footnote: * Score: 1 = low; 2 = moderate; and 3 = high. **Data quality/availability: 1 = poor; 2 = satisfactory; and 3 = good*

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/.

AUSTRALIAN TRADE AND INVESTMENT COMMISSION. 2020. Australian Critical Minerals Prospectus 2020.

BLENGINI, G A, NUSS, P, DEWULF, J, NITA, V, PEIRÓ, L T, VIDAL-LEGAZ, B, LATUNUSSA, C, MANCINI, L, BLAGOEVA, D, PENNINGTON, D W, PELLEGRINI, M, MAERCKE, A V, ŠOLAR, S V, GROHOL, M, and CIUPAGEA, C. 2017. EU Methodology for Critical Raw Materials Assessment: Policy Needs and Proposed Solutions for Incremental Improvements. *Resources Policy*, Vol. 53, 12–19.

BLOODWORTH, A, PETAVRATZI, E, and GUNN, G. 2019. Metals and decarbonisation: a geological perspective.

BRITISH GEOLOGICAL SURVEY. 2021. World Mineral Statistics Database [online]. Last updated March 2021 [cited December 2021]. Available from https://www2.bgs.ac.uk/mineralsuk/statistics/wms.cfc?method=searchWMS

BROWN, T. 2018. Measurement of mineral supply diversity and its importance in assessing risk and criticality. *Resources Policy*, Vol. 58, 202–218.

BUNDESANSTALT FÜR GEOWISSENSCHAFTEN UND ROHSTOFFE (BGR). 2021. Volatilitätsmonitor September 2021 [online]. Last update October 2021 [cited November 2021]. Available from https://www.bgr.bund.de/DE/Themen/Min_rohstoffe/Produkte/Volatilitaetsmonitor/vm_21_09.pdf;jsessionid=464B59F4905A2077E8C11FF3F2BCC133.2_cid292?__blob=publicationFile&v=2

COBALT INSTITUTE. 2021. 'State of the Cobalt market' report.

CROWSON, P. 2011. Mineral reserves and future minerals availability. *Mineral Economics*, 24, 1-6.

DEPARTMENT FOR TRANSPORT. 2021. Decarbonising Transport, A Better, Greener Britain.

EHELIYAGODA, D, ZENG, X, and LI, J. 2020. A method to assess national metal criticality: the environment as a foremost measurement. *Humanities & Social Sciences Communications,* Vol. 7, Article number: 43.

EUROPEAN COMMISSION. 2010. Study on the review of the list of Critical Raw Materials - Final Report.

EUROPEAN COMMISSION. 2017a. Methodology for establishing the EU list of critical raw materials. Guidelines.

EUROPEAN COMMISSION. 2017b. Study on the review of the list of Critical Raw Materials - Final Report.

EUROPEAN COMMISSION. 2020a. Study on the EU's list of Critical Raw Materials - Final Report.

EUROPEAN COMMISSION. 2020b. Critical Raw Materials for Strategic Technologies and Sectors in the EU - a Foresight Study.

EUROPEAN COMMISSION. 2020c. Study on the EU's list of Critical Raw Materials - Factsheets on Critical Raw Materials.

FRASER, J, ANDERSON, J, LAZUEN, J, LU, Y. HEATHMAN, O, BREWSTER, N, BEDDER, J, and MASSON, O. 2021. Study on future demand and supply security of nickel for electric vehicle batteries. Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-29139-8, doi:10.2760/212807, JRC123439.

GRAEDEL, T E, ALLWOOD, J, BIRAT, J-P, RECK, B K, SIBLEY, S F, SONNERMANN, G, BUCHERT, M and HAGELÜKEN, C. 2011. Recycling Rates of Metals – A Status Report. United Nations Environment Programme (UNEP).

GRAEDEL, T. GUNN, G, and TERCERO ESPINOZA, L. 2014. Metal resources, use and Criticality. In Critical Metals Handbook, GUNN, G. (editor).

HM GOVERNMENT. 2020a. Energy white paper: Powering our net zero future.

HM GOVERNMENT. 2020b. The Ten Point Plan for a Green Industrial Revolution. Policy Paper.

HM GOVERNMENT HOFMANN. 2021. Net Zero Strategy: Build Back Greener. Policy Paper.

HM REVENUE and Customs. 2021. UK Trade Info. *Overseas Trade Statistics (monthly, quarterly and annual), Guide to the Classification for Overseas Trade Statistics* [online]. Available from www.uktradeinfo.com

HOFMANN, M, HOFMANN, H, HAGELÜKEN, C and HOOL, A. 2018. Critical raw materials: A perspective from the materials science community. *Sustainable Materials and Technologies*, Vol. 17.

HOUSE OF LORDS. 2021. Battery strategy goes flat: Net-zero target at risk. Science and Technology Select Committee. HL Paper 53.

INTERNATIONAL ENERGY AGENCY. 2021. The Role of Critical Minerals in Clean Energy Transitions. *World Energy Outlook Special Report*.

LUSTY, P A, BLOODWORTH, A, and STEPHENSON, M. 2020. Reserve Judgment: focus effort on decarbonisation not depletion.

MALALA, O N, and ADACHI, T. 2021. Japan's critical metals in the medium term: a quasi-dynamic approach incorporating probability. *Mineral Economics*, https://doi.org/10.1007/s13563-021-00262-7

MEADOWS, D H, RANDERS, J and MEADOWS, D L. 1972. Limits to Growth. (New York: Universe Books.)

MCCULLOUGH, E, and NASSAR, N T. 2017. Assessment of critical minerals: updated application of an early-warning screening methodology. *Mineral Economics*, Vol. 30, 257–272.

MCNULTY, B A, and JOWITT, S M. 2021. Barriers to and uncertainties in understanding and quantifying global critical mineral and element supply. *iScience*, 1;24(7):102809. doi: 10.1016/j.isci.2021.102809.

NASSER, N T, and FORTIER, S M. 2021. Methodology and Technical Input for the 2021 Review and Revision of the U.S. Critical Minerals List. *United States Geological Survey*. Open-File Report 2021–1045.

NASSAR, N T, GRAEDEL, T E, and HARPER, E M. 2015. By-product metals are technologically essential but have problematic supply. *Science Advances 3 April 2015*. Vol. 1, Issue 3.

NASSAR, N T, BRAINARD, J, GULLEY, A, MANLEY, R, MATOS, G, LEDERER, G, BIRD, L R, PINEAULT, D, ALONSO, E, GAMBOGI, J, and FORTIER, S M. 2020. Evaluating the mineral commodity supply risk of the U.S. manufacturing sector. *Science advances*, 6.

NATIONAL RESEARCH COUNCIL. 2008. Minerals critical minerals and the U.S. economy. Washington DC: the National Academies.

NATURAL RESOURCES CANADA. 2021. Canada's critical minerals list 2021.

OFFICE FOR NATIONAL STATISTICS. 2009. UK Standard Industrial Classification of Economic Activities 2007 (SIC 2007). Structure and explanatory notes [online]. Available from https://www.ons.gov.uk/methodology/ classificationsandstandards/ ukstandardindustrialclassificationofeconomicactivities/uksic2007

OFFICE FOR NATIONAL STATISTICS. 2020. UK Manufacturers' Sales by Product (PRODCOM) *UK Statistics Authority* [online]. Available from https://www.ons.gov.uk/surveys/informationforbusinesses/ businesssurveys/ukmanufacturerssalesbyproductprodcom

OFFICE FOR NATIONAL STATISTICS. 2021a. Regional gross value added (balanced) by industry: all International Territorial Level (ITL) regions. Dataset [online]. Last updated 11 June 2021. Available from https://www.ons.gov.uk/economy/grossvalueaddedgva/datasets/nominalandrealregionalgrossvalueaddedbalancedbyindustry

OFFICE FOR NATIONAL STATISTICS. 2021b. UK National Accounts, The Blue Book: 2021. Chapter 1: Industrial Analyses [online]. Available from https://www.ons.gov.uk/economy/grossdomesticproductgdp/compendium/ unitedkingdomnationalaccounts thebluebook/2021

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT (OECD). 2020. Methodological note to the Inventory of Export Restrictions on Industrial Raw Materials.

PRIME MINISTER OF AUSTRALIA. 2021. Backing Australia's critical minerals sector. Media Release 28 Sep 2021. Available from https://www.pm.gov.au/media/backing-australias-critical-minerals-sector

RENNER, S, and WELLMER, F W. 2020. Volatility drivers on the metal market and exposure of producing countries. *Mineral Economics*, Vol. 33, 311–340.

SCHMIDT, M. 2021. The Revised German Raw Materials Strategy in the Light of Global Political and Market Developments. *Review of Policy Research*, Vol. 38, 49–75.

SCHRIJVERS, D, HOOL, A, BLENGINI, G A, CHEN , W, DEWULF, J, EGGERT, R, VAN ELLEN, L, GAUSS, R, GODDIN, J, HABIB, K, HAGELÜKEN, C, HIROHATA, A, HOFMANN-AMTENBRINK, M, KOSMOL, J, LE GLEUHER, M, GROHOL, M, KU, A, LEE, M, LIU, G, NANSAI, K, NUSS, P, PECK, D, RELLER, A, SONNEMANNA, G, TERCERO, L, THORENZW, A, and WÄGER, P A. 2020. A review of methods and data to determine raw material criticality. *Resources, Conservation and Recycling*, Vol. 155, 104617.

TALENS PEIRO, L, NUSS, P, MATHIEUX, F, and BLENGINI, G. 2018. Towards Recycling Indicators based on EU flows and Raw Materials System Analysis data. EUR 29435 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-97247-8, doi:10.2760/092885, JRC112720.

UNITED NATIONS STATISTICS DIVISION. 2021. UN Comtrade Database [online]. Available from https://comtrade.un.org/

UNITED STATES DEPARTMENT OF ENERGY. 2021. Critical Minerals and Materials: U.S. Department of Energy's Strategy to Support Domestic Critical Mineral and Material Supply Chains (FY 2021-FY 2031)

WATARI, T, NANSAI, K, and NAKAJIMA, K. 2020. Review of critical metal dynamics to 2050 for 48 elements. *Resources, Conservation & Recycling,* Vol. 155, 104669.

WELLMER, F W, and HAGELÜKEN, C. 2015. The Feedback Control Cycle of Mineral Supply, Increase of Raw Material Efficiency, and Sustainable Development. *Minerals,* Vol. 5, 815–836.

WORLD BANK GROUP. 2020. Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition.

WORLD BANK GROUP. 2021. Worldwide Governance Indicators, 2021 Update. Available from https://info.worldbank.org/governance/wgi/

WORLD PLATINUM INVESTMENT COUNCIL. 2020. Substitution among platinum group metals. *60 seconds in platinum.*

YUNIS, J, and ALIAKBARI, E. 2021. Annual survey of mining companies, 2020. *Fraser Institute*.