How to evaluate raw material vulnerability – an overview

Christoph Helbig*,[a], Lars Wietschel[a], Andrea Thorenz[a], Axel Tuma[a]
*Address correspondence to: christoph.helbig@wiwi.uni-augsburg.de
[a] Resource Lab, Institute of Materials Resource Management, University of Augsburg,
Universitaetsstr. 16, 86159 Augsburg, Germany

Published in: Resources Policy 48 (2016), 13-24. http://dx.doi.org/10.1016/j.resourpol.2016.02.003

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.

Keywords

raw material; criticality; vulnerability; resources; risk analysis

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 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., 2015).

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 Figure 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 vulnerability assessments are used, mixed and weighted to different extents in the studies.

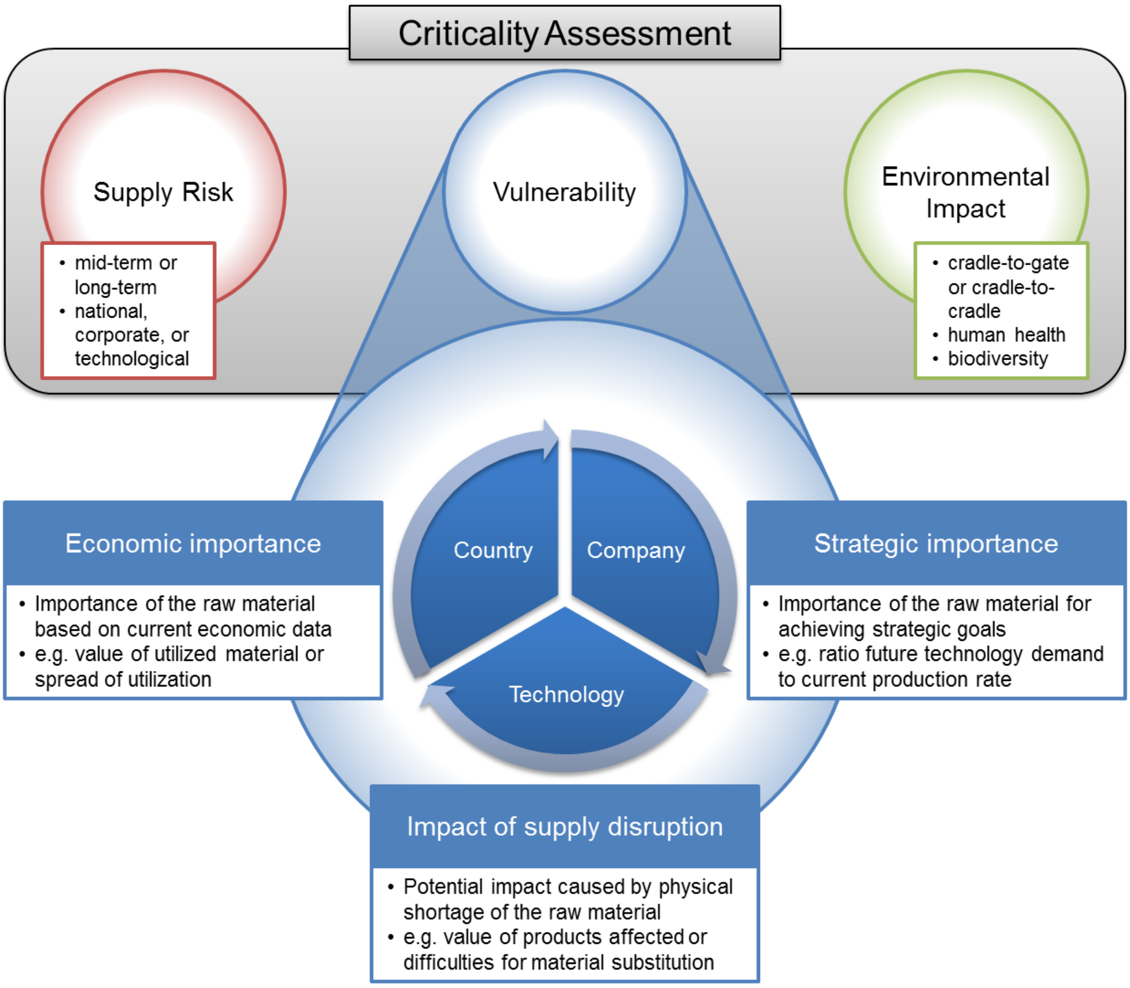

Figure 1: Characteristics of contemplated vulnerability approaches

The main differentiation of the supply risk evaluations is their time horizon, expressed either in years or in relative expressions (e.g., “long-term”). Differences in the vulnerability dimension are more complicated – revealed by various terms for raw material vulnerability evaluations. The first contemplated study, published in 2008 by the United States National Research Council implemented a two-dimensional criticality matrix and designated the dimension of interest as *impact of supply restriction* for evaluating the *importance* of raw materials (U.S. National Research Council, 2008). Further studies use specified terms such as *economic importance* (European Commission, 2014; Gandenberger et al., 2012) or *importance to clean energy* (US Department of Energy, 2011). A demonstration of the *importance* can be considered a positive way of designating the dimension, whereas other studies demonstrate a threat and consequentially use the term *vulnerability* (AEA Technology and Defra, 2010; Erdmann et al., 2011; Parthemore, 2011) or the more specified *vulnerability to supply restriction* (Graedel et al., 2012). The meaning of the term in this case is the identification of a weak spot, namely, a raw material that would cause heavy damage if it was unavailable; vulnerability here does not evaluate the likelihood of a supply restriction. Terms such as *impact of supply restriction* (Duclos et al., 2008), *exposure to disruption* (Roelich et al., 2014) or *economic risk* (Goe and Gaustad, 2014) represent the future scenario perspective of vulnerability assessments. Former overviews have stated that all these different terms can more or less be interchanged with each other (Speirs and Gross, 2013). Duclos et al. (2008) described the aim of their assessment as a “challenge of global competition for materials” that requires companies to “know where a shortage can hurt and then plan around it” (Duclos et al., 2008).

Some studies use indicators without directly mentioning terms such as criticality or vulnerability (Angerer et al., 2009; Moss et al., 2013). However, for the purpose of this article, these studies are still counted as criticality studies considering raw material vulnerability, as they assess effects of possible supply restrictions. For simplicity and readability reasons, in the following discussion, *vulnerability* will be the main term used.

Studies differ concerning their scope: they evaluate vulnerability on either the corporate, national or technological level. The only study considering multiple scopes is from Graedel et al. (2012), who assess vulnerability on the corporate, national and global levels. For this purpose, the global level is matched with other assessments on the technological level. Selecting a specific scope has an impact on the set of indicators and their specific calculation. However, a joint evaluation of the levels is adequate, as frequently used indicators are used in all three of them.

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

Level	Study	Title	Target
Multi	Graedel et al. (2012) *corporate, national & 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 Decarbonisation 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

Table 2 shows that all 16 evaluated criticality studies assess vulnerability, 13 of them also assess raw material supply risks and 4 of them additionally assess the environmental impact emerging from the usage of the raw materials. An aggregation to the vulnerability value, if necessary, is usually conducted through (weighted) averages or the multiplication of indicator values. If an aggregation of the vulnerability result to a criticality value is required, it is often through a positioning within a matrix or a vector length. Assessments that only evaluate raw material criticality due to supply risks (without evaluating raw material vulnerability) are not listed here and can be found in the previous supply risk overview by Achzet and Helbig (2013).

Table 2: Criticality dimensions and aggregation logic used in observed criticality studies that use vulnerability to supply restrictions as a dimension

Level	Study	Vul	SR	Eco	Criticality aggregation	Vulnerability aggregation
Corporate	Duclos et al. (2008)	✓	✓	×	Matrix	Average
	Graedel et al. (2012)	✓	✓	✓	Vector length	Weighted average
National	U.S. National Research Council (2008)	✓	✓	○	Matrix	Maximum
	AEA Technology and Defra (2010)	✓	✓	×	Not aggregated	Average
	Erdmann et al. (2011)	✓	✓	○	Matrix	Weighted average
	Parthemore (2011)	✓	✓	×	Not aggregated	Not aggregated
	Gandenberger et al. (2012)	✓	○	×	Not aggregated	Multiplicative
	Graedel et al. (2012)	✓	✓	✓	Vector length	Weighted average
	European Commission (2014)	✓	✓	✓	Matrix	Multiplicative
	Beylot and Villeneuve (2015)	✓	×	×	Only 1 target value	Only 1 target value
	Hatayama and Tahara (2015)	✓	✓	✓	Score	Score
Technological	Angerer et al. (2009)	✓	○	×	Only 1 target value	Only 1 indicator
	US Department of Energy (2011)	✓	✓	×	Matrix	Weighted average
	Graedel et al. (2012)	✓	✓	✓	Vector length	Weighted average
	Moss et al. (2013)	✓	✓	×	Not aggregated	Not aggregated
	Goe and Gaustad (2014)	✓	✓	✓	Not aggregated	Not aggregated
	Roelich et al. (2014)	✓	✓	×	Only 1 target value	Multiplicative
	Simon et al. (2014)	✓	✓	×	Index value	Multiplicative

Vul: Vulnerability, SR: Supply Risk, Eco: Ecological Risk
✓: considered, ○: partly considered, ×: not considered

Some methodologies of criticality assessments were adopted by other studies, updated or slightly adapted by follow-up publications. For example, the European Commission (2010) approach was used as methodological basis for other criticality assessments at the national level within the European Union, such as the *Policy Document on Raw Materials* in the Netherlands (Dutch Ministry of Foreign Affairs, 2013). The methodology of AEA Technology and Defra (2010) was used by Scottish policy makers for evaluating their resource vulnerability (Kind et al., 2011). The Yale University working group split their publications into a methodology article and several application case articles (Graedel et al., 2015, 2012; Harper et al., 2015, 2014; Nassar et al., 2015, 2012; Nuss et al., 2014; Panousi et al., 2015). In the case of a methodical adoption, only the primary paper is considered, whereas in the case of a methodical update, changed indicators are introduced separately.

3 Vulnerability indicators

Indicators with a similar interpretation are summarized into categories to quantify their usage. Figure 2 presents a one-to-one mapping of indicator categories and vulnerability assessments. Whereas a total number of 18 different indicator categories were identified from the 18 vulnerability assessments, only six of these indicators have been used more than twice and will be described in detail: *substitutability, value of products affected, future demand-to-supply ratio, strategic importance, value of utilized material* and *spread of utilization*. The other indicators were used by only one or two assessments and are therefore described more briefly afterwards.

	Corporate		National									Technological						
	Duclos et al. (2008)	Graedel et al. (2012) *corporate*	U.S. National Research Council (2008)	AEA Technology and Defra (2010)	Erdmann et al. (2011)	Parthemore (2011)	Gandenberger et al. (2012)	Graedel et al. (2012 *country*	European Commission (2014)	Beylot and Villeneuve (2015)	Hatayama & Tahara (2015)	Angerer et al. (2009)	US Department of Energy (2011)	Graedel et al. (2012) *technology*	Moss et al. (2013)	Goe and Gaustad (2014)	Roelich et al. (2014)	Simon et al. (2014)
Substitutability	✓	✓	✓	✓	✓	✓	✓	✓					✓	✓				
Value of products affected	✓	✓					✓		✓	✓						✓		
Future demand to supply ratio			✓		✓	✓						✓			✓			
Strategic importance		✓				✓							✓				✓	✓
Value of utilized material	✓		✓					✓								✓		
Spread of utilization					✓			✓						✓				
Ability to pass-through cost increases	✓	✓																
Change in demand share					✓						✓							
Import dependence						✓		✓										
Target group's demand share	✓				✓													
Ability to innovate		✓						✓										
Change in imports					✓													
Company concentration						✓												
Consumption volume				✓														
Mine production change											✓							
Price sensitivity																	✓	
Primary material price																✓		
Recyclability						✓												

Figure 2: One-to-one mapping of the 18 vulnerability indicator categories and the 18 raw material vulnerability assessments

Many of the vulnerability indicators listed in Table 3 are either qualitative assessments or relative expressions, which is why arbitrary units and percentages appear often. For some indicators, it is possible to use quantitative values such as mass flows or monetary values. Some vulnerability indicators have already appeared in supply risk assessments (Achzet and Helbig, 2013), particularly those indicators that overlap with possible risk mitigation strategies (e.g., substitution or recycling). A lack of these risk-reducing factors increases the impact of supply disruptions (thus a part of vulnerability assessments), whereas having these opportunities reduces the likelihood of supply disruptions and can thus be included in supply risk assessments. We discuss different interpretation opportunities for each of these double-use indicators individually. In the following subchapters 3.1 to 3.7, indicators are further described concerning their measurement, possible thresholds, and their weightings in the corresponding vulnerability assessments.

Table 3: Indicators: number, frequency and unit of indicators used for evaluating vulnerability in the selected studies

Indicator	#Corp	#Nat	#Tech	Σ	Unit	SR
Substitutability	2	5	3	8*	Qualitative, %	✓
Value of products affected	2	3	1	6	USD, EUR, %	×
Future demand to supply ratio	0	3	2	5	Qualitative, %	✓
Strategic importance	1	1	3	5	Qualitative, %	✓
Value of the utilized material	0	2	1	4	USD, USD/kg, %	×
Spread of utilization	0	2	1	3	% Population , Stock-to-reserve-ratio	×
Ability to pass-through cost increases	2	0	0	2	Qualitative	×
Change in demand share	0	2	0	2	%	×
Import dependency	0	2	0	2	%	✓
Target group's demand share	1	1	0	2	%	×
Ability to innovate	1	1	0	1*	Qualitative	×
Change in imports	0	1	0	1	%	×
Company concentration	0	1	0	1	Qualitative	✓
Consumption volume	0	1	0	1	kg	×
Mine production change	0	1	0	1	%	×
Price sensitivity	0	0	1	1	%	×
Primary material price	0	0	1	1	USD	×
Recyclability	0	1	0	1	Qualitative	✓

*: Graedel et al. (2012) define the same indicator for different levels, which are only counted once.
SR: The indicator is also used as a supply risk indicator in some criticality assessments

3.1 Substitutability

The most frequently applied indicator for vulnerability is *substitutability*, used in 8 out of 16 studies. The usage of substitutability as a vulnerability indicator is summarized in Table 4. Substitutability can be interpreted as an aspect of both supply risk and vulnerability (Achzet and Helbig, 2013). In the supply risk interpretation, a supply shortage is less likely if some producers can easily use substitutes, lowering the overall demand for the material (Duclos et al., 2008; European Commission, 2014; Pfleger et al., 2015). As an indicator of the vulnerability dimension, feasible substitution options display a reduced importance compared with a resource without proper substitutes (Graedel et al., 2013, 2012; U.S. National Research Council, 2008). Substitutability of a material can be considered on multiple levels in product development: one can distinguish between *material substitution, technological substitution, functional substitution, quality substitution* and *non-material substitution* (Kausch et al., 2014) . Substitution can be performed at the *conceptual, sub-assembly, component* or *composition* level (Habib and Wenzel, 2016). Research on finding substitutes at either level is also a frequently proposed policy recommendation for resources evaluated as critical. Consequently, multiple projects at the national or global level are conducted, such as the European CRM_InnoNet “Substitution of Critical Raw Materials”. Some projects focus on obtaining the use of an application by either type of substitution (CRM_InnoNet, 2015). Other projects aim for the substitution of certain raw materials in specific technologies (Graedel et al., 2013). Examples of the substitution of raw materials can be the use of aluminum instead of copper for wires or the recent research and development efforts concerning rare earth free permanent magnets – for example, for electric vehicles.

Although there are remarkable efforts to quantify the potential of substitution, so far there is no generic approach to evaluate the substitutability of a raw material. All studies used expert opinions to estimate substitutability, mostly on a four- or five-point rating scale. Most of these estimations were nontransparent and therefore cannot easily be adapted or improved by future criticality approaches. The Yale University research group published a comprehensive summary of potential substitutes for 62 different metals in all their major uses (Graedel et al., 2013).

Graedel et al. (2012) divide the indicator substitutability into four equally weighted sub-indicators. These four substitutability indicators of Graedel et al. (2012) together are weighted the highest of all studies, with 33.3%, whereas Erdmann et al. (2011) gave the substitutability only a 10% weight in their criticality assessment. Three of Graedel and colleagues’ indicators are also the only indicators with a threshold given: substitutes showing twice the environmental impacts, price or net import reliance than the evaluated raw material are assessed with the highest possible vulnerability score.

Table 4: Usage of *substitutability* as a vulnerability indicator

Criterion	Measurement	Threshold	Weight	Study
Availability of substitutes	Expert opinion, 5-point rating scale	n/a	25.0%	Duclos et al. (2008)
	Expert opinion, 4-point rating scale	n/a	25.0%	US Department of Energy (2011)
	Expert opinion, 3-point rating scale	n/a	not aggregated	AEA Technology and Defra (2010)
	Expert opinion, 3-point rating scale	n/a	not aggregated	Parthemore (2011)
Substitute performance	Expert opinion, 5-point rating scale weighted by application share	n/a	8.3%	Graedel et al. (2012) *corporate, national & global*
Substitutability, technical & economical	Expert opinion, 4-point rating scale weighted by application share	n/a	not aggregated	Gandenberger et al. (2012)
	Expert opinion, 4-point rating scale	n/a	10.0%	Erdmann et al. (2011)
Share of products for which substitution is difficult or impossible	Expert opinion, (%)	n/a	n/a	U.S. National Research Council (2008)
Substitute availability	Supply risk value of the substitute	n/a	8.3%	Graedel et al. (2012) *corporate, national & global*
Environmental impact (EI) ratio	$ER = 50 \times \frac{\text{EI (substitute)}}{\text{EI (raw material)}}$	Capped at twice the environmental impact	8.3%	Graedel et al. (2012) *corporate & national*
Price ratio (PR)	$PR = 50 \times \frac{\text{price (substitute)}}{\text{price (raw material)}}$	Capped at twice the price	8.3%	Graedel et al. (2012) *corporate & global*
Net import reliance (IR) ratio	$IRR = 50 \times \frac{\text{IR (substitute)}}{\text{IR (raw material)}}$	Capped at twice the import reliance	8.3%	Graedel et al. (2012) *national*

3.2 Product value

In six studies, the *value of the products affected* by a possible supply disruption is used as an indicator for vulnerability, as seen in Table 5. This indicator assesses the potential damage of a total supply disruption of a resource, considering only the occurrence of each raw material in a product but not the quantity. To place the exposed revenue in relation, it is often compared to the total economic output of a national economy or a company. Beylot and Villeneuve (2015) additionally quantify the value added of services dependent on the metal supply based on a hybrid monetary physical input-output analysis. Part of their result is a comparison of the product-specific contribution to the total metal requirement with the share of product value added. Their calculation of the final *national economic importance* of a material is debatable because the index negatively correlates with the number of products and services utilizing the material. Another emerging problem with quantifying the value of products affected can be the difficulty of obtaining data on product composition. For companies in the IT industry, copper will likely be included in all their products; this information is well known, and therefore, the value of products affected by a copper supply disruption is close to the total value of the products. At the same time, it may be difficult to assess which products include spice metals such as platinum group metals, at least unless environmental regulations (e.g., REACH or RoHS) or socio-political regulations (e.g., Dodd-Frank-Act) apply to these elements.

The value of products affected can be critical in assessing vulnerability; for example, the European Commission used the *value of products affected*, referring to the GDP of Europe as its only vulnerability indicator (European Commission, 2014). Graedel et al. (2012) weighted this indicator as only 11.1% in their vulnerability assessment. Graedel et al. (2012) classifies a metal as highly critical for a company whenever more than 5% of the revenue is dependent on that resource.

Table 5: Studies using the *value of products affected* as the vulnerability indicator

Criterion	Measurement	Threshold	Weight	Study
Value of products affected	$\frac{\sum_s \text{share of consumption(s)} \times \text{value added(s)}}{\text{GDP (Europe)}}$	n/a	100.0%	European Commission (2014)
	Total revenue of affected products	Threshold not transparent	25.0%	Duclos et al. (2008)
	Total revenue share of affected products	> 5% rated with max. criticality	11.1%	Graedel et al. (2012) *corporate*
	Total production value	n/a	not aggregated	Gandenberger et al. (2012)
	Economic value by sector	n/a	not aggregated	Goe and Gaustad (2014)
	Total value added of products & services by metal	n/a	not aggregated	Beylot and Villeneuve (2015)

s = megasector

3.3 Future demand

In 5 out of 16 studies, the *ratio between the future demand and current or recent supply* has been used as an indicator for vulnerability. In all five cases, the assessments were at the national or technological level. Table 6 presents an overview of the usage of this indicator in criticality assessments. This indicator differs from most of the other indicators in that the value is based on future prospects and not on present or historical data. The general conception is that “ramp-up” materials are of particular importance, whether for a national economy or a technology that is meant to be implemented on a wide scale, such as low-carbon energy or resource-efficient technologies. A limited availability of essential raw materials can become an enormous problem for the rollout of emerging technologies, such as PV solar cells (Kavlak et al., 2015). For a national economy or strategy, this can be considered as more important than handling supply disruptions of existing technologies and widely utilized materials. This indicator has also been used as a measure for supply risk with a reversed interpretation: Reliance on future technology materials is a threat for technologies, whereas emerging technologies with their rapid demand growth can also be a problem for continuous raw material supply. Today, most emerging technologies rely on spice metals or companion metals (Angerer et al., 2009).

Erdmann et al. (2011) adopted the method of Angerer et al. (2009) and reported a demand impulse of over 200% until 2030, the highest vulnerability rating. Whereas Angerer et al. (2009) used the ratio between the future demand and the current or recent supply as the only indicator, Erdmann etal. (2011) weighted the indicator as 20%. All the other studies do not provide a threshold or weight for this indicator.

Table 6: Studies using the *future demand to supply ratio* as the vulnerability indicator

Criterion	Measurement	Threshold	Weight	Study
Future demand	$\frac{\text{2030 demand from future technologies}}{\text{2006 supply}}$	n/a	100.0%	Angerer et al. (2009)
		≥200% demand impulse 2030	20.0%	Erdmann et al. (2011)
	EU Energy Road map 2050, own calculation	n/a	not aggregated	Moss et al. (2013)
	Expert opinion	n/a	not transparent	U.S. National Research Council (2008)
	Qualitative assessment	n/a	not aggregated	Parthemore (2011)

3.4 Strategic importance

In 5 of the 16 considered studies, the so-called *strategic importance* of the raw material is used as an indicator for raw material vulnerability. Table 7 gives an overview of the usage of this indicator. Strategic importance is either taken as an indicator evaluating raw material needs arising from strategic future technologies or as an indicator assessing future raw material needs to secure the status of a country. Three of the five studies examined national strategies toward clean energy technologies. Whereas Roelich et al. (2014) and Simon et al. (2014) investigated the rollout of a certain technology, the US Department of Energy (2011) considered *clean energy demand* to be a strategic goal and assessed the raw materials necessary to serve this strategic demand. Parthemore (2011) examined the raw materials for the US government's most important defense and energy requirements. Only Graedel used this indicator in connection with future revenue that is at risk of resource scarcity. The high weighting (50% to 100%) of this indicator by three of the examined studies is remarkable; by contrast, Graedel et al. (2012) weighted it with only 11.1%. No particular thresholds for the interpretation of strategic importance were given by any study.

Table 7: Studies using *strategic importance* as the vulnerability indicator

Criterion	Measurement	Threshold	Weight	Study
Strategic importance	$\sum \text{importance (expert judgement)} \times \frac{\text{weight share in active material}}{\text{specific capacity of material}}$	n/a	100.0%	Simon et al. (2014)
	$\text{goal sensitivity} = \frac{\text{goal certain technology}}{\text{goal green energy overall}}$	n/a	50.0%	Roelich et al. (2014)
	Expert opinion, 4-point rating scale	n/a	11.1%	Graedel et al. (2012) corporate
	Qualitative assessment	n/a	not aggregated	Parthemore (2011)
Clean energy demand	deployment x market share x material intensity	n/a	75.0%	US Department of Energy (2011)

3.5 Material value

In 4 studies, the *value of the utilized material* has been considered as an indicator for raw material vulnerability, for which Table 8 gives an overview. Compared with the indicators described before, the value of the utilized material is easier to quantify, as data can be directly collected from corporate or economic statistics. Only if composite materials or products are purchased (for which their composition may be unknown), data collection may become more problematic. In contrast with the indicator *value of products affected*, this indicator implies that a supply shortage will lead to increased raw material prices rather than a physical supply disruption. The considered risk is not decreasing revenue, but rather increasing material costs caused by supply restrictions.

Only Graedel et al. (2012) give a threshold and a weighting for this indicator: Raw materials with a 0.1% value share concerning the national GDP are considered to have the highest criticality, accounting for one-sixth of the total vulnerability assessment in the national scope. In the study of Duclos et al. (2008), the value of the utilized material is not used as an indicator assessing the raw material vulnerability but as a bottleneck to prioritize the resources of interest. Therefore, this indicator is given a higher importance than all other indicators.

Table 8: Studies using the *value of the utilized material* as the vulnerability indicator

Criterion	Measurement	Threshold	Weight	Study
Value of utilized material	$\frac{\text{metal price × apparent consumption}}{\text{GDP}}$	≥0.1% rated with max. criticality	16.7%	Graedel et al. (2012) national
	metal price × metal use	n/a	bottleneck	Duclos et al. (2008)
	US consumption in USD 2006	n/a	n/a	U.S. National Research Council (2008)
	US consumption in USD	n/a	not aggregated	Goe and Gaustad (2014)

3.6 Spread of utilization

Spread of utilization is used by three studies with the highest weighting given by Graedel et al. (2012) on the *global* level, which is displayed in Table 9 (Erdmann et al., 2011; Graedel et al., 2012; Harper et al., 2014). For the methodology of the Yale University working group, the approximation of this indicator established by Graedel et al. (2012) was replaced by the indicator *material assets* (MA), implemented by Harper et al. (2014). The indicator material asset considers that a resource can be of higher importance for the population of a certain country compared with the rest of the world. Erdmann et al. (2011) named the indicator the *sensitivity of the value chain* and assessed the extent of a resource crisis on the German economy on a four-point rating scale by experts. The weighting of the spread of utilization in the vulnerability assessments varies between 16.7% in the national perspective of Graedel et al. (2012) and 50% in its global perspective. No specific thresholds were given by any of the studies.

Table 9: Studies using *spread of utilization* as the vulnerability indicator

Criterion	Measurement	Threshold	Weight	Study
Spread of utilization	Expert opinion, 4-point rating scale	n/a	25.0%	Erdmann et al. (2011)
	$\sum_{i=0}^{n}$ population utilizing end-use(i)×material share end-use(i)	n/a	16.7%	Graedel et al. (2012) *national*
		n/a	50.0%	Graedel et al. (2012) *global*
Material assets	$\log_{10}\left[\left(\frac{\text{national per capita in use stock}}{\text{global in use stock + reserves}} \times 10^{12} + 1\right)\right] \times 40$	n/a	16.7%	Harper et al. (2014) *national*

i: material of interest

3.7 Occasionally used indicators

There are twelve more vulnerability indicators that are used by a maximum of two different criticality assessments, all of them listed in Table 3. For these indicators, an affiliation with one of the six previously mentioned indicator groups or an additional indicator group was not identified. Rare utilization of an indicator does not necessarily mean low quality. It is also possible that the indicator has a narrowed focus or that it has just recently been added to the list of possible vulnerability indicators and might be used more frequently in subsequent assessments. Four indicators were used twice in the 16 criticality studies: the *ability to pass-through cost increases*, the *change in demand share,* the *import dependence* and the *target group's demand share*.

The *ability to pass-through cost increases* was used by two studies to evaluate corporate vulnerability (Duclos et al., 2008; Graedel et al., 2012). In both studies, this indicator is assessed by a qualitative expert opinion. The indicator evaluates the corporate possibility to pass material cost increases to their customers. Price asymmetries in which some market players can obtain a resource cheaper than others make it difficult to pass cost increases to customers. The *change in demand share* was used by two studies to evaluate the change in a resource demand compared with the global resource demand over a certain period (Erdmann et al., 2011; Hatayama and Tahara, 2015). Hatayama and Tahara (2015) implemented a second indicator belonging to this category, the *domestic demand growth for specific uses*. Changes in the resource demand for specific technologies indicate raw material vulnerability. The *import dependence* was used to evaluate the vulnerability of countries by two different studies (Graedel et al., 2012; Parthemore, 2011). Graedel et al. (2012) calculate the net import reliance by accounting material flows of a country, including imports, exports, and stock changes in comparison with the apparent consumption. The *target group's demand share* was used by two studies to assess the importance of a material on either the national or corporate level compared with the global demand (Duclos et al., 2008; Erdmann et al., 2011). Erdmann et al. (2011) argue that a high demand share of a certain material compared with the global demand indicates the importance of a material for a country. This indicator does not consider the fact that industrial sectors utilizing the material can be relatively unimportant to the national economy.

All other indicators are used by only one of the mentioned studies. The *ability to innovate* was implemented by Graedel et al. (2012) for evaluating the resource vulnerability of companies and nations. This indicator evaluates a company or country as a whole but does not help to evaluate the importance of a single material. The *change in imports* was used for assessing the resource vulnerability of countries. This indicator measures the change in dependence from foreign resource suppliers (Erdmann et al., 2011). The *country concentration* was used for evaluating the US dependence on foreign resource suppliers. It is argued that resource supply can be used as a political instrument for placing a country under pressure (Parthemore, 2011). In other criticality studies, this indicator can be utilized for evaluating the supply risk (Achzet and Helbig, 2013). The *consumption volume* was used to assess the material vulnerability of Great Britain (AEA Technology and Defra, 2010). This indicator employs absolute values in the assessment and does not make any difference in the considered materials. For example, fish consumption in an economy is compared with the demand for rare earth elements, which is difficult to interpret, as the assessment follows a mass-based approach. *Mine production change* was used once as an indicator assessing the global raw material demand change (Hatayama and Tahara, 2015). *Price sensitivity* was used as a technology specific indicator for evaluating the share of costs of a certain resource in a technology (Roelich et al., 2014). This indicator, which is particularly helpful on the technological level, assesses the impact of a raw material price increase on the overall price of a technology. The material price development of a technology is highly significant for any technology rollout scenarios. Consequently, this indicator helps to assess whether the rollout can be affected strongly by price changes in certain raw materials. The *primary material price* was considered by one study for evaluating the resource vulnerability of different photovoltaic technologies. However, the primary material price in USD/kg does not provide information regarding the consumption volume and the contribution to the overall price of a technology. *Recyclability* was used by one study to evaluate the raw material vulnerability of the US (Parthemore, 2011), while several other studies used recyclability for evaluating the supply risk of a raw material (Achzet and Helbig, 2013).

4 Case study

Throughout the 16 considered studies on resource criticality, 20 separate assessments were performed. The Yale University working group performed assessments with different scopes; the US Department of Energy, with different time horizons. The vulnerability results can vastly differ based on the scope, time horizon and target of each study. Approximately 100 different raw materials and natural resources were assessed in the examined 20 assessments. Figure 3 gives an overview of the final results of elements that were considered in at least five different assessments. The color indicates the final vulnerability value calculated by each assessment, after a linear normalization of all results, with red colors representing high vulnerability and blue colors low vulnerability. Gray cells imply that no final vulnerability values were calculated by the corresponding study or that the given value could not be normalized and hence is not comparable to other results. Groups were identified in which some studies did not distinguish between contained raw materials, such the rare earth elements or the platinum group metals. Due to diverging study scopes, assessment targets and reference years, the comparison between results and interpretation requires caution. The specific characteristics of each study can lead to deviating vulnerability values. The results of individual vulnerability indicators are exemplified by two metals: The mass metal copper and the rare earth element neodymium are sometimes represented by the rare earth element group or by the light rare earths. The case study also serves to demonstrate data acquisition.

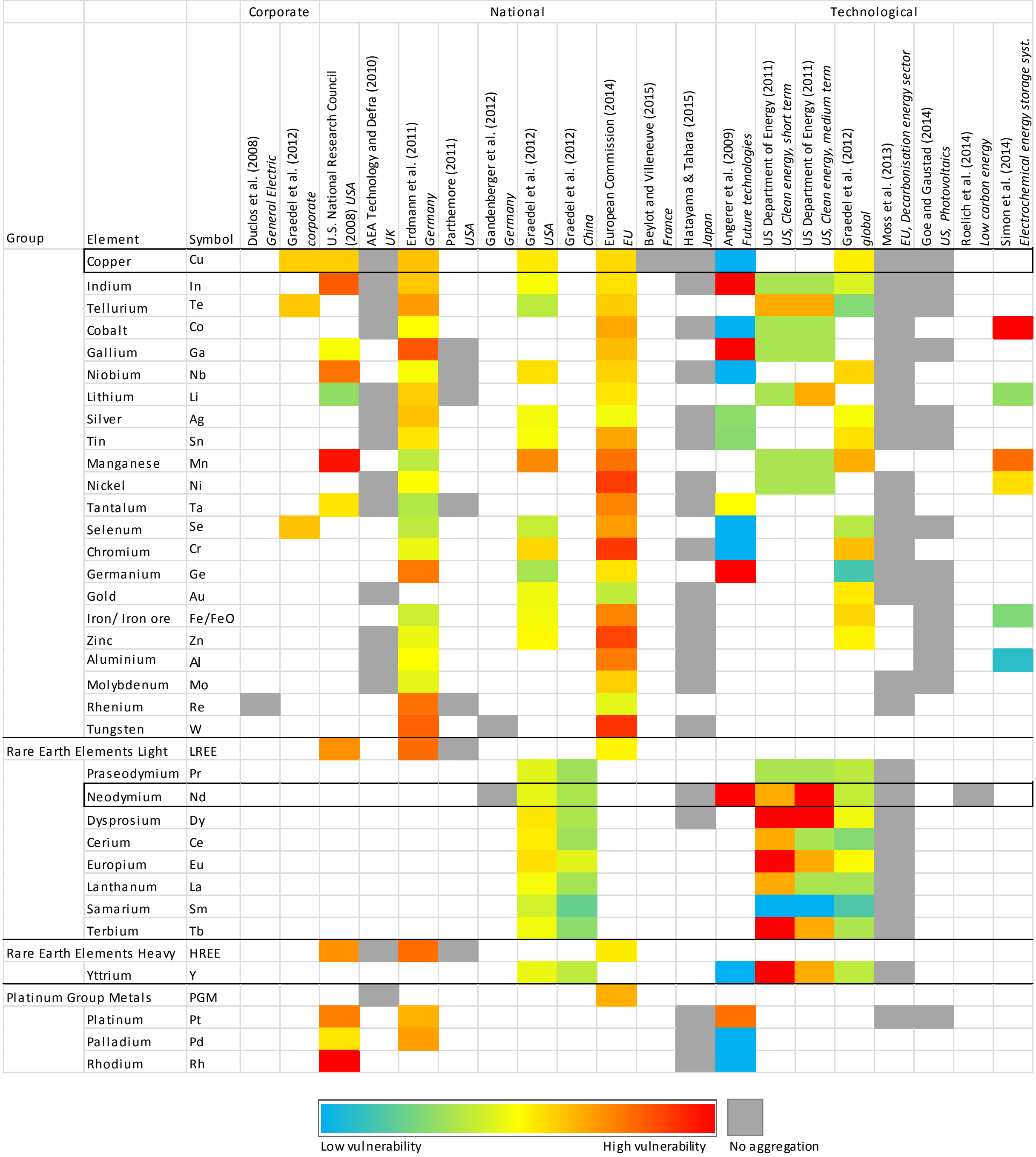

Figure 3: Overview of the vulnerability assessment results of elements and element groups evaluated at least four times in the criticality assessments. Copper and neodymium are highlighted for the sake of the case study

Table 10 reveals that *substitutability* for the mass metal copper is considered in six of the contemplated studies. These studies mostly agree that substitutes exist for most copper applications. However, a substitution is often associated with a lower performance or a higher price. Substitutability values for neodymium and light rare earth elements achieve more critical values because the special advantages of REEs are rarely found in elements outside the REE family (Nassar et al., 2015). For copper, the poor performance of substitutes is a critical factor, while the environmental impact ratio is non-critical. For neodymium, the performance of the substitutes is the critical factor (Nassar et al., 2015, 2012). The U.S. National Research Council (2008) calculated that for 15% of the copper-based products, substitution is impossible, whereas for neodymium-based applications, this value is 44%. Erdmann et al. (2011) used values based on expert assessments that were made for the European Commission (2014) study and used as a supply risk indicator in that assessment. AEA Technology and Defra (2010) estimated the substitutability of copper as unproblematic and also named possible substitutes for certain applications. They assess the situation for neodymium as more strained because substitutes show a lower performance. Parthemore (2011) generally agrees that a substitution of neodymium in the US is possible, whereas the US Department of Energy rates the substitutability as more strained (Parthemore, 2011; US Department of Energy, 2011).

The *future demand to supply ratio* of copper was assessed by four studies with consistently small vulnerability values, while all five studies that contemplated neodymium estimated the criticality in that context as high. Erdmann et al. (2011) derived their values from Angerer et al. (2009) and neodymium with the most critical value for the German economy. Angerer et al. (2009) stated that the copper demand from future technologies in 2030 will be approximately 24% and the neodymium demand approximately 382% of 2006's production. Moss et al. (2013) based their calculation on the EU Energy Roadmap 2050 and reckoned that the copper demand of decarbonization technologies is approximately 1% of the expected supply, whereas this value for neodymium rises to 8% (European Commission, 2015; Moss et al., 2013).

For copper and neodymium the indicator v*alue of the utilized material* was calculated by three studies. The mass metal copper is widely spread over nearly all industrial sectors, which leads to a high monetary consumption volume compared with the GDP. Therefore, this indicator is rated by high criticality values for copper, whereas neodymium is assessed as much less critical, as illustrated by the results of the Yale University working group (Nassar et al., 2015). For neodymium, they calculated this indicator separately for China. The neodymium-dependent industry in the US is small compared with the GDP, and the criticality thereby is almost rated as zero, while the same indicator for China is rated distinctly higher (Nassar et al., 2015). The second direct comparison leads to similar results. The US NRC calculates a value of 16.6 billion USD of utilized copper and above 1 billion USD for utilized neodymium in 2008 in the US (U.S. National Research Council, 2008). A study published six years later calculated 65.4 billion USD of utilized copper for the US and mentioned USGS as the data source (Goe and Gaustad, 2014).

The *value of affected products* for copper was evaluated by four studies, but only for one assessment in the case of neodymium. Nassar et al. (2012) introduced a hypothetical photovoltaic manufacturer for assessing corporate vulnerability. The challenge of this indicator is the data acquisition. Companies often do not know which material or what share of a material is used in a certain product or component. Certain companies and organizations are making efforts to overcome this problem by extending product data bases with material information, e.g., *The International Material Database System (IMDS)* of the automotive industry (IMDS Data, 2015). It would be a good practice to gain better information about the materials used in products because this information is also required for efficient recycling management. A direct comparison of the European Commission (2014) calculated similar values for neodymium and copper. Goe and Gaustad (2014) stated that 21% of the US GDP is dependent on copper, with the data derived from the US Bureau of Economic Analysis (Goe and Gaustad, 2014; U.S. Bureau of Economic Analysis, 2013). Beylot and Villeneuve (2015) introduced an indicator based on an *Input-Output Analysis*, in which services dependent on a raw material are considered in calculating the national economic importance. In the case of France, copper induces the generation of 1.869 billion euros of domestic value added. This value is calculated by an input-output analysis that also considers the value added by services (Beylot and Villeneuve,2015).

The *strategic importance* of copper was calculated by Nassar et al. (2012) at the corporate level only. The criticality of the hypothetical photovoltaics manufacturer was rated in the medium range. This indicator was evaluated by three studies for neodymium, and in two of them, a higher criticality rating was given. Roelich et al. (2014) computed that, in 2015, 5% of the UK's rollout strategy of decarbonizing electricity generation is exposed to neodymium supply disruption. This value is calculated for every year until 2049, where 2045 achieves the highest value, with 28%. This prediction is based on a study from the Department for Energy and Climate Change (DECC), which developed the UK's pathway toward low carbon technologies (Department of Energy and Climate Change, 2011; Roelich et al., 2014). Parthemore (2011) agrees that neodymium is strategically important for the US (US Department of Energy, 2011).

Copper is virtually used in every area of life, particularly in industrial countries. Consequently, the indicator *spread of utilization* was assessed with the maximum possible criticality rating at the national level for Germany and the US (Erdmann et al., 2011; Nassar et al., 2012). Nassar et al. (2015) rated the indicator for neodymium three times more critical for the US than for China (35.8 to 10.9), but compared with copper, its values are still in the lower criticality range for both countries. By contrast, Erdmann et al. (2011) reported that neodymium is widely used in the German economy. The global spread of utilization, evaluated by Nassar et al. (2015), achieves very low values. This disparity might be attributed to the utilization of neodymium mainly in high-tech industries, whereas the utilization is more evenly spread in industrial countries.

Table 10: Individual indicator results for the raw materials copper and neodymium. *: The neodymium value is based on the evaluation of all rare earth elements together

Indicator	Study	Description or scale	Copper	Neodymium
Substitution	Nassar et al. (2012) *corporate*	0-100	39	
	Nassar et al. (2012) *country*	0-100	35	
	Nassar et al. (2015) *USA*	0-100		62.5
	Nassar et al. (2015) *China*	0-100		54.8
	Erdmann et al. (2011)	0-1	0.56	87%
	U.S. National Research Council (2008)	Share for which substitution is impossible	15%	0.44%*
	AEA Technology and Defra (2010)	Qualitative description of substitutes	For most applications, proper substitutes exist	Substitutes are available for many applications but generally are less effective*
	Parthemore (2011)	Critical - Not critical		Critical*
	US Department of Energy (2011)	1-4		3
	Nassar et al. (2012), Nassar et al. (2015) *technology, global*	0-100	28	69.2
Future demand to supply ratio	Erdmann et al. (2011)	0-1	0.3	
	U.S. National Research Council (2008)	1-4	1	3*
	Parthemore (2011)	Critical - Not critical		Critical*
	Moss et al. (2013)	Decarbonization technologies demand a share of the expected supply	1%	8%
	Angerer et al. (2009)	Material demand of future technologies in 2030 compared with the current supply	24.00%	382.00%
Strategic Importance	Nassar et al. (2012) *corporate*	0-100	38	
	Parthemore (2011)	Critical - Not critical		Critical*
	US Department of Energy (2011)	1-4		3
	Roelich et al. (2014)	Proportion of technology rollout exposed to neodymium supply disruption (in 2015)		5%
Value of products affected	Nassar et al. (2012) *corporate*	0-100	88	
	European Commission (2014)	0-10	5.76	5.21*
	Beylot and Villeneuve (2015)	Not available yet	4.27*10^-3	
	Goe and Gaustad (2014)	0-100% of GDP	21.00%	
Value of utilized material	Nassar et al. (2012) *country*	0-100	97	
	Nassar et al. (2015) *USA*	0-100		0.5
	Nassar et al. (2015) *China*	0-100		24.2
	U.S. National Research Council (2008) *USA*	Monetary consumption in the USA in 2008	16,625 Mio USD	>1000 Mil USD*
	Goe and Gaustad (2014) *USA*	Monetary consumption in the USA in 2014	65,448 Mio USD	
Spread of utilization	Nassar et al. (2012) *country*	0-100	100	
	Erdmann et al. (2011)	0-1	1	
	Nassar et al. (2012), Nassar et al. (2015) *technology, global*	0-100	78	7.4

5 Discussion and conclusion

Raw material vulnerability is an ambivalent term. All across the 18 herein analyzed vulnerability assessments, its interpretation is manifold. The characteristics of the vulnerability assessments differ concerning their scope and target and vary with respect to the consideration of economic importance, strategic importance and impact of supply disruption, resulting in varying terms. In general, this part of the criticality assessments attempts to evaluate the importance of a raw material for a specific company, economy or technology on a quantitative or semi-quantitative basis. This approach is suitable to identify those elements with the highest economic or strategic importance or with the highest damage potential in the case of a supply restriction situation. A vulnerability assessment enables further investigation of the resilience aspects in the supply chain.

The different assessments all use an indicator-based approach but have different approaches to define what a relevant raw material is. The 18 identified indicators target qualitative aspects, such as substitutability or strategic importance, or follow a quantitative approach, measuring (for example) the value of the utilized material or products. They may also attempt to measure the current or future use of a material, be it in monetary values or in relation to the stocks of current products. A vulnerability assessment is very often attached to a supply risk assessment, either performed parallel to or in advance of the supply risk assessment. In the latter case, the vulnerability assessment serves as a filter, attempting to identify raw materials for which a supply risk evaluation has high priority. Future criticality assessments should ensure that their indicator selection, for vulnerability as well as for the supply risk dimension, follows the risk matrix approach. While supply risk indicators should evaluate the likelihood of a raw material supply disruption scenario, vulnerability should evaluate the potential scale of damage caused by these scenarios (in monetary or strategic terms). As the scope and target differ, so may the indicator set, but not all of the identified vulnerability indicators were consistent with this approach.

The examples of copper and neodymium revealed how single indicator results can be presented and compared. For interpreting aggregated vulnerability or criticality scores, understanding the applied indicators is crucial. Whereas, for example, neodymium achieves high vulnerability values in studies at the technological level, industrial applications using neodymium are a niche leading to lower vulnerability scores at the national level. For copper, the opposite is true: It is a mass metal necessary for most electric and electronic applications and therefore is essential for the entire modern economy. However, there are no expectations for sudden market shifts in the copper market due to future technologies.

The present overview on vulnerability can help future criticality assessments to select vulnerability indicators, corresponding thresholds and weightings best fitted for the corresponding focus of the assessment and to harmonize criticality assessment methods. The individual indicators presented in this overview must be further validated, possibly with considerations of economic damage of real case supply shortages in past years, as for rare earth elements or helium. Overall, a periodic update of criticality evaluations, including an assessment of raw materials with the highest vulnerability to supply restrictions, may serve as a step toward a more sustainable raw material usage and increased resilience at the corporate, national or technological levels.

6 Acknowledgements

This work was supported by the Bavarian State Ministry of Education, Science and the Arts in form the of the graduate program “Resource strategy concepts for sustainable energy systems” at the Institute of Materials Resource Management (MRM) of the University of Augsburg, Germany.

References

Achzet, B., Helbig, C., 2013. How to evaluate raw material supply risks-an overview. Resour. Policy 38, 435–447. doi:10.1016/j.resourpol.2013.06.003

AEA Technology, Defra, 2010. Review of the Future Resource Risks Faced by UK Business and an Assessment of Future Viability. Report for the Department for Environment, Food and Rural Affairs (Defra), London, UK.

Angerer, G., Marscheider-Weidemann, F., Lüllmann, A., Erdmann, L., Scharp, M., Handke, V., Marwede, M., 2009. Raw Materials for Emerging Technologies. Frauenhofer IRB Verlag, Stuttgart.

Beylot, A., Villeneuve, J., 2015. Assessing the national economic importance of metals: An Input–Output approach to the case of copper in France. Resour. Policy 44, 161–165. doi:10.1016/j.resourpol.2015.02.007

Carpenter, M., Sanders, G., 2009. Strategic Management: Concepts, 2/E. Pearson Prentice Hall, New Jersy.

CRM_InnoNet, 2015. Critical Raw Materials Innovation Network [WWW Document]. URL http://www.criticalrawmaterials.eu/ (accessed 7.3.15).

Department of Energy and Climate Change, 2011. The Carbon Plan: Delivering our low carbon future. Energy 218.

Duclos, S.J., Otto, J.P., Konitzer, D.G., 2008. Design in an Era of Constrained Resources: as Global Competition for Materials strains the Supply Chain, Companies must know where a Shortage can hurt and then plan around it. Mech. Eng. 132, 36–40.

Dutch Ministry of Foreign Affairs, 2013. Policy Document on Raw Materials 1–16.

Erdmann, L., Behrendt, S., Feil, M., 2011. Kritische Rohstoffe für Deutschland. KfW Bankengruppe, Berlin.

European Commission, 2015. 2050 Energy Strategy [WWW Document]. URL https://ec.europa.eu/energy/en/topics/energy-strategy/2050-energy-strategy (accessed 7.20.15).

European Commission, 2014. Report on Critical Raw Materials for the EU: Report of the Ad hoc Working Group on defining critical raw materials. European Commission, Brussels, Belgium.

European Commission, 2010. Critical raw materials for the EU, Report of the Ad-hoc Working Group on defining critical raw materials. Eucom 39, 1–84. doi:10.1002/eji.200839120.IL-17-Producing

Gandenberger, C., Marscheider-Weidemann, F., Ostertag, K., Walz, R., 2012. Die Versorgung der deutschen Wirtschaft mit Roh- und Werkstoffen für Hochtechnologien – Präzisierung und Weiterentwicklung der deutschen Rohstoffstrategie. TAB Arbeitsbericht.

Glöser, S., Faulstich, M., 2014. Analyse kritischer Rohstoffe durch Methoden des multivariaten Statistik, in: Teipel, U., Reller, A. (Eds.), 3. Symposium Rohstoffeffizienz Und Rohstoffinnovationen. Fraunhofer Verlag, Nürnberg, pp. 53–80.

Glöser, S., Tercero Espinoza, L., Gandenberger, C., Faulstich, M., 2015. Raw material criticality in the context of classical risk assessment. Resour. Policy 44, 35–46. doi:10.1016/j.resourpol.2014.12.003

Goe, M., Gaustad, G., 2014. Identifying critical materials for photovoltaics in the US: A multi-metric approach. Appl. Energy 123, 387–396. doi:10.1016/j.apenergy.2014.01.025

Graedel, T.E., Barr, R., Chandler, C., Chase, T., Choi, J., Christoffersen, L., Friedlander, E., Henly, C., Jun, C., Nassar, N.T., Schechner, D., Warren, S., Yang, M., Zhu, C., 2012. Methodology of Metal Criticality Determination. Environ. Sci. Technol. 46, 1063–1070. doi:10.1021/es203534z

Graedel, T.E., Harper, E.M., Nassar, N.T., Nuss, P., Reck, B.K., 2015. Criticality of metals and metalloids. Proc. Natl. Acad. Sci. 4257–4262. doi:10.1073/pnas.1500415112

Graedel, T.E., Harper, E.M., Nassar, N.T., Reck, B.K., 2013. On the materials basis of modern society. Proc. Natl. Acad. Sci. U. S. A. 2013. doi:10.1073/pnas.1312752110

Graedel, T.E., Nuss, P., 2014. Employing Considerations of Criticality in Product Design. JOM 66, 1–7. doi:10.1007/s11837-014-1188-4

Graedel, T.E., Reck, B.K., 2015. Six Years of Criticality Assessments: What Have We Learned So Far? J. Ind. Ecol. 1–8. doi:10.1111/jiec.12305

Habib, K., Wenzel, H., 2016. Reviewing resource criticality assessment from a dynamic and technology specific perspective – using the case of direct-drive wind turbines. J. Clean. Prod. 112, 3852–3863. doi:10.1016/j.jclepro.2015.07.064

Harper, E.M., Diao, Z., Panousi, S., Nuss, P., Eckelman, M.J., Graedel, T.E., 2015. The criticality of four nuclear energy metals. Resour. Conserv. Recycl. 95, 193–201. doi:10.1016/j.resconrec.2014.12.009

Harper, E.M., Kavlak, G., Burmeister, L., Eckelman, M.J., Erbis, S., Espinoza, V., Nuss, P., Graedel, T.E., Sebastian Espinoza, V., 2014. Criticality of the Geological Zinc, Tin, and Lead Family. J. Ind. Ecol. 1–17. doi:10.1111/jiec.12213

Hatayama, H., Tahara, K., 2015. Criticality Assessment of Metals for Japan's Resource Strategy. Mater. Trans. 56, 229–235. doi:10.2320/matertrans.M2014380

IMDS Data, 2015. International Material Data System [WWW Document]. URL http://imdsdata.org/whatisimds/ (accessed 7.3.15).

IW Consult GmbH, 2011. Rohstoffsituation Bayern – keine Zukunft ohne Rohstoffe.

Kausch, P., Bertau, M., Gutzmer, J., Matschullat, J., 2014. Strategische Rohstoffe - Risikovorsorge. Springer Spektrum, Berlin. doi:10.1007/978-3-642-380704-2

Kavlak, G., McNerney, J., Jaffe, R.L., Trancik, J.E., 2015. Metals Production Requirements for Rapid Photovoltaics Deployment. Energy Environ. Sci. 8, 1651–1659. doi:10.1039/C5EE00585J

Kind, V., Walker, L., Muse, J., McLean, C., Hale, V., Sussams, J., McGregor, L., Duncan, D., 2011. Raw materials critical to the Scottish economy 89.

Moss, R.L., Tzimas, E., Willis, P., Arendorf, J., Tercero Espinoza, L., 2013. Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector. European Commission, Joint Research Centre, Intitute for Energy and Transport.

Nassar, N.T., Barr, R., Browning, M., Diao, Z., Friedlander, E., Harper, E.M., Henly, C., Kavlak, G., Kwatra, S., Jun, C., Warren, S., Yang, M.Y., Graedel, T.E., 2012. Criticality of the geological copper family. Environ. Sci. Technol. 46, 1071–1078. doi:10.1021/es203535w

Nassar, N.T., Du, X., Graedel, T.E., 2015. Criticality of the Rare Earth Elements. J. Ind. Ecol. 1–11. doi:10.1111/jiec.12237

Nuss, P., Harper, E.M., Nassar, N.T., Reck, B.K., Graedel, T.E., 2014. Criticality of Iron and Its Principal Alloying Elements. Environ. Sci. Technol. 48, 4171–4177. doi:10.1021/es405044w

Panousi, S., Harper, E.M., Nuss, P., Eckelman, M.J., Hakimian, A., Graedel, T.E., 2015. Criticality of Seven Specialty Metals. J. Ind. Ecol. 1–17. doi:10.1111/jiec.12295

Parthemore, C., 2011. Elements of Security: Mitigating the Risks of U.S. Dependence on Critical Minerals. CNAS June.

Pfleger, P., Lichtblau, K., Bardt, H., Bertenrath, R., 2015. Rohstoffsituation der bayerischen Wirtschaft.

Roelich, K., Dawson, D.A., Purnell, P., Knoeri, C., Revell, R., Busch, J., Steinberger, J.K., 2014. Assessing the dynamic material criticality of infrastructure transitions: A case of low carbon electricity. Appl. Energy 123, 378–386. doi:http://dx.doi.org/10.1016/j.apenergy.2014.01.052

Simon, B., Ziemann, S., Weil, M., 2014. Criticality of metals for electrochemical energy storage systems – Development towards a technology specific indicator. Metall. Res. Technol. 111, 191–200. doi:10.1051/metal/2014010

Speirs, J., Gross, R., 2013. Materials Availability : Comparison of material criticality studies - methodologies and results Working Paper III.

U.S. Bureau of Economic Analysis, 2013. Gross-DomesticProduct-(GDP)-by-Industry Data [WWW Document]. URL http://www.bea.gov/industry/gdpbyind_data.htm (accessed 7.15.15).

U.S. National Research Council, 2008. Minerals, Critical Minerals, and the U.S. Economy. The National Academies Press, Washington, DC.

US Department of Energy, 2011. Critical Materials Strategy. U.S. Department of Energy, Washington.