Criticality of raw materials – a clarification and redefinition of the term worldwide

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ABSTRACT

Though not new in the literature, the term criticality of raw materials has become prevalent in recent years, referring to the importance and vulnerability of resources in various industries and technological advancements. However, criticality is perceived differently worldwide and is influenced by many more parameters than the supply disruption risk. This work comprehensively analyses the definition and determination of criticality for minerals and metals worldwide. The review examines the parameters used to assess criticality, considering factors such as supply and demand dynamics, geopolitical risks, market fluctuations, national security, environmental, and social and cultural considerations. The aim is to offer an in-depth understanding of the diverse conditions and perceptions surrounding criticality through a detailed review of research articles, technical reports, and industrial and governmental publications. The authors explore how different regions, countries and stakeholders define and prioritise critical raw materials based on their specific economic, political, environmental, social, and cultural contexts. By synthesizing the findings, this study aims to establish a more complete and broad understanding of the multifaceted nature of criticality assessment. It highlights the importance of simultaneously considering various parameters and factors when evaluating the criticality of raw materials. The culmination of these discussions will aid in developing a unified global term for raw materials criticality. The outcomes of this research will improve informed decision-making, resource management strategies, and the development of sustainable practices in the critical minerals and metals industry.

INTRODUCTION

The global economy strongly depends on minerals and metals, essential for manufacturing various goods, such as electronics, automobiles and clean energy technology (Nansai *et al*, 2014). Especially as the demand for renewable energy continues to grow, the demand for minerals and metals will rise exponentially in the following years. The supply of critical commodities necessary for this transition must pick up sharply over the coming decades to meet the global net zero emissions goals. The aforementioned is one of the many parameters determining specific minerals and metals critical in several countries worldwide.

It is understood that commodities like rare earth elements, lithium, nickel, cobalt and others have not always been critical, nor will they be forever. The increasing demand for specific minerals and metals at certain periods of time inspires nations and organisations to inspect their criticality situation, aiming to ensure supply security in the foreseeable future (Eheliyagoda, Zeng and Li, 2020). However, since governments, industries and organisations view criticality from different lenses, defining a singular term is challenging.

Criticality generally refers to the current value of minerals and metals to the economy and the potential risks associated with their supply chains (Girtan *et al*, 2021). The definition and determination of raw materials criticality are not agreed upon, leading to varying assessments across different countries and regions (Blengini *et al*, 2017; Eheliyagoda, Zeng and Li, 2020). As a result of the lack of standardisation, the process of comparing and prioritising critical minerals and metals can be complicated and unclear, which may adversely affect the supply chains.

In the literature, we can find several parameters that determine criticality. Geological scarcity is one of the most significant factors, along with geopolitical instability, prices of the commodities and their applications that depend on market trends and technological advances. Nonetheless, there are several gaps in evaluating mineral and metal criticality. These gaps include (Daw, 2017):

- Inconsistency in the number of parameters and conditions used to evaluate commodities' criticality.
- Insufficient description of criticality assessment methodologies and evaluation frameworks.
- Analyses of criticality assessments in different countries and regions are limited.
- Critical minerals and metals are not always adequately understood in terms of the supply chain and other risks associated with them.

These gaps need to be addressed for several reasons. Firstly, filling these gaps can contribute to developing a globally stable and secure supply of minerals and metals (Hayes and McCullough, 2018). As a second benefit, it can assist in mitigating supply chain risks and reduce supply disruptions' economic impact (Schrijvers *et al*, 2020). As well as developing sustainable mining practices and promoting more circular economic performance, it can contribute to the development of a sustainable mining sector (Vidal *et al*, 2022). In mining projects, especially in polymetallic deposits, a mineral or metal's status as either the primary product or a byproduct can substantially influence its criticality status (Mammadli *et al*, 2022). Understanding the interaction of these factors is vital for conducting more robust criticality evaluations.

The concept of criticality is becoming more popular, though further research is needed to establish a standard definition and methodology for assessing criticality (Jin, Kim and Guillaume, 2016). It is also necessary to evaluate criticality assessments across countries and regions, and better understand supply chain risks associated with critical minerals and metals (Achzet and Helbig, 2013).

Hence, this work provides a comprehensive overview of how criticality is defined and determined for minerals and metals worldwide. It is crucial to comprehend raw materials' strategic significance and vulnerabilities in today's linked world when the demand for many resources is rising. In the context of this study, criticality includes a thorough identification of metals and minerals considering their economic, environmental, geopolitical and technical implications. Consequently, strategies can be formulated concerning managing mineral resources and mitigating supply chain risks.

LITERATURE REVIEW

Given the dynamic nature and popularity of the topic, many researchers have been dealing with the criticality of raw materials. However, how researchers, organisations, governments and nations define criticality is discussed hereinafter. This work is based on the review of existing literature, so an initial review of criticality assessments is discussed in this section. A more detailed discussion of how criticality is determined by nations that are major stakeholders of the global critical raw materials industry is done as the central core of this paper.

Criticality assessments

Critical mineral and metal assessments constantly evolve as new research and technologies emerge. Criticality assessments are typically based on supply risk, currently the most widely used approach. A mineral or metal supply disruption is evaluated based on the likelihood and potential impacts (Farjana *et al*, 2019). Various indicators are considered to determine the criticality of a mineral or metal, such as production concentration, reserve distribution and political stability (Graedel *et al*, 2012).

Nevertheless, this approach is known to be limited, particularly for its narrow focus on economic and geopolitical aspects. It is, therefore, necessary to develop more comprehensive and integrated approaches that consider a wider range of factors, such as environmental and social implications (Eheliyagoda, Zeng and Li, 2020). Furthermore, the dynamic and complex nature of supply chains for several minerals and metals must be considered.

As a result, innovative approaches to criticality assessments have become increasingly popular. Stakeholder engagement and circular economy strategies are also incorporated into this process, as well as advanced data analytics and modelling techniques (Watari *et al*, 2019). Such approaches aim to provide more accurate and comprehensive criticality assessments and promote more sustainable and resilient supply chains. There has been a rapid advancement in critical minerals and metals assessment in recent years (Glöser *et al*, 2015). These critical resources face several complex and interrelated challenges.

It is possible to assess criticality using a variety of methodologies and frameworks found in many papers, articles and government publications. It should be noted that the definition of what constitutes critical material differs across these methodologies and frameworks. The necessity of criticality assessment of minerals has evolved due to various factors, including changes in global supply chains, increased demand for certain minerals driven by technological advances, and increasing concern over the risks associated with mineral extraction and processing, sustainability and environmental impacts (Eheliyagoda, Zeng and Li, 2020).

Definition of criticality

The vast majority of researchers worldwide have been working on defining which minerals and metals are considered critical based on each nation's boundary conditions. Some others approach 'criticality' as a framework or a concept through which the minerals and metals can be classified as critical or not (Frenzel *et al*, 2017; Blengini *et al*, 2017; Eheliyagoda, Zeng and Li, 2020). There are sporadic descriptions and references of the definition of criticality in assessment reports, governmental publications and numerous research papers (Eheliyagoda, Zeng and Li, 2020). While some disagree on the definition of criticality, most agree that it refers to the economic significance of a mineral or metal. The term also refers to its vulnerability to disruptions in supply.

Nevertheless, few discussions and research outcomes are solely addressing the definition of the term. Such an event was held in June 2021 by the Critical Minerals Association in the UK (CMA, 2021). CMA organised a discussion on how a critical mineral can be defined and what determines the 'criticality' of a metal or mineral. Experts from governmental agencies, mining companies, consulting groups and other stakeholders attended this event.

Hence, this work analyses the term criticality in detail and aims to initiate a discussion that could end up with a global definition.

METHODOLOGY

Based on the research gaps identified, a multi-faceted and comprehensive literature review approach was utilised in this research project. The review included academic journals, technical reports, government publications and industry documents. The purpose of this methodological blend is to provide an overview of the criticality of minerals and metals worldwide. The vast number of publications and the diversity of sources led to a cross-comparison of data and consultancy from experts around the globe. The discussions with experts were not in an officially structured form (interviews or surveys), hence no references are made to specific people. The aim of these contacts and of the whole review is to uncover existing discussions on criticality, assessment parameters and the perspectives presented in global discourse.

It would be impossible to cover the globe and accumulate all opinions and definitions of criticality in one paper. Hence, this research focuses on eight main actors in the field of critical raw materials: Australia, Canada, China, the European Union, India, Japan, the United Kingdom and the United States of America. The selection of these countries and regions lies in the fact that these eight are significant suppliers and/or consumers of critical minerals and metals and rely heavily on them for their industries and technological advancement. At the same time, they face challenges related to the reliable and sustainable supply of these resources, as some are scarce or subject to market fluctuations and geopolitical risks. As a result, these countries and regions have a strategic interest in understanding the criticality of raw materials.

The influence of some of the players mentioned above in the criticality of raw materials may be more significant than others. However, it is not in the scope of this work to prioritise the suppliers or the consumers of critical minerals and metals. Hence, the status of the different countries and regions is discussed alphabetically.

The analysis continues with the evolution of the term ‘criticality of raw materials’ and an effort is made to narrow down the terminology and for the first time give a global definition.

DISCUSSION ON THE VARIOUS CRITICALITY APPROACHES

The diversity of conditions that govern the eight aforementioned major stakeholders of the critical raw materials sector leads to different approaches to criticality. For some countries, minerals and metals are critical due to lack of domestic production and their insecure supply. For some others, it is the opposite; the vast production of commodities in high demand elsewhere casts them as critical (or strategic) for the producers.

Australia

Australia is a resource-rich country with abundant critical raw materials such as lithium, nickel and rare earth elements (Barakos, Dyer and Hitch, 2022). Unlike other countries, Australia is not concerned about running out of these resources, as they have significant reserves and can continue to export them globally. Therefore, their focus on criticality is less about resource scarcity and more about the strategic value of these resources. A crucial turning point in the nation’s strategic planning for its mineral and metal resources was reached with the publication of the 2013 Australian government report on 33 critical commodities. This study was produced as part of Australia’s efforts to comprehend its contribution to supplying essential commodities required by several global sectors and technology (Skirrow *et al*, 2013).

In the 2019 Critical Minerals Strategy, the Australian Government created a blueprint for managing vital mineral resources sustainably. Consequently, the Critical Minerals Facilitation Office (CMFO) was established to advise and support the industry, particularly research, development and international collaborations on critical mineral matters (Department of Industry, Innovation and Science, 2019). Government-funded research projects, like those by the Cooperative Research Centre for Optimising Resource Extraction (CRC ORE), are innovating in critical minerals processing. Another notable initiative is the University of Queensland’s exploration of extracting these minerals from mine waste (Van der Ent, Parbhakar-Fox and Erskine, 2021).

Key publications include ‘The 2018 Critical Minerals in Australia’ report, which comprehensively analyses the status, challenges and opportunities tied to Australia’s critical minerals. It underscores their significance to the economy, innovation and sustainability. It advocates for joint efforts among industry, academia and government to tackle related challenges. The ‘2019 critical minerals strategy’ by the Australian Government, which outlines three primary actions to promote the sector: attracting investments, fostering innovation and focusing on infrastructure development. This strategy emphasises the importance of responsibly developing these resources to support Australia’s economic and strategic interests (Department of Industry, Innovation and Science, 2019). A 2022 report updates Australia’s approach to critical minerals, adding two minerals to their list due to their strategic importance (Department of Industry, Science, Energy and Resources, 2022). Key government actions involve de-risking projects, boosting R&D and strengthening international ties.

The most recent publication in 2023 by the Grattan Institute entitled: ‘Critical minerals: delivering Australia’s opportunity,’ discusses Australia’s potential as a significant global supplier of critical minerals (Wood, Reeve and Suckling, 2023). It stresses the importance of these minerals to modern tech and Australia’s economy while highlighting the associated challenges. The report recommends a strategy that promotes R&D, responsible mining practices and international collaboration. Finally, it is worth noting that the South Australian Government’s declaration of copper as a critical raw material in August 2023 was driven by economic and clean technology considerations (Government of South Australia, 2023).

Canada

Canada is another significant supplier of critical raw materials such as cobalt and lithium, but also a consumer of many others. The Canadian government recognises the strategic significance of these resources and is investing in research and development to enhance its domestic production and support emerging technologies development.

Minerals and other natural resources are not assessed for criticality according to a single standardised methodology in the country. However, as part of Canada's resource strategy and economic interests (NRCan, 2022), the government and various national research institutions have conducted studies that evaluate the criticality of raw materials. An example is the Natural Resources Canada (NRCan), the federal department responsible for the country's natural resources. NRCan has led reports and development activities about critical minerals in Canada. Minerals that are considered 'critical' in Canada must meet the following criteria (NRCan, 2022):

- it is essential to Canada's economic security and its supply is threatened
- specifically necessary for the nation's transition to a low-carbon economy
- a sustainable source of highly strategic critical minerals for their partners and allies.

According to these criteria, the Canadian government identified 31 minerals as being 'critical' in their most recent assessment (Maloney, 2021). The authors further express that 'as critical minerals are the foundation on which modern technology is built, the growing demand for them represents a generational opportunity for Canada' (NRCan, 2022).

China

For China, criticality may not be the correct expression as the nation is responsible for the production of several critical raw materials; it is more about strategic than critical like Australia. According to Andersson (2020), critical minerals and metals have been utilised as essential materials since the publication of the 13th five-year plan in China (2016–2020). In contrast to the US and the European Union, China does not view criticality as a primary concern, as they possess abundant critical raw materials resources and the know-how to process them. Instead, China approaches the issue of raw materials from a strategic perspective, recognising the importance of securing reliable access to key resources to support its economic growth and global influence.

The significance of raw materials to China stems from several factors, such as the production dominance where China is a leading producer and exporter of key commodities like rare earth elements and tungsten (Castillo and Purdy, 2022). This gives it a controlling position in global supply chains, influencing market dynamics and prices. As a result of Chinese firms investing in advanced processing technologies and manufacturing capabilities, China excels in downstream processing and value-added manufacturing of critical minerals and metals. China's trade policies and export controls on critical minerals and metals can adversely affect global supply chains and access to these resources.

Despite being a major producer, China's domestic supply is threatened by resource depletion, environmental concerns, regulatory shifts and geopolitical tensions. These challenges can affect global availability and pricing. Another factor is global consumption, as China's rapid economic expansion, urbanisation, industrialisation, and renewable energy goals have made it a significant consumer of critical minerals and metals, further elevating their importance in global supply chains.

China conducts its own evaluations to assess the criticality of minerals and metals for domestic needs and strategic objectives (Yan *et al*, 2021). Their three-dimensional system relies on three leading indices:

- Supply safety index: It characterises the risk associated with material supply, considering elements like sustainability, reliance and tolerance.
- Domestic economy index: It evaluates the material's importance to the national economy based on its value in each end-use.
- Environmental risk index: It considers environmental factors, categorising metals according to toxicity, waste produced during manufacturing and the impact of environmental protection measures.

The report identifies 24 metals as critical based on supply risk and economic fluctuations, with 18 metals exhibiting higher criticality when environmental risk is also considered (Yan *et al*, 2021). The methodology can be applied to evaluate critical materials in specific sectors like lithium batteries, aircraft engines, and energy storage devices, areas expected to draw global attention and competition in the future.

European Union

The European Union's lack of critical raw materials and reliance on external sources presents a significant concern regarding their supply chain stability. The EU's focus on criticality is determined by recognising the importance of securing access to key resources for their economy and technological advancement (Blengini *et al*, 2017). With the increasing demand for critical minerals to support emerging technologies such as electric vehicles and renewable energy, the EU's dependence on external suppliers poses a significant risk to their competitiveness in these industries (Grohol, Veeh and European Commission, 2023).

Europe evaluates critical raw materials (CRMs) to ensure sustainable economic, environmental, and social outcomes for its industries, fostering innovation, technological advancement and supply chain resilience (European Commission, 2023). The EU has established a methodology for identifying CRMs, considering economic importance and supply risk. Since 2011, the EU has released five CRM lists, increasing the number of identified CRMs in each subsequent assessment.

To determine the criticality of a material for the EU, the assessment considers its economic importance, contribution to the trade balance, end-use applications and value-added (Martins and Castro, 2020). The supply risk is evaluated by considering factors like production concentration, export stability and potential supply disruptions (Figure 1).

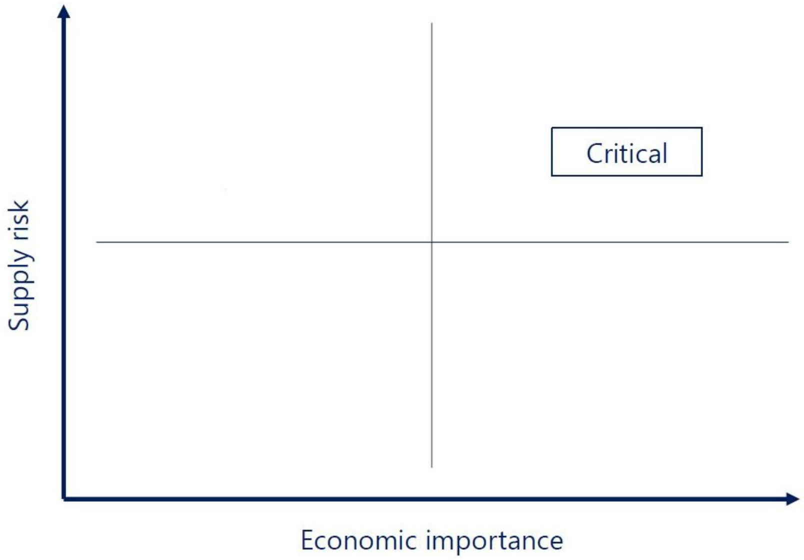


FIG 1 – A simplified chart showing the determination of criticality based on supply risk and economic importance (European Commission, 2023).

Recent key publications on the EU's approach include:

- The 2017 'EU methodology for critical raw materials assessment' critiques the existing approach and suggests incorporating environmental and social indicators, life cycle assessments and comprehensive CRM supply chain databases.
- Martins and Castro's (2020) article proposes a circular economy approach to tackle raw material depletion in the EU, emphasising reduced consumption, recycled materials and product reuse and repair.

- Godoy León and Dewulf's (2020) article introduces a framework for assessing data quality on CRMs, exemplified with cobalt. This framework aims to improve the accuracy and reliability of CRM information to aid sustainable policies and better decision-making.

The latest report by the European Union, 'Study on the critical raw materials for the EU 2023,' identifies 34 critical raw materials and examines their use, production and trade patterns. The two-step methodology considers economic significance, supply chain risks, environmental and social impacts and alternative materials. To ensure resilience and strategic autonomy in achieving green and digital transitions, access to CRMs is essential for the EU's political objectives, including the European Green Deal, REPowerEU Communication and Joint Communication on Defense Investment Gap Analysis and Way Forward.

India

Among other nations, India also recognises the importance of critical minerals and metals for its economic growth, technological advancements and national security (Chadha and Sivamani, 2022). Hence, the government has actively secured access to critical minerals and metals through various policies and strategies, by investing in research and development and by establishing partnerships with other nations. In 2016, the Centre for Social and Economic Progress (CSEP), a think tank based in India that conducts research and analysis on a wide range of social, economic and policy issues, evaluated the criticality of non-fuel minerals in this country. The updated CSEP study was based on the EU methodology (2017), while the previous study was built on the EU methodology in 2014 (Chadha and Sivamani, 2021). Two main factors determine criticality for India:

- Economic importance: A mineral that is no longer available in the supply chain has an impact on the national economy.
- Supply risk: Based on the concentration of mineral extraction in some countries and the quality of governance in these countries, the supply risk indicator of the criticality assessment attempts to assess the vulnerability of the global mineral supply chain.

It was determined that lithium, niobium and strontium have the highest economic importance, based on their substitutability potential, among 11 selected minerals. The authors also indicate that the study provides policy highlights on enhancing domestic mineral exploration and extraction, along with assurances of other sources, to ensure uninterrupted supplies of critical minerals. Nevertheless, the growth of clean technology has dependably been the primary goal in both formal government criticality assessments and informal evaluations conducted within India.

In a recent report by Isetani *et al* (2022), India and Japan collaborated on energy security and critical raw materials (CRM). The report highlights India's rapid growth in the e-waste sector and suggests that recycling CRM from e-waste could enhance CRM security instead of relying solely on mining minerals (Isetani *et al*, 2022). Furthermore, due to a lack of capacity for fostering technical innovations and research and development in utilising their abundant terrestrial resources, Japanese capital could help facilitate industrial development in India. This means the potential for collaboration on critical raw materials (CRM) supply chains between Japan and India is vast. Throughout official and non-official assessments of India, the target was clean technology.

Japan

Japan relies heavily on raw materials to sustain its highly advanced technology sector. The Japanese government has developed strategies to reduce its dependence on foreign sources, promote recycling and reusing critical materials and increase domestic production.

Given its limited domestic reserves, Japan's dependency on critical metals for its high-tech and renewable energy industries is a significant concern (Hatayama and Tahara, 2015). As such, Japan heavily relies on imports and has undertaken measures to ensure a stable supply. One such measure was the establishment of the National Evaluation and Development Organization (NEDO) in 2009, which conducted Japan's first official criticality assessment of metals used in advanced technologies and industries (NEDO, 2009).

NEDO's assessment categorised metals into five risk categories of 12 components. Though not explicitly using the term 'criticality', the assessment evaluated the critical metals for Japan, examining 39 minor metals. A single criticality score was calculated based on the results. NEDO identified 14 of 39 metals as essential minerals, assigning one to three points for each of the 12 components.

In 2015, Hatayama and Tahara assessed the criticality of Japan's 22 common metals, which the government deems strategic. Their assessment had a scale of 1 to 32, with minerals scoring 18 or higher considered necessary (Hatayama and Tahara, 2015). The same year, the Japan Oil, Gas and Metals National Corporation (JOGMEC) evaluated supply risk and economic importance of minerals, including recycling rates (Miyamoto, Kosai and Hashimoto, 2019).

In Japan, the most recent official assessment was conducted and released by the Ministry of Economic, Trade and Industry of Japan (METI) in 2020. The assessment identified 35 critical commodities with the help of 11 risk factors (METI, 2020).

United Kingdom

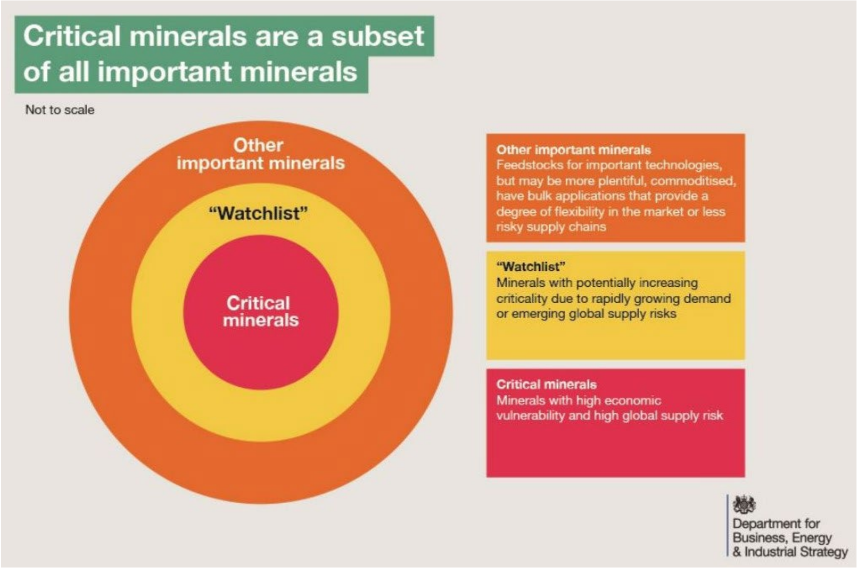
The United Kingdom's departure from the European Union has impacted its access to critical raw materials, as it can no longer rely on the EU's supply chain network. As a result, the UK has become increasingly interested in addressing criticality concerns to ensure the stability of its supply chain. In collaboration with other stakeholders, the British Geological Survey (BGS) published a 2021 report entitled 'UK Criticality Assessment of Technology Critical Minerals and Metals'. The report examines the criticality of various minerals and metals in developing and deploying advanced technology in the United Kingdom.

The report evaluates the criticality of technology-critical minerals and metals based on various factors, including their economic importance, supply risk, environmental and social impacts and future demand for emerging technologies (BGS, 2021). In addition, it provides insight into the availability, affordability and sustainability of the minerals and metals essential to the UK's technology-based industries.

Various high-tech applications require minerals and metals, such as rare earth elements, lithium, cobalt, platinum group metals, tungsten and tantalum. Materials such as these are used in various advanced technologies, including renewable energy, electric vehicles, aerospace, defence systems, electronics and other advanced technologies crucial to the UK's economic growth, innovation and societal well-being.

The report provides an exhaustive analysis of the supply chain risks, vulnerabilities and opportunities related to these critical minerals and metals, both globally and within the UK. In addition to recommendations for policy, regulatory, and strategic interventions to improve the resilience of the UK's supply chains for technology-critical minerals and metals, the report also contains recommendations for policy, regulatory and strategic interventions.

To underpin the dynamics of criticality and the long-term nature of their assessment strategy, BGS in collaboration with the Critical Minerals Intelligence Centre (CMIC) will evaluate the criticality of raw materials on an annual basis (Department for Business, Energy and Industrial Strategy, 2023). The assessment will be done through an impartial and evidence-based process and the establishment of a 'watchlist' of minerals and metals that are deemed to be increasing in criticality (Figure 2).



Other important minerals
Feedstocks for important technologies, but may be more plentiful, commoditised, have bulk applications that provide a degree of flexibility in the market or less risky supply chains

"Watchlist"
Minerals with potentially increasing criticality due to rapidly growing demand or emerging global supply risks

Critical minerals
Minerals with high economic vulnerability and high global supply risk

FIG 2 – Schematic of critical minerals, as a subset of all important minerals (Department for Business, Energy and Industrial Strategy, 2023).

United States of America

The United States' focus on criticality is driven by concerns regarding its defence system and national security. The US recognises that access to critical minerals and materials is essential for developing and deploying advanced defence technologies such as radar systems, missiles and aircraft (Hammond and Brady, 2022). The US also identifies that dependence on foreign sources for these materials poses a significant risk to national security and economic competitiveness (Gulley, Nassar and Xun, 2018).

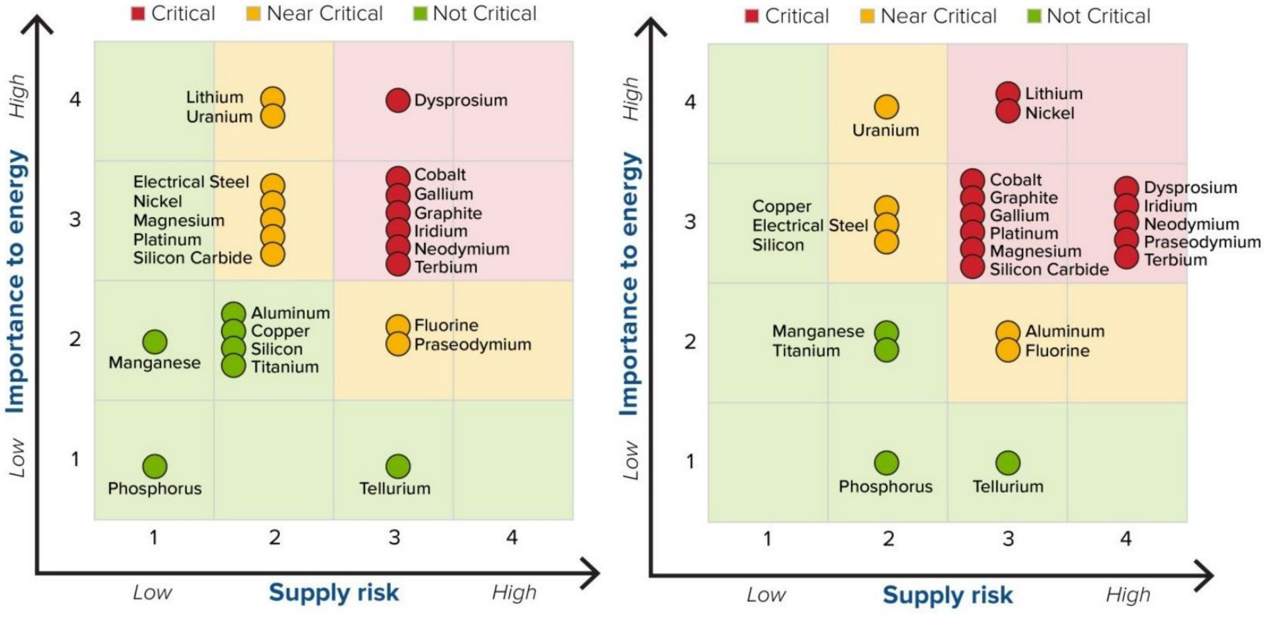
The National Research Council (NRC) was established by the US National Academy of Sciences in 1916 to support its mission of advancing knowledge and advising the federal government by bringing together a wide range of scientists and technologists. The NRC, now the principal operating agency for the National Academy of Sciences and the National Academy of Engineering, provides services to the government, public and scientific and engineering communities (American Institute of Physics, 2023). It has developed a framework for criticality assessments, defining criticality as the importance of a mineral to the nation's economy and security, considering both supply risk and importance.

The methodology for criticality assessments includes quantitative, semi-quantitative and qualitative evaluations. It considers factors like geographical concentration, production, exports, political and regulatory factors and the importance of the mineral to various industries. The Department of Energy released a report in 2010 on critical minerals in emerging clean energy technologies, emphasising the need for collaboration and innovation to ensure responsible sourcing and management of critical minerals (Fortier *et al*, 2021).

In 2016, the Department of Science and Technology of the US developed its first assessment of critical minerals, using a consistent methodology and a scale from 0 to 1 to assess potential criticality. They calculated a geometric mean based on three key indicators: supply risk (R), production growth (G) and market dynamics (M). In 2019, the Congressional Research Service prepared a report on critical minerals, discussing policy tools the US government can use to promote the development of critical minerals.

The United States Geological Survey (USGS) published the 'USGS Critical Minerals Review' in 2021, providing an update on the global supply of critical minerals and identifying emerging trends and issues that could affect their supply and demand. In 2022, the USGS released the '2022 critical minerals' report, listing 50 critical minerals, including 15 new commodities (Mosley, 2022). The report outlines challenges and recommendations for improving the resilience and sustainability of the critical mineral supply chain in the US, such as expanding domestic mining and recycling, improving data collection and analysis and encouraging international cooperation. In the latest report (US DOE,

2023) two criticality matrices are included based on the supply risk and importance to energy (Figure 3); one for short-term (2020–2025) and one for long-term criticality (2025–2035).



(a) (b)

FIG 3 – (a) Short-term (2020–2025) and (b) Long-term (2025–2035) criticality matrices based on the most recent assessment in the US (US DOE, 2023).

EVOLUTION OF THE TERM CRITICALITY

As noted throughout the discussions, 'criticality' has transformed into a confusing term based on diverse conditions and parameters around the globe. Initially, the term was used to refer to the vulnerability of supply chains in various industries during periods of disruption or geopolitical tension (Eheliyagoda, Zeng and Li, 2020). In this case, it referred to the adverse effects of a shortage of particular minerals and metals on industrial sectors, technological advancement and economic stability.

The concept of criticality evolved to encompass broader dimensions as the global economy became more interconnected and dependent on intricate supply networks. Besides merely considering supply chain disruptions, it included geopolitical risks, environmental issues, social and cultural factors and national security considerations. The development of this emerging trend has been attributed to the growing complexity of global resource markets and the recognition of the interdependence between raw materials, sustainability and national interests.

The word 'criticality' has become even broader in recent years. There is a greater understanding that supply disruptions cannot be regarded as the sole determinant of mineral and metal criticality. As a result, it requires a holistic approach that considers the interrelationships among economic, environmental, societal and technological factors. As a result of this general viewpoint, it is acknowledged that their scarcity does not solely determine the criticality of certain minerals and metals but also by their strategic importance, the role they play in green technologies and their contribution to national and international prosperity (Martins and Castro, 2020).

According to certain countries' criticality concepts, their targets differed despite sharing similar meanings. Australia and China, for instance, target to secure their sources and demonstrate their strategic commodities under the criticality term. Demand highlights the criticality concept as resource-dependent countries such as EU and Japan scarcity (Andersson, 2020).

Criticality has demonstrated its significance beyond industry and economics as discourse on the topic has matured. Sustainable development, circular economy principles and international relations are all interconnected. In its evolution, criticality has shifted from an emphasis on immediate supply risks to a broader perspective that acknowledges the intricate web of factors contributing to the global importance of minerals and metals.

Additionally, as resource supply chains intertwine across economies everywhere, certain regions endowed with plentiful raw materials have adopted a distinctive perspective. These resource-rich regions have acquired a dual connotation when dealing with ‘criticality’. They acknowledge the inherent vulnerability of supply chains but also emphasise their strategic importance. There is a growing perception that mineral and metal resources are not merely at risk of disruption in supply but are also essential components in the drive for economic development and technological advancement.

There is a new meaning to the term ‘criticality’ in these strategic regions, indicating these resources’ significant role in strengthening national economies. In the context of industrial development, innovation and the advancement of key sectors, such resources are considered ‘strategic’. Consequently, the emphasis shifts from crisis-driven supply risk to an economic opportunity-driven focus. Considering the same set of resources from different perspectives based on regional circumstances demonstrates the evolving nature of the criticality concept. These regions provide insight into the multifaceted nature of criticality assessments by acknowledging resources’ strategic role and potential supply vulnerability.

Thus, it is essential to recognise that criticality nowadays is not simply about the risk of scarcity but also the potential for economic prosperity. As awareness grows of the interconnectedness of resources and societal progress, this shift in perception also occurs. This expanded understanding of criticality highlights the importance of comprehensive strategies that consider both vulnerability and strategic significance as the demand for minerals and metals continues to surge worldwide. In this way, sustainable and balanced resource management practices can be fostered globally.

Global definition of criticality

The literature review and the discussions enhanced the understanding of global mineral and metal criticality. It is difficult to narrow down all the findings and determine a simple definition of criticality with just a few words. Nevertheless, a framework for the term is proposed in this section.

The concept of criticality in the context of minerals and metals reflects the interaction of economic, environmental, geopolitical, social and cultural factors. This term refers to the importance and vulnerability of specific resources within various industries, technologies and social advancements. In addition to assessing the risk of supply disruptions, criticality includes an inclusive assessment of the broader impacts of mineral scarcity or disruption on economies, security, innovation and sustainability.

There are several aspects to this definition of criticality, including the dynamics of supply and demand, geopolitical risks, market fluctuations, national security concerns, environmental impacts and cultural considerations. The concept of supply risk has also evolved over the years, covering a more comprehensive range of parameters. Besides being essential for industrial production, minerals and metals have far-reaching effects on national economies, technological advancements and social welfare.

Additionally, criticality recognises that its assessment is contextual. According to specific circumstances and perspectives, different regions, countries and stakeholder groups may prioritise different aspects of criticality. Depending on the region, economic growth may be emphasised while environmental sustainability or social equity may be prioritised. Using the term ‘criticality’ strategically in specific regions where abundant raw materials are considered essential for fostering economic growth and technological advancement is possible.

CONCLUSIONS

As a result of this research, there has been an enhanced understanding of the criticality of minerals and metals worldwide. It is evident from examining the term’s evolution that it encompasses many factors beyond supply disruption.

It was found that the literature review delved into the intricate dimensions of criticality, highlighting the significance of supply-demand dynamics, geopolitical vulnerabilities, market fluctuations, national security concerns and socio-cultural influences in defining criticality. This expanded perspective enhances our understanding of the challenges and opportunities associated with ensuring the sustainable availability of these resources.

Interaction with experts played a pivotal role in the enhancement of this research. The insights from various professionals spanning academia, industry, policymaking, and various aspects of the critical raw material value chain have highlighted the complexity of evaluating criticality based on economic considerations, environmental sustainability, social equity and cultural nuances. It is clear from these insights that a comprehensive approach is necessary to assess the criticality of minerals and metals. Future work entails a more systematic recording of stakeholders' knowledge and expertise through interviews and surveys.

This study has a broad impact on a wide range of beneficiaries. Criticality assessment provides researchers with a solid foundation to build their studies. This information can be utilised by stakeholders, including industries and businesses, to make strategic decisions regarding the procurement of resources and the management of risk. Policymakers must have nuanced perspectives to formulate regulations that ensure the availability and sustainability of resources within a global context. Additionally, transparent resource management practices contribute to the general public's responsible consumption of critical minerals and metals.

Furthermore, this research provides opportunities for optimisation. Understanding that criticality has multidimensional characteristics, strategies can be developed to mitigate supply risks, navigate market volatility and strengthen resource sustainability. An integrated approach incorporating economic, environmental, social, and cultural aspects of resource management promises to lead to more balanced decisions and more effective resource management.

Overall, this study goes beyond traditional notions of criticality, advocating for a holistic approach to evaluation. The world must understand minerals and metals, considering their increasing dependence on them. This study contributes to a more robust, sustainable and global approach to critical raw materials by integrating diverse parameters and expert insights.

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