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The impact of technological innovation on critical materials risk dynamics

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ABSTRACT

As the technologies we use as a society have advanced, so have the materials used in these technologies. Some of these materials are exotic and highly specialized, making them particularly vulnerable to supply disruptions and supply disruptions particularly impactful. Such materials are designated as "critical" materials. Their level of criticality can be identified by accounting for a number of factors related to their supply risk and the extent to which a supply disruption would impact business operations or society at large. We highlight current methodologies used to assess materials criticality, how these assessments are used to reduce materials-related risk and to what extent there is room for improvement. Particularly, this paper reviews critical materials designations from the United States Department of Energy, the European Union, and the General Electric Company, and how they have changed over the period from 2008 to 2014. The changes suggest that the factors considered in criticality ratings have different natural time scales, and that criticality changes occur both due to supply-side risk mitigation as well as demand-side responses. Response options, whether on the supply or demand side, also span a range of time scales and the interaction between factors with different time scales can play a significant role in the dynamics. To date, many published analyses are snapshots in time. A detailed understanding of how risk profiles evolve remains an open question. The importance and impact of demand-side responses such as recycling, substitution and new technological development are discussed.

1. Introduction

Modern society uses a wide range of raw materials and these materials go through cycles of surplus and shortage [1]. Efforts to anticipate materials shortages were renewed in 2008 with the National Resource Council (NRC) study, which introduced the concept of materials criticality [2]. Critical materials are designated as such because they are vulnerable to supply disruptions and such disruptions would have significant adverse impacts for businesses and society at large. The criticality of a given material or element is often considered along two dimensions, namely the level of *supply risk* and the *impact* a supply disruption would have. Criticality analyses use different factors that measure the exposure of a given material to each of these dimensions, and may also consider risks associated with a third dimension, environmental factors [3,4]. Factors are aggregated to create a score for each material along each dimension [5,6]. Virtually all published assessments are snapshots in time. Assessments can be a valuable tool in planning policy both at the industry and government levels [7,8]. They can also be used to identify and mitigate supply chain risks [9]. For example, the U. S. Department of Energy (DOE) established a Critical Materials Institute (CMI) to coordinate and provide strategic focus to efforts to address critical materials relevant to the US energy infrastructure.

In order to use these tools to inform policy, it is important to understand the drivers of materials criticality as well as how criticality changes over time. Generally, the criticality of a given material can change due to market responses, geopolitical factors, and technology development. Retrospective studies of market trends and geopolitics can provide insight into historical criticality trends [5,10]. Minerals and metal markets are difficult to accurately forecast for many of the same reasons as energy markets. To-date efforts can be categorized into two general approaches. Top-down approaches posit different scenarios for economic and political landscapes and then work out the materials market implications [6,11]. The logical consequences of particular narratives related to economic growth, government policy, or socio-political situations can be explored using sensitivity analyses and statistical tools. However, top-down approaches have difficulty capturing technological innovations that introduce non-linear changes in materials use patterns [12,13]. Bottom-up approaches attempt to reconstruct dynamics from different links in the supply chain. Agent-based dynamic material flow models can capture interactions by segmenting the links in the supply chain [10,14,15]. As with any modeling, both top-down

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Table 1
Comparison of critical materials weights used in computing composite supply risk score.

Supply risk scoring	Yale [3]	DOE [6.7]	GE	BGS [22]	EU [8,24]
Materials (year of publication)	62 (2015)	14 (2010) 16 (2011)	33 (2008) 53 (2012)	52 (2011) 41 (2012)	41 (2010) 54 (2014)
Physical availability	33%	50%	22%	29%	
Reserves/Depletion time	1/6	2/5	1/9	1/7	
Companion production	1/6	1/10	1/9		
Recycling rate				1/7	Included
Production	67%	40%	33%	56%	
Producer concentration	1/6	1/5		2/7	Included
Producer stability	1/6				
Producer governance	1/6	1/5	1/6	2/7	
Producer policy	1/6		1/6		
Market factors		10%	45%	14%	
Price volatility			1/9		
Substitutability			1/6	1/7	Included
Competing demand		1/10	1/6		

and bottom-up approaches rely on the quality of the assumptions used in the modeling.

It is essential to recognize that changes in criticality are induced by both exogenous shocks to a supply chain or usage pattern, as well as endogenous market responses to such shocks. Technological innovation can introduce inflection points that can shift materials use patterns, which may increase or decrease the criticality level of a particular material or materials. For example, the maturation of nickel-base superalloys, coupled with a shortage of cobalt in the 1950′s lead to a shift towards the former [16]. Beginning in the late 1980s, a transition from halophosphate phosphors to rare earth-baed triphosphor blends gradually boosted demand for certain rare earth elements (REE) [17]. The microelectronics industry routinely introduces new materials-enabled devices. The implication is that increased usage of such exotic materials comes at the cost of increased criticality. There is also a bright side to technological development: advances in technology are not limited to initiating material uses, rather can also lead to decreased usage of critical materials. Progress in production, manufacturing and recycling methods can drastically reduce the demand for various materials [18,19]. There can also be interactions between technological innovation and supply. For example, a second shortage of cobalt in the 1970's was a contributing factor to the development and adoption of NdFeB magnets as a substitute for SmCo magnets [20]. One challenge that we will face with these criticality assessment tools is whether they can accurate anticipate crises early enough to allow meaningful action.

This paper considers the dynamics of materials criticality with a special focus on the role and consequences of technological innovation. The discussion is organized into four parts. The first section introduces definitions of criticality and how criticality scores are assigned. The second part reviews assessments by the DOE, the European Union (EU), and the General Electric Company (GE) and how they changed over a period of one to four years. The third part considers how risk evolves. The final section makes some observations on how technological innovation responds to materials criticality, with an emphasis on the nature of substitutes and time tables around their development. Examples will be drawn from GE's experiences in responding to its materials criticality challenges and the recent literature on REEs, given the extensive public discussion of these materials. Technology-driven inflection points in the usage of various materials are briefly discussed. The paper concludes with some implications for the materials development community.

2. Definitions of criticality

A first comment on criticality assessments is that they are dependent upon the scope of the review. The time scales and interests of the DOE, EU and GE differ and this will impact the ratings. Materials that GE considers critical to GE due to exposure from its manufacturing supply chain for a specific product line related to medical imaging may not be as critical to the DOE as it considers clean energy materials requirements a decade in the future. Exposure to the coking coal supply challenge may be less of a concern to both GE and the DOE, but for slightly different reasons. For instance, it is less related to the DOE's medium- to long-term energy goals, and it is not directly related to GE's most pressing supply concerns. This is an important point when considering dynamics because individual technological developments and their implementation would be expected to have a both larger and faster impact on criticality at the company level.

Criticality assessments take into account two key dimensions associated with materials risks. The first dimension is *supply risk*, or how susceptible a material is to supply disruption. The other is the *impact* caused by a shortage. Typical assessments focus on specific materials of interest and assign a risk score to each material in each dimension. Scoring is sensitive to the interests of the organization performing the assessment: producers and users may rate supply risk differently, as might companies active in different industries. Materials are then plotted along the two axes and materials that score above a threshold are designated critical. Some analyses, such as the one performed by the Yale group also include an environmental impact axis in their assessments [3].

Scores for supply risk and impact of disruption are generally composite indices that take into account several factors. In considering dynamics, an appreciation of the different factors that contribute to criticality scoring allows one to consider how they change with time and to consider interaction effects. Tables 1 and 2 summarize how five organizations compute the supply risk and impact of disruption. Despite some differences in terminology and relative weighting of factors, most assessments focus on the same contributing factors. Four of the five methodologies compute risk score as the weighted sum of various factor scores, while the EU approach uses multiplicative formulae.

Factors that contribute to supply risk include physical availability, production, and market factors.

Physical availability is tied to global reserves, co-production, and recycling rates. Co-production refers to the fact that many elements are produced as by-products of a primary ore body [3,21]. Production factors include geographic concentration, geopolitical stability, and policy. Refining and distribution bottlenecks are also captured in production scores. This factor is especially important when considering materials that may have only a few capable refiners or suppliers. A third category includes market factors such as price volatility, the availability of substitutes, and competing demand between different end use industries. The competition between different industries is particularly