Which materials are 'critical' and 'strategic'

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1. Introduction

Raw materials are essential to the global economy and for maintaining and improving our quality of life. Recent years have witnessed a rapid growth in the use and demand for metals or industrial minerals used in high-technology products. Availability of these materials at competitive prices is essential for advances in high-technology products, clean-energy technology, and commercializing new inventions. Most demand and supply analyses emphasize technical, economic, environmental, and social parameters, and technologic breakthroughs. 'Criticality analysis' does the same, but focuses on identifying and evaluating the risks and impacts of supply disruptions on the economy, national security, implementing green energy programs, or other initiatives, depending on the interests of the organization that commissions the study. Metals that are commonly perceived as 'critical' or 'strategic' are rare earth elements (REE), tantalum (Ta), niobium (Nb), lithium (Li), beryllium (Be), gallium (Ga), germanium (Ge), indium (In), zirconia, and graphite.

For many materials (e.g., limestone, silica sand, iron) reserves, resources, and producing mines are abundant and widely distributed. For these materials, future supply is not at risk and can be crudely assessed by using the ratios of (global reserve/yearly production) and (global resource/yearly production). For other materials (e.g., heavy rare earth elements [HREE], Nb, antimony [Sb]) the assessment is more complex. Factors such as authoritarian regimes, monopoly- or oligopoly-type market conditions, political instability, and potential or existing regional conflicts can threaten reliable supply, and analyses must account for these risks. Furthermore, some high-technology metals are derived as a by-product of base-metal extraction (e.g., Ga, Ge, In). Supply of these metals is tied directly to production levels of related base metals. Their level of production cannot be easily increased independently of the main base-metal co-product without a major increase in their price.

According to the Webster's New Collegiate Dictionary (1975), the distinction between 'critical' ("indispensable for the weathering, solution, or overcoming of a crisis") and 'strategic' ("required for the conduct of war <materials> or necessary to or important in the initiation, conduct, or completion of strategic plan") may be seen as subtle or non-existent. These definitions are more or less in line with current European use (e.g., European Commission, 2011 and 2014a), where 'critical' materials are considered to be of high economic or trade importance, whereas 'strategic' materials are those essential to a country's defence. In North America, Ishee et al. (2013), defined a mineral as 'critical' if it is essential to a vital sector of the US economy and a mineral as 'strategic' if it is "important to the Nation's economy, particularly for defense issues; doesn't have many replacements; and primarily comes from foreign countries". However, the same publication (Ishee et al., 2013), acknowledges that US government-wide definitions do not exist. Similar to government publications, the distinction between the terms 'critical' and 'strategic' is largely lost in scientific and technical publications, trade journals, and newspapers.

Herein we summarize lists of critical and strategic materials prepared by the European Commission (EC), the US Department of Defense (DoD), and the US Department of Energy (DoE), emphasizing that lists of critical and strategic materials differ, based on whether the criticality analyses is being applied to the general economy (EC), the military (DoD), or clean-air technologies (DoE), and that these lists change through time due to technological breakthroughs, political pressures and instabilities, and depletion of resources. We underline that the designation of a material as 'critical' or 'strategic' depends on the subject and focus of study; therefore, if the terms 'critical' and 'strategic' are used, they should be clearly defined in an early portion of the publication and should not be applied out of context.

2. Case studies

2.1. 'Critical' raw materials from the economic point of view: the European Commission

With a long mining history, most major near-surface deposits in Europe have been mined out. Some deposits in densely populated areas are undeveloped due to strict environmental regulations. Therefore, discovery, permitting, and development of new mines in Central and Western Europe appear more difficult relative to other parts of the world. Securing reliable access to raw materials at competitive prices is an ongoing concern for most industrialized European countries (e.g., United Kingdom and Germany) and is reflected in several studies (e.g., Erdman et al., 2011; British Geological Survey, 2012; European Commission 2011, 2014a, b).

The European Commission released its first report on critical raw materials for the EU in 2011, updating it in 2014 (European Commission, 2011, 2014a, b), with plans to produce revised versions every three years. The methodology used in both studies is identical. Economic importance was determined by assessing the proportion of each material associated with industrial mega-sectors at an EU level. These proportions were then combined with the mega-sectors' gross value added to the EU's gross domestic product (GDP). The total was then scaled according to the total EU GDP to define an overall economic importance for the material. To quantify the supply risk, the European Commission relied on the World Governance Indicator (WGI). The WGI includes factors such as voice and accountability, political stability and absence of violence, government effectiveness, regulatory quality, rule of law, and control of corruption (European Commission, 2014a). Both iterations identified critical metals in terms of two key factors: 1) importance to the economy of the European Union; and 2) an estimate of the level of risk associated with supply of each material under consideration.

The 2011 study identified 14 materials as critical from a starting list of 41 non-energy, non-food materials. This list included cobalt (Co), fluorspar, graphite, magnesium (Mg), platinum group elements (PGE), REE (yttrium [Y], scandium [Sc], lanthanum [La], cerium [Ce], praseodymium [Pr], neodymium [Nd], samarium [Sm], europium [Eu], gadolinium [Gd], terbium [Tb], dysprosium [Dy], holmium [Ho], erbium [Er], thulium [Tm], ytterbium [Yb], and lutetium [Lu]), tungsten (W), Ta, Sb, Be, Ga, Ge, In, and Nb (European Commission, 2011).

The 2014 study started with a list of 54 materials and identified 19 as critical (Fig. 1). The extended list included 7 new abiotic materials and 4 biotic materials, including coking coal. For the purpose of this document, biotic materials are omitted. In addition to this expansion, the REE were subdivided into 'heavy' and 'light' categories (European Commission, 2014a). The current list of critical inorganic materials specific to the European community includes: borates, chromium (Cr), fluorspar, magnesite, natural graphite, phosphate rock, heavy REE, light REE, silicon metal, Sb, Be, Co, Ga, Ge, In, Mg, Nb, PGE, and W (European Commission, 2014a). Tantalum and Sc were downgraded to non-critical in the 2014 study.

2.2. Critical and strategic materials from the military point of view: US Department of Defense

A study commissioned by the US Department of Defense (US DoD) considered the stockpile requirements and availability of 76 materials (US Department of Defense, 2013). It identified 23 materials that would exhibit 'shortfalls' during

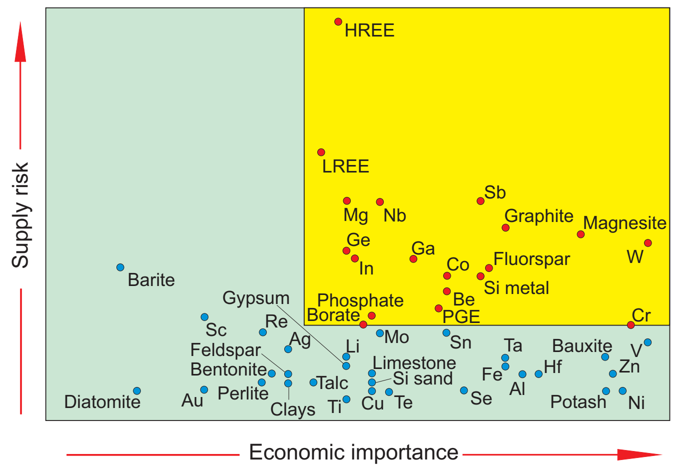

Fig. 1. Critical inorganic materials for the European Union. Criticality field in yellow, individual critical materials as red dots. Modified from European Commission (2014a). HREE–heavy rare earth elements, LREE–light rare earth elements, Mg–magnesium, Ge–germanium, In–indium, Nb–niobium, Ga–gallium, PGE–platinum group elements, Co–cobalt, Be–beryllium, Sb–antimony, Si–silicon, W–tungsten, Cr–chromium, Sc–scandium, Au–gold, Re–rhenium, Ag–silver, Li–lithium, Ti–titanium, Cu–copper, Mo–molybdenum, Te–tellurium, Sn–tin, Se–selenium, Ta–tantalum, Fe–iron, Al–aluminum, Hf–hafnium, Zn–zinc, Ni–nickel, V–vanadium.

a hypothetical 4-year time interval consisting of one year of all out conflict involving the USA followed by three years of recovery (starting in 2015 and lasting until the end of 2018). Referred to as 'critical and strategic', the materials determined to be in shortfall are tin (Sn), aluminum oxide fused (Al_2O_3), bismuth (Bi), manganese (Mn), silicon carbide (SiC), fluorspar (acid grade), Sb, W, Ta, Ge, Be, Cr, Dy, Er, Ga, Tb, Tm, Y, Sc, and four proprietary materials including three types of carbon fibers and a rare earth oxide (Fig. 2).

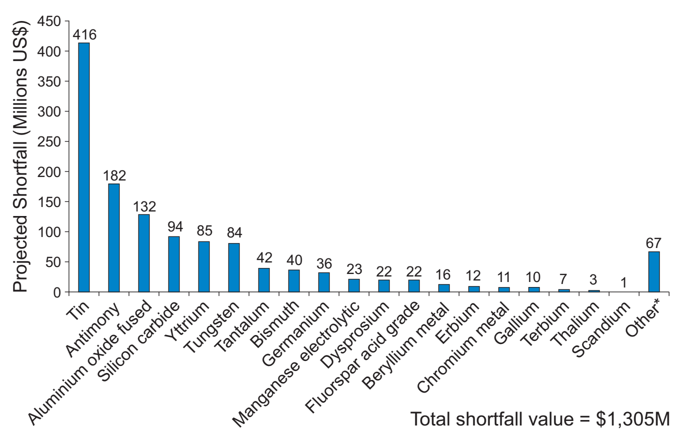

Fig. 2. Projected (2015-2018) shortfalls for 23 critical and strategic materials identified by US Department of Defense. Other* includes three types of carbon fiber and a rare earth oxide (details were not disclosed for proprietary reasons). All shortfall values in 2012 US dollars. After US Department of Defense (2013).

2.3. Critical materials from the clean energy point of view: US Department of Energy

A report prepared by the US Department of Energy Office of Policy and International Affairs (US Department of Energy, 2011) highlighted the importance of 16 elements needed to develop clean technologies (e.g., wind turbines, electric vehicles, photovoltaic thin films, and energy-efficient lighting), and light REE (especially La and Ce) as catalysts to produce gasoline. The criticality of these materials was assessed for the periods 2011 to 2015 and 2015 to 2025. Both assessments were based on: 1) the importance to clean energy; and 2) the level of supply risk. In the assessment for 2015 to 2025 (Fig. 3), Nd, Dy, Eu, Y, and Tb were considered critical, Li and tellurium [Te]) were considered near-critical, and Ce, La, Sm, Pr, Mn, Co, In, Ga, and nickel non-critical. In the earlier assessment period, Li was judged as non-critical, whereas Ce, La, Te, and In were classified as near-critical. Dy, Eu, Nd, Tb, and Y remained on the critical list during both assessment periods.

3. Summary

Table 1 summarizes the results of four criticality studies released since 2011. The document released by the European Commission (2011) lists all REE plus 13 other materials. The European Commission (2014) identified 5 industrial minerals, REE (excluding Sc), PGE and 10 other metals, and coking coal as critical. The list of strategic and critical materials prepared for the US Department of Defense (2013) reported 23 materials as strategic and critical, including SiC, fused Al_2O_3, fluorspar, 7 REE (one of them not shown on Table 1), 10 metals, and 3

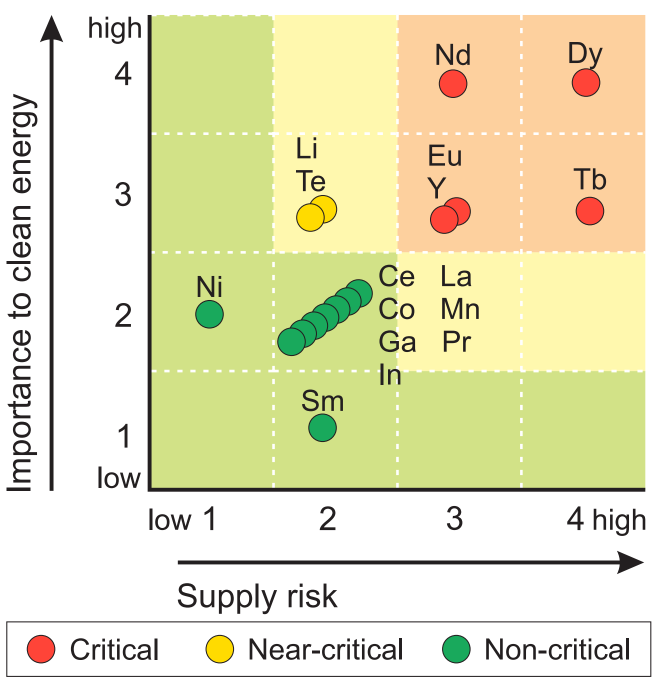

Fig. 3. US Department of Energy criticality matrix of 16 elements for 2015-2025, based on importance to clean energy and supply risk. Modified from US Department of Energy (2011).

Table 1. Results of four criticality studies discussed in the paper. Abbreviations: EU Com–European Commission, US DoD–US Department of Defense, US DoE–US Department of Energy. US DoE divided results into critical and near-critical; near-critical materials are shown by unfilled circles.

Material	EU Com 2011	EU Com 2014	US DoD 2013	US DoE 2011
Al_2O_3			●	
Be	●	●	●	
Bi			●	
Borates		●		
Ce	●	●		
Co	●	●		
Cr		●	●	
Dy	●	●	●	●
Er	●	●	●	
Eu	●	●		●
Fluorspar	●	●	●	
Ga	●	●	●	
Gd	●	●		
Ge	●	●	●	
Graphite	●	●		
Ho	●	●		
In	●	●		
La	●	●		
Li				○
Lu	●	●		
Magnesite		●		
Mg	●	●		
Mn			●	
Nb	●	●		
Nd	●	●		●
PGE	●	●		
Phosphate		●		
Pr	●	●		
Sb	●	●	●	
Sc	●		●	
Si		●		
SiC			●	
Sm	●	●		
Sn			●	
Ta	●		●	
Tb	●	●	●	●
Te				○
Tm	●	●	●	
W	●	●	●	
Y	●	●	●	●
Yb	●	●		

types of carbon fiber (not shown in Table 1). The report of the US Department of Energy (2011) found 5 REE (Nd, Dy, Eu, Y, and Tb) to be critical and 2 metals (Li and Te) to be near-critical for the period of 2015 to 2025 (Fig. 3; Table 1). Thirteen materials are common to at least three of the studies and only three elements (Dy, Tb, and Y) are common to all four studies.

4. Conclusion

Lack of consistency in use of the terms 'critical' and 'strategic' leads to misunderstandings, miscommunications, and potentially misrepresentations. Which materials are considered critical depends to a large extent on the priorities and objectives of the organization or country that commissions the study. Therefore, if the terms 'critical' and 'strategic' are used, they should be clearly defined and should not be applied out of context. The lists of critical and strategic materials produced by the European Commission (2011 and 2014), the US Department of Defense (2013), and the US Department of Energy (2011) differ significantly and illustrate this point. The longest list of critical materials comes from the European Commission (2014), which considered risks to overall economy, and was broad in focus. The shortest list comes from the highly focused study of the US Department of Energy, which considered only the supply risks for materials essential to develop clean air technologies. Lists of critical materials change with time because of breakthroughs in technology, political instabilities in major producing countries, environmental pressures, and discovery, development, or exhaustion of resources.

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