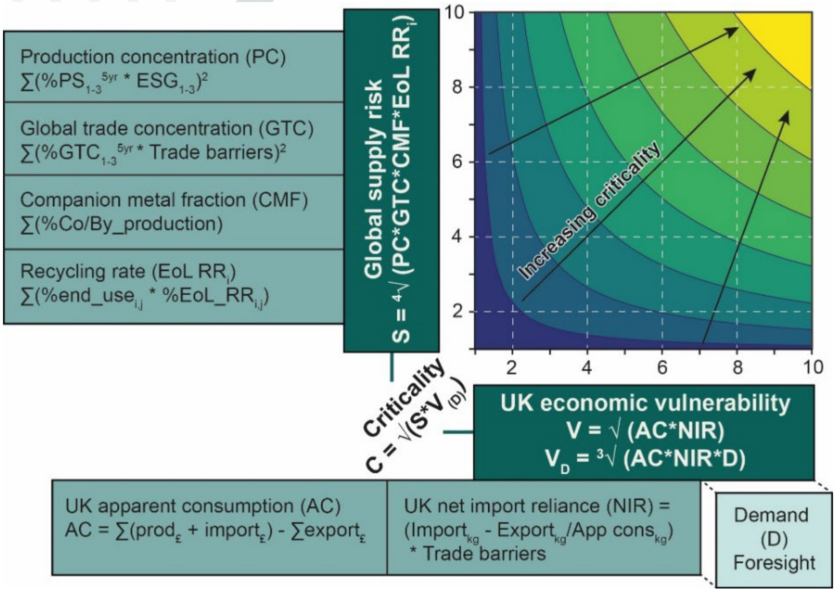
UK Critical Minerals
Intelligence Centre

Review and development of the methodology and data used to produce the UK Criticality Assessment of Technology-critical Minerals

Decarbonisation and Resource Management Programme

External Report OR/23/044



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BRITISH GEOLOGICAL SURVEY

DECARBONISATION AND RESOURCE MANAGEMENT PROGRAMME

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Review and development of the methodology and data used to produce the UK Criticality Assessment of Technology-critical Minerals

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Editor

A Bloodworth

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Foreword

Minerals will 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
- grow the advanced manufacturing sector
- mitigate risks to national security
- deliver economic prosperity
- create opportunities for UK businesses in critical mineral supply chains domestically and internationally

This report has been produced by the British Geological Survey (BGS) and is supported by the Department for Business & Trade-funded UK Critical Minerals Intelligence Centre (CMIC). CMIC aims to provide up-to-date, accurate, high-resolution data and dynamic analyses on primary and secondary minerals resources, supply, stocks and flows of critical minerals, in the UK and globally. Its work supports delivery of the UK Critical Minerals Strategy, which aims to improve the security of supply of critical minerals by accelerating the UK’s domestic capabilities, collaborating with international partners and enhancing international markets.

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Summary

This report was produced by the British Geological Survey (BGS), which hosts the UK Critical Minerals Intelligence Centre (CMIC). The aim of the study was to review the methodology used to produce the 2021 UK Critical Mineral List, with the objective of refining the criticality indicators and associated data for the next UK Criticality Assessment.

The first part of the report summarises the methodology employed during the 2021 UK criticality assessment ('2021 CA') (Lusty et al., 2021). It describes the list of candidate materials (CMs) considered in the 2021 CA study and the indicators selected to evaluate their criticality. A review of the major criticality assessments (CAs) conducted by other nations and industry is also presented, discussing objectives, methodological best practices, and inherent limitations.

Many governments have published national CA studies in the last decade. Most use a similar, mainly quantitative, approach to determine a numerical rating of relative criticality among numerous CMs. However, it is evident that CAs are flexible and can be adapted in both scope and scale to reflect the needs and objectives of the commissioner. In broad terms, CAs can be used to identify the business opportunities for resource-rich jurisdictions or the supply chain vulnerabilities for major resource-consuming nations. As a result, the methodology and scope of reviewed CAs largely depend on objectives and access to reliable, high-quality, national, and global datasets.

An in-depth review of the 2021 CA methodology is presented, including the proposed list of CMs to be evaluated. The list is now expanded from 26 to 82 CMs, including individual elements and industrial minerals. Each indicator and its associated metrics are evaluated alongside discussion regarding retaining, modifying, or discontinuing the indicator. Mathematical best practice on aggregation of indicators and the graphical representation of the candidate material in a criticality space are also reviewed and presented. The major developments are presented in Table 1.

Table 1 Major developments from this review of the 2021 CA.

Methodological improvements	
Indicator scoring	A harmonised approach to scoring each indicator and combining them using the geometric mean, on a scale of 1 to 10, is developed. Using this mathematical function instead of the arithmetic mean or simply summing the indicator scores results in more robust representation of indicator scores that are expressed in different units. This is particularly important for combining indicators in a single criticality dimension and for generating final criticality score for each CM. This scoring is also preferable to binning the data into categories, which leads to losses in data resolution and artificially inflates differences between categories.
Critical space representation	More accurate representation of the critical space using convex isocritical contours rather than orthogonal thresholds is adopted following applied risk management theory. This significant modification stems from the issue of interpretating risk matrices using logarithmic scales transposed to CA using linear agglomerated scales. The revised critical space permits a more logical representation of the degrees of criticality, as a function of supply risk (*S*) and economic vulnerability (*V*).
Candidate material list	An expanded list will be assessed, increasing from 26 to 82 CMs based on clear selection criteria (Table 2).
Environmental, social, governance (ESG) score	Calculation of a composite ESG score is developed for each mineral-producing country based on a combination of: • World Governance Index (WGI) • Human Development Index (WDI) • Environmental Performance Index (EPI) This is used as a weighting factor when calculating certain indicators, for which the ESG performance of the producing jurisdiction represents a risk factor. • $ESG(i) = \sqrt[3]{(\mathrm{EPI(i)} * \mathrm{HDI(i)} * \mathrm{WGI(i)})}$
Discontinued indicators	
Price volatility	Discontinued due to concerns regarding its validity as an indicator of economic vulnerability. The wide range of CMs' traded forms and associated respective price variations, and the challenge of obtaining reliable price data for certain CMs, prevent a price volatility indicator being employed in a consistent way for all CMs.
Substitutability	Assigning a single value to the substitution index is not an accurate reflection of the range and scale of potential substitutability in all applications and industrial sectors. It is inevitably highly subjective and cannot be undertaken in a consistent and reliable manner for all CMs.

Modified or replaced indicators	
Production concentration	The use of the Herfindahl-Hirschman index (HHI) is modified in the production concentration indicator (PCI) to incorporate a weighting factor of the production share by the ESG score in the supply risk (*S*) dimension. • $PCI = (\sum_{i=1}^{3} 5\ yr\ avg.\%\ of\ global\ production(i) *\ ESG(i))^2$
Recycling rate	The recycling rate is modified to reflect the end-of-life efficiency with which a material contained in a product is collected, pre-treated and recycled. This indicator reflects global, rather than UK-specific, recycling rates. Consequently, this indicator has been moved to the supply risk (*S*) dimension. • $EoL\_RR_i = \sum_{J=1}^{n} end\_use_{i,j} \times EoL\_RR_{i,j}$
Production evolution	Replaced with a UK mineral demand indicator following compilation of foresight studies covering the technologies essential for decarbonisation, such as heat pumps, photovoltaic cells, fuel cells, electrolysers, wind turbines, batteries, nuclear technologies, and traction motors.
Global trade concentration	Refined to include all traded forms of the CMs that correspond to the mining and refining stages. The share of each country's imports will be weighted by trade restrictions. The global trade concentration indicator was a component of the UK economic vulnerability (*V*) dimension in the previous UK CA. However, because the indicator assesses global trade flows, it is more appropriate to be included as part of the global supply risk (*S*) dimension. • Global imports ($(x)_a^z$) = Σ[imports ($(x)_a^z$,y)] • Net imports ($(x)_a^z$,y) = imports ($(x)_a^z$,y) - exports ($(x)_a^z$,y) • Share of net import ($(x)_a^z$,y) = Net imports($(x)_a^z$,y) / Global imports ($(x)_a^z$) • $GTC = (\sum_1^3 5\ yr\ avg.of\ share\ (y)\ of\ net\ import\ (x)_a^z * trade\ barriers\ (y))^2$
UK gross-value added (GVA)/UK apparent consumption	Due to issues with data availability and consistency for calculating the UK GVA, this indicator is replaced by UK apparent consumption based on UK trade data using monetary values (£) rather than volumes. • $\text{Apparent consumption (x)} = \sum(\text{production(£) } (x)_a^z + \text{import(£) } (x)_a^z) - \sum \text{export(£) } (x)_a^z$
Unchanged indicators	
Companion metal fraction	Although companionality datasets are dated, no recent update has been produced covering the whole range of CMs. The method remains similar to the previous CA.
Import reliance indicator	This indicator remains calculated as the UK net import reliance (NIR) weighted by trade restrictions. • NIR = (imports - exports / apparent consumption) * trade restrictions (y)

The report concludes with a discussion on the limitations of CAs and future areas for development, with a summary of the revised methodology that BGS proposes to use in future UK CAs.

1 Introduction and background

In 2021, the British Geological Survey (BGS) was commissioned by the (then) Department for Business, Energy and Industrial Strategy (BEIS) to produce a ‘Criticality Assessment of Technology-critical Minerals and Metals’, also referred to as an ‘assessment of minerals critical to the UK’, herein referred to as the ‘2021 CA’. BEIS wanted to improve understanding of:

- the minerals and metals most critical to the UK
- potential changes in future demand for minerals and metals, and their drivers
- the impact of shifts in demand on the UK economy and security of mineral raw material supply

The 2021 CA was undertaken over a six-week period, commencing on 1 November 2021 (Lusty et al., 2021). The results of the 2021 CA were presented to the BEIS Critical Minerals Expert Committee in December 2021; the accompanying report was delivered to BEIS in January 2022 and was published in June 2022.

During the project, a methodology was developed for the identification of those minerals and metals most critical to the UK, which was based on international best practice and BGS knowledge of UK supply chains and available data. Several recommendations were made for improving this methodology in order to strengthen its UK focus and to increase its consideration of future demand patterns and criticality for the UK. This was to be implemented by reviewing the indicators used and enhancing the quality and UK relevance of the underpinning data. Consultation with stakeholders who have detailed knowledge of global demand and supply of individual materials and potential issues for the UK economy was also advocated.

2 Overview of the UK criticality assessment 2021

2.1 CANDIDATE MATERIALS

Twenty-six 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 disruption (Table 2). Due to the time constraints on the project, the CMs included those materials most commonly classified as 'critical' in other national and regional assessments. Energy minerals, construction raw materials, biotic materials, gases, and most industrial minerals were excluded from this assessment (Lusty et al., 2021).

Table 2 Candidate materials evaluated in the 2021 criticality assessment (Lusty et al., 2021).

Candidate material		
Antimony (Sb)	Magnesium (Mg)	Silicon (Si)
Beryllium (Be)	Manganese (Mn)	Strontium (Sr)
Bismuth (Bi)	Molybdenum (Mo)	Tantalum (Ta)
Cobalt (Co)	Nickel (Ni)	Tellurium (Te)
Gallium (Ga)	Niobium (Nb)	Tin (Sn)
Germanium (Ge)	Palladium (Pd)	Titanium (Ti)
Graphite (C)	Platinum (Pt)	Tungsten (W)
Indium (In)	Rare earth elements (REE)	Vanadium (V)
Lithium (Li)	Rhenium (Re)	

2.2 GLOBAL SUPPLY RISK

Three indicators were used to estimate the global supply risk (*S*) for each CM:

- production concentration
- companion metal fraction
- recycling rate

These are described and the rationale for their use summarised in Table 3.

Table 3 Summary of global supply risk indicators used in the 2021 criticality assessment.

Indicator	Rationale	Description	Main data sources	Year of data publication
Production concentration	S increases with greater concentration of production and is also influenced by governance factors in 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, 2022)	2015 to 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 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	EU's list of critical raw materials (European Commission et al., 2020a)	2020

2.3 UK ECONOMIC VULNERABILITY

The UK economic vulnerability (*V*) was calculated from six indicators:

- production evolution
- price volatility
- substitutability
- global trade concentration
- UK import reliance
- UK gross value-added contribution

These are described and the rationale for their use is summarised in Table 4.

Table 4 Summary of UK economic vulnerability indicators used in the 2021 criticality assessment (see Lusty et al. (2021) for further information).

Indicator	Rationale	Description	Main data sources	Year published
Production evolution	High growth rates in mineral demand 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 to 2018
Price volatility	Fluctuating commodity prices can impact producing and consuming countries.	Price volatility over the period January 2016 to December 2021.	DERA Volatilitätsmonitor (BGR, 2023)	2016 to 2020
Substitutability	Substitution may reduce the economic impact of material supply disruption.	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 et al., 2020a)	2020
Global trade concentration	Countries that dominate global imports of a material can control the production and trade of products further down the value chain.	Global trade concentration calculated from the share of trade in a CM that is taken by the top three net importing countries.	UN Comtrade Database	2015 to 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 (NIR), calculated from trade data and modified by the degree of concentration of UK trading partners, governance in these countries and any trade restrictions.	UK Trade Information (HM Revenue & Customs, 2023); BGS World Mineral Statistics database; PRODCOM (Office for National Statistics, 2020); Worldwide Governance Indicators (World Bank, 2022); Inventory of Export Restrictions (OECD, 2020)	2023; 2015 to 2019;2020; 2022; 2020
UK gross-value added (GVA) contribution	Raw materials 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 two-digit level ‘manufacturing’ codes, against which GVA is reported.	Application shares (various); GVA data (Office for National Statistics, 2021a, Office for National Statistics, 2021b).	Various; 2021

2.4 RESULTS

The evaluation of each indicator was based on the quantitative aggregation of a range of relevant metrics for each CM. The derived scores for each indicator were weighted according to their importance to *S* and *V*, then summed to produce an estimate of *S* and *V* for each CM. Weighted *V* indicator values were plotted against weighted *S* indicator values for each CM to produce a criticality matrix (Figure 1). Thresholds assigned to *S* and *V* were used to distinguish CMs with 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* (Table 5). These constitute the UK Critical Minerals List 2021.

2.5 DATA SOURCES AND RECOMMENDATIONS

In the 2021 CA, the data were derived from publicly accessible databases and from the scientific literature. The availability, quality and relevance of those data are major influences on the reliability of the criticality ranking. Up-to-date, high-quality data directly relevant to the objectives of this study are available for world mineral production. In contrast, data on UK trade partners and traded volumes are less informative. For several CMs (mostly minor metals) the trade data are commonly aggregated with other commodities and thus lack the granularity needed for this assessment. For some other indicators, notably recycling rates, companion metal fraction and substitutability, up-to-date and consistent datasets for all CMs are not available. In such cases, estimates are based on qualitative expert judgement rather than on quantitative data.

The 2021 CA also noted that the reliability of the findings could be improved by refinement of the methodology, in particular by focusing on the selection of more appropriate indicators and by using UK-focused data of higher quality wherever possible. It could 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 to determine appropriate interventions to ensure security of supply.

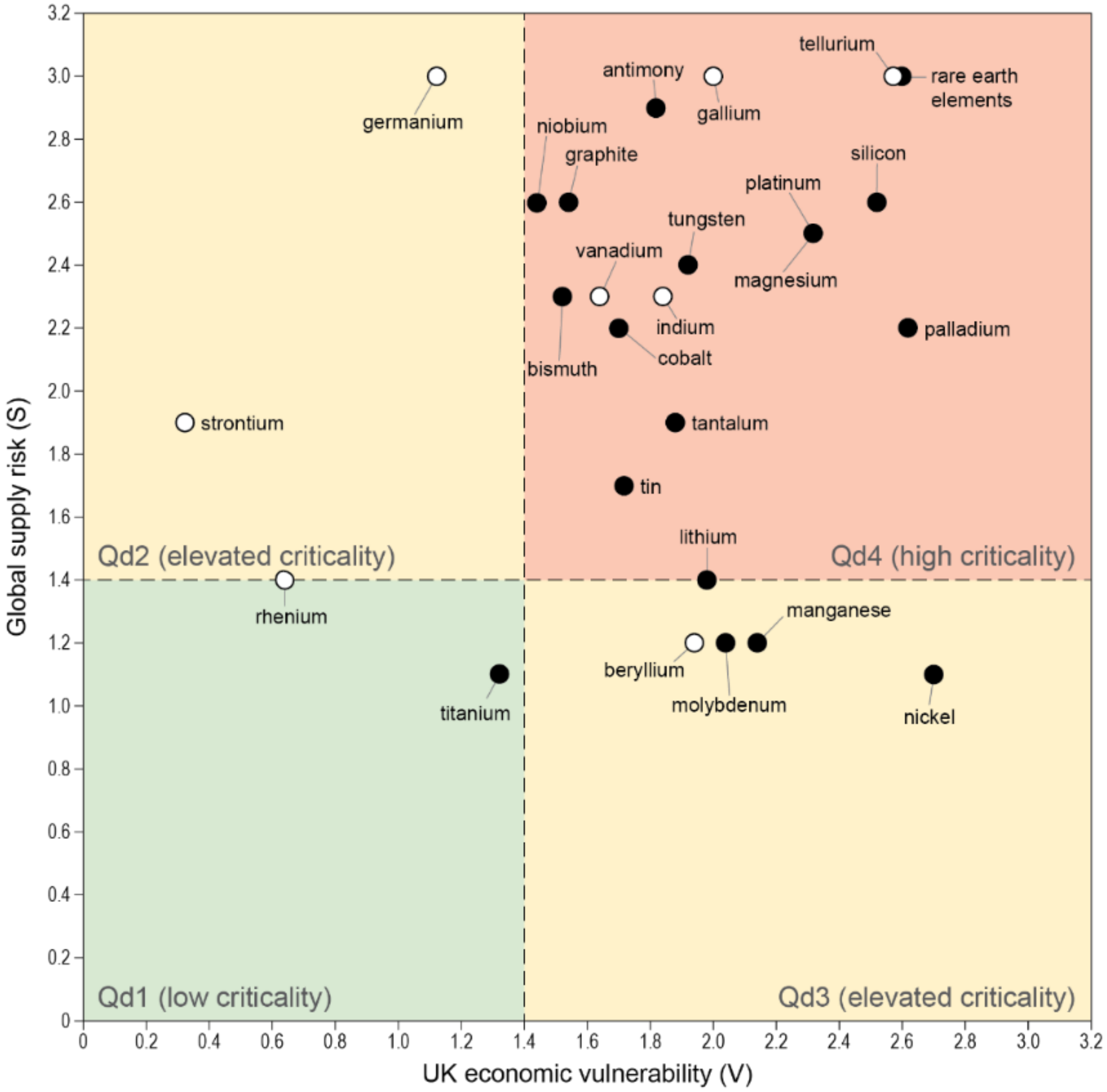


Figure 1 Assessment of 26 candidate materials (CMs) potentially critical to the UK. The horizontal axis of the criticality matrix reflects the economic vulnerability of the UK (*V*) to a potential supply disruption and the vertical axis reflects the likelihood of supply disruption, termed global supply 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 CMs that were scored on all nine indicators. Open symbols represent those CMs for which one or more *V* indicators are absent due to no data. Therefore, for these CMs, the aggregated *V* scores are not based on the full set of six *V* indicators (Lusty et al., 2021).

Table 5 UK critical minerals list 2021 (see Lusty et al. (2021) for further information).

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

3 Review of international practice in criticality assessment methodology

3.1 INTRODUCTION

As resource-consuming countries have become ever-more dependent on imports of materials, they are increasingly vulnerable to supply disruption. Government and industry are therefore concerned about what materials are at risk and the severity of the consequent impacts. This information can then be used to develop strategies to mitigate the effects of supply disruption. As a result, many criticality assessments (CAs) have been published in the past 15 years by governments, non-governmental organisations, academics and commercial companies (Schrijvers et al., 2020).

However, **it is important to stress that there is no universal methodology for CA and, consequently, there is no single, correct, or fixed list of critical raw materials (CRMs)**. The methodology adopted and the derived results depend on who is asking the question and for what purpose. For example, resource-rich jurisdictions that are significant exporters of minerals, such as Canada and Australia, have different purposes for producing critical minerals lists than countries such as the United Kingdom (UK and South Korea, or unions such as the European Union (EU), that are almost entirely dependent on imports for critical minerals.

CA is generally undertaken by evaluating two key dimensions: the likelihood of supply disruption, commonly termed supply risk (S) and the impact of, or vulnerability (V) to supply disruption. **The latter is generally estimated by measuring the economic importance (EI) of the industrial sectors that depend on supply** (Figure 2).

Some CA studies have also attempted to incorporate environmental risk through the use of indicators that address issues such as pollution, energy and water use, resource management, environmental regulation and quality of governance (Graedel et al., 2012, Malala and Adachi, 2022, Yan et al., 2021). With growing global concern about environmental, social and governance (ESG) issues related to raw materials supply and use, these topics will likely assume greater importance in future CA studies because of their potentially serious impacts on maintaining secure and sustainable supplies.

CA is carried out by analysing a range of indicators that are judged to reflect *S* and *V* in some way. The indicators are quantified from relevant metrics to derive values for *S* and *V*, which, in turn, are used to determine a criticality value (*C*) for each CM. CMs are then generally classified as critical or non-critical according to whether they exceed a particular threshold value. However, it should be emphasised that **criticality is actually a matter of degree and not of state**: it is not analogous to an either/or situation or to the position of an on/off switch (Figure 3). What is most important is where a material sits, in a range from low to high *C* values. **Given the method by which C is calculated and the uncertainties in the underlying data, those CMs with C values lying just below the chosen threshold should not be ignored**.

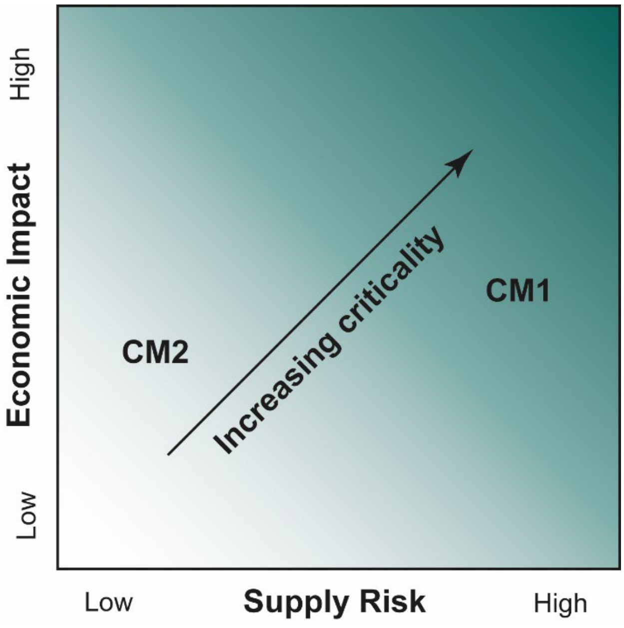


Figure 2 Criticality is generally estimated based on two dimensions: supply risk and economic impact of supply restriction. In this two-dimensional matrix, CM1 has a higher degree of criticality than CM2.

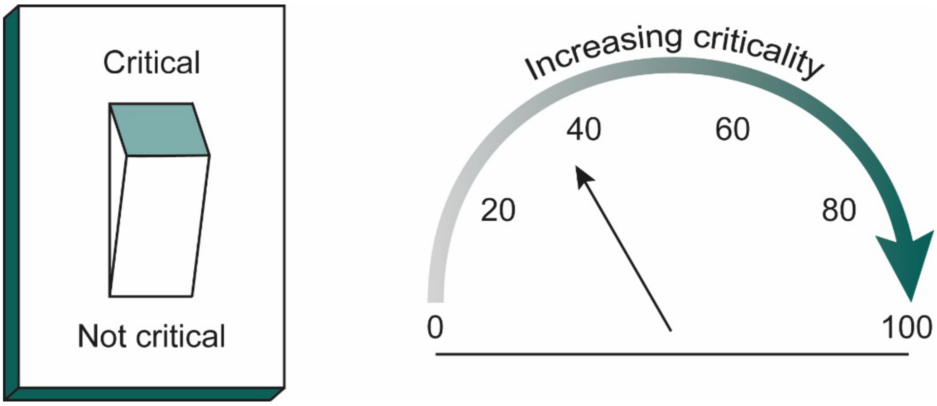


Figure 3 Criticality is best described as a continuum between low to high levels of criticality (right) rather than a discrete on/off criticality state (left).

The metrics used in CA are derived from a wide range of sources such as databases, scientific papers and technical publications relating to a plethora of subjects, including:

- global production and refining of mineral raw materials
- governance standards in producing countries
- consumption
- trade
- commodity prices
- recycling rates

The fundamental premise of CA is to determine the relative criticality of the CMs according to a set of indicators that can be quantified across the board for all CMs. **The CA should, therefore, use reliable data for all the metrics for each CM so that the relative criticality is assessed**

with confidence. However, this is rarely the case because data may be of low quality or entirely absent for some metrics and some CMs.

The data issue is generally most problematic for minor metals that are used mainly in new technologies in small quantities. Our knowledge base for these is limited because, until recently, they had limited industrial application. Our understanding of their life cycle is generally much poorer than that of major industrial metals, such as iron, aluminium and copper, which have long been used in manufacturing.

The methodology used in a quantitative analysis of criticality generally follows a series of steps:

1. Selection of CMs
2. Selection of indicators for *S* and *V*
3. Selection of metrics to quantify the indicators
4. Acquisition of data for all metrics for each CM
5. Analysis of data, resolution of quality issues and identification of gaps
6. Aggregation of metrics and calculation of scores for each indicator for each CM
7. Aggregation of scores to derive an overall rating for *S* and *V* for each CM
8. Distinction between critical and non-critical CMs, including definition of thresholds for *S* and *V*
9. Display and communication of results

Ideally, for a robust determination of relative criticality, reliable data would be available for all metrics and for all CMs over the same period. If these conditions are not met, then estimates must be made, which inevitably introduces subjectivity and undermines the quality of the CA. In some cases, where there is no reliable data for a particular CM, a qualitative assessment based on experience and expert knowledge is the only viable option. However, the results of such a subjective evaluation cannot be directly compared with those of a quantitative analysis.

3.2 PREVIOUS NATIONAL CRITICALITY ASSESSMENTS

Many governments have published national CA studies in the last decade. Most use a similar, mainly quantitative, approach to determine a numerical rating of relative criticality among numerous CMs.

However, several criticality studies carried out in other countries follow a fundamentally different (mainly qualitative) approach that focuses on an analysis of the ability of those countries to meet the growing global need for raw materials through increased and improved mineral exploration, extraction, processing, manufacturing, and recycling. This leads to the creation of jobs and prosperity in these countries. Notable examples of the application of this approach include the critical minerals lists produced by Canada and Australia.

Canada's Critical Minerals List identifies 31 minerals and metals considered essential for the sustainable economic success of Canada and its trading partners (Government of Canada, 2022). This list was developed using a criteria-based approach in consultation with provinces and territories as well as exploration, mining and manufacturing industries and associations.

The Australian government considers 26 resource commodities to be critical minerals. These have been selected by assessing Australia's geological endowment and resource potential in the light of global technology needs, particularly those of partner countries such as the USA, UK, Japan, India, South Korea and Canada (Australian Government, 2021)

The government of South Africa has also published a list of raw materials critical for economic growth and required to support the shift to a low-carbon economy (South Africa Government Gazette, 2022). It focuses on those raw materials of which it has significant resources that might be exploited for consumption domestically and overseas. A major aim in publishing the list is to boost the competitiveness of South Africa's mining industry by attracting mineral investment and promoting mineral exploration and development. The list, comprising 18 critical minerals or mineral groups, is based on a qualitative evaluation by government and industry stakeholders. It is also significant to note that no distinction was made in this analysis between CRMs and strategic minerals. They are used interchangeably in South Africa to refer to minerals that are of national importance whose supply is at risk (Khan et al., 2022).

The government of India published a list of CRMs in a strategy document aimed at highlighting the potential impacts of raw material supply constraints on its manufacturing sector and thus developing policy options to mitigate supply risk (Gupta et al., 2016). The methodology employed was derived from that of the EU (European Commission, 2011; European Commission, 2014) using similar indicators to obtain quantitative estimates for supply risk and economic importance. Using data from 2011 for a candidate list of 49 materials, 34 were identified as 'most critical' or 'moderately critical'.

Based on various assumptions about the future global economy and a qualitative assessment of future changes in the manufacturing sector of India's economy, they also evaluated materials likely to become critical to India by 2030. It was concluded that seven minerals or materials should be added to the 'most critical' category compared with 2011. These were beryllium, chromium, germanium, graphite, rhenium, tantalum and, zirconium.

Unlike many resource-poor countries with growing industrial needs, South Korea has not published a list of CRMs. Minerals in South Korea are classified as 'legal', 'strategic' or 'rare metals'. Fifty-nine minerals are classified as legal for domestic exploration and extraction, whilst eight minerals fall in the strategic category. These include:

- bituminous coal
- copper
- iron ore
- lithium
- nickel
- rare earth elements (REE)
- uranium
- zinc

These are all considered to play a substantial role in the national economy and security.

Although there is no standard definition of a 'rare metal' in South Korea, the term has many similarities with critical minerals as defined elsewhere, for example, increasing demand, concentrated production and elevated risk of supply disruption. The rare metal classification also considers the crustal abundance of an element and difficulties in extracting it from its host ores, aspects which are seldom considered in CA. Without providing any methodological information, Lee and Cha (2021) presented a list of 35 rare metals in South Korea. Most of these are also found in critical minerals lists from other countries such as the USA, EU and Japan (European Commission et al., 2020a; Malala and Adachi, 2022; US National Archives, 2022).

The importance of CRMs is, therefore, clearly recognised in South Korea. Recommendations for a new resource strategy have been made, which include the expansion of measures to enhance a circular economy, stockpiling of rare metals and resource development both domestically and overseas (Lee and Cha, 2021). Diversification of the supply chain to reduce reliance on China and Japan is also recommended.

3.2.1 Detailed descriptions and evaluations

Several national and regional CA studies published in the last decade merit detailed description and evaluation of the methodologies used.

3.2.1.1 EUROPEAN UNION

The European Commission (EC) has published five CA studies for the EU

- European Commission, 2011
- European Commission, 2014
- British Geological Survey et al., 2017
- European Commission et al., 2020a
- European Commission et al., 2023a

Each is based on two criticality dimensions, *S* and economic importance (EI), and is an update of the preceding study.

Although the EC has continually aimed for backward compatibility in order to highlight changes and to identify trends, the methodology has evolved to some extent with each iteration. At the same time, the number of CMs has increased from 41 in 2011 to 87 in 2023. Whilst the indicators and metrics have remained essentially the same, the usage of some and the calculations involved have been changed and the quality of some of the supporting data has been improved.

The EC has also made increased use of expert consultation to provide authoritative technical and market insight, confirmation of assumptions and estimation of missing values. This has been accomplished chiefly through a series of stakeholder workshops focused on individual CMs (European Commission et al., 2023a).

The content of the derived CRM list has also changed in response to the methodological improvements and changing market conditions, although many CRMs remained critical in all five assessments. The main features of the most recent EU assessment (European Commission et al., 2023a) are summarised in Table 6. The EU methodology is described in Blengini et al. (2017). Further details of individual metrics, data sources and data quality, with worked examples, are given in a technical report (European Commission et al., 2023a).

The EI value is derived by first assigning the raw material applications of each CM to the appropriate EU manufacturing sector at the NACE 2 (2 digit) level. The EI is the weighted sum of the application shares according to the gross value added (GVA) of each NACE 2 sector. These values are multiplied by a ‘substitute index for economic importance’, which is related to substitute cost and technical performance (Blengini et al., 2017).

S is a function of production concentration, governance standards in producing countries, EU import reliance, substitutability and recycling rates. Where data are available, *S* is calculated separately for two life-cycle stages: extraction (mine production) and processing (refining). In the latest EU assessment, 40 materials were assessed separately at the extraction and processing stages (European Commission et al., 2023a).

For each CM, the square of the shares of global production is multiplied by the scaled World Governance Indicators (WGI) values for each producing country (World Bank, 2022). Where adequate data exist, similar calculations are made for those countries that actually supply materials to the EU. When the EU import reliance is 100 per cent, the *S* calculation uses the average of the global supply and the actual sourcing to the EU. Where the EU is independent, or almost independent, of imports, the global supply mix is disregarded, and the risk is calculated based solely on the actual sourcing of the material to the EU. These concentration risks are multiplied by a trade variable, which reflects export taxes, quotas and embargoes for each CM and producing country. In this way, two measures of *S* related to production concentration — one global and one for supply to the EU — were incorporated into the analysis (Blengini et al., 2017).

Table 6 Summary of selected criticality assessments.

CA	Scope	CMs	Dimensions	Life cycle stages evaluated	Indicators	Metrics	Age of data	Data manipulation	Criticality ranking method	No. CRMs
European Commission et al. (2023a)	EU	87	• Supply risk (SR) • Economic importance (EI)	• Extraction • Processing (where data available)	• SR: production concentration • EU net import reliance • EI: GVA contribution	• Global production concentration • Production concentration of EU sources • WGI of producers • Import reliance • Trade restrictions • Recycling rate • Substitution indices • GVA by weighted sum of application shares	2012 to 2020 (where available)	No weighting of indicators; SR and EI values normalised	Critical if threshold values for both SR and EI are exceeded	34
US Geological Survey (2022); US National Archives (2022)	USA	54	• Supply risk (SR)	• Extraction • Processing (where data available)	• Disruption potential (DP) • Trade exposure (TE) • Economic vulnerability (EV)	• DP: global production concentration • Ability to supply • Willingness to supply • TE: net import reliance • EV: for each industry • Value added expenditure on each CM • Operational profit	2007 to 2018	Geometric mean of 3 indicators; values normalised and recency weighted	Critical if the geometric mean of the 3 indicators exceed a threshold value	50 in final US Critical Mineral List (2022)
Malala and Adachi (2022)	Japan	18	• Vulnerability to supply restriction • Supply restriction	• ?	• Economic contribution • Probability distribution functions • Production concentration	• Metal price • Contribution of metal to GDP • Global production concentration • Production concentration of import partners weighted by WGI	2000; 2005; 2011; 2015 (separate years)	No weighting; vulnerability and risk values normalised	Normalised values plotted in 2D matrix with isocriticality contours. Arbitrary division, no threshold defined	9 (of which only 6 listed in abstract)
Yan et al. (2021)	China	64	• Supply safety (SS) • Domestic economy (DE) • Environmental risk (ER)	• ? entire life cycle?	For SS: • sustainability risk • reliance risk • tolerance risk For DE: • value of end use • market value	• Substitutability • Recycling rate • Import reliance • Traffic condition reliance • PPI • H • WGI • Consumption structure • National industries classification • GNP	2015 to 2019	No weighting; values normalised in range 1 to 10	Plotted in 2D and 3D space with isocriticality contours defined and threshold value of 2	18 in 3D 24 in 2D (excluding ER)

					For ER: • autotoxicity risk • risk of pollutants	• Market value index for metal • Toxicity grade for metals • Release of pollutants • EPI				
World Materials Forum (2022)	Global	58	• Supply risk	• Extraction • Processing	• Lifespan of reserves • Uncertainty of supply • Political exposure of supply • Environmental performance • Recycling • Uncertainty of demand • Substitutability	• Global reserves; annual production; WGI • Water and energy footprint • Current recycling rates • Qualitative assessment of demand drivers • Availability of alternative materials	?	No weighting; each indicator scored 1, 2 or 3 for each CM. 7 indicator values summed to derive a composite value for C.	No thresholds. C ranking based on value of composite index derived from 7 indicators	Five risk levels defined: very high to low
DERA (2021)	Global	• 53 raw materials • 27 refined metals • 217 traded products	• Supply risk	• Extraction, processing and intermediate products	• Country concentration • Country risk	• Global production concentration (HHI) • Country risk (WGI) weighted by share of global production	2018	No weighting; country concentration and country risks classified low, medium, high	Plotted in 2D space with two orthogonal thresholds on each axis	3 risk groups defined: low, medium and high

Extraction = mine production; processing = smelting and/or refining.

EU import reliance is calculated from data on EU imports, exports, and domestic production, again for both extraction and processing stages where data allow their separate treatment. A second substitute index for *S* is used as a modifying factor to reflect the degree to which substitution might mitigate the risk of supply disruption. Further modification is provided by integrating the end-of-life recycling input rates, so that higher recycling rates equate to increased supply risk mitigation. The methodology used in the latest EU study is summarised in Figure 4 (European Commission et al., 2023a).

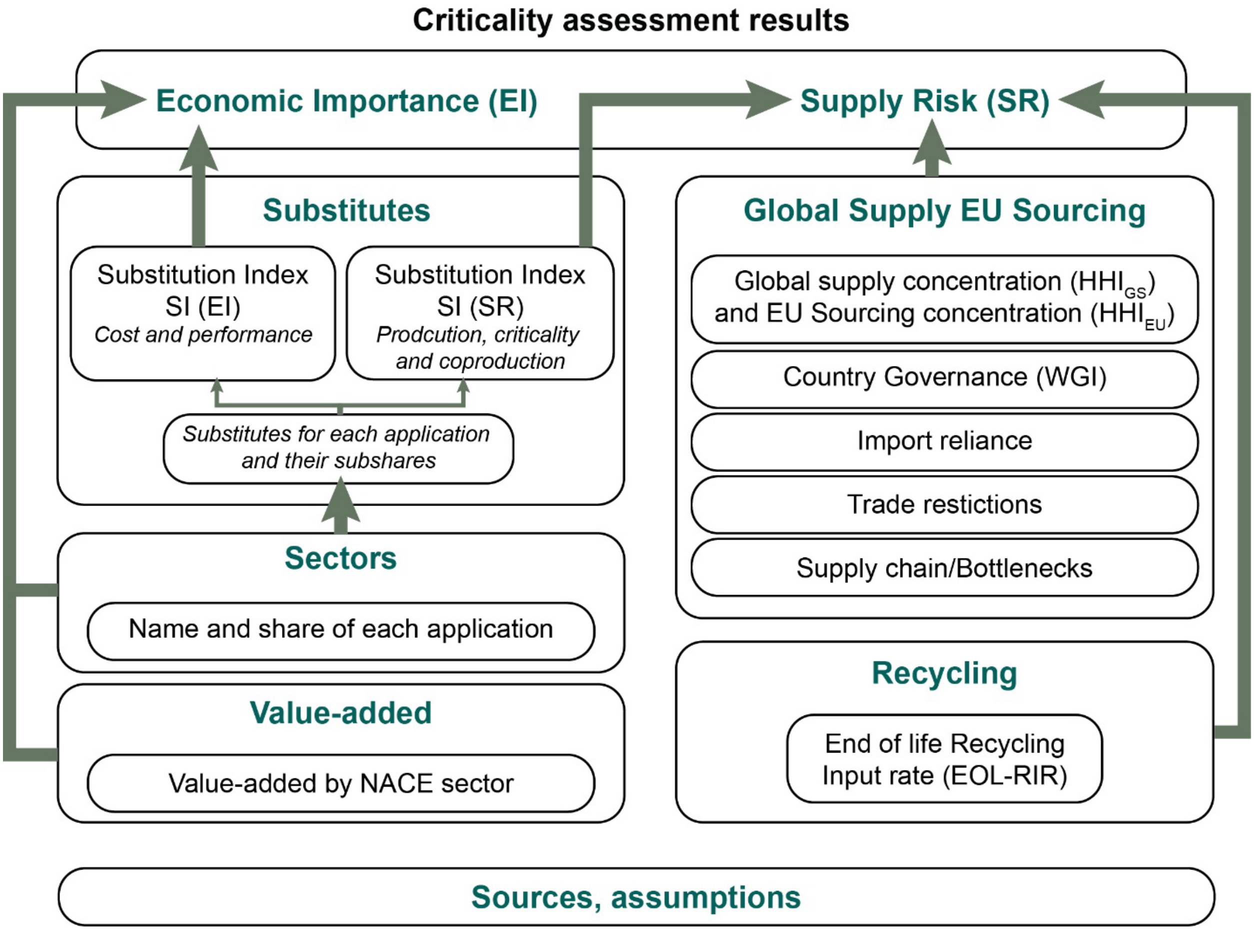


Figure 4 Outline of the European Union criticality assessment methodology (reproduced from European Commission et al. (2017) under the CC BY 4.0 licence).

Where two stages of the supply chain were assessed, only the one with the highest *S* value was incorporated in the final analysis of EU criticality. The *S* and EI values are normalised and plotted in a 2D matrix. A material is classified as critical to the EU economy if both its *S* and EI values exceed arbitrary threshold values for each dimension of this matrix (Figure 5).

The selection of threshold values to distinguish critical and non-critical raw materials is not discussed in reporting the results of the analysis (European Commission et al., 2023a). However, it is noted that the thresholds adopted remain the same as in previous EU CAs. **It is also important to note that future demand and supply levels are not incorporated into this analysis**. However, the extensive factsheets for each CM, which were published with the CA in 2020, provide commentary on all aspects of the CM life cycle including a brief, qualitative assessment of future demand and supply scenarios (European Commission et al., 2020b; European Commission et al., 2020c). These factsheets were updated for the 2023 EU criticality assessment (SCRREEN2, 2023).

In 2023, the EU also introduced the concept of ‘strategic raw materials’ (SRMs). An SRM is defined on the basis of its importance to green and digital technologies as well as defence and space applications (European Commission et al., 2023b). This was calculated from the amount of raw material required and the future global demand for these technologies. A total of 16 raw materials were classified as strategic in this way. Of these, 14 were also identified as critical according to the CA methodology. Copper and nickel were the only SRMs that do not exceed the *S* and EI thresholds for criticality, but they are, nevertheless, included in the list of CRMs because of their strategic importance.

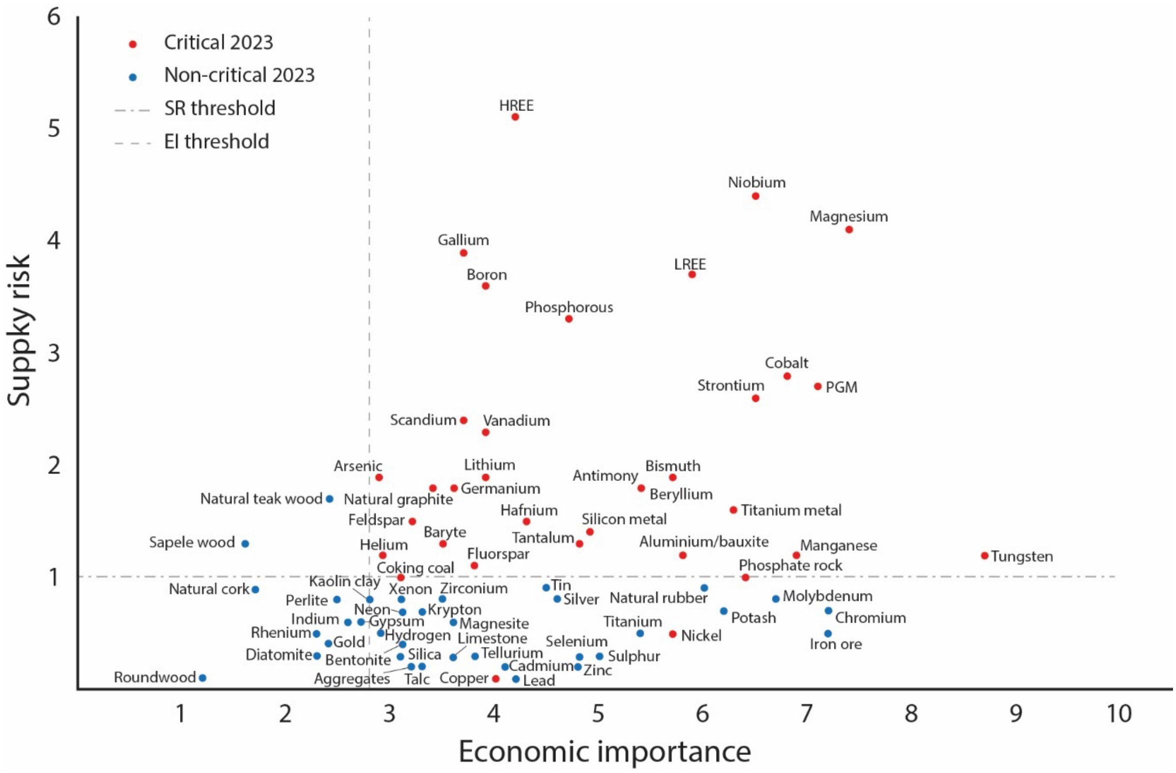


Figure 5 Results of the EU2023 criticality assessment (copper and nickel do not meet the threshold values for criticality but are included in the list of critical minerals because they are strategic raw materials) (reproduced from European Commission et al. (2023a) under the CC BY 4.0 licence).

3.2.1.2 UNITED STATES OF AMERICA

Several CA studies have been carried out by government and academia in the USA. The first was undertaken in 2008 in response to growing concerns about the availability of minerals and metals in the light of increasing resource nationalism, growing geopolitical instability and the dominance of China in the supply and consumption of many commodities (National Research Council, 2008). Subsequently, the US Department of Energy undertook two criticality assessments based on material supply risk and importance to energy (US Department of Energy et al., 2010; US Department of Energy et al., 2011). These studies identified priority critical materials requiring particular attention based on projections of energy technology demand under various scenarios. These scenarios looked at expected changes in both global technology deployment and material intensity.

The research group at Yale University has also been a leading player in CA for over a decade. Notable assessments with potential global application include Graedel et al. (2012), and Graedel et al. (2015a).

The first comprehensive CAs undertaken by the US government were published by the National Science and Technology Council (2016; 2018) and subsequently refined by the United States Geological Survey (USGS) (Fortier et al., 2018; McCullough, and Nassar, 2017). These studies were essentially 'country agnostic', undertaking an assessment of supply risk at a global scale using data for 2007 to 2014 inclusive. Potential criticality was calculated from the geometric mean of three indicators:

- production concentration, modified by the WGI of producing countries
- production growth
- market dynamics, based on the variation in commodity prices over the defined time period

Critical and non-critical populations were separated by hierarchical cluster analysis. The derived draft critical minerals list, published in 2018, comprised 35 materials from an initial 77 CMs (Fortier et al., 2018).

The US government is legally required to review and update the CA methodology and conduct a new analysis at intervals not exceeding three years. Following public review and consultation, a final critical minerals list (CML) was published in 2022 (US Geological Survey and the Department of the Interior, 2022). This comprised 50 mineral commodities, with the increase from 35 in 2018 due largely to the splitting of the rare earth elements (REE) and platinum-group metals (PGM) into individual entities. The Energy Act of 2020 explicitly excluded fuel minerals from the definition of critical minerals so uranium, which had been assessed in 2018, was not included in the 2021 revision (US Department of Energy, 2020).

Minerals were included in the US CML based on, in order:

- a quantitative evaluation where sufficient data were available
- a semi-quantitative evaluation of whether the supply chain had a single point of failure (SPOF)
- a qualitative assessment when other evaluations were not possible

The most recent CA methodology was developed from the 2018 version by the addition of indicators focusing on US supply and economic vulnerability (Nassar et al., 2020; Nassar and Fortier, 2021). The analysis was conducted on 52 non-fuel mineral commodities, including the REEs and PGMs as single entities. Multiple production stages were assessed for eight commodities for which data were available. Data for the period 2007 to 2016 were used in the initial analysis (2020) but this was extended to 2018 in the latest iteration (2021). The supply risk (S) to the USA was calculated as the geometric mean of three indicators (also termed 'supply risk components'):

- the likelihood of a foreign supply disruption, termed 'disruption potential' (DP)
- the dependence of US manufacturing on foreign supplies, 'trade exposure' (TE)
- the vulnerability of the US manufacturing sector to a supply disruption, 'economic vulnerability' (EV)

Accordingly, supply risk is calculated from this equation:

$$S = \sqrt[3]{(DP * TE * EV)}$$

DP is calculated from the share of world production of an individual country modified by an 'ability to supply' index (ASI) or a 'willingness to supply' index (WSI), whichever is the greater. The ASI is based on the policy potential index (PPI) published by the Fraser Institute, which is derived from an annual survey of mining and exploration companies that evaluates numerous countries and jurisdictions (Fraser Institute et al., 2021).

The recently renamed Policy Perception Index (PPI), is a measure of the attractiveness of a country's policy climate to mineral investment (Fraser Institute et al., 2021). It is a composite index based on numerous factors including:

- environmental regulation
- legal and fiscal systems
- uncertainty over protected areas
- infrastructure availability
- social and community development
- trade barriers
- political stability
- security
- availability of skilled labour
- quality of the geological database

The WSI assumes that the stronger the relations between a supplier country and the USA then the less likely it is that that country will deliberately disrupt supply. As described in Nassar et al. (2020), WSI is calculated from three metrics:

- trade ties with the USA
- shared values
- military cooperation

The TE indicator is a measure of the degree of exposure to foreign supply disruptions. It is calculated from the US net import reliance as a proportion of US apparent consumption of each CM. Import reliance is derived from US import and export data, together with government and industry stock adjustments. Apparent consumption is calculated from domestic production, imports, exports, and stock adjustments.

The EV indicator is a complex measure of an industry's relative economic vulnerability to a supply disruption. It is based on the premise that those manufacturers that are less profitable are less able to withstand a price shock due to supply disruption than a more profitable company. Furthermore, manufacturers that have large expenditures on a given commodity are more vulnerable than those with lower expenditure on that commodity.

EV is calculated from each industry's added value, its expenditure on each commodity and its operational profit (Nassar et al., 2020). Industry-specific vulnerabilities are summed across all applicable industries to produce a commodity-specific assessment. Those industries that make a greater contribution to the US economy are thus weighted more heavily than others.

Discrimination between critical and non-critical materials using a threshold was accomplished by hierarchical cluster analysis in the first instance (Nassar et al., 2020). However, in the latest iteration (Nassar and Fortier, 2021), thresholds were assigned to each of the three supply risk indicators (DP, TE and EV), based on expert knowledge and experience (Table 7). The combination of these thresholds through a geometric mean defines the criticality threshold to evaluate the scores of each CMs. When the geometric mean of these three threshold criteria exceeded a particular value, the CM was included on the critical minerals list. Data for the years 2007 and 2018 inclusive were used in the evaluation, but more recent data were weighted more highly than earlier years to balance multi-year trends and recent events. This adjustment, termed 'recency weighting' by the USGS, is described in Nassar and Fortier (2021).

Table 7 Threshold criteria for each supply risk component used in the latest US criticality assessment (reproduced from Nassar and Fortier (2021). (ASI: ability to supply index; WSI: willingness to supply index.)

Supply risk component			
	Disruption potential	**Trade exposure**	**Economic vulnerability**
Threshold criteria descriptions	Global production of the commodity outside the USA was concentrated so that one-half was from a single country that was less able or less willing to continue to supply to the USA than the average country (specifically defined as the 75th percentile ASI and WSI indicators), or an equivalent production distribution that resulted in the same normalised score.	One-half of US consumption of the commodity was obtained from foreign sources.	Annual expenditures on the commodity were equal to the median commodity expenditure (across all commodities and years evaluated) in a manufacturing industry that had a below average (75th percentile) operating profits-to-value-added ratio, or equivalent normalised score.
Normalised score corresponding to threshold criteria (0 to 1 scale)	0.20	0.50	0.64

The values determined for the three supply risk dimensions are shown on the graph (Figure 6) and in the heat map (Figure 7). The latter also shows the threshold value selected to identify those materials included on the US Critical Mineral List.

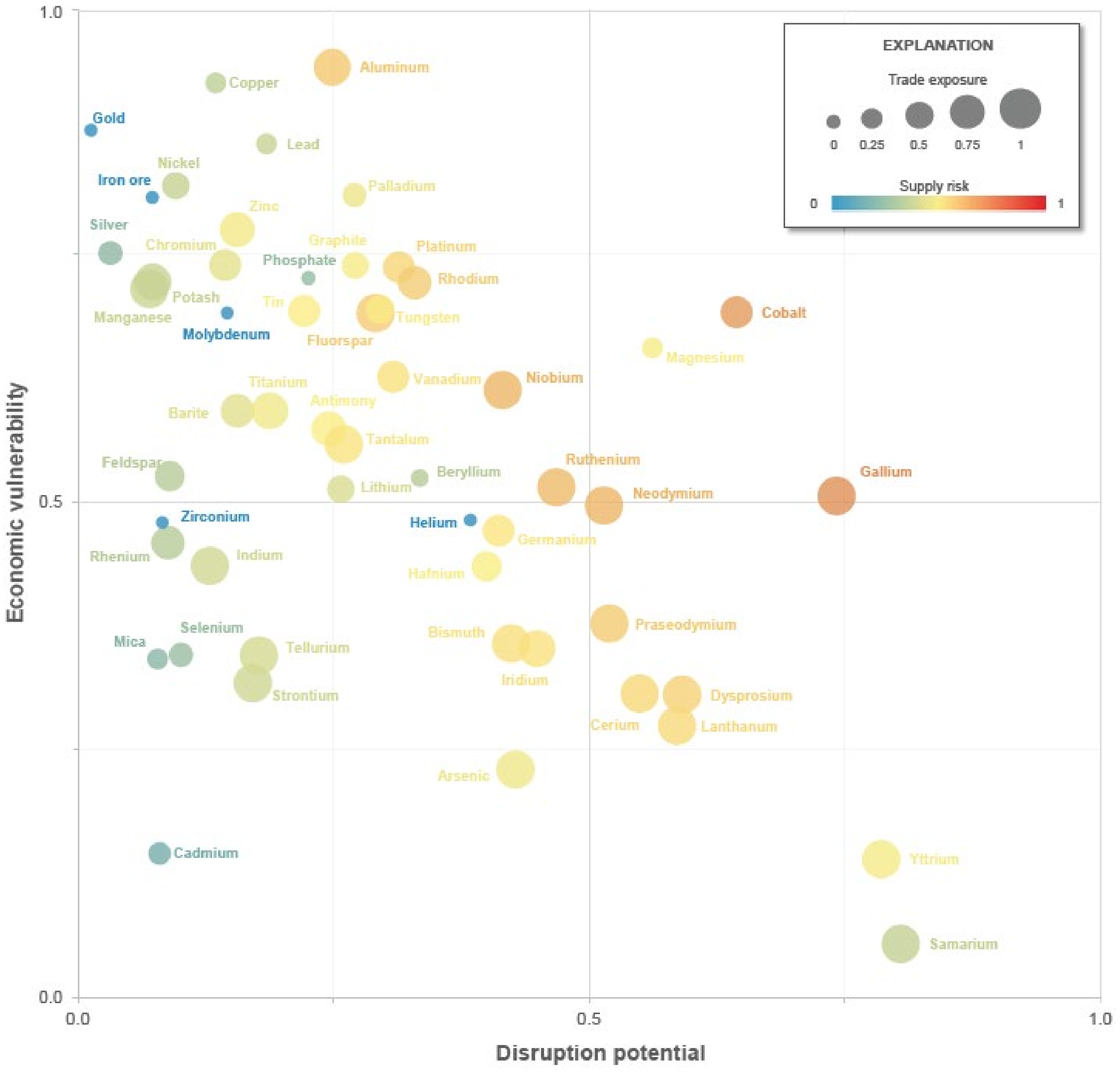
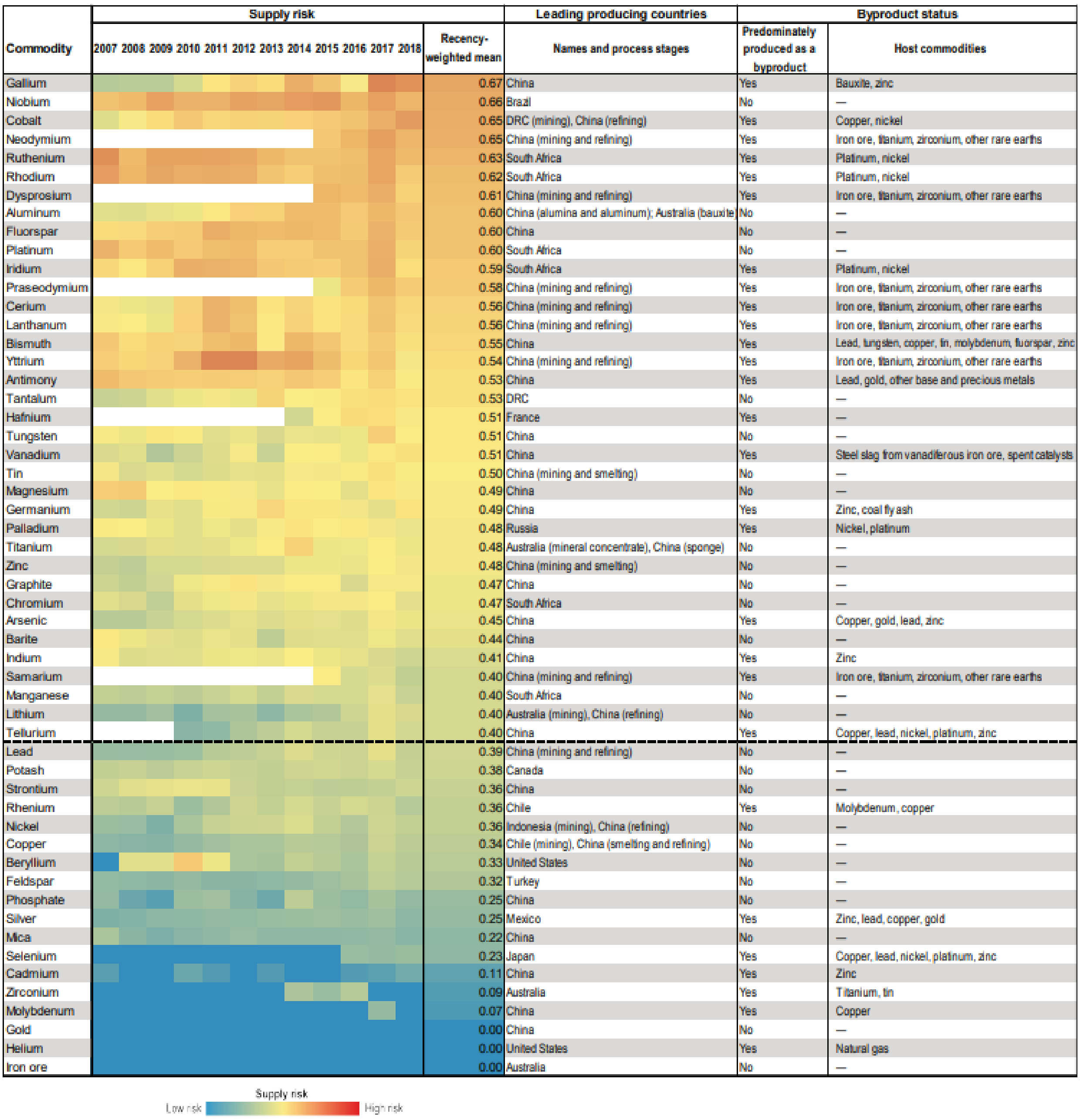


Figure 6 Results of the assessment of mineral commodity supply risk for the 2021 review and revision of the US Critical Mineral List. The graph shows the disruption potential (horizontal axis), economic vulnerability (vertical axis), trade exposure (point size) and overall supply risk (point shade) for various mineral commodities in 2018. For some commodities, indicator scores are rounded to avoid disclosing company proprietary data. (Reproduced from Nassar and Fortier (2021).)



Commodity	Supply risk													Leading producing countries	Byproduct status	
	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Recency-weighted mean	Names and process stages	Predominately produced as a byproduct	Host commodities
Gallium													0.67	China	Yes	Bauxite, zinc
Niobium													0.66	Brazil	No	—
Cobalt													0.65	DRC (mining), China (refining)	Yes	Copper, nickel
Neodymium													0.65	China (mining and refining)	Yes	Iron ore, titanium, zirconium, other rare earths
Ruthenium													0.63	South Africa	Yes	Platinum, nickel
Rhodium													0.62	South Africa	Yes	Platinum, nickel
Dysprosium													0.61	China (mining and refining)	Yes	Iron ore, titanium, zirconium, other rare earths
Aluminum													0.60	China (alumina and aluminum); Australia (bauxite)	No	—
Fluorspar													0.60	China	No	—
Platinum													0.60	South Africa	No	—
Iridium													0.59	South Africa	Yes	Platinum, nickel
Praseodymium													0.58	China (mining and refining)	Yes	Iron ore, titanium, zirconium, other rare earths
Cerium													0.56	China (mining and refining)	Yes	Iron ore, titanium, zirconium, other rare earths
Lanthanum													0.56	China (mining and refining)	Yes	Iron ore, titanium, zirconium, other rare earths
Bismuth													0.55	China	Yes	Lead, tungsten, copper, tin, molybdenum, fluorspar, zinc
Yttrium													0.54	China (mining and refining)	Yes	Iron ore, titanium, zirconium, other rare earths
Antimony													0.53	China	Yes	Lead, gold, other base and precious metals
Tantalum													0.53	DRC	No	—
Hafnium													0.51	France	Yes	—
Tungsten													0.51	China	No	—
Vanadium													0.51	China	Yes	Steel slag from vanadiferous iron ore, spent catalysts
Tin													0.50	China (mining and smelting)	No	—
Magnesium													0.49	China	No	—
Germanium													0.49	China	Yes	Zinc, coal fly ash
Palladium													0.48	Russia	Yes	Nickel, platinum
Titanium													0.48	Australia (mineral concentrate), China (sponge)	No	—
Zinc													0.48	China (mining and smelting)	No	—
Graphite													0.47	China	No	—
Chromium													0.47	South Africa	No	—
Arsenic													0.45	China	Yes	Copper, gold, lead, zinc
Barite													0.44	China	No	—
Indium													0.41	China	Yes	Zinc
Samarium													0.40	China (mining and refining)	Yes	Iron ore, titanium, zirconium, other rare earths
Manganese													0.40	South Africa	No	—
Lithium													0.40	Australia (mining), China (refining)	No	—
Tellurium													0.40	China	Yes	Copper, lead, nickel, platinum, zinc
Lead													0.39	China (mining and refining)	No	—
Potash													0.38	Canada	No	—
Strontium													0.36	China	No	—
Rhenium													0.36	Chile	Yes	Molybdenum, copper
Nickel													0.36	Indonesia (mining), China (refining)	No	—
Copper													0.34	Chile (mining), China (smelting and refining)	No	—
Beryllium													0.33	United States	No	—
Feldspar													0.32	Turkey	No	—
Phosphate													0.25	China	No	—
Silver													0.25	Mexico	Yes	Zinc, lead, copper, gold
Mica													0.22	China	No	—
Selenium													0.23	Japan	Yes	Copper, lead, nickel, platinum, zinc
Cadmium													0.11	China	Yes	Zinc
Zirconium													0.09	Australia	Yes	Titanium, tin
Molybdenum													0.07	China	Yes	Copper
Gold													0.00	China	No	—
Helium													0.00	United States	Yes	Natural gas
Iron ore													0.00	Australia	No	—

Figure 7 Heat map displaying the supply risk for all mineral commodities examined for 2007 and 2018 in the 2021 review and revision of the US critical minerals list. Warmer shades indicate a greater degree of supply risk. Commodities are listed in descending order of their recency-weighted mean supply risk score, which was calculated using quantitative criteria for 2015 to 2018. Commodities with a recency-weighted mean supply risk score greater than or equal to 0.40 (as indicated by the dashed horizonal line) are recommended for inclusion on the US Critical Minerals List based on the quantitative criteria. Years for which insufficient data were available are not coloured. (Reproduced from Nassar and Fortier (2021).)

Where the USA was a net exporter of a CM, the assessment methodology of Nassar et al. (2020) gave a TE score of 0 and thus an overall *S* of 0. However, being a net exporter does not indicate immunity to supply disruption. If the US economy is reliant on a single domestic producer that reduces its production level or ceases to operate, then the USA may become exposed to supply disruption from overseas sources. In the 2021 analysis, any CM for which there was a domestic single point of failure (SPOF) was automatically included in the US CML (Nassar and Fortier, 2021). Materials that fell into this category included beryllium, zirconium, and nickel, which were therefore incorporated into the US CML published in 2022.

In a few instances where there were major data gaps, a qualitative assessment was made by the USGS in the 2021 analysis. This included some commodities in the 2018 US CML such as caesium, rubidium, scandium and several REEs. Given that the USA has been wholly reliant on imports of these commodities for many years and the available information suggests that their production is highly concentrated in a few countries, all these commodities remained in the 2022 US CML.

3.2.1.3 JAPAN

The earliest reporting of metals critical to the economy of Japan was conducted by the New Energy and Industrial Technology Organization in 2009. This study evaluated 39 minor metals for 12 indicators related to mineral supply risk and expected demand growth (New Energy and Industrial Technology Development Organization, 2009). Fourteen of the CMs were designated as ‘important’ minerals. This is synonymous with the term ‘critical’, although that designation was not widely used at the time.

A subsequent study (Hatayama and Tahara, 2015) developed the earlier approach by including an extra indicator of supply risk and by adding eight metals to the CMs. These additional metals, termed ‘common metals’, were designated as ‘strategic’ in Japan’s resource strategy published in 2012 (Hatayama and Tahara, 2015).

Overall, 13 indicators were evaluated under five categories (Table 8):

- supply risk
- price risk
- demand risk
- recycling restriction
- potential risk

’Potential risk’ relates to the potential ecotoxicity of each CM, which could restrict its future use.

The values for each of the five categories were aggregated to provide a ranking. The aggregate values for each CM were then weighted subjectively to yield a criticality ranking:

- 25 per cent each to:
    - supply risk
    - price risk
    - demand risk
- 20 per cent to recycling restriction
- 5 per cent to potential risk

Table 8 Indicators and weighting used in the 2015 assessment of critical raw materials for Japan. (Reproduced from Hatayama and Tahara (2015).)

Category	**Component**	**Rating rules**				**Weighing factor**
		0	1	2	3	
Supply risk	Depletion time	>150 yrs	100 to 150 yrs	50 to 100 yrs	>50 yrs	0.58
	Concentration of reserves	<70%	70 to 80%	80 to 90%	>90%	0.58
	Concentration of ore production	<70%	70 to 80%	80 to 90%	>90%	0.58
	Concentration of import trading partners	<70%	70 to 80%	80 to 90%	>90%	0.58
	Sufficiency of mineral interest	>75	50 to 75	25 to 50	<25	0.58
Price risk	Price change	<125%	125 to 150%	150 to 200%	200%<	1.46
	Price variation	<125%	125 to 150%	150 to 200%	200%<	1.46
Demand risk	Mine production change	<125%	125 to 150%	150 to 200%	200%<	0.97
	Domestic demand growth	<125%	125 to 150%	150 to 200%	200%<	0.97
	Domestic demand growth for specific uses	<125%	125 to 150%	150 to 200%	200%<	0.97
Recycling restrictions	Stockpiles	Prepared	None			2.33
	Recyclability	Implemented	Partly implemented	Quite limited		2.33
Potential risk	Possibility of usage restrictions	Safe	Potentially harmful	Harmful		0.88

It is pertinent to note that this evaluation included reserve depletion times and reserve concentration by country neither of which are included in other national CA studies. As has been noted by many authors neither of these factors have any geological validity because ore reserves are poorly known, dynamic entities, which cannot be used to provide reliable information about the future availability of raw materials (Lusty and Gunn, 2014; Crowson, 2011).

This assessment also included an indicator termed ‘sufficiency of mineral interest’, which reflects the level of Japanese ownership of mineral resources overseas that might be considered a means of mitigating supply disruption.

This study concluded that understanding those factors that contribute to criticality for each CRM is more important than the aggregated results. They advocated tailoring mitigation such as resource development overseas, recycling, substitution and stockpiling to each CRM .

A recent study by academic researchers developed a ‘quasi-dynamic’ methodology for the identification of CMs for Japan (Malala and Adachi, 2022). They identified six metals out of 18 CMs as critical for Japan in four separate years (2000, 2005, 2011 and 2015). The methodology involves the estimation of two dimensions, vulnerability to supply restriction and supply risk.

Vulnerability was calculated by first measuring the economic contribution of each CM to Japan's GDP. This quantity is multiplied by a price change probability function based on the past years metal price evolution to include a sensitivity parameter akin to volatility.

- $Vul_i = EC_i * C_i \Sigma [\log[price_i . X] * Prob_i (X)]]$

Where Vul_i is the vulnerability of metal i in Japan's economy. EC_i is the economic contribution of metal i to Japan's GDP. C_i is the quantity of metal i consumed in Japan in a particular year; $price_i$ is the price of the metal i X is the percentage change in the price of metal i, and $Prob_i$ (X) is the probability that the price of metal i changes by X per cent.

Historical real annual metal price data from the USGS was used to estimate probability distributions for each metal's absolute price changes. The underlying premise is that supply disruption sends a signal to the market, stimulating a price response; by analysing that response, the economic vulnerability can be determined. The results were normalised to obtain a vulnerability in the range 0 to 10.

The *S* dimension was derived from three indicators:

- global production concentration
- production concentration for those countries from which Japan imports its minerals
- WGI values of the import partners

The risk is calculated as the product of the Herfindahl-Hirschman index (HHI) (global producers), the HHI (import partners) and the WGI (import partners):

- *S* = HHI (global producers) * HHI (import partners) * WGI (import partners)

A high *S* score reflects a high degree of production concentration with a significant share of supply to Japan derived from a few countries that have low governance standards.

Metals that scored high in both vulnerabilities to supply disruption and supply restriction (risk) were considered critical. **Criticality levels were defined by vector length, with each point on a particular curve located at an equal distance from the origin thus defining 'concave' contours for the critical space.** However, the interpretation of such distance as a representation of criticality is debatable (Frenzel et al., 2017) and discussed later in the section of this report dealing with critical space representations.

3.2.1.4 CHINA

A comprehensive criticality assessment focused on China was published in 2021 (Yan et al., 2021). An integrated methodology for metal criticality was established based on consideration of the entire metal life cycle from mining and refining to recycling. Data for the period 2015 to 2019 were used where available. A quantitative evaluation of three dimensions of criticality was undertaken for 64 CMs:

- supply safety (SS)
- domestic economy (DE)
- environmental risk (ER)

SS is evaluated from three indicators:

- sustainability
- reliance
- tolerance risk

It is calculated from the import reliance modified by a substitutability index, recycling rate and global production concentration (HHI), with the latter modified by the WGI values for the producing countries. The substitutability index values are those used in previous EU CAs (European Commission, 2014; British Geological Survey et al., 2017), whilst recycling rates were taken from various sources including Graedel et al. (2011a; 2011b) and various USGS mineral commodity summaries.

The DE index is based on consideration of the value of the end use in the Chinese economy and the market value of the CM (see Figure 8).

The ER is based on the risk of autotoxicity and the toxicity risk of pollutants from various metrics for each CM. This includes the toxicity grade, the proportion of waste discharge to the environment in the production process, and the impact of the related environmental protection measures taken by various countries. The latter is derived from the Environmental Performance Index (EPI) published annually by Yale University (Wolf et al., 2022). The EPI ranks 180 countries based on 40 performance indicators.

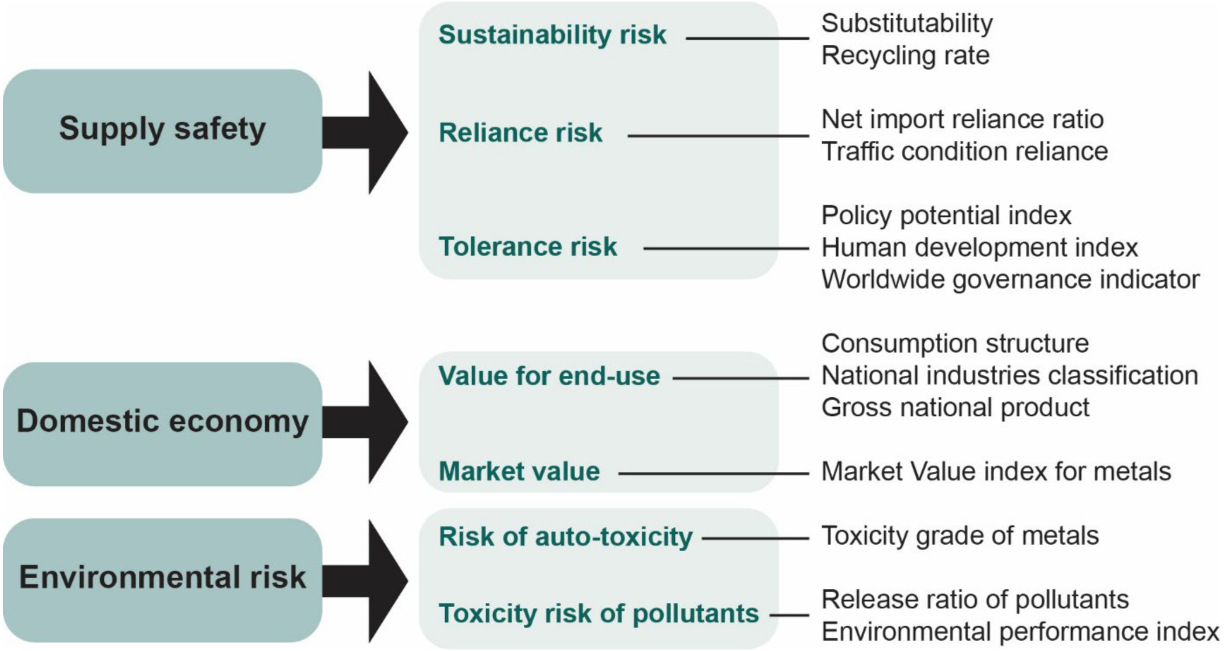


Figure 8 Schematic outline of criticality assessment methodology for China. (Reproduced from Yan et al. (2021) under the CC BY 4.0 licence)

Two-dimensional criticality was calculated as the product of the SS index and the DE index resulting in convex isocriticality contour lines. CMs with 2D criticality values less than an arbitrary threshold value of two are not critical because they have a sustainable supply chain and relatively small EI, whilst those CMs with values exceeding two represent a higher degree of criticality and require further evaluation.

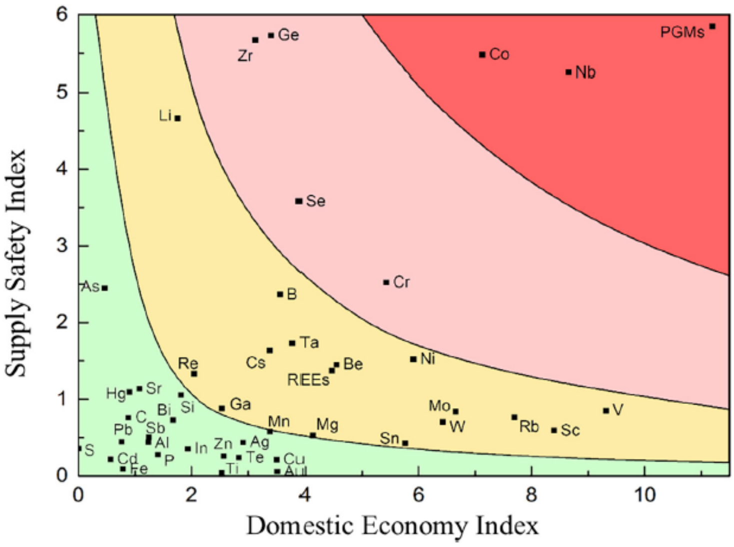


Figure 9 Criticality of elements on the two-dimensional matrix Note the appropriate use of convex isocritical contour lines so that risk = vulnerability * likelihood. (Reproduced from Yan et al. (2021) under the CC BY 4.0 licence.)

When S and EI are considered, a total of 24 metals are classified as critical. When environmental risk is added, those CMs with relatively high values for all three dimensions are classified as critical. This led to the identification of 18 critical metals (Figure 10).

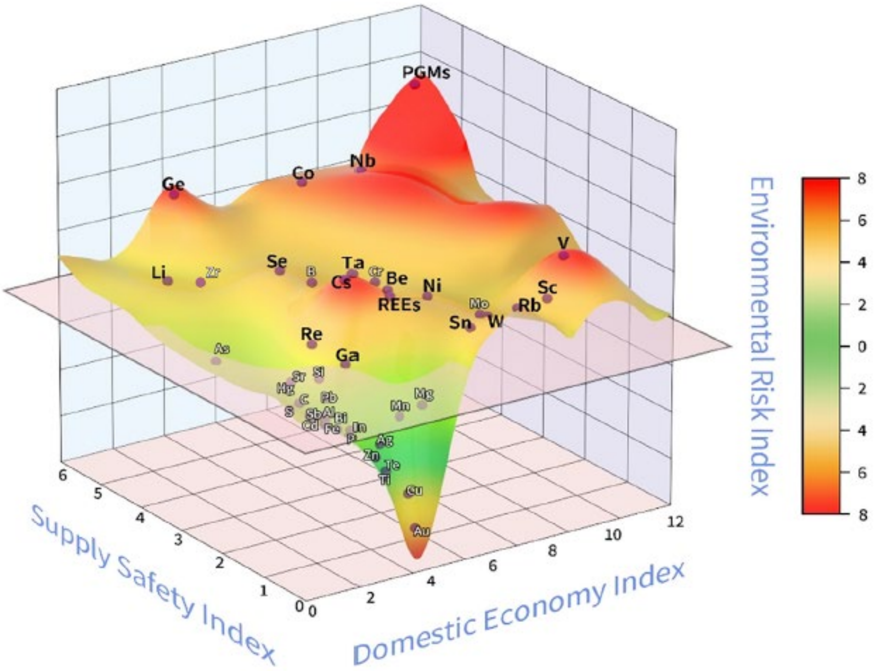


Figure 10 Criticality of elements in 3D space (critical metals are marked with black bold font; non-critical metals are marked with smaller white font). (Reproduced from Yan et al. (2021) under the CC BY 4.0 licence.)

3.2.1.5 WORLD MATERIALS FORUM

The World Materials Forum has provided an annual assessment of the criticality of a broad range of raw materials since 2015 (World Materials Forum, 2022). The analysis undertaken by the French Geological Survey (BRGM) in conjunction with consultants CRU and McKinsey. It is global in scope and based on the evaluation of seven indicators of supply risk. The EI of the CMs is not explicitly considered.

The following indicators are assessed quantitatively:

- lifespan of known reserves
- uncertainty of supply based on the anticipated supply deficit from demand/supply scenarios
- political exposure of supply, based on global production concentration modified by the WGIs

Three indicators are assessed qualitatively:

- supply chain recycling
- uncertainty of demand based on the predictability of the main demand drivers
- the availability of substitute materials

An environmental performance indicator was added to the assessment in 2021 (BRGM et al., 2021). This is based on a combination of six quantitative and qualitative indicators; most were derived from the OekoReiss II Project, which was funded by the German Federal Ministry for Environment and ended in June 2020 (Dehoust et al., 2020).

The qualitative indicators employed were:

- preconditions for acid mine drainage
- mining method
- use of auxiliary substances (chemicals and toxic reagents)

Quantitative indicators were:

- environmental governance, using EPI for 180 countries
- size of energy demand
- water stress index for 42 raw materials with available data

Based on expert judgement, each of the 58 CMs evaluated is assigned a value in the range 1 to 3 for each of the seven indicators. These values are summed, without weighting, to provide a composite index value for the criticality of each CM. **No distinction is made between critical and non-critical materials by using a single threshold value. Rather, according to its value for the composite index, each CM is assigned to one of five risk categories, ranging from low risk to very high risk**. Significant changes relative to the previous annual CA are also highlighted and their implications discussed.

3.2.1.6 GERMANY

The German Mineral Resources Agency (DERA) first published a criticality list in 2012 (DERA, 2012). Since then, it has been updated biennially with the most recent version published in 2021 using data for the year 2018 (DERA, 2021).

The DERA approach differs significantly from other CAs as it analyses only the supply risk dimension, using just two indicators. It does not assess economic vulnerability. Moreover, the analysis includes the evaluation of *S* not only for mine production of individual raw materials, but **also separately assesses various intermediate and traded products derived from these raw materials**. The aim of these assessments is to help German companies identify weaknesses in the supply chains of their raw materials and products so that they can adjust their procurement strategies and mitigate against possible supply disruption.

However, the assessment is not specific to Germany as the indicators used evaluate the global market. The results can also be used by other countries.

The 2021 analysis comprised 53 raw materials derived from mine production (25 metals, 27 industrial minerals and coking coal) and 27 refined metals. It also analysed 217 traded products derived from these metals and industrial minerals. The study does not describe how the CMs were selected.

The first indicator is country concentration (that is, production concentration), based on the HHI, which has also been used in many other CAs. A low HHI value indicates that the market is distributed among many participants, whilst a high value indicates market concentration in a certain country or company.

For this analysis, global mine and refined production data were collected by the German Federal Institute for Geosciences and Natural Resources (BGR) (Figure 11). To calculate the country concentration of traded products, the net exports of the relevant harmonised system (HS) codes from all countries were used. All materials were classified into low, medium or high country concentration based on their HHI values using thresholds set by the US Department of Justice and the Federal Trade Commission (2010).

The second indicator assesses the country risk of a raw material or traded product by using a weighted ranking of the governance standards in the countries in which it is produced. The WGIs are used for this purpose, which provides an aggregated ranking of the six WGI indicators with values between -2.5 and +2.5 (Kaufmann et al., 2010). The ranks of each producing country are multiplied by their share of world production to derive a country risk for the raw material or traded product. The country risk is divided into low-, medium- and high-risk categories.

Table 9 Threshold values for the two indicators of supply risk used in the DERA criticality assessment.

Indicator	Low	Medium	High
Country concentration (HHI)	<1500	1500 < *x* < 2500	>2500
Weighted country risk (WGI)	> +0.5	-0.5 < *x* < +0.5	< -0.5

The CMs are plotted against one another in a 2D matrix with the threshold values for each indicator used to identify three risk groups: low, medium and high (Figure 12). In the most recent assessment, 45 per cent of all CMs were classified as high risk (137 of 297 analysed materials). Forty per cent of all mined raw materials, 70 per cent of all refined materials and 42 per cent of all traded products were also classified as high risk.

The historic development of country concentration and country risk over a period of up to 58 years is included in the report published by DERA in 2021 (Figure 12). The results for 2021 are compared with those from previous assessments to identify recent changes and highlight trends over extended periods.

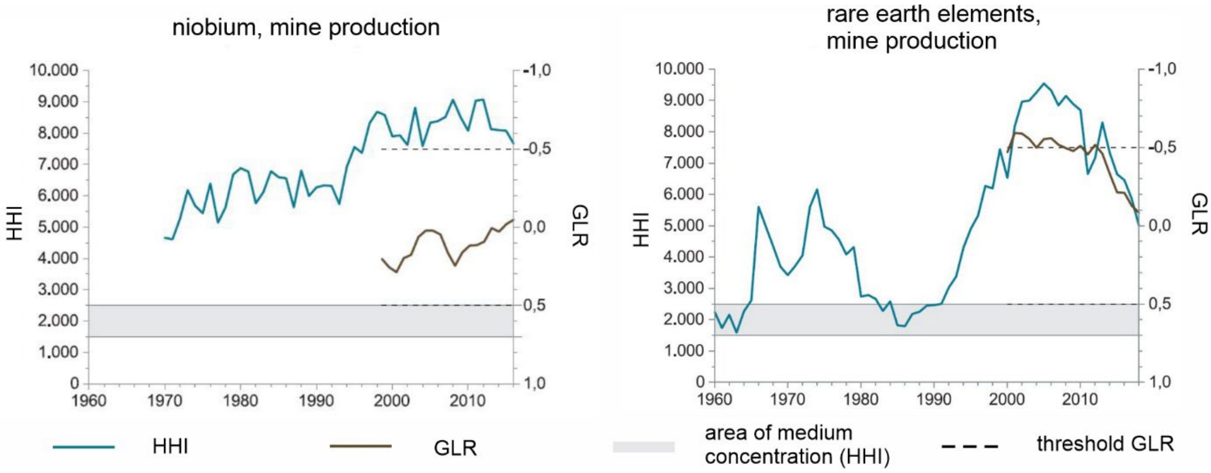
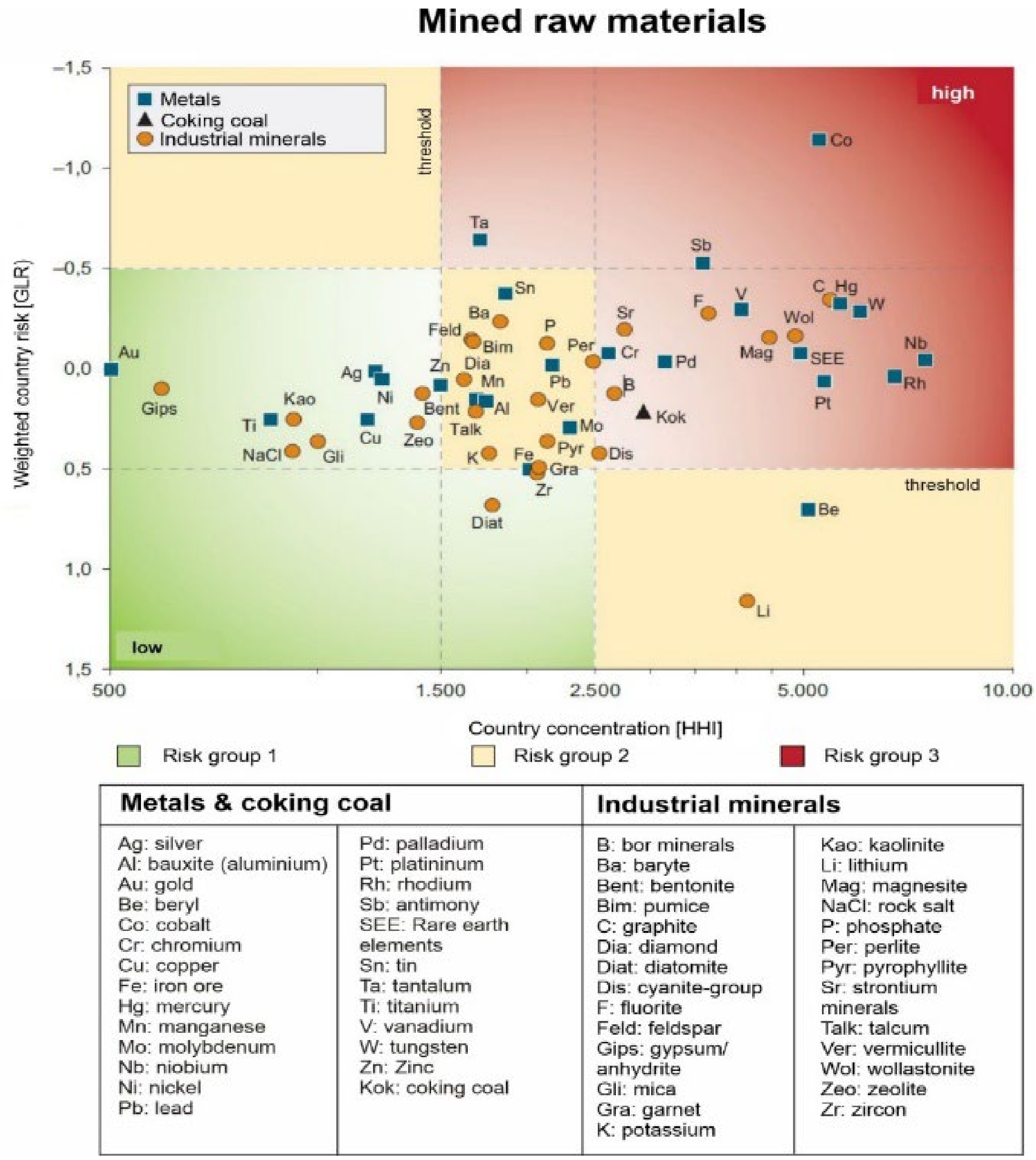


Figure 11 Historic development of the Herfindahl-Hirschman index (HHI) and weighted country risk (GLR) for mine production of niobium and rare earth elements. (Translated and reproduced from DERA (2021) with permission.)

The inclusion of intermediate traded products derived from mining and processing in the analysis allows differences between these materials to be identified. For example, mine production of copper has a low country concentration and medium country risk and is therefore ranked in the low-risk group. The three largest producers (Chile, Peru and China) together account for 48 per cent of global mine production. However, the trade of copper ores and concentrates (that is, mine products) has a high country concentration: the largest net exporters (Chile, Peru and Australia) account for 78 per cent of the market and it is therefore classified as high risk. Thus, there is a large discrepancy in the risk levels between mine production and the trade of products (ores and concentrates). This can be partly explained by export restrictions applied by countries on mined products. As a result, only small amounts of the materials produced from mining are exported and available to the market, whilst the majority is further processed in its country of origin. **This demonstrates the importance of considering the actual form of traded raw materials when assessing the criticality of a metal or mineral.**



Metals & coking coal

Ag: silver
Al: bauxite (aluminium)
Au: gold
Be: beryl
Co: cobalt
Cr: chromium
Cu: copper
Fe: iron ore
Hg: mercury
Mn: manganese
Mo: molybdenum
Nb: niobium
Ni: nickel
Pb: lead
Pd: palladium
Pt: platininum
Rh: rhodium
Sb: antimony
SEE: Rare earth elements
Sn: tin
Ta: tantalum
Ti: titanium
V: vanadium
W: tungsten
Zn: Zinc
Kok: coking coal

Industrial minerals

B: bor minerals
Ba: baryte
Bent: bentonite
Bim: pumice
C: graphite
Dia: diamond
Diat: diatomite
Dis: cyanite-group
F: fluorite
Feld: feldspar
Gips: gypsum/ anhydrite
Gli: mica
Gra: garnet
K: potassium
Kao: kaolinite
Li: lithium
Mag: magnesite
NaCl: rock salt
P: phosphate
Per: perlite
Pyr: pyrophyllite
Sr: strontium minerals
Talk: talcum
Ver: vermicullite
Wol: wollastonite
Zeo: zeolite
Zr: zircon

Figure 12 Country concentration and weighted country risk of mined raw materials for the year 2018. (Translated and reproduced from DERA (2021) with permission.)

Although the DERA CA does not evaluate the economic vulnerability of the German economy to supply disruption, the study does highlight the import reliance of Germany on specific traded products. Although net import reliance is not actually presented, the analysis notes that Germany is one of the top three global importers of 77 of the analysed materials, almost half of which are classified as high risk. The results of the DERA assessments are also published on an interactive online platform called ‘ROSYS’, where country risk and production concentration are illustrated on a world map (DERA, 2022). Data on historical production and trade are also available from this source.

3.3 DISCUSSION

CAs play an important role in decision making by both governments and industry. They are used in selecting materials, designing products, making investments, establishing trade agreements, identifying research priorities and developing policy. However, our review of several major CAs highlights how individual countries have developed their own assessment methodologies and generated lists of critical minerals based on their own industrial needs and their strategic assessment of supply risks.

The CMs assessed, as well as the number and identity of those deemed critical, also varies considerably. This diversity has been highlighted by McNulty and Jowitt (2021), which identified 74 different CRMs in 25 CA studies. Considerable variation in the results of these assessments was noted: some materials, such as indium and certain REEs, were classified as critical in all 25 studies, whilst copper, iron, and lead were critical in only a single study.

Furthermore, assessments of mineral criticality reflect market and political conditions at a particular point in time and are subject to change. This is demonstrated by variations in the results of assessments repeated periodically by a particular organisation or government, such as the EU and the World Materials Forum. **While this variation may reflect real change in market conditions over time, part of it may also be ascribed to methodological changes** or to the use of improved data for the metrics used in determining the values for each indicator.

It is notable that, for the first time since it started publishing a list of CRMs in 2011, indium is not included in the latest CRM list for the EU (European Commission et al., 2023a).

There is also considerable variation in the terminology used for materials at risk of supply disruption. While the term ‘critical’ is generally used to indicate an economically important material at risk of supply disruption, other terms are widely used in place of ‘critical’, albeit commonly without clear definition. The term ‘strategic’ has for many years been associated with importance to national security and defence, although it is sometimes used interchangeably with ‘critical’. The recent publication of a strategic minerals list by the EU expands that definition so that it is now intended to take account of the importance of a material for the green and digital transition as well as in defence and space applications (European Commission et al., 2023b).

Other terms used to convey the concept of criticality include ‘rare’ metals and ‘important’ metals, although their usage is generally confined to one country or CA. **Whatever terminology is used it is essential that it is clearly defined and communicated to all stakeholders.**

At the same time, the methodology used for the assessment of criticality should be fully described to ensure clear understanding of how the evaluation has been carried out, noting the indicators used and the underlying metrics. Although some assessments provide complete transparency in their methodology and underlying data (for example, Nassar and Fortier (2021); European Commission et al. (2023a)), many others do not comply with these requirements. Additionally, whilst **quantitative evaluation is preferred for the reliable determination of criticality, in many cases a qualitative estimation has to be made instead, where data is absent or of low quality.** This reliance on expert judgement is inevitably subjective and leads to a less robust classification.

CA starts with the selection of the materials to be evaluated, commonly referred to as ‘candidate materials’ (CMs). The CM list varies in length and composition from country to country. Most older CA studies, between 2008 and 2015, assessed a relatively small number (less than 20) of materials deemed to be potentially highly vulnerable to supply disruption. More recently, **CAs have tended to evaluate a broader spectrum of materials, with commonly more than 50 CMs**. This reflects increasing concerns about supply security as new, low-carbon technologies consume a broader palette of materials in ever-increasing amounts.

Most CAs involve the assessment of two dimensions of criticality:

- an estimation of supply risk (*S*) or the likelihood of the disruption of supply of materials from overseas sources
- an estimation of the economic vulnerability (*V*) of a country's manufacturing industry to supply disruption

These are commonly determined by evaluating the economic importance of each material to the manufacturing sector of the country.

A material is designated 'critical' where the values for *S* and *V* both exceed specified thresholds. A third dimension, termed 'environmental risk' (or similar), has also been evaluated in some CAs and materials designated 'critical' where all three threshold values are exceeded. The validity of such an approach is discussed later in this report. However, environmental, social and governance (ESG) issues, such as pollution, human health, biodiversity and indigenous peoples, are seldom thoroughly or systematically assessed in a quantitative manner. In most CAs, ESG factors are taken into account in a relatively simplistic manner, which involves use of the World Governance Index (WGI) as a factor that modifies supply risk indicators such as production or trade concentration.

Other indices such as the Environmental Performance Index (EPI) and the Human Development Index (HDI) have also been used in some CAs. However, it is important to note that these and WGI relate to a particular country or jurisdiction rather than to the production of a mined or processed material. They can only be used as qualifiers to indicators such as production or trade concentration and are not criticality indicators in their own right.

Most CAs evaluate risk at the mining stage of the supply chain, although (where data permit) some also assess criticality at other points. For example, the recent EU studies evaluated supply risk at both the mining and refining stages (European Commission et al., 2020a; European Commission et al., 2023a). The stage identified with the highest risk (termed the 'bottleneck') was used in the criticality ranking of the CMs. No published CAs evaluate the comparative risks of the CMs throughout their respective supply chains.

The indicators chosen for evaluation of the supply risk and economic importance dimensions vary considerably in number and scope (Figure 13). At its simplest, supply risk is estimated on the basis of only two indicators and two metrics (DERA, 2021). In contrast, several indicators — each estimated from a wide range of metrics — are used in other CAs, such as those published for China (Yan et al., 2021) and by the World Materials Forum (2022).

Where a CA is repeated for a particular jurisdiction, the indicators may be **retained in each iteration to ensure backward compatibility and facilitate the identification of changes and trends**. In other cases, such as the CAs published by the US government, the methodology has changed from being essentially country-agnostic to one more focused on the supply risks and the economic importance of raw materials to US industry (Nassar and Fortier, 2021; McCullough and Nassar, 2017).

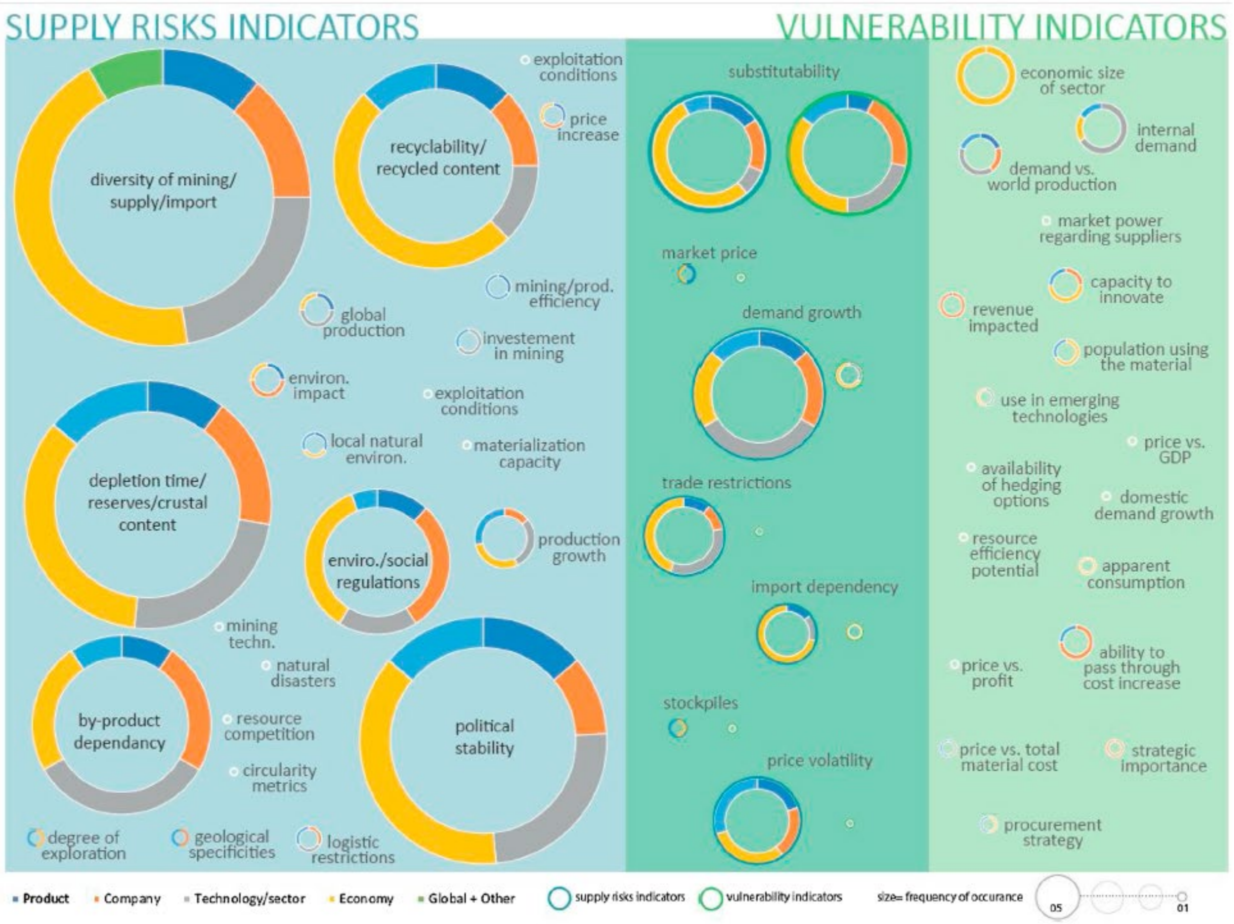


Figure 13 Indicators for the probability of a supply disruption and/or the vulnerability to a supply disruption, their frequency of use and the scope in which they are used. Detailed tables with background information are provided in Section S2 and S3 of SI-D. (Schrijvers et al. (2020) CC-BY-NC-ND licence.)

Regardless of the indicators used, it is the underlying metrics used in their evaluation that ultimately determine the reliability of the criticality ranking. **As more CMs are evaluated, the data requirement increases and the importance of using high-quality, relevant data for all CMs over the same period of time becomes ever greater**.

There is no consensus on what metrics should be used for a particular indicator nor on how the metrics should be combined, weighted or normalised. This makes it difficult to provide robust indicator scores and to compare between individual CAs.

The final stage in CA normally involves the definition of threshold values for each criticality dimension (generally *S* and *V*). Those materials for which both threshold values are exceeded, are classified as critical. A variety of methods have been used to establish these threshold values, some using statistical methods such as cluster analysis, but most involving subjective expert judgement. **While this separation of critical and non-critical materials is simple to make and clearly understood by all stakeholders, it remains fundamentally flawed.** Criticality is a measure of risk, a combination of *S* and *V*, a continuum from low to high. In other words, it is a matter of degree rather than of state.

Given the data uncertainties in many of the metrics, it is important not to ignore those CMs that fall just below the threshold(s). Most CAs do not report uncertainty ranges or present a sensitivity analysis of the results.

The consequences on the analysis results of using old, low-quality or irrelevant datasets are seldom discussed. This may result in the reliability of the results being overestimated. **CAs are**

based on existing data and consequently look backward in time. Very few assessments are based on a systematic evaluation of future demand and supply, chiefly because reliable, national forecasts of demand and supply are not available for all CMs for the same period. Additionally, most projections have been proven wrong time and time again when looking more than a few years in the future, as the development of such models takes the current market dynamic and observed trend as a pre-requisite for extrapolation.

Disruption of observed trends by technological improvements, global events (pandemic; war), or geopolitical decisions commonly affects the rate of adoption or use of technologies and their associated commodities. Consequently, CAs seldom provide reliable insight into future problems of mineral and metal supply or demand. A few published foresight studies focused on particular technologies or manufacturing sectors provide more useful, in-depth consideration of the future demand-supply balance (for example, clean energy; transport; defence) (US Department of Energy et al., 2010; US Department of Energy et al., 2011; (Joint Research Centre (European Commission) et al., 2023). **However, such foresight studies are very different from criticality assessment.** They are based on top-down analysis of specific technologies and applications rather than a bottom-up analysis of demand and supply of individual materials. **Consequently, they are separate from and should be used as a complement to CAs**.

The latest EU foresight study (Joint Research Centre (European Commission) et al., 2023) explores the potential vulnerabilities and dependencies of 15 technologies in five strategic sectors for the EU economy, namely:

- renewables
- electric mobility
- industry
- information and communications technology
- aerospace and defence

The report investigates the supply chain structure of technologies, identifying the relevant materials, components and assemblies. It explores potential bottlenecks at different points in the supply chain, by assessing supply risks and future demands for the main raw materials needed in the selected technologies, based on various scenarios and market trends.

4 A revised criticality assessment methodology for the UK

4.1 SELECTION OF CANDIDATE MATERIALS

The candidate materials (CMs) for evaluation are those minerals and metals that are currently important, or likely to become important, to the UK industry.

Materials meeting the following characteristics have been excluded:

- hydrocarbons, including all forms of oil, gas, coal, and associated products
- biotic materials such as rubber and wood.
- gases, except for hydrogen and helium
    - hydrogen is of growing economic importance because of its role in the clean energy transition. It is also used in important industrial sectors, including:
        - refining petroleum and metals
        - producing fertiliser
        - processing foods
        - rocket fuel (in liquid form)

      hydrogen will also become increasingly important as a fuel source for vehicles and electricity generation (BEIS, 2022a)
    - helium is included because it has been identified as critical in other studies (Appendix 1). It is used in:
        - medical technology
        - scientific research
        - high-technology manufacturing
        - space exploration and defence (Anderson, 2018; Olafsdottir and Sverdrup, 2020)
- highly processed materials, such as radionuclides, that are produced by fission in nuclear reactors or other highly specialist facilities and are used only in small quantities for specific purposes
    - these include a host of radionuclides such as:
        - molybdenum 99
        - iodine 131
        - xenon 133
        - other radioactive materials used to produce radiopharmaceutical products for diagnostic and therapeutic procedures and for research and development (National Research Council Committee, 2009; Houses of Parliament, 2017)
- construction minerals, such as aggregates derived from crushed rock, sand and gravel.
    - whilst of great economic importance, these are produced in very large quantities within the UK and most are consumed locally (Mankelow et al., 2021; The Crown Estate, 2022). As such, their market characteristics are distinct from almost all other mineral commodities and assessing them alongside other CMs is inappropriate.

Certain elements that occur together in nature are mined as groups of co-products or by-products of the extraction of other minerals and metals, such as copper, lead and zinc. Examples include the 17 REEs and the six PGMs. **Data for many aspects of the value chains of individual REEs are not publicly available and, because they generally occur together in nature, it is recommended that the REEs are treated as a single entity in this analysis.** In contrast, some relevant data are available for the five most important individual PGMs (platinum, palladium, rhodium, ruthenium, and iridium), which can, therefore, be treated independently. Osmium is excluded because it has few industrial applications and data availability is very limited.

On this basis, **a list of 81 candidate materials has been compiled for the evaluation of their criticality to the UK economy** (Table 10). This includes materials in the ‘watch list’ (iridium, manganese, nickel, phosphates and ruthenium), as defined in the Critical Minerals Strategy (BEIS, 2022b), which are considered likely to increase in criticality in the future as a result of changes in global demand and supply.

We have also distinguished CMs where data availability allows a quantitative assessment of criticality for those CMs for which only a qualitative evaluation (in bold) can be made because of the lack of publicly available data (Table 10). Furthermore, it is essential to point out that the criticality assessment (CA) will consider the multiple forms each CM can take to capture their use in the wider economic system and manufacturing stages.

Table 10 Candidate materials to be considered in the next assessment of minerals critical to the UK. Only a qualitative evaluation of criticality those CMs in **bold** can be made because of the lack of publicly available data.

Individual elements: 51		
Aluminium (Al)	**Helium (He)**	Silver (Ag)
Antimony (Sb)	**Hydrogen (H)**	Sodium (Na)
Arsenic (As)	Indium (In)	Strontium (Sr)
Barium (Ba)	Iron (Fe)	Sulfur (S)
Beryllium (Be)	Lead (Pb)	Tantalum (Ta)
Bismuth (Bi)	Lithium (Li)	Tellurium (Te)
Boron (B)	Magnesium (Mg)	**Thallium (Tl)**
Cadmium (Cd)	Manganese (Mn)	**Thorium (Th)**
Carbon (C (as graphite))	Mercury (Hg)	Tin (Sn)
Caesium (Cs)	Molybdenum (Mo)	Titanium (Ti)
Chromium (Cr)	Nickel (Ni)	Tungsten (W)
Cobalt (Co)	Niobium (Nb)	Uranium (U)
Copper (Cu)	Phosphorus (P)	Vanadium (V)
Fluorine (F)	Potassium (K)	Zinc (Zn)
Gallium (Ga)	Rhenium (Re)	Zirconium (Zr)
Germanium (Ge)	**Rubidium (Rb)**	
Gold (Au)	Selenium (Se)	
Hafnium (Hf)	Silicon (Si)	
Industrial minerals: 25		
Barytes	Kaolin clay	Pyrophyllite
Bentonite	Kyanite	Rock salt (NaCl)
Borates	Limestone	Silica sand
Diamonds	Magnesite	Talc
Diatomite	Natural graphite	Vermiculite
Feldspar	Perlite	Wollastonite
Fluorspar	Phosphate rock	Zeolite
Garnet	Pumice	
Gypsum	Pyrites	
Rare earth elements (REEs): 17 (lanthanides (15), scandium + yttrium; treated as a single group)		
Lanthanum (La)	**Gadolinium (Gd)**	**Ytterbium (Yb)**
Cerium (Ce)	**Terbium (Tb)**	**Lutetium (Lu)**
Neodymium (Nd)	**Dysprosium (Dy)**	
Promethium (Pm)	**Holmium (Ho)**	
Samarium (Sm)	**Erbium (Er)**	**Scandium (Sc)**
Europium (Eu)	**Thulium (Tm)**	**Yttrium (Y)**
Platinum group metals (PGMs)		
Iridium (Ir)	Platinum (Pt)	Ruthenium (Ru)
Palladium (Pd)	Rhodium (Rh)	

4.2 INDICATORS FOR SUPPLY RISK

4.2.1 Production concentration

When the production of a commodity originates from a few countries, this concentration may increase the risk of supply disruption. The risk related to production concentration can be assessed at either the mining or refining stages of a value chain. Published CAs, including those undertaken by the EU, UK, and USA, have tended to focus on the mining stages of a value chain when assessing production concentration rather than the refining stages. This has largely been driven by the availability of consistent, global-scale, time-series production data for ores and concentrates, although many minor metals lack primary production data.

Ideally, production concentration would be assessed for both the upstream and downstream stages of a given value chain, because in many cases a material may be mined in one country and refined in another. For example, although much of the world's lithium is mined in Australia, global production of refined lithium compounds is dominated by China. **When both mining and downstream refining production concentration can confidently be assessed, the highest level of concentration should be assessed in the criticality analysis.** However, data for the production of many refined materials, especially the minor metals (for example, gallium, germanium, indium or tellurium), either do not exist or are incomplete. It is therefore not possible to assess production concentration for ores and concentrates and refined materials at the same scale or across similar timeframes.

BGS routinely collects production data for ores and concentrates for a wide range of metals and minerals, although data for refined materials are confined to a few commodities (for example, cobalt, copper, gallium, germanium, indium, lead, nickel, selenium, tellurium and zinc). It should also be noted that, for the reported production for these minor metals, data are mostly estimated values as refinery output is commonly not reported, especially for by-product metals.

Company concentration — when the production of a given commodity is distributed across multiple countries whilst being dominated by one or few companies — is another factor to potentially consider when evaluating production concentration. For example, a large proportion (more than 80 per cent) of global niobium production originates from the Araxa mine in Brazil, which is solely owned by CBMM. However, about 30 per cent of CBMM's shareholding is equally split between a Chinese consortium and a Japanese/South Korean consortium (CBMM, 2021). This raises another salient point about company concentration and foreign ownership of mining and refining operations: the foreign owner may represent a very different level of risk than the host country. This combination of ownership effectively further compresses the supply base and contributes to increased risk.

When considering company concentration, it is also important to look at company structure (private versus publicly listed), joint ventures and binding offtake agreements, which can all affect supply risk (*S*) and supply chain complexity. However, this information is likely to be available for few commodities, particularly where privately owned companies dominate, as they typically do not report on their activities. These data availability issues also extend to companies that recover by-product metals, because production levels for these are commonly not reported, even by publicly listed companies.

In the previous UK CA (Lusty et al., 2021) there were three steps to calculating the Production Concentration Index (PCI), which was based on a modified Herfindahl-Hirschman index (HHI).

1. Calculation of un-normalised HHI:

    - $\text{HHI} = S1_1^2 + S2_2^2 + S3_3^2 + S1_n^2$

    Where, in this equation, *S* represents the market share of each producer in turn and *n* represents the total number of producers.

2. Calculation of normalised HHI:

    - HHI* = (HHI-1/*n*)(1-1/*n*)

    Where HHI* represents the normalised version, HHI is the un-normalised version of the index and *n* is the total number of producers.

3. PCI values were calculated for each CM:

    - PCI = % of global production^2 * average WGI

Firstly, five-year mineral production averages were calculated for each country. These were summed to generate an average world total production for each CM. This was used to calculate the per cent share of global production for each country.

Secondly, a five-year average world governance indicator (WGI value (World Bank, 2022) was calculated for each country over the same time period.

The third step was to calculate the PCI by squaring the per cent share of global production for each country and multiplying that value by the respective average WGI. This included the quality and stability of governance in the producing countries in 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 to reflect the increasing supply risk associated with production concentration.

4.2.1.1 RECOMMENDATIONS FOR FUTURE APPLICATION

The use of the HHI is to be modified in future UK CAs.

The reason for this change includes the subjectivity in setting threshold values separating different levels of market concentration. For example, in the UK, an HHI over 2000 indicates a highly concentrated market, whereas in the USA, the equivalent threshold is 2500. Additionally, a modified HHI, unlike a traditional HHI, has neither a point of reference nor an upper limit. A conventional HHI has an upper limit of 10 000 and HHI values over 2000 are understood to be problematic.

In contrast, the modified HHI, as used in the previous UK CA, can generate values in excess of 25 000 that can be difficult to interpret. Furthermore, HHI can be used in either a normalised or un-normalised way (Brown, 2018). Un-normalised HHI is much more sensitive to the number of producers than normalised HHI, meaning that using a normalised HHI when the number of producers changes over time may give a false impression of market concentration.

Given the growing significance of environmental, social and governance (ESG)-related factors in raw material supply, it is necessary to consider how they can be incorporated in future UK criticality assessments. Previously, following common international practice, WGI was used to weight production concentration. However, WGI is principally a measure of governance, not environmental performance or social responsibility. **To improve the inclusion**

of ESG factors, the following additional performance indicators are considered as proxy in absence of internationally accepted ESG standards in the mining sector:

- Human Development Index (HDI) (Conceição et al., 2022; United Nations Development Programme, 2023)
- Environmental Performance Index (EPI) (Wolf et al., 2022)

Once scaled (1 to 10), these data can either be reported separately alongside production concentration figures or they can be used to weight the production concentration directly. The first option is attractive as trends in the EPI, HDI and WGI data are maintained; however, EPI and HDI are modifying factors on production concentration and do not in themselves directly affect supply risk. Another option is to combine the EPI, HDI and WGI figures to calculate an ‘ESG’ factor that can be used to weight the production concentration figures. A benefit of this approach is that the modifying factors have a direct impact on the calculated supply-risk figures and there is a clear link between a producing country and its ‘ESG’ ranking.

Production concentration is an important measure of the risk to supply of a raw material, especially during the mining stage of a value chain. In the previous UK study (Lusty et al., 2021) this indicator used BGS World Mineral Production data for ores and concentrates and WGI data from the World Bank.

It is proposed that, in the next UK CA, the production share data for the top three producing countries is modified not only by their WGI values, but also by their respective values for the HDI (Conceição et al., 2022, United Nations Development Programme, 2023) and for the EPI (Wolf et al., 2022). Use of these three indices will allow a wide range of ESG factors that might affect the risk to supply of a CM to be taken into account.

Production concentration will continue to be calculated using a five-year average for the top three producers, as this approach considers the temporal variation in mineral production data. For EPI, HDI and WGI, data for the most recent year normalised to a similar 1 to 10 scale will be used and combined through a geometric mean into an ESG score for weighting purposes. These ESG weighted production shares are then squared to produce a modified HHI index. The results are normalised onto a 1 to 10 scale for ease of manipulation.

- $PCI = (\sum_{i=1}^{3} 5\ yr\ avg.\%\ of\ global\ production(i)\ *\ ESG(i))^2$
- $ESG(i) = \sqrt[3]{(EPI(i) * HDI(i) * WGI(i))}$

4.2.2 Companion metal fraction

The minerals and metals derived from a deposit may be categorised according to the economic contribution they make to the extractive operation from which they are sourced. The material that is the major source of revenue is termed the ‘main product.’ In some cases, however, a mining operation is only viable where a deposit contains several economically significant elements that are extracted together as a group, referred to as ‘co-products’. Lead and zinc, copper and nickel, REEs and PGMs are common examples of co-products. However, certain metals are not extracted from the ores in which they are the dominant element; rather, they are derived as ‘by-products’ from the ores of more abundant and widely used ‘parent’ metals, such as aluminium, copper, lead and zinc, in which they occur as ‘daughter’ elements (Graedel et al., 2014; Nassar et al., 2015). The daughter elements are present in smaller quantities and are recovered as a by-product if market conditions are favourable and appropriate extraction technology is installed.

The market availability of by-products is inherently linked to the production of their parent metals. In most metallurgical operations, the processing is tailored for optimal recovery of the main product with the daughters discarded to the waste stream. In the event of a disruption to the supply of the parent material, or where there is a sharp upturn in demand for the daughter, it may not be possible to maintain adequate and sustainable supplies of the by-product.

The companion metal fraction, also termed ‘companionality’, is a measure of the proportion of global production of a material that is derived from the extraction of another commodity. The only published comprehensive assessment of companionality was produced by Nassar et al. (2015), which found that 38 of the 62 metals assessed (61 per cent) have more than 50 per cent of their global production obtained as a companion. It also reported that 18 of these 38 metals are characterised by a high degree of production concentration and have very low rates of recycling of end-of-life products. Together, these factors constitute a potentially high risk of future supply disruption; the companion metal fraction has consequently been used as an indicator of supply risk in several CAs, including the 2021 CA (Schrijvers et al., 2020; Lusty et al., 2021).

Owing to the historically limited application of many critical raw materials (CRMs), the knowledge base on their modes of occurrence and geological abundance is limited to our understanding of their association with major historical commodities. The adequacy of future supply from primary sources is therefore difficult to estimate. There is a lack of information on the abundance and deportment of by-product metals in operating mines and identified deposits. Furthermore, little exploration for new resources of by-product metals has been carried out because of their low value relative to main product commodities, which determine the economic viability of any new discovery. **The paucity of information is exacerbated by the absence of obligation to publish the concentration and distribution of by-product metals when reporting reserves and resources of the main products**.

The degree of companionality of a CM is therefore likely to have a significant effect on its supply risk. Various workers have attempted to improve on the use of simple companionality to quantify the supply potential of by-product metals using complex statistical and deterministic modelling (Frenzel et al., 2015; Frenzel et al., 2017). These authors developed a new quantitative indicator for future availability, known as the ‘time to maximum extraction as a by-product’ (TMEB). This is based on the historic average annual growth rate of utilised supply potential, which measures the percentage of the extractable by-product recovered in the past. This is extrapolated into the future to determine when maximum extraction of the by-product will be achieved. By-products with a relatively short TMEB are considered to be associated with a relatively high risk of supply shortage (Frenzel et al., 2017).

Whilst this indicator may provide some useful information regarding the future availability of by-product metals, it cannot be applied to a broad range of by-products because of the lack of reliable data on current production and supply potential. It also involves subjective estimation of future supply trends at a time when demand for many by-products is escalating with considerable research underway to improve the efficiency of metallurgical recovery and to deploy it more widely.

The geological availability of many by-product metals is considered unlikely to restrict supply in the medium- and long-term. The supply risk is mitigated where the by-product can be supplied from more than one geological source. For example, gallium can be extracted from three main sources: bauxite, zinc sulfide ores and coal. Frenzel et al. (2016) concluded that significant increases in gallium production from these materials is possible without corresponding increases in the production of the parent metal. Similarly, most cobalt is a by-product of mining copper and nickel from ores of two principal types. However, cobalt is also known to be enriched in a range of other geological environments, which might prove to host additional cobalt resources given adequate research and exploration effort (Petavratzi et al., 2019).

Changes in mineral processing can also have a significant impact on the availability of by-product metals. An example is the expansion of Indonesian nickel production from laterite ores using high-pressure acid leaching (HPAL) that produces mixed hydroxide precipitate containing both nickel and cobalt; this means Indonesia is now the world’s second-largest cobalt producer and production will continue to grow as more HPAL is installed. In contrast, almost all tellurium and selenium production is linked to copper extraction using hydrometallurgical technology and future availability from other sources is highly uncertain.

In general, the main constraint on the future supply of by-product metals from primary sources is not geological availability, but the amount of installed production capacity. However, it is important to recognise that establishing new plant infrastructure for by-product recovery can take several years and any investment is subject to numerous economic and geopolitical uncertainties (Petavratzi and Gunn, 2022).

4.2.2.1 RECOMMENDATIONS FOR FUTURE APPLICATION

It is proposed that the companionality indicator employed in the previous 2021 CA (Lusty et al., 2021; Nassar et al., 2015) continues to be used. This indicator is based on a comprehensive dataset, covering the majority of the CMs that will be assessed in the next UK study. Where data are lacking, the companionality will be estimated based on published research and expert knowledge. Although the published values for companionality date from 2008, there are no alternative datasets, and the data are calculated in a transparent and consistent manner for all 62 metals reported. Although companionality is likely to be dynamic in character, with production from other deposit types possible as supply responds to changing demand, the values for most commodities are unlikely to change rapidly. However, it will be important to monitor future changes as more effort is expended on exploration for by-product metals, on extraction from different primary sources and on improving the efficiency of metallurgical processing.

4.2.3 Recycling rates

The recycling of metals from end-of-life (EoL) products is a potentially important source of material to complement supply from mineral ores (primary supply). Secondary supply effectively diversifies the supply base thus reducing the associated supply risk.

The production of metals from recycled stocks is often reported to be more energy efficient than primary production and can therefore contribute to reductions in greenhouse gas emissions (EUROFER, 2012; Kullmann et al., 2022).

The proportion of feedstock provided by recycling of minerals and metals, termed the ‘recycling rate’, is commonly included in the assessment of supply risk in CAs (Tercero Espinoza, 2021; Graedel et al., 2022). However, **there is a wealth of terminology associated with the recycling of metals. These terms require clear definition if the contribution to supply from secondary sources is to be measured in a consistent manner** for a wide range of materials derived from EoL products in many different countries.

Figure 14 provides an agnostic value chain for material flows. It identifies the different points in the system, in which key terms, such as the end-of-life recycling input rate (EoL RIR) and the end-of-life recycling rate (EoL RR) are referred to.

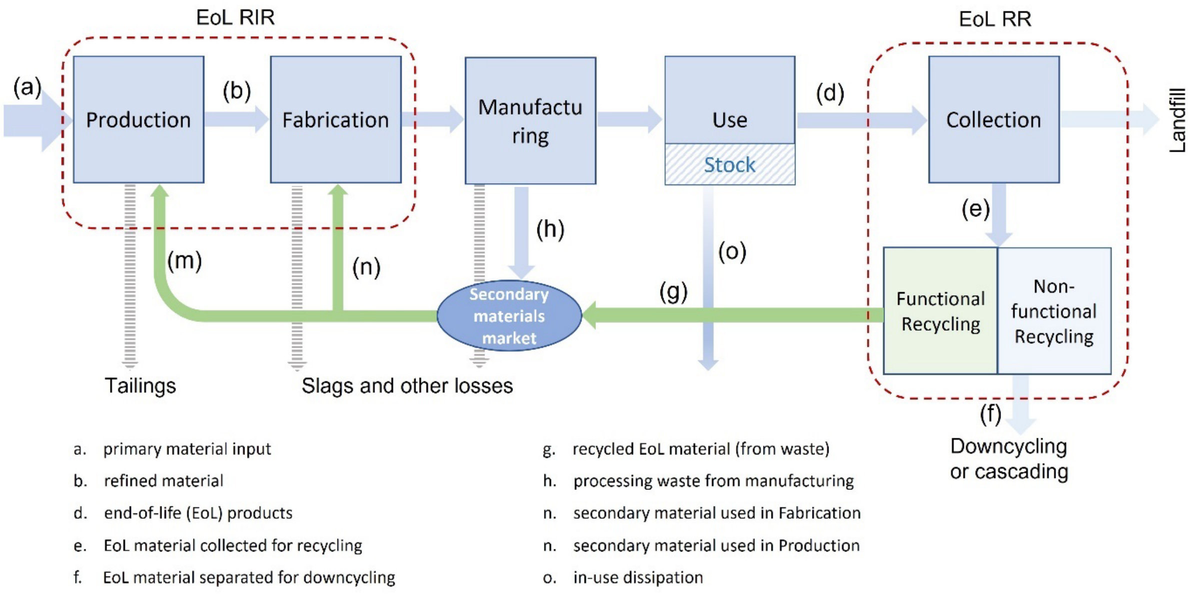


Figure 14 Agnostic value chain of the life cycle of metals. (Modified from Graedel et al. (2011a).) Copyright © United Nations Environment Programme 2011.

Key terms to consider when discussing and assessing recycling and the equations that represent them are given below. The equations are described using the annotated flows of Figure 14 (EUROFER, 2012; Graedel et al., 2011a).

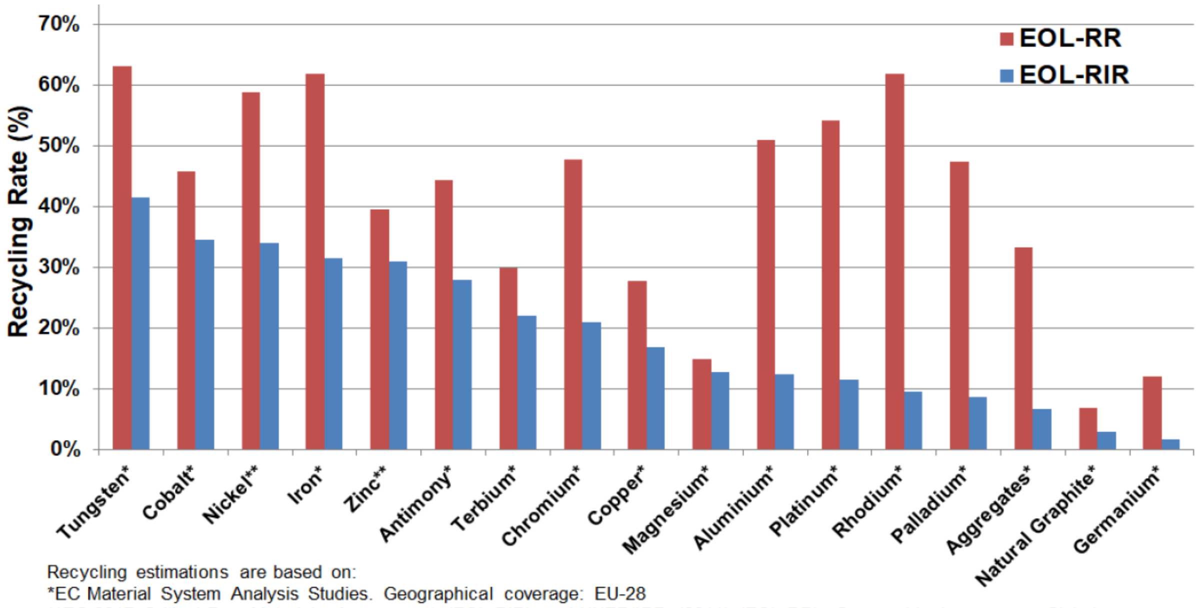
- EoL Collection Rate (EoL CR): how much EoL material is collected and enters the recycling chain, excluding material that is landfilled
    - calculated using the equation CR = e / d
- EoL Recycling Processing Rate (EoL RPR): signifies the processing efficiency of recycling (the yield), also termed recovery rate
    - calculated using the equation RPR = g / e
- EoL RR: measures the efficiency with which a material contained in EoL products is collected, pre-treated and finally recycled
    - calculated using the following equations:
        - functional: $RR_{\text{functional}} = g / d$
        - non-functional: $RR_{\text{Non-functional}} = f / d$
    - the terms functional and non-functional recycling are defined later
- EoL RIR: refers to the proportion of secondary material in the total input of material production
    - equivalent to the recycled content rate frequently applied to products
    - calculated using the equation RIR = (m + n) / (a + m + n)
- Functional recycling (also known as short-loop recycling): refers to recycling that preserves the properties of the contained materials, permitting recycled materials to be returned to production and manufacturing processes that generate an intermediate material, component or product
- Non-functional recycling (also referred to as long-loop recycling): represents the portion of EoL recycling in which the material is collected as EoL waste and incorporated in an associated large-magnitude material stream, in which the material's original functionality is lost as it is typically not possible to recover it from the stream
    - leads to 'downcycling', in which the material feeds into a different type of product, rather than its original use

In certain CAs that include recycling as part of the assessment methodology, it is not always obvious which recycling rate has been used in the analysis. This is due to the lack of data available to permit the consistent calculation of any of the previously defined recycling rates for all CMs. It is also very challenging to define a single recycling rate for all parallel applications of a particular material worldwide. These data are not readily available and, in most cases, data on recycling rates in specific industrial applications or describing national-level performance are rarely specific to CRMs. In addition, the available data on recycling are commonly several years old and therefore do not represent the current situation.

The EoL RIR, the recycled content centric indicator, which was used in the EU and UK CAs (European Commission et al., 2020a; Lusty et al., 2021), **is in principle the best indicator to use in a CA. However, due to the data inconsistencies and many gaps described earlier, it is very difficult to calculate at global level and for the entire list of CMs**.

The EoL RIR and EoL RR are distinct, and they describe different parts of a material's value chain. The EoL RIR represents the secondary feedstock share in a production process, whereas the EoL RR is representative of the efficiency in waste management. As the EoL RIR is derived from the EoL RR, in terms of the proportion of secondary versus primary inputs, the RIR is naturally lower, a proportion of the EoL RR (Figure 15). An efficient recovery and recycling system leads to higher EoL RR (for example, for some of the major and precious metals), but does not necessarily translate into equivalent, higher EoL RIR due to stocks dynamics and the availability of products at EoL. The contribution of secondary material may be low relative to primary sourcing despite a high EoL RR.

The routes to market for a secondary material typically mirror the primary material flows. A secondary material can be used in domestic processing, fabrication and manufacturing or it can enter the international marketplace. Furthermore, recycled materials are commonly downcycled, rather than contributing to the feedstock requirements for their original applications. Whilst this provides an additional source of supply for downcycled end-use applications, it does not contribute to supply of typically higher purity and commonly higher-specification material. Nonetheless, the total supply of the material is higher even when downcycling is prevalent. These factors, combined with commodity-specific considerations, explain the discrepancy between EoL RR and EoL RIR.



Recycling estimations are based on:
*EC Material System Analysis Studies. Geographical coverage: EU-28
**EC 2017 Critical Raw Materials Assessment (EOL-RIR) and UNEP/IRP (2011) (EOL-RR). Geographical coverage: Global

Figure 15 A comparison of the end-of-life recycling rate (EoL-RR) and end-of-life recycling input rate (EoL-RIR) for selected materials (European Commission et al., 2018). © European Union, 2018.

4.2.3.1 RECOMMENDATIONS FOR FUTURE APPLICATION

Given the poor quality and age of most EoL RIR data and a lack of reliable data on stocks in circulation, it is proposed that the revised methodology will take the following approach to estimating the potential contribution from recycling to supply risk mitigation.

- Calculation of the EoL-RR for the end-use applications of each candidate material based on the methodology outlined by Graedel et al. (2022)
    - calculated using this equation:

$$EoL\_RR_i = \sum_{J=1}^{n} end\_use_{i,j} \times EoL\_RR_{i,j}$$

    - EoL RR_i indicates the EoL RR of the i^{th} element of the selected CMs
    - $end\_use_{i,j}$ denotes the percentage of the j^{th} end use of the i^{th} element
    - $EoL\_RR_{i,j}$ indicates the end-of-life recycling rate of the j^{th} end use of the i^{th} element
- A worked example is provided in Table 11

Once EoL RR have been calculated for all the CMs, statistical approaches to identify the most suitable clustering will be used to rank the values on a 1 to 10 scale.

For the reasons described, the EoL RR is likely to give greater values than comparable EoL RIR. For inclusion in the CA, where high scores equate to higher supply risk, the EoL RR will be inverted after normalisation to a 1 to 10 scale, so that a high EoL RR will produce a low score. **This approach will reflect the global rather than UK situation regarding EoL RR, hence the indicator will form a component of the global supply risk dimension**.

Table 11 Example of end-of-life recycling rate (EoL RR) calculation for chromium.

Application	Global market share (%)	EoL RR (%)
Metallurgical grade austenitic stainless steel	40	70
Metallurgical grade ferritic stainless steel	34	70
Alloy steel	19	5
Chemical grade	3	0
Foundry applications	3	0
Refractory applications	1	0
Total EoL RR (%)	**53**	

The contribution of secondary raw materials to mitigating security of supply risk should also be represented in the UK economy vulnerability dimension by incorporating the EoL RIR indicator. However, this is challenging as it requires detailed data on stocks in use and on the EoL flows of CMs in the domestic economy. There are very few data available on EoL stocks and flows in the UK economy. Although trade statistics provide data on waste and scrap, they do not clearly describe material forms and content or the waste generation process, making it difficult to use this data for calculating EoL RIR. Accurate, reliable data on waste generation, recycling and recovery would be essential for an appropriate quantification of embedded CRM flows. Furthermore, data on the recycled content of imported materials are typically unavailable, which means it is impossible to precisely calculate the recycled content of the total input of metal production (Graedel et al., 2011b).

4.3 INDICATORS FOR UK ECONOMIC VULNERABILITY

4.3.1 Production evolution

This indicator aimed 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 USGS (Lusty et al., 2021; McCullough and Nassar, 2017)) a high value for this indicator was considered to increase vulnerability (*V*). Although high growth rates have been achieved in the past because of increased mining or refining, it is uncertain if such growth rates can be maintained in the future, particularly when ESG performance is the foremost consideration. Not only is increasing supply dependent on the continual identification of new mineral and metal resources, 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 mined.

Given the forecasts of future rapid demand growth for many technology metals (Watari et al., 2020; International Energy Agency, 2021; Lusty et al., 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 period. Available forecasts vary not only in the timescale and materials considered, but also in their geographical coverage and industrial sectors examined.

Changes in global production levels between 2010 and 2018 were used to calculate a compound annual growth rate (CAGR) for that period for each CM. The rates were then ranked into three categories to reflect the growing demand for a CM and its potential impact on economic vulnerability.

4.3.1.1 RECOMMENDATIONS FOR FUTURE APPLICATION

It is proposed that **production evolution is replaced with a UK mineral demand indicator following compilation of foresight studies covering the technologies essential for decarbonisation**, such as:

- heat pumps
- photovoltaic cells
- fuel cells
- electrolysers
- magnets
- batteries
- nuclear technologies
- traction motors

The indicators will be ranked on a scale of 1 to 10, with higher scores representing a high anticipated increase in demand that is likely to influence the UK's vulnerability. These sector-specific deep dives will quantify future UK demand for the considered technologies. Although the foresight studies are anticipated to capture a large part of the use of some CMs, not all CMs will be covered. Similarly, the foresight studies being sector specific will not capture the entirety of the demand for each considered CM.

The CA remains a snapshot in time of CM use in an economy aiming to present the risks and vulnerabilities taking place at the time of the assessment.

4.3.2 Price volatility

Price volatility is a measure of the fluctuation of the price of a commodity, ideally evaluated under its different forms, over a given period. Depending on the business type, trade and frequency of transactions, the period over which volatility is defined can range from a day to several years. Rapid escalation of the price of a commodity within this temporal reference window, termed a ‘price spike’, may arise in the event of a supply disruption or because of a sudden increase in demand.

The notion of market volatility derives from these price fluctuations when they extend beyond the standard price variability defined by the period of reference. Thresholds for price volatility are often defined as the standard deviation of the last day, week, 14 days, or month (depending how closely a market is monitored and the volume and frequency of transactions). A market is defined as volatile if the new asking or selling price falls out of the defined envelope calculated over the reference period. **Importantly, this highlights that the notion of volatility is a transient characteristic marking abrupt periods of change and does not affect price evolution over periods longer than the reference period**.

The frequency of volatile market events and whether the market reverted to its previous equilibrium over a given period could be used as an indicator of market instability. However, this is commodity dependent and requires a deep understanding of trading patterns and of data transparency, which are currently lacking. **The fact that the reference period for defining volatility changes between commodities is further evidence that this indicator is ill-suited for use as a screening tool in CA**. This may explain why price volatility has seldom been used in CAs.

Nonetheless, price uncertainty is a serious consideration for the economies of both producing and consuming countries. Price volatility is a deterrent to investment in new mining and processing capacity, whilst consumers rely on secure supplies within an acceptable price range.

Price volatility is driven by discrepancies between demand and supply in the global marketplace. For many minor metals, especially those produced as by-products, price volatility has historically been considered to be high compared with the major industrial metals (Renner and Wellmer, 2020).

The elevated price volatility apparently associated with minor metals may be ascribed to various factors, including:

- small number of producers
- few consumers and end-use applications
- lack of market transparency leading to ill-informed decision making
- inelasticity of producing markets in the light of ramping up demand due to production being dependent on another commodity

However, research at Colorado School of Mines on 30 minerals and metals identified considerable variation in price volatility depending on the time period considered and the price data used (Redlinger and Eggert, 2016). Using average annual prices over a 50-year period up to 2013, by-products were found to be about 50 per cent more volatile than those produced as main products. However, analysis of monthly price data for 2005 to 2015 revealed a much more varied picture, with less contrast between the volatility of by-products and main products. This may, in part, be attributed to by-products not being traded on commodity exchanges and the fact that there are few reported transactions in any one month. This may give the impression that by-product prices are more stable than for mineral commodities that have much more liquid markets, such as copper.

DERA (of the BGR) collects and analyses price data for a wide range of minerals and metals. It publishes monthly bulletins describing key changes in commodity prices and price volatility (BGR, 2023). Analysis of the variation in price volatility over many years suggests that there is no simple relationship between the degree of volatility and the scale of production or the by-product status of individual commodities.

The variation in price volatility since January 2014 for selected metals is illustrated in Figure 16. The price volatility of cobalt, a by-product metal commonly classified as critical, is much lower (average 24 per cent) than that of iron ore (33 per cent) over the same period. Iron ore was classified as critical in only one of 25 CA studies reported by McNulty and Jowitt (2021). In contrast, the price volatility of tungsten, a technology metal commonly classified as critical, averages only 12 per cent, whilst copper, a major industrial metal that until recently has rarely been classified as critical, has an average price volatility of 15 per cent since the beginning of 2014.

Given the definition of volatility explained above, **it is unclear how commodities with highly different trade volumes and intensities can be evaluated in a common period of reference** and such comparisons would be over-simplistic. Volatility may be caused by many factors specific to the prevailing market conditions for a particular raw material. What is considered normal volatility for one commodity may be very unusual for another. Furthermore, given the dynamic state of the commodity markets, short-term variations might be insignificant with ‘equilibrium’ returning after a certain period. The lack of transparency in the price data for some minor or by-product metals may also obscure true price variations.

Additional complexity may be introduced on account of the way in which price volatility is calculated, with daily prices possibly yielding results that are significantly different from those based on monthly prices, as done by DERA. It would therefore be very difficult to obtain reliable price volatility data for all CMs for a particular period, all calculated in a consistent manner or relevant to the individual CM market dynamic and trade intensity.

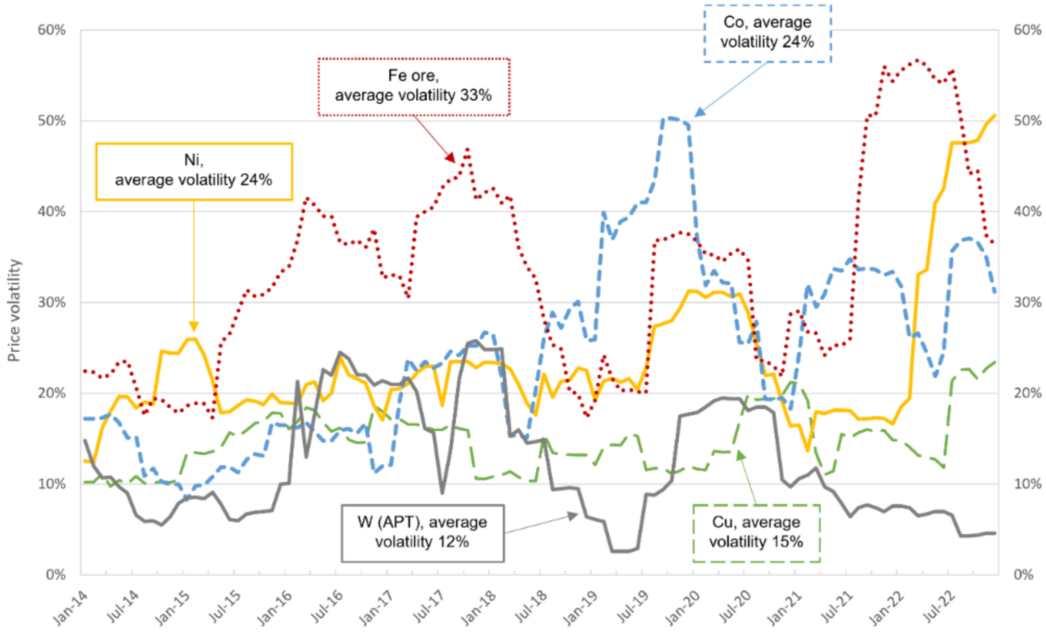


Figure 16 Variation in price volatility for selected metals between January 2014 and January 2023. Price volatility is the average monthly volatility for the preceding 12 months. (Data from BGR (2023).)

4.3.2.1 RECOMMENDATIONS FOR FUTURE APPLICATION

Although price volatility was previously used as an indicator of economic vulnerability in the 2021 CA and it is a clear indication of market sentiment, it is proposed that using it as a criticality indicator be abandoned.

The relationship between price volatility and supply risk is not simple. Employing price volatility in a robust way as an indicator of economic vulnerability would require significant further work focusing on how to interpret the indicator and its associated data and establishing appropriate reference periods for individual CMs. Its effective and consistent use also assumes the availability of reliable price data for all CMs. Nevertheless, price volatility is indicative of a market imbalance with potentially serious impacts on suppliers and consumers and should therefore be monitored to identify appropriate mitigation.

4.3.3 Substitutability

The replacement of one material by another in a particular application is sometimes considered as a means of lowering criticality, either by reducing material supply restrictions or by mitigating the economic impact of supply disruption. This is termed ‘elemental substitution’, where one element replaces another in a specific product or technology. Other levels of substitution are also recognised, most notably technological substitution, where one technology is substituted for another to provide a specific function. Numerous examples of technological substitution are provided by the replacement of carbon-based technologies with ‘clean’ alternatives, such as the substitution of the electric motor for the internal combustion engine in automotive transport. Substitution may also be accomplished at the system level, where a wholly different system is used to achieve a particular outcome.

In the previous 2021 CA, substitutability was used as an indicator of the potential to reduce economic vulnerability to supply disruption. This index was based on the estimated cost and performance of the substitute material in all major applications of the CM. The value of the substitution index for each CM was derived from the EU 2020 CA, which is the only publicly available list (European Commission et al., 2020a).

In the UK study, each CM was assigned one of three values of substitutability for use in the calculation of economic vulnerability:

1: substitution is considered feasible and substitute materials are currently available
3: substitution is not deemed possible
2: other CMs that are regarded as potentially substitutable

The degree to which criticality might be alleviated by elemental substitution has been incorporated in various CAs through the development of a substitution index (Schrijvers et al., 2020). This is a measure of the feasibility of using a substitute material to effectively fulfil a particular function of the candidate material. **This substitutability normally relates to the effect of substitution on reducing the economic impact of supply disruption. It is derived through consideration of the technical and cost performance of the available substitutes for a particular application.**

However, in the EU CA methodology, an additional substitutability index is used (Blengini et al., 2017; European Commission et al., 2020a). This second index reflects the degree to which supply risk (*S*) might be mitigated with a substitute material. It is based on an assessment of all factors involved in the supply of the substitute including its physical availability, its own criticality status and several other, mainly economic and sustainability, issues.

For elemental substitution to be effective, the substitute material should provide the same functionality and level of performance as the material it replaces at a similar economic cost. This is generally only potentially possible where the substitute has similar chemical properties to the material to be replaced. Graedel et al. (2015b) undertook a systematic evaluation of the substitution potential for 62 different metals in all their major uses with a view to determining the degree to which material substitution is likely to be successful. It concluded that, for 12 of the metals studied, the potential substitutes for their major uses were either inadequate or appeared not to exist at all. It also found that substitutes offering a high level of technical performance were not available for any of the major uses of any of the 62 elements.

Elements that have the best potential substitute performance are, in fact, those from the same group as the candidate material, for example the REEs and PGMs. For this reason, considerable research has focused on the substitution of PGMs and REEs in various catalyst applications and in permanent magnets, respectively (Løvik et al., 2018; Critical Minerals Institute, 2022) .

PGMs have a wealth of physical and chemical properties that make them useful in numerous industrial sectors, including:

- automotive
- chemical and petroleum
- electrochemical
- electronics
- medical
- glass manufacture

However, their rarity in the Earth's crust and the high level of global production concentration contribute to their high prices, which have long been incentives to search for alternatives. Examination of the factors influencing the potential substitution of PGMs in their major industrial uses has concluded that opportunities for substitution are limited (Nassar, 2015). The main reasons for this are issues related to technical performance, economic considerations, and the physical availability of substitute material.

Given that PGMs are co-products from the same ores, the ability to substitute one for another in the event of a supply disruption is very limited. In some applications, such as in autocatalysts used to control exhaust emissions, platinum can be substituted for palladium (and vice versa) according to prevailing price differentials. Alternative cheaper materials, such as base metal oxides (copper; cobalt), may have some desirable properties but generally do not offer the same level of technical performance as PGMs in autocatalysts.

In addition to performance and cost penalties, which may be impractical or impossible to overcome, it is also necessary to fully evaluate all the consequences of material substitution in a particular application. For example, Kawajiri et al. (2022) examined the technical and environmental issues associated with the substitution of indium tin oxide (ITO) by aluminium zinc oxide (AZO) in flat panel displays used in televisions, monitors and personal electronic devices. By undertaking life cycle assessments, it concluded that the environmental burden is reduced through this substitution. At the same time, indium (a relatively rare metal that is a by-product of zinc extraction) is replaced by aluminium, which is abundant in the Earth's crust and available at relatively low cost.

A variety of other possible disincentives to substitution also need to be considered. These include the cost of modifying plant and infrastructure and the time taken to do so. Additionally, investment in research and development and manufacturing infrastructure, and associated technology 'lock-in', can inhibit technological substitution, even when positive cost, sustainability and security of supply benefits are evident. In certain sectors, such as aerospace, strict certification processes for the design of aircraft and all components mean changing materials that contribute to the performance of the overall materials system is rarely feasible, even when substitutions may be technically possible. The impact on recycling may also be significant because a recycling plant is typically designed to handle specific products and to optimise recovery of certain metals. Consequently, in the event of significant and prolonged elemental substitution, the recycling technology employed is likely to require modification and the nature of the derived secondary products will change.

4.3.3.1 RECOMMENDATIONS FOR FUTURE APPLICATION

Most CMs have a wide variety of industrial applications, each with its own performance and cost requirements. Consequently, there may be numerous options for elemental substitution of an individual CM. Assigning a single value to the substitution index is not an accurate reflection of the range and scale of potential substitutability in all applications. It is inevitably highly subjective and cannot be undertaken in a consistent and reliable manner for all CMs. For a particular niche application, it may be possible to find an alternative material that offers adequate technical performance at a reasonable cost. In contrast, there are few available options for criticality mitigation based on substitution in major industrial applications. In such circumstances it is likely to be more effective to focus research on using potentially critical materials more efficiently (thrifting) and by recycling them more widely and more effectively.

Faced with potential supply disruption, elemental substitution is rarely likely to be a panacea. Its simplistic use within CA, as a mitigation of the economic impacts of supply disruption, should be discontinued.

4.3.4 Global trade concentration

An indicator of global trade concentration (GTC) was used in the 2021 CA 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 a CM can control the production and trade of products further down the value chain and have the capability to develop their own vertically integrated supply chains. 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 the products that use them.

This indicator identified the largest net importers for each CM and ranked them based on their share of the global total. 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 those materials. Average import and export values for the five-year period 2015 to 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 GTC indicator was based on the material form assessed to be most important to the UK in terms of total volumes imported. For each CM, the percentage share of global net imports taken by the top three importing countries was aggregated and the GTC ranked to reflect these shares.

4.3.4.1 RECOMMENDATIONS FOR FUTURE APPLICATION

It is recommended that this indicator is applied in a similar way in future UK CAs. However, the indicator will be refined so that it will take account of all traded forms of the CM ($(x)_a^z$) that correspond to the mining and refining stages.

Analysis of the trade data (imports and exports; average of five-year period) will use the following equations to derive the GTC for each form of a CM:
- global imports: $((x)_a^z) = \Sigma[\mathit{imports}\ ((x)_a^z, y)]$
- net imports: $((x)_a^z, y) = \mathit{imports}\ ((x)_a^z, y) - \mathit{exports}\ ((x)_a^z, y)$
- share of net import: $((x)_a^z, y) = \mathit{net\ imports}((x)_a^z, y)\ /\ \mathit{global\ imports}\ ((x)_a^z)$
- GTC: $(\sum_1^3 5\ yr\ avg.of\ share\ (y)\ of\ net\ import\ (x)_a^z * trade\ barriers\ (y))^2$
    - x describes the CM under various forms a to z $((x)_a^z)$
    - y describes the country

The next stage involves the identification of the top three countries with the greatest GTCs. The GTC percentages of the top three countries will be combined to produce an overall global concentration. These will be ranked based on their global concentration percentage using a method similar to that for the PCI (see Section 4.2.1). The output of this assessment will be a GTC value for different material forms of a particular commodity.

The UN Comtrade database is the key data source used in this assessment. However, others (such as the International Trade Centre database and the World Integrated Trade Solutions (World Bank database)) may be accessed if appropriate data are not available from UN

Comtrade, or when data issues arise that require validation using other international data systems.

The increase in the number of CMs and the requirement to analyse the trade in various forms of those materials will greatly increase the work involved in the application of this indicator. An example is provided in Table 12, where the various traded material forms of molybdenum, based on the top three exporting countries, are shown. In principle, all traded forms of molybdenum should be assessed. However, this would be very time consuming and not necessarily justified for a broad screening process of this type. Therefore, the indicator will concentrate on the major traded forms of the CM, using the global total quantity and value of traded material as the basis for selection.

Table 12 Traded forms of molybdenum.

HS code	Material form
261310	Molybdenum ores and concentrates: roasted
261390	Molybdenum ores and concentrates: other than roasted
282570	Molybdenum oxides and hydroxides
284170	Salts; molybdates
720270	Ferro-alloys: ferro-molybdenum
810210	Molybdenum: articles thereof, including waste and scrap, powders
810291	Molybdenum: unwrought, including bars and rods obtained simply by sintering, waste and scrap
810292	Molybdenum: bars and rods, other than those obtained simply by sintering, profiles, plates, sheets, strip and foil
810293	Molybdenum: wire
810299	Molybdenum: articles n.e.s. in heading no. 8102

The coloured rows of Table 13 are those that would be considered in the assessment, to ensure the inclusion of trade flows that describe both the mine and refining stages of production, and those important to the UK (HS 810291 — molybdenum; unwrought, including bars and rods obtained simply by sintering, waste and scrap). This filtering approach will reduce the number of material forms to be assessed for each CM.

Although this process will identify the key traded forms for each CM, it is likely that missing data and inconsistencies will become apparent during data interpretation and analysis. These will require refinement of the mapping of trade codes. Furthermore, it is important that the list of traded commodities used in the GTC assessment includes the key traded forms of commodities that are critical to the UK. Therefore, the final list of traded forms of the commodities will require alignment with the UK net import reliance indicator.

The GTC indicator was a component of the UK economic *V* assessment in the previous criticality study. However, the indicator assesses the global trade flows of commodities, and **it is therefore more appropriate for it to be included in the global *S* assessment**.

Table 13 Molybdenum exports in 2021; the total trade value (US dollars) and quantity (t) of the top 3 exporters for the various material forms. The highlighted rows represent the major traded forms of material.

HS code	Description	Partner	Total trade value: top 3 exporters (1000USD)	Total trade quantity: top 3 exporters (t)
261310	Molybdenum ores and concentrates: roasted	World	2 309 407	120 429
261390	Molybdenum ores and concentrates: other than roasted	World	1 770 997	113 732
720270	Ferro-alloys: ferro-molybdenum	World	1 260 741	55 264
282570	Molybdenum oxides and hydroxides	World	488 349	19 686
810291	Molybdenum: unwrought, including bars and rods obtained simply by sintering, waste and scrap	World	184 523	5 256
284170	Salts; molybdates	World	124 773	6 433
810210	Molybdenum: articles thereof, including waste and scrap, powders	World	69 313	1 495
810292	Molybdenum: bars and rods, other than those obtained simply by sintering, profiles, plates, sheets, strip and foil	World	64 356	892
810299	Molybdenum: articles n.e.s. in heading no. 8102	World	56 356	635
810293	Molybdenum: wire	World	43 884	10 267

4.3.5 UK import reliance

The UK is heavily reliant on imports of raw materials and intermediate products such as refined metals and chemical compounds. It is therefore important to consider the volume of these materials imported by the UK as well as their countries of origin.

In the previous 2021 CA (Lusty et al., 2021) import reliance was calculated by extracting UK import and export data for each CM from the UK Trade Information dataset for a five-year period (HM Revenue & Customs, 2023). Production data were obtained from the BGS World Mineral Statistics database (British Geological Survey, 2021) and UK Manufacturers' Sales by Product (PRODCOM) (Office for National Statistics, 2020) for the same five-year period.

The contained metal content of the traded forms was calculated based on established metal content estimates. The average tonnage of contained metal in the imports, exports and production for this period was used to calculate the UK’s apparent consumption and its net import reliance (NIR), based on the following equations:

- apparent consumption: imports(kg) + production(kg) - exports(kg)
- NIR: imports(kg) - exports(kg) / apparent consumption(kg)

For most CMs, this calculation was carried out for multiple forms of traded materials, including ores and concentrates, metals, compounds, waste or scrap, etc. However, the net import reliance values used in the CA were based on the single material form in which the UK has the largest trade.

The import reliance indicator also considered where each CM imported by the UK was sourced. In particular, the existence of trade barriers, such as export quotas and tariffs, and the standard of governance in each country supplying the UK were taken into account. This was accomplished by weighting the NIR for each CM according to the average WGI value for each exporting country and also according to the existence of any trade restrictions between the UK and those countries from which UK imports were sourced (OECD, 2020).

Data relating to trade agreements, trade barriers and willingness to trade will be sourced from the World Trade Organisation (World Trade Organisation, 2022), the Organisation for Economic Co-operation and Development (Kowalski and Legendre, 2023) and the British Government.

4.3.5.1 RECOMMENDATIONS FOR FUTURE APPLICATION

The possession of shared or common values with the UK is another possible modifying factor to weight NIR. However, the categorisation of shared values is subjective and difficult to quantify in many cases. Whilst it would be straightforward to determine a measure of shared values in some ‘extreme’ cases, assessment of the degree of having values in common with the UK would be more difficult for many other countries.

Many of the underpinning principles of shared values, at the country level, are related to democracy, individual liberty and rule of law (HM Government, 2018). These principles closely align with those used by the World Bank to calculate their WGI index. We therefore propose to use the WGI index as a proxy for shared values in the next UK CA. Additionally, having shared values does not necessarily translate into equivalent trade opportunities. Notably, despite similar WGI scores and many shared values between the EU, USA and UK, each bloc imposes various tariff barriers and preferential tax advantages to other trade partners to gain some form of competitive advantage in investment and trade.

In the next UK CA, import reliance will be calculated in the same way as in the 2021 CA with a weighting factor from trade barriers:

- UK import reliance: NIR * trade restrictions

4.3.6 UK gross value added contribution

The indicator of the gross value added (GVA) contribution was used in the assessment to include an evaluation of the significance of each CM and any intermediate products to the UK economy, particularly the manufacturing sector. The methodology was broadly based on the same indicator used in the two previous EU CAs (British Geological Survey et al., 2017; European Commission et al., 2020a).

Initially, the end-use share of each CM was identified from a variety of sources. Subsequently, these end-use applications were mapped to the relevant UK manufacturing sectors with the help of the UK Standard Industrial Classification (SIC) of Economic Activities 2007 (Office for National Statistics, 2007). The SIC classifies all UK economic sectors in a hierarchical, five-digit system. The end uses were grouped into their relevant manufacturing section by using a two-digit level and the description of the economic sectors (for example, ‘20: Manufacture of chemicals & chemical products’). Finally, the regional GVA (balanced) for each of the SIC codes were extracted from the Office of National Statistics (Office for National Statistics, 2021a; Office for National Statistics, 2021b). The GVA from each relevant manufacturing sector is multiplied by the end-use share of the CM to calculate the GVA contribution of the material to each sector. These can then be summed up to estimate the total GVA contribution of the CM to UK manufacturing.

- $UK\ GVA_{CM} = \sum_{CM} A_i \times Q_i$
  - A = end use application share
  - Q = sectoral GVA

The UK GVA contribution was ranked as:

1: less than £8 billion (low)
2: £8 billion to £13 billion (medium)
3: more than £13 billion (high)

As already highlighted in the 2021 CA, there are several uncertainties and limitations associated with this indicator.

Firstly, data availability on end-use applications is poor for many CMs and different sources had to be used that vary in age and geographical scope. Some of the data are more than ten years old, which is especially problematic for CMs where the end-use share has changed dramatically in the last years (for example, cobalt use in batteries). Data for specific UK end uses were not available and the geographical scope of the datasets varies between global and European end-use shares. Likewise, the nomenclature of end uses can vary: first use or end use of a material is not always strictly defined, leading to inconsistencies in the data.

Secondly, there is an uncertainty in mapping the end uses to the relevant manufacturing sectors using SIC codes. It is not always clear which manufacturing sector is tied to the various end uses and, in some cases, the end use is applied in more than one manufacturing sector. The two-level SIC codes do not provide enough granularity in the data to map the end uses to their specific sectors. For example, the second-largest end use of platinum is in jewellery, which is part of SIC code 32, ‘Other manufacturing’. However, this code includes many other manufacturing sectors such as the manufacturing of sport goods, where platinum is not used. Thus, the GVA of SIC code 32 is likely to overestimate the contribution of platinum in this case. A better estimate of the UK GVA contribution from each CM would need higher resolution in the GVA for more detailed SIC codes (for example, four-digit level). However, this was not feasible in the original assessment due to time constraints.

Finally, it is debatable whether the GVA estimates provided by the Office of National Statistics represent a good estimate for the economic importance of a CM to the UK economy. The data are of high quality and regularly updated, but some components produced in one sector may subsequently be used in another manufacturing sector. Such relationships between different sectors cannot be considered. Moreover, indirect effects of the GVA are not considered in the provided GVA estimates. This includes the GVA contribution of other industries along the supply chain of the manufacturing sectors (indirect GVA) and the contribution to the gross domestic product from the consumption enabled through salaries and wages in the sector.

Economic models to estimate indirect and induced GVA have been done for the wind industry (BiGGAR Economics, 2012) and carbon capture and storage (TUC and CCSa, 2013). In addition, the GVA can only reflect the economic importance of a CM in production activities. However, the final demand and consumption of a certain material in the UK may differ to the materials that are produced. The perspective of consumer may therefore also be important to consider in this indicator.

4.3.6.1 RECOMMENDATIONS FOR FUTURE APPLICATION

There are several issues with data availability and consistency for the UK GVA indicator on both metrics used (that is, end-use application share and GVA data on UK manufacturing sectors). A different indicator based on a more consistent dataset would be more suitable to measure the importance of each CM to the UK economy.

The UK apparent consumption is suggested as an alternative indicator. It broadly captures the demand for all CMs in multiple forms in the UK industry. The apparent consumption can be calculated by adding UK imports and production of each CM and intermediate products together and subtracting their exports. Import and export data can be retrieved from the UK Trade Information dataset (HM Revenue & Customs, 2023) and UK production from the BGS World Mineral Statistics database (Idoine et al., 2022). The apparent consumption is also used in the import reliance but, for that indicator, the monetary value of the trades is used rather than their physical weight. Using the apparent consumption has the advantage that only two data sources are needed, which ensures consistency in the indicator data across all CMs. Nevertheless, in common with the GVA, it is difficult to include the end-use consumption in this approach as only products used in the processing and manufacturing sector are included. Component manufacturing, end products and their imports and exports cannot be accounted for as data for material contents in different products are, in most cases, not readily available.

- Apparent consumption $(x) = \sum(production(£)\ (x)_a^z + import(£)\ (x)_a^z) - \sum export(£)\ (x)_a^z$
    - (x) represents a CM
    - ‘ a’ and ‘ z’ represent the range of the traded form considered of (x)

4.4 CALCULATION OF SCORES FOR SUPPLY RISK AND VULNERABILITY

4.4.1 Aggregation methods and weightings

Each indicator considered in the dimensions of V and *S* is obtained through a mathematical formula or by combining numerous metrics. The various composite indices, such as WGI, EPI and HDI, commonly used in CA are a good example of the agglomeration process. For instance, the EPI is the aggregated score of 40 performance indicators spread within 11 categories of various importance (Wolf et al., 2022). **Aggregating such a combination of unrelated variables, expressed on various scales into one score is best done through a geometric mean, which is the nth root of the product of n numbers**.

In contrast to a simple product or an arithmetic mean, the use of the geometric mean is recommended when dealing with correlated variables or variables in different units or dimensions. It is commonly used by financial analysts performing calculation on investments (temporally correlated data series), biologists for studying population dynamics or risk analysts when combining scores from vastly different factors such as the EPI. The multiplicative nature of the geometric mean, as opposed to the additive component of the arithmetic mean, maintains proportionality and gives a more robust evaluation of the central tendency of the population by minimising the weight of outliers.

Despite this intrinsic property, we propose that all indices used in the next CA are normalised to a common scale of 1 to 10 before being aggregated through a geometric mean. This process will be applied at the indicator level, if its calculation requires combining multiple indices into one (for example, combining WGI, EPI and HDI as the ESG score with country mineral production shares to calculate the PCI) and when combining all indicators into a final global *S* or V dimension score. This normalisation is essential, as a geometric mean can only compute positive non-null numbers, a transformation required for indices that extend into negative values. Additionally, this brings indices and indicators expressed on variable scales to a comparable one and avoids arbitrary weighting.

It is important that, as far as is practicable, **this normalisation process is done over the full ‘potential range’ of the data and not the ‘observed range’ of the population**. For example, if the scores for an index range between 5 and 22, it is essential to identify the full range of the scoring scale to conduct the normalisation rather than using the observed minimum and maximum of the population. Failure to do so will distort the distribution of the data on the new scale and artificially inflate differences between data that would otherwise be statistically similar. In contrast, in the case of indicators that are calculated through the amalgamation of numerous indices or scores, the propagation of the ‘potential range’ of each index (to determine the aggregated scale) will result in most scores falling within a narrow range, owing to accumulation of central tendency probabilities. For these indicators, the observed range should be used to normalise the scale.

The process of rescaling data is also highly preferable to grouping data into bins of low-to-high ranking and attributing a score to each class. Reducing a complex set of data to a simple score can mask important details and reduce the overall resolution of the CA. This approach results in a significant loss of granularity and distorts its true distribution.

In summary, all components that are being combined to calculate an indicator are rescaled and then their geometric mean is calculated. If an indicator is calculated based on a defined formula, the scores produced are then rescaled considering the potential data range and not observed minima and maxima as far as is possible. Once all indicators have been calculated for a dimension, the dimension score is obtained by taking the geometric mean of the contributing indicators.

Following this methodology, employing the multiplicative properties of the geometric mean has a limiting impact on the use of arbitrary weighing of indicators when used. **Due to the distributive nature of a product, applying various coefficients to artificially amplify or reduce the importance of a given indicator will have no effect on the relative ranking of each CM**. Accordingly, this results in greater transparency, with less reliance on subjective expert judgement.

4.5 DEFINITION OF THRESHOLD VALUES FOR SUPPLY RISK, VULNERABILITY AND PRESENTATION OF RESULTS IN A CRITICAL SPACE

Despite their common goal, CA methodologies vary greatly as each dimension of criticality does not correspond to a single, easily quantifiable entity, but rather represents the aggregation of multiple components, indicators and indices. Owing to the country-centric perspective of most assessments, the ability to access relevant the national data required for quantitative assessment will also influence the number and scope of the indicators included in each dimension.

Irrespective of these variations, once scores for each axis have been calculated, all CA studies would ideally follow a similar logic in their representation of the position of a commodity in criticality space and in the classification of that commodity as more or less critical. Most CAs have taken the approach of using risk matrices to evaluate the criticality of the CMs under consideration. Risk matrices, also referred to as probability impact grids (Figure 17), are commonly employed in project risk management or safety engineering (Smith, 2013; Smith et al., 2014). They plot the probability of occurrence of an event against its potential impact or level of severity. **Importantly, these two variables are quantified on a logarithmic scale, where the increment from one risk level to the next represents a factor of 10 increase in likelihood or impact. In such matrices, the logarithmic scales allow for a linear representation of risk increments diagonally**.

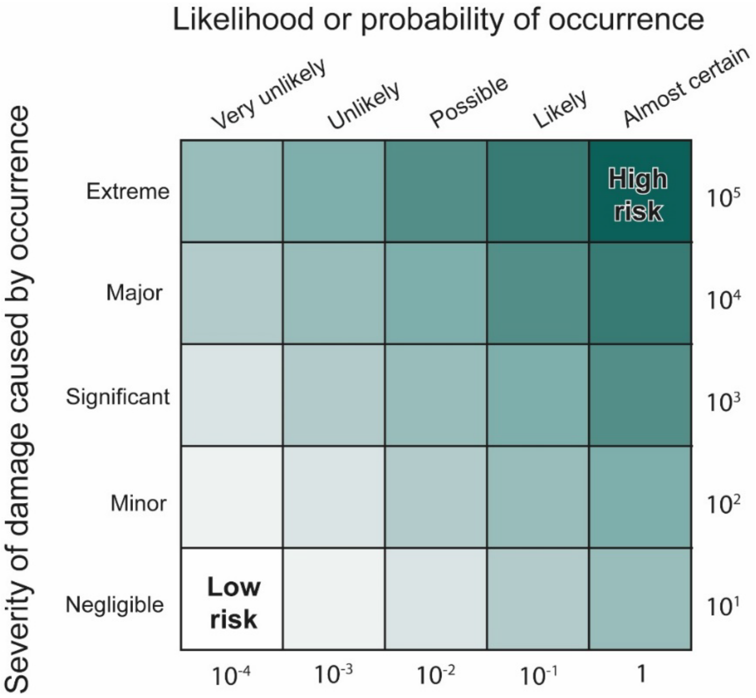


Figure 17 General risk assessment matrix, also referred to as impact grid matrix, commonly used in environmental risk and engineering risk management. Note the use of logarithmic scales in such an approach.

In risk management, risk is defined as the product of the probability of occurrence of a specific event and the damage it would cause if it were to happen:

- risk = probability of occurrence * consequence

In the context of raw material criticality assessment, this could be reformulated as:

- criticality = supply risk * economic impact

Given the complexity of these dimensions of criticality, translation to traditional qualitative risk management categories (low-to-high impact; rare-to-certain occurrence) is not easily carried out. **The results of applying this simple equation are therefore better represented by a gradient of criticality in a two-dimensional space**, **with isocritical contours of convex shape due to their non-logarithmic scales** (Figure 18). This aspect has generally been overlooked in previous CA studies, which have represented logarithmic risk classification categories in linear, two-dimensional space.

4.5.1 Impact of convex critical space

The representation of criticality contours in a 2-dimensional matrix using non-logarithmic scales creates serious issues of visualisation and interpretation if fixed values are considered to define linear criticality thresholds. **This results in criticality not increasing in a linear manner according to the two axes that define it**. **The issue is most serious in the area located close to the intersection of the two threshold values defined to separate critical and non-critical CMs**. In this vicinity, low, medium, and high criticality space occur very close to one another. Consequently, small changes in the values of the metrics used and their weighting would have a significant impact on the classification of any CM located close to this intersection, thus diminishing the robustness of the assessment.

Beyond the use of simple thresholds, several other methods for subdivision of the critical matrix space have been proposed and previously discussed in this report. These include the definition of subdomains of various criticality levels characterised by their low/medium/high supply risk and low/medium/high vulnerability (Erdmann et al., 2011). This approach resulted in six domains of irregular size and shape, suggesting a rather subjective approach to their definition.

The use of a third dimension has also been applied to CAs in various ways. The third axis is commonly used to represent the ‘environmental implications’ of the extraction, refining and processing of a commodity (Graedel et al., 2012, Yan et al., 2021), although Nassar and Fortier (2021) included ‘trade exposure’ as a third dimension in their CA for the USA. The graphic representation of the scores of each commodity therefore results in a cloud of points in three dimensions. In this configuration, the criticality of an individual commodity has commonly been represented by the vectorial length of that commodity in the Euclidian space of the diagram; in other words, how far that commodity is located from the origin of the diagram (Graedel et al., 2012).

This approach can also be represented in 2D diagrams, leading to criticality contours with a concave, rather than convex, shape (Malala and Adachi, 2022). Although such an approach has merit in representing contours for commodities having similar distance from the origin, the interpretation of this distance as a measure of criticality is debatable (Frenzel et al., 2017). The major issue is that, in this configuration, the criticality level is derived from the sum of the two or three dimensions considered, rather than by their product (risk = likelihood * vulnerability). In effect, this creates scenarios in which a commodity with a high *S*, but low environmental risk/trade exposure and low *V*, for instance, has a similar criticality level to a commodity with medium-high scores on all three indicators.

The most recent US CA identified this issue and applied correct risk factors for the determination of the overall ‘supply risk’ or criticality (Nassar and Fortier, 2021). This was calculated as the geometric mean of the three dimensions (supply risk = $\sqrt[3]{}$ (X * Y * Z)) used in their study, effectively turning the convex curves shown in Figure 18 into 3-dimensional convex envelopes.

4.5.2 Discussion

All CAs have the representation of their CMs in a 2D or 3D space in common, for ease of communication. **Following classic risk theory, the criticality score of each CM can be calculated as the product of its score on each indicator. However, in the case of raw material CAs, use of the geometric mean of the indicators is recommended instead of a simple product.** The reason is that, compared to a classic impact grid matrix, indicators forming the axes of a CA are multicomponent aggregates of mineral production, economic, social, and political indices.

The definition of a criticality threshold for each axis (**criticality dimension**) **is perhaps the most subjective stage in the CA process**. Given the high level of aggregation of various indices of different types in each dimension, defining the threshold for critical or non-critical scores is difficult and has, in most previous studies, been based on subjective decisions made by the authors (Frenzel et al., 2017). While scoring all CMs is a relatively standard mathematical process, defining where to position the threshold line on this criticality gradient will vary according to the experience, expertise, and awareness of the authors. Some metrics included in the indicators have internationally recognised thresholds. For example, the HHI, which measures market concentration (US Department of Justice and the Federal Trade Commission, 2010), is variously considered as:

- competitive, when HHI is less than 1500
- moderately concentrated, when HHI is between 1500 and 2499
- highly concentrated, when HHI is more than 2500

Thus, if all components of a criticality dimension have clearly identifiable thresholds, their geometric mean may be used to define the threshold value for the axis. **However, most indices used in raw material CAs lack such clear distinctions and their use inevitably involves a degree of subjectivity**.

All authors should provide clear definition and justification of how their thresholds were derived. Alternatively, in an earlier Japanese CA, the middle point of each axis was arbitrarily adopted as the threshold (Hatayama and Tahara, 2015). The most recent review of the methodology for defining a US critical minerals list used a series of threshold criteria, providing a clear description of each and its corresponding normalised scores (Nassar and Fortier, 2021). While this transparency is highly desirable, the methodology inevitably remains subjective and country-centric. Defining when a particular dimension becomes critical relies on perceived risk and any existing mitigation. The threshold values used in the US CA, whilst informative from a methodological perspective, cannot be transposed at face value for application in other countries' CAs.

4.5.3 Recommendations

Given that *S* and *V* are each calculated from several unrelated variables using different units, use of the geometric mean is the most reliable way to integrate the data for the various indicators and thus to estimate criticality for each CM. Its use is, therefore, recommended in future UK CA studies.

Determination of a threshold separating critical and non-critical space inevitably remains subjective. Threshold values should be explicitly defined for each criticality dimension based on stakeholder consultation and expert analysis of the available data, as has been implemented in the most recent evaluation conducted for the USA (Nassar and Fortier, 2021).

Replotting the results of the previous 2021 CA using appropriate geometric isocritical contours and using the geometric mean to aggregate indicators in each criticality dimension leads to some significant changes (Figure 18). Note that the scoring process of each CM was not updated based on the presented methodology and only the aggregation and representation methods have been changed for illustrative purposes here. CMs that were lacking data were given the minimal potential score in this revaluation rather than no scores.

As the effect of outliers (high or low) is minimised whilst consistent low or high scores are magnified, the positions of some elements are reshuffled in the criticality space. Tin appears now as one of the least critical elements of all CMs, together with titanium. Convex isocritical contours also highlight the similar level of criticality for nickel, manganese, and graphite, albeit for different reasons of supply risk and economic impact. A similar assessment arises for indium, cobalt, and silicon.

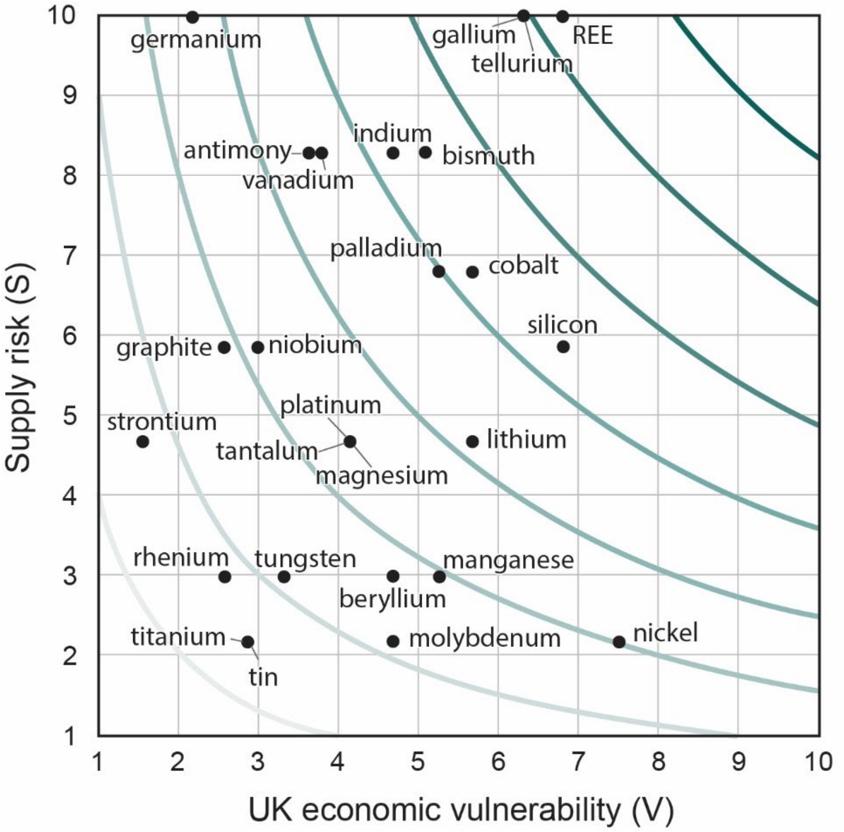
In this revised 2021 CA, most CMs are skewed to the left of the critical space as none reach a *V* score superior to 7.6 (nickel), whilst four CMs score 10 on the *S* dimension. This distribution is a direct result of two parameters:

- an imbalance in the number of indicators in each dimension means that, for a CM to score high in *S*, only three maximum scores are required whilst six indicators are scored in *V*, reducing the likelihood of consecutive maximum scores
- using classified scores for most indicators (for example, 1, 2 or 3), rather than a continuous scale, results in CM scores limited to certain ranges

Both methodological issues are rectified by the proposed scaling methodology to be applied in the next CA and through using a more balanced number of indicators in each dimension (Figure 19).

If a criticality threshold is agreed, using appropriate geometric critical space effectively results in an enlargement of the area considered of high criticality compared to orthogonal threshold limits. **This implies that any CM that plots well above the threshold value on one axis does**

not necessarily require an above-threshold score on the second axis to remain critical. Similar observations were pointed out by Glöser et al. (2015) in the EU and US CAs (European Commission, 2014).



Candidate	Criticality
rare earth elements	8.2
gallium	7.9
tellurium	7.9
bismuth	6.5
silicon	6.3
indium	6.2
cobalt	6.2
palladium	6.0
vanadium	5.6
antimony	5.5
lithium	5.2
germanium	4.7
magnesium	4.4
platinum	4.4
tantalum	4.4
niobium	4.2
nickel	4.0
manganese	4.0
graphite	3.9
beryllium	3.7
molybdenum	3.2
tungsten	3.1
rhenium	2.8
strontium	2.7
tin	2.5
titanium	2.5

Figure 18 2021 CA matrix plotted using dimensions calculated with geometric means and using geometric isocritical contours. Note that the indicators were not recalculated as per the proposed revised methodology. This graph serves the purpose of illustrating the effect of geometric mean aggregation and convex isocritical contours.

5 Discussion

5.1 CRITICALITY ASSESSMENTS: PAST, PRESENT AND FUTURE

CAs are becoming increasingly important for both industry and policymakers as a tool to inform investments, and to develop risk mitigation strategies and policy interventions and partnerships. These assessments are flexible and can be adapted in scope and scale to reflect the needs and objectives of the commissioner, be they a company, industry sector or nation state. As is apparent from the varied nature of the CAs of Australia, USA, Japan, EU, UK and South Africa, their primary objectives can be to identify either the business opportunities for resource-rich jurisdictions or supply chain vulnerabilities for major resource-consuming nations.

Over the last 15 years, these assessments have typically been conducted using an array of continuously evolving methodologies of variable complexity. CAs from the USA and EU that are updated regularly with enhancements whilst trying to maintain some consistency in the approach with previous iterations form a good example of this trend. The increasing complexity of these assessments reflects the growing awareness of the risk along the entire CM value chain, improved data and an expanding range of CMs.

Despite these developments, most CAs remain focused on initial stages of the value chain (mineral production and processing) owing to the greater availability of datasets on mineral production relative to those on processed and refined commodities. However, several developed countries producing CAs that explore their vulnerability to mineral supply disruption have relatively low dependence on imports of ores and concentrates. Their true reliance and supply risk is seldom accurately reflected in the trade of unprocessed ores and concentrates, but rather associated with intermediate refined products or materials embedded in finished and semi-finished parts, assemblies, and products. The true reliance of the economy on critical minerals is therefore masked, as most CMs end in dissipative end uses in a diverse range of products in which their presence is difficult to track. The lack of data means that no published quantitative CAs take account of CRMs embedded in imported products.

This challenge and the lack of visibility along CM supply chains means the USA has introduced the concept of a ‘single point of failure’ (SPOF) in its assessment methodology. This indicator is used to define a CM as critical, irrespective of the score of other criticality dimensions, if a single stage of the supply chain is highly concentrated or controlled by a single entity, company, or country, even when this company is American and operates in the USA. This follows the logic that any instability in the business model of a company could lead to cessation of activities, effectively limiting the production of the intermediate or end product, however economically important.

The SPOF concept can only be applied to technologies and their embedded commodities for which the midstream and downstream processing and manufacturing landscape are well known, and therefore does not apply to the majority of CMs. Furthermore, a SPOF may only apply to one technological application of a CM, whilst its other end uses remain sufficiently diverse to not be considered critical. This duality of perspective on the criticality of a CM, or that of the technology it is embedded into, questions whether it is the technology or the CM that is to be evaluated.

Another important risk factor related to the SPOF concept is that of companies’ ownership. In their current application, CAs capture the level of diversification or concentration of a market in relation to the geographical distribution of production and refining centres. The SPOF concept should be extended to take account of risk factors relating to company ownership. A market may appear diversified if production of a CM originates from several countries or locations; however, production may be controlled by a single company. Alternatively, a market may be diverse with multiple centres of production and various companies actively producing, but a single investor may own a dominant share of these entities, creating a similar risk level to a SPOF as defined in the US CA. Major Chinese investments in the development of mining and refining activities in Africa would represent an example of the latter type of SPOF, whilst the uranium market, which is dominated by a handful of producers operating in multiple countries, would represent the former type.

Whilst evaluating commodity markets at the company ownership level is desirable to provide a clearer understanding of supply risk, collating data on all the entities involved in the supply chain is prohibitively time consuming and is unlikely to be available for all CMs. Nonetheless, it is important to recognise this type of risk when evaluating supply chains and it further highlights the limitations of CA in terms of its ability to fully represent the nuances of complex market and supply chain dynamics.

Combining indicator scores for each CM obscures the granularity of the data and the reasons for criticality of a CM. Plotting the 2021 CA scores using the revised methodology (Figure 18) gives similar criticality levels for nickel, manganese, graphite, niobium, and germanium; however, these scores arise from contrasting supply risk and economic vulnerability factors. Understanding the individual factors that contribute to criticality of a CM is more important than the aggregated result, as only detailed evaluation of these factors can identify appropriate mitigation measures. Given the dynamic and international nature of material supply chains, it is essential to understand the global context for each CRM to determine how best to assure secure and sustainable supplies to the UK on an individual material's basis.

CAs are an early warning system and represent a valuable screening tool to identify CMs that are of greatest economic importance and at risk of supply shortage. To be quantitative and transparent, CAs generally use current, public-domain data and therefore represent an assessment based on past events and trends that do not necessarily capture future needs or challenges. To make CAs forward looking and better at 'anticipating criticality', consideration should be given to the inclusion of expert-driven qualitative assessments of future material demand. To be employed with confidence, such forecasting must capture long-term policy and industrial trends. Furthermore, the uncertainty in the prediction significantly increases with time, owing to greater uncertainty.

Whilst forecasting mineral requirements for the deployment of technology over the next 5 to 10 years can be done with reasonable confidence, as it is based on recent trends and relatively mature technologies, this time frame is considered too short to implement meaningful policy interventions. It is therefore necessary to look at a 15- to 20-year horizon and incorporate a degree of uncertainty through the evaluation of scenarios that consider different levels of policy ambition, various economic outcomes and a range of technology deployment rates, as well as the possibility of step change or disruptive technologies. Such forecasts need to take a top-down, sectorial approach, considering technological systems that are anticipated to become of growing economic or strategic importance in the future.

Complementing a conventional CA with targeted foresight studies on strategic technologies and sectors would help to:

- address the data availability challenges previously discussed when using a bottom-up approach
- identify possible SPOFs as technology-specific supply chains are examined
- provide a forward-looking dimension to the CA

The results of each foresight analysis could be scaled in a similar manner to that of other indicators and trends could be drawn for CMs in the criticality space, showing how anticipated mineral demand impacts the quantitative CA. As the currently planned foresight studies are restricted to a limited number of technologies and associated commodities, demand data will not be available for all CMs. Similarly, the sector-specific foresight study may not capture the entire market of a commodity.

It is proposed that, where demand data is available for a CM, two scores are calculated and presented in the critical space. The first score is common to all CMs that will exclude the demand indicator, and the second is for the subset of CMs for which demand data is available.

The latter will permit an assessment of the impact of future demand projections on the current level of criticality.

5.2 WATCHLIST, CRITICAL AND STRATEGIC COMMODITIES

Work on criticality has interchangeably used the terms ‘strategic’ and ‘critical’ to define similar groups of materials: commodities of growing economic importance with a high risk of supply disruption. **Such commodities are not necessarily needed in large quantities but are enablers of technologies and industries that cannot operate without them at the level of performance or efficiency expected**.

In its latest assessment, the EU introduced the term ‘strategic’ raw material (SRM) in addition to ‘critical’ raw material. This was to represent a subset of CMs that are not classified critical by the quantitative CA analysis, but anticipated to become of increasing importance, possibly critical, in the future, owning to increased demand.

The concept of a strategic raw material (SRM), in the context used by the EU, is dependent on projections of future needs, with the uncertainties previously discussed. The EU also includes mineral reserves in its assessment of SRMs, the values for which also have significant uncertainty as they are, by nature, dynamic over time. Accordingly, using existing mineral reserves as an indicator of future material availability is flawed. It appears that there was a desire within the EU to highlight the potential supply risk associated with a larger group of commodities that are not defined as ‘critical’ by their established methodology.

In future UK assessments, it is recommended that the term ‘strategic’ is not used but rather a watchlist is retained to ensure that the CMs not classed as critical but are of growing economic or strategic importance are formally recognised.

5.3 SUMMARY OF PROPOSED REVISED METHODOLOGY

This report reviewed several CAs produced globally to understand methodological best-practice, in order to revise the indicators used in the 2021 CA (Lusty et al., 2021). The major developments are summarised in (Table 14).

Table 14 Summary of methodological improvements, modifications, deletions, and new indicators in the revised methodology for the future UK criticality assessment.

Methodological improvements	
Indicator scoring	A harmonised approach to scoring each indicator and combining them using the geometric mean, on a scale of 1 to 10, is developed. Using this mathematical function instead of the arithmetic mean, or simply summing the indicator scores, results in a more robust representation of indicator scores that are expressed in different units. This is particularly important for combining indicators in a single criticality dimension and for generating final criticality score for each CM. It is also preferable to binning the data into categories, which leads to losses in data resolution and artificially inflates differences between categories.
Critical space representation	More accurate representation of the critical space using convex isocritical contours rather than orthogonal thresholds is adopted following applied risk-management theory. This significant modification stems from the issue of interpreting risk matrices using logarithmic scales transposed to CA using linear agglomerated scales. The revised critical space permits a more logical representation of the degrees of criticality, as a function of *S* and V.
Candidate material list	An expanded list of CMs will be assessed, increasing from 26 to 82 based on clear selection criteria (Table 1).
Environmental, social, governance (ESG) score	Calculation of a composite ESG score for each mineral-producing country based on a combination of WGI, WDI and EPI is developed. This is used as a weighing factor when calculating certain indicators, for which the ESG performance of the producing jurisdiction represents a risk factor. • $ESG(i) = \sqrt[3]{(EPI(i) * HDI(i) * WGI(i))}$
Discontinued indicators	
Price volatility	Discontinued due to concerns regarding its validity as an indicator of economic vulnerability. Furthermore, the wide range of CMs' traded forms, the associated respective price variations and the challenge of obtaining reliable price data for certain CMs prevent a price volatility indicator being employed in a consistent way for all CMs.
Substitutability	Assigning a single value to the substitution index is not an accurate reflection of the range and scale of potential substitutability in all applications and industrial sectors. It is inevitably highly subjective and cannot be undertaken in a consistent and reliable manner for all CMs.
Modified or replaced indicators	
Production concentration	The use of HHI is modified in the production concentration indicator (PCI) to incorporate a weighting factor of the production share by the ESG score in the *S* dimension. • $PCI = (\sum_{i=1}^{3} 5\ yr\ avg. \%\ of\ global\ production(i) * ESG(i))^2$

Recycling rate	The recycling rate is modified to reflect the end-of-life efficiency with which a material contained in a product is collected, pre-treated, and recycled. This indicator reflects global, rather than UK specific recycling rates. Consequently, this indicator has been moved to the supply risk (S) dimension. - $EoL\_RR_i = \sum_{J=1}^{n} end\_use_{i,j} \times EoL\_RR_{i,j}$
Production evolution	Replaced with a UK mineral demand indicator following compilation of foresight studies covering the technologies essential for decarbonisation such as heat pump, photovoltaic cells, fuel cells, electrolysers, magnets, batteries, nuclear technologies, and traction motors.
Global trade concentration	Refined to include all traded forms of the CMs that correspond to the mining and refining stages. The share of each country's imports will be weighted by trade restrictions. The global trade concentration indicator was a component of the UK economic vulnerability (*V*) dimension in the previous UK CA. However, because the indicator assesses global trade flows, it is more appropriate to be included as part of the global supply risk (S) dimension. - Global imports ($(\mathrm{x})_\mathrm{a}^\mathrm{z}$) = Σ[imports ($(\mathrm{x})_\mathrm{a}^\mathrm{z}$,y)] - Net imports ($(\mathrm{x})_\mathrm{a}^\mathrm{z}$,y) = imports ($(\mathrm{x})_\mathrm{a}^\mathrm{z}$,y) - exports ($(\mathrm{x})_\mathrm{a}^\mathrm{z}$,y) - Share of net import ($(\mathrm{x})_\mathrm{a}^\mathrm{z}$,y) = net imports($(\mathrm{x})_\mathrm{a}^\mathrm{z}$,y) / global imports ($(\mathrm{x})_\mathrm{a}^\mathrm{z}$) - $GTC = (\sum_1^3 5\ yr\ avg. of\ share\ (y)\ of\ net\ import\ (x)_a^z * trade\ barriers\ (y))^2$
UK gross-value added/UK apparent consumption	Due to issues with data availability and consistency for calculating the UK GVA, this indicator is replaced by UK apparent consumption based on UK trade data using monetary values (£) rather than volumes. - $Apparent\ consumption\ (x) = \sum(production(£)\ (x)_a^z + import(£)\ (x)_a^z) - \sum export(£)\ (x)_a^z$
Unchanged indicators	
Companion metal fraction	Although companionality datasets are dated, no recent update has been produced covering the whole range of CMs. The method remains similar to the previous CA.
Import reliance indicator	This indicator remains calculated as the UK NIR, weighted by trade restrictions. - NIR = (imports - exports / apparent consumption) * trade restrictions (y)

The inclusion of each indicator in the supply risk or economic vulnerability dimension is summarised in Figure 19, alongside a representation of the revised critical space.

The proposed methodology will allow the calculation of a criticality score for each CM and produce a ranking from low to high criticality (Figure 18). Defining a fixed threshold separating critical from non-critical materials remains highly subjective and such a binary classification does not adequately represent the complexity of the underlying assessment. Unless thresholds based on international best practices or internal government and industry evaluation of acceptable levels of risk can be determined for each indicator, the use of arbitrary thresholds should be avoided.

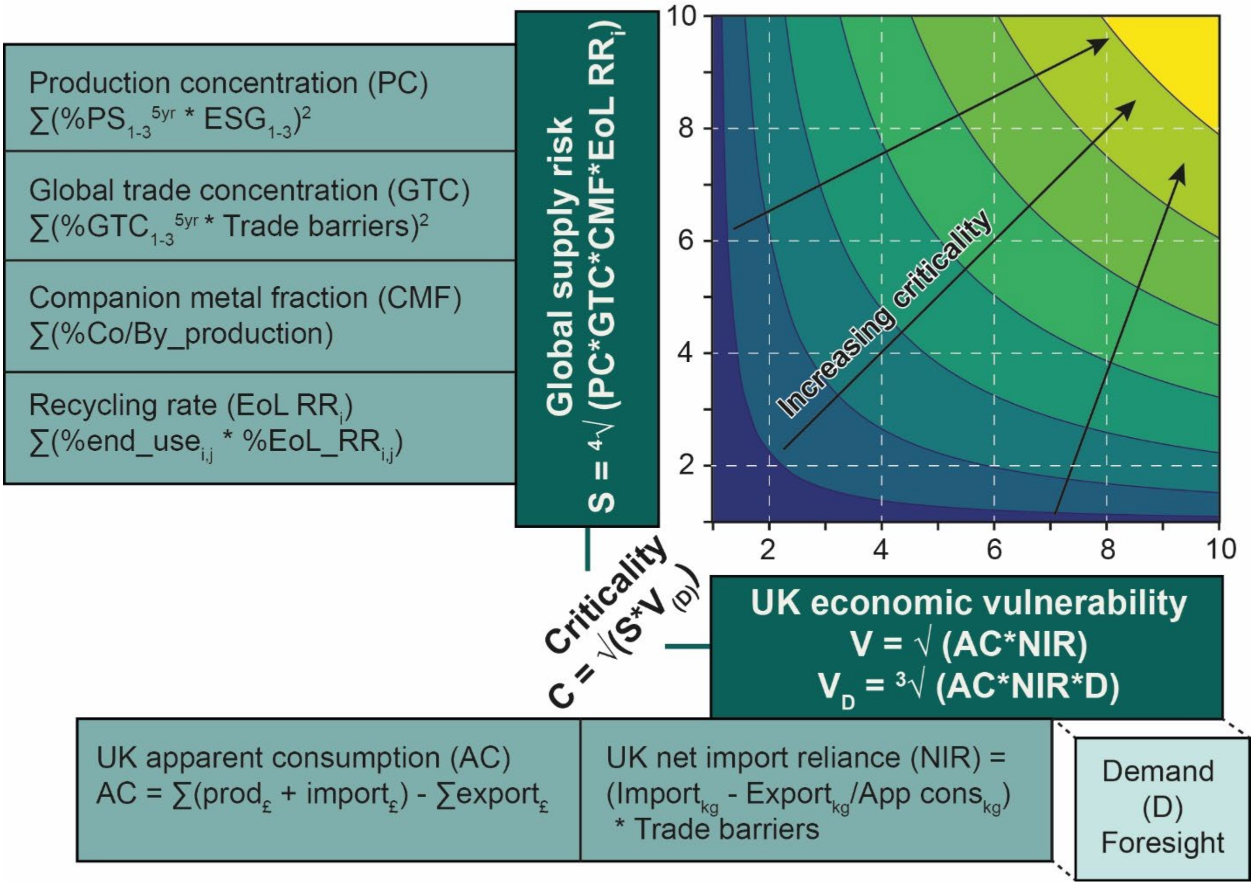


Figure 19 Summary of proposed criticality assessment method with simplified equations and representation of the geometry of isocritcal contours. Note that two equations are provided for the economic vulnerability dimension, as the demand indicator based on foresight study will not apply to all CMs. A second score, V_D, will be calculated for candidate materials covered by the foresight studies. For details on each indicator and associated calculations, see main text.

Appendix 1 Materials that have been designated as critical in different countries

Atomic number	Symbol	Element	Critical in Australia (2022)	Critical in Canada (2021)	Critical in the European Union (2020)	Critical in Japan (2019)	Critical in the United States (2022)	Critical in India (2016)	Critical in China (2021)	Critical in South Korea (2020)	Critical in South Africa (2022)	Critical in Germany (2022)	Critical in the UK (2021)	Critical in how many countries?
1	H	Hydrogen												0
2	He	Helium	🟩	🟩			🟩							3
3	Li	Lithium	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩	10
4	Be	Beryllium	🟩		🟩	🟩	🟩	🟩	🟩	🟩			🟩	8
5	B	Boron			🟩	🟩			🟩	🟩				4
6	C	Carbon	🟩	🟩	🟩	🟩	🟩	🟩					🟩	7
7	N	Nitrogen												0
8	O	Oxygen												0
9	F	Fluorine		🟩	🟩	🟩	🟩							4
10	Ne	Neon												0
11	Na	Sodium												0
12	Mg	Magnesium	🟩	🟩	🟩	🟩	🟩		🟩	🟩			🟩	8
13	Al	Aluminium	🟩	🟩	🟩		🟩							4
14	Si	Silicon			🟩	🟩				🟩			🟩	4
15	P	Phosphorus			🟩					🟩				2
16	S	Sulfur												0
17	Cl	Chlorine												0
18	Ar	Argon												0
19	K	Potassium		🟩			🟩							2
20	Ca	Calcium												0
21	Sc	Scandium	🟩	🟩	🟩	🟩	🟩		🟩					6
22	Ti	Titanium	🟩	🟩	🟩	🟩	🟩			🟩				6
23	V	Vanadium	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩			🟩	9
24	Cr	Chromium	🟩	🟩		🟩	🟩	🟩	🟩	🟩	🟩			8

25	Mn	Manganese	■	■		■	■		■	■				6
26	Fe	Iron									■			1
27	Co	Cobalt	■	■	■	■	■	■	■	■	■		■	10
28	Ni	Nickel		■		■			■	■	■			5
29	Cu	Copper		■							■			2
30	Zn	Zinc		■										1
31	Ga	Gallium	■	■	■	■	■	■	■	■			■	9
32	Ge	Germanium	■	■	■	■	■	■	■	■				8
33	As	Arsenic					■			■				2
34	Se	Selenium				■			■	■				3
35	Br	Bromine												0
36	Kr	Krypton												0
37	Rb	Rubidium				■	■		■					3
38	Sr	Strontium			■	■	■			■				4
39	Y	Yttrium	■	■	■	■	■	■						6
40	Zr	Zirconium	■			■	■	■	■	■				6
41	Nb	Niobium	■	■	■	■	■	■	■	■			■	9
42	Mo	Molybdenum		■		■			■	■				4
43	Tc	Technetium												0
44	Ru	Ruthenium	■	■	■	■	■	■	■	■	■			9
45	Rh	Rhodium	■	■	■	■	■	■	■	■	■			9
46	Pd	Palladium	■	■	■	■	■	■	■	■	■		■	10
47	Ag	Silver												0
48	Cd	Cadmium								■				1
49	In	Indium	■	■	■	■	■	■		■			■	8
50	Sn	Tin		■			■		■	■			■	5
51	Sb	Antimony	■	■	■	■	■	■		■			■	8
52	Te	Tellurium		■		■	■			■			■	5
53	I	Iodine												0
54	Xe	Xenon												0
55	Cs	Caesium		■		■	■		■	■				5
56	Ba	Barium			■	■	■			■				4
57	La	Lanthanum	■	■	■	■	■	■	■	■	■		■	10
58	Ce	Cerium	■	■	■	■	■	■	■	■	■		■	10
59	Pr	Praseodymium	■	■	■	■	■	■	■	■	■		■	10

60	Nd	Neodymium	■	■	■	■	■	■	■	■	■		■	10
61	Pm	Promethium	■	■	■	■	■	■	■	■	■		■	10
62	Sm	Samarium	■	■	■	■	■	■	■	■	■		■	10
63	Eu	Europium	■	■	■	■	■	■	■	■	■		■	10
64	Gd	Gadolinium	■	■	■	■	■	■	■	■	■		■	10
65	Tb	Terbium	■	■	■	■	■	■	■	■	■		■	10
66	Dy	Dysprosium	■	■	■	■	■	■	■	■	■		■	10
67	Ho	Holmium	■	■	■	■	■	■	■	■	■		■	10
68	Er	Erbium	■	■	■	■	■	■	■	■	■		■	10
69	Tm	Thulium	■	■	■	■	■	■	■	■	■		■	10
70	Yb	Ytterbium	■	■	■	■	■	■	■	■	■		■	10
71	Lu	Lutetium	■	■	■	■	■	■	■	■	■		■	10
72	Hf	Hafnium	■		■	■	■			■				5
73	Ta	Tantalum	■	■	■	■	■	■	■	■			■	9
74	W	Tungsten	■	■	■	■	■		■	■			■	8
75	Re	Rhenium	■			■	■	■	■	■				6
76	Os	Osmium	■	■	■	■	■	■	■	■	■			9
77	Ir	Iridium	■	■	■	■	■	■	■	■	■			9
78	Pt	Platinum	■	■	■	■	■	■	■	■	■		■	10
79	Au	Gold												0
80	Hg	Mercury												0
81	Tl	Thallium				■				■				2
82	Pb	Lead									■			1
83	Bi	Bismuth	■	■	■	■	■	■		■			■	8
84	Po	Polonium												0
85	At	Astatine												0
86	Rn	Radon												0
87	Fr	Francium												0
88	Ra	Radium												0
89	Ac	Actinium												0
90	Th	Thorium												0
91	Pa	Protactinium												0
92	U	Uranium		■			■							2
93	Np	Neptunium												0
94	Pu	Plutonium												0

95	Am	Americium												0
96	Cm	Curium												0
97	Bk	Berkelium												0
98	Cf	Californium												0
99	Es	Einsteinium												0
100	Fm	Fermium												0
101	Md	Mendelevium												0
102	No	Nobelium												0
103	Lr	Lawrencium												0
104	Rf	Rutherfordium												0
105	Db	Dubnium												0
106	Sg	Seaborgium												0
107	Bh	Bohrium												0
108	Hs	Hassium												0
109	Mt	Meitnerium												0
110	Ds	Darmstadtium												0
111	Rg	Roentgenium												0
112	Cn	Copernicium												0
113	Nh	Nihonium												0
114	Fl	Flerovium												0
115	Mc	Moscovium												0
116	Lv	Livermorium												0
117	Ts	Tennessine												0
118	Og	Oganesson												0
		Coking coal			🟩						🟩			2

Glossary

Abbreviation	Full term
2021 CA	Criticality assessment of technology-critical minerals and metals
ASI	Ability to supply index
AZO	Aluminium zinc oxide
BEIS	Department for Business, Energy & Industrial Strategy
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (German Federal Institute for Geosciences and Natural Resources)
BGRM	Bureau de Recherches Géologiques et Minières (French Geological Survey)
BGS	British Geological Survey
C	Critical value
CA	Criticality assessment
CAGR	Compound annual growth rate
CM	Candidate material
CMIC	Critical Minerals Intelligence Centre
CML	Critical minerals list
CRM	Critical raw material
DE	Domestic economy
DERA	Deutsche Rohstoffagentur (German Mineral Resources Agency)
DP	Disruption potential
EI	Economic importance
EoL	End-of-life
EoL CR	End-of-life collection rate
EoL RIR	End-of-life recycling input rate
EoL RPR	End-of-life recycling processing rate
EoL RR	End-of-life recycling rate
EPI	Environmental performance index
ER	Environmental risk
ESG	Environmental, social and governance
EU	European Union
EV	Economic vulnerability
GTC	Global trade concentration
GVA	Gross value added
HDI	Human development index
HHI	Herfindahl-Hirschman index
HPAL	High-pressure acid leaching
HS	Harmonised System
ITO	Indium tin oxide
MC	Military cooperation
NIR	Net import reliance
OECD	Organisation for Economic Co-operation and Development
PCI	Production concentration index

PGM	Platinum-group metal
PPI	Policy potential index
PRODCOM	UK Manufacturers' Sales by Product
REE	Rare earth elements
S	Supply risk
SIC	Standard industrial classification
SPOF	Single point of failure
SRM	Strategic raw material
SS	Supply safety
TMEB	To maximum extraction as a by-product
UK	United Kingdom of Great Britain and Northern Ireland
USA	United States of America
USGS	United States Geological Survey
V	Vulnerability
WGI	World governance indicators (World Bank)
WSI	Willingness to supply index
WTO	World Trade Organisation

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