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How to evaluate raw material vulnerability - An overview

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ABSTRACT

Companies, economies and technologies are vulnerable to supply disruptions or price peaks of specific raw materials. Multiple research groups worldwide have proposed methodologies for determining the criticality of raw materials, including assessments on the vulnerability to supply restrictions. These raw material vulnerability assessments use manifold indicators but are not consistent concerning their selection, calculation, interpretation and weighting. Their indicators estimate a raw material's economic importance or its significance for a strategic goal, or they inform regarding the impact of supply disruptions. Here, we provide an overview of 18 vulnerability assessments in 16 recent criticality studies. Our results reveal 18 different vulnerability indicators, among which a set of six indicators is frequently used and therefore might be recommended for decision makers. The range of possible vulnerability assessment results is exemplified by evaluations of the transition metal copper and the rare earth neodymium. Our overview can serve as a starting point for future raw material criticality assessments concerning the selection of vulnerability indicators and appropriate calculation and weighting methods.

1. Introduction

Analyses of critical raw materials have been added to the family of system-analytical assessment tools in recent years. The term 'criticality' describes an evaluation of the holistic importance of a resource, which can be interpreted as an assessment of the risks connected with resource production, use and end-of-life (Graedel and Nuss, 2014). Criticality assessments always have an interdisciplinary character, which connects them with different aspects of importance or risks from other disciplines and evaluations of resilience. A major differentiation has become the triad of supply risk, environmental implications and vulnerability to supply restriction. Supply risk expresses the likelihood of a supply disruption situation (potentially only for selected countries, companies or technologies due to focused export policies or controls), which may also be revealed by an increased price level (Achzet and Helbig, 2013). Environmental implications evaluate the damage caused by raw material extraction or usage and thereby indirectly assess the likelihood of emerging environmental regulations or negative impacts on the public image of the material (Glöser and Faulstich, 2014). The dimension of environmental implications was introduced by Graedel et al. (2012) as an extension of previous matrix-based approaches (European Commission, 2014; U.S. National Research Council, 2008). The third term, vulnerability to supply restriction, is generally meant to describe the potential damage caused by an involuntarily reduced utilization of a material, whether due to physical shortage, increased competition or market regulation. Here, we focus on a review of raw material vulnerability assessments within criticality assessments. The article is a follow-up to the previously presented overview concerning raw material supply risk evaluation (Achzet and Helbig, 2013). The research method remains the same: we analyze the scope and focus of criticality assessments that evaluate raw material vulnerability; we list and categorize their indicators and describe different calculation options for indicators that are frequently used. Some studies from the supply risk overview reappear, but the list has been updated with recent studies that include raw material vulnerability assessments.

Vulnerability assessments rely mostly on internal information to identify the most relevant materials for a company, a country (whether for economic, environmental or security/defense reasons) or a technology. The question of relevance and strategic importance is linked to classical assessments from strategic management (e.g., SWOT analysis, Value Chain analysis), which are however focused on products rather than raw materials (Carpenter and Sanders, 2009). Considering vulnerability and supply risk as two dimensions of economic risks in raw material value chains follows the approach of classical risk assessment, where a potential scale of damage and the probability of occurrence of a scenario are considered to assess a risk level (Glöser et al., 2015). For raw material utilization, criticality assessments serve as this type of

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risk level evaluation, although considered scenarios of many studies remain intangible. For example, the European Commission (2010) carefully describes its four indicators and data sets for supply risks but never defines what it calls a "shortage of material".

The approach of criticality assessments is indicator-based and requires a normalization of data to a common scale for each indicator. Indicators are aggregated through weighted averages or algorithms in each target value (i.e., supply risk, environmental implications or vulnerability) and are eventually aggregated to a criticality score or placed in a criticality space (Achzet and Helbig, 2013). Criticality assessments may lead to policy recommendations for a more sustainable or resilient use of raw materials – depending on their scope and target. These recommendations can vary between extended monitoring and reporting of material flows and utilization (European Commission, 2014), the substitution of critical raw materials (CRM_InnoNet, 2015; Erdmann et al., 2011), or the search for secure raw material sources or increased material utilization in production (Graedel et al., 2015b).

Graedel and Reck, (2015) highlighted the need for holistic approaches including a large variety of importance factors, the consideration of specific target customers, a periodic update of criticality assessments with a transparent methodology as well as a harmonized methodology. To get closer to these goals, a detailed and direct comparison of existing methods and covered aspects can help identifying strengths and weaknesses of individual approaches and serve as an orientation towards a structured and well-designed indicator-based vulnerability determination.

Beginning with the methodology of indicator analysis and a presentation of considered studies, the article continues with a detailed description of indicators used most frequently in vulnerability assessments. Less frequently used indicators are described more briefly. The applicability of vulnerability assessments is demonstrated by a case study of the raw materials copper and neodymium. The article ends with a discussion and conclusion.

2. Method

Sixteen criticality studies including a vulnerability analysis into their assessment were evaluated for this review, with publication years ranging from 2008 to 2015. These studies include peer-reviewed journal articles, research project reports and policy reports. To our knowledge, this sample includes the methodologies of all (semi-)quantitative vulnerability assessments published in the past ten years in either the English or the German language. Only studies that used another publication's methodology were excluded. All of the evaluated studies are listed in Table 1.

The characteristics of contemplated studies differ as raw material criticality assessments are determined by their respective scope and target, which is displayed in Fig. 1. The scope can be distinguished between the corporate, national, global and technological levels, whereas the targets vary between an assessment of economic importance, strategic importance and the potential impact of supply disruptions. Evaluating the economic importance of a raw material focusses on current (or past) economic data. It therefore highlights the status-quo of raw material utilization without any scenarios. By contrast, the strategic importance assessment focusses on the potential emerging from the extended, future use of a raw material. The third focal point for vulnerability, namely, impact of supply disruption, analyses the potential damage caused by disruption scenarios. All three characteristics of

Table 1
Evaluated vulnerability studies and their respective focus and target.

Level	Study	Title	Target
Multi	Graedel et al. (2012) corporate, national and global	Methodology of metal criticality determination	Methodology for the assessment of metal criticality at the global, national and corporate levels
Corporate	Duclos et al. (2008)	Design in an era of constrained resources	Identification of critical raw materials for general electric
National	U.S. National Research Council (2008)	Minerals, critical minerals, and the US economy	Analysis of critical minerals for the modern US society
	AEA Technology and Defra (2010)	Review of the future resource risks faced by UK business and an assessment for future viability	Identification of essential resources for the UK industry that are most at risk of future scarcity
	Erdmann et al. (2011)	Critical raw materials for Germany (German: "Kritische Rohstoffe für Deutschland")	Identification of critical raw materials for German companies
	Parthemore (2011)	Elements of security	Analysis of the risks of US dependency on critical materials
	Gandenberger et al. (2012)	Supply of the German high-tech sector with raw materials (German: "Die Versorgung der Deutschen Wirtschaft mit Roh- und Werkstoffen für Hochtechnologien")	Further development of German resource policies
	European Commission (2014)	Report on critical raw materials for the EU	Identification of critical raw materials for the European Union
	Beylot and Villeneuve (2015)	Assessing the national economic importance of metals: An input–output approach to the case of copper in France	Consideration of the value added by services dependent on a certain material. The domestically induced value added by a metal is separated into the value added by products and services
	Hatayama and Tahara (2015)	Criticality assessment of metals for Japan's resource strategy	Japan's criticality of 22 metals in 2012. Support in developing Japan's resource strategy
Technological	Angerer et al. (2009)	Raw materials for emerging technologies (German: "Rohstoffe für Zukunftstechnologien")	Estimation of additional resource demand from future technologies
	US Department of Energy (2011)	Critical materials strategy	Identification of critical metals for clean energy technologies
	Moss et al. (2013)	Critical metals in the path towards the decarbonization of the EU energy sector	Identification of the raw material requirement and raw material criticality of green energy technologies necessary for the EU's decarbonization strategy
	Goe and Gaustad (2014)	Identifying critical materials for photovoltaics in the US: a multi-metric approach	Identification of critical materials for photovoltaics in the US
	Roelich et al. (2014)	Assessing the dynamic material criticality of infrastructure transitions: a case of low carbon electricity	Assessment of the dynamic material criticality of the infrastructure
	Simon et al. (2014)	Criticality of metals for electrochemical energy storage systems – development towards a technology specific indicator	Development towards specific indicators for individual technologies