Resources Policy 50 (2016) 169–176

Contents lists available at ScienceDirect

Resources Policy

journal homepage: www.elsevier.com/locate/resourpol

Criticality on the international scene: Quo vadis?

Jo Dewulf[a,b,*], Gian Andrea Blengini[a,c], David Pennington[a], Philip Nuss[a], Nedal T. Nassar[d]

[a] European Commission – Joint Research Centre, Institute for Environment and Sustainability (IES), Via E. Fermi 2749, 21027 Ispra, Italy
[b] Research Group ENVOC, Ghent University, Coupure Links 653, B-9000 Ghent, Belgium
[c] Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
[d] United States Geological Survey (USGS), 12201 Sunrise Valley Dr, Reston, VA 20192, United States

ARTICLE INFO

Keywords:
Criticality
(Raw) materials
Supply risk
Supply disruption
Vulnerability
Economic consequences

ABSTRACT

This paper brings a discussion on the current state-of-the-art in criticality assessment in an international context. It analyzes the status of resource criticality concepts and their calculation methods. The current practice often exhibits a common two-axis assessment framework but the way the two axes are further operationalized shows heterogeneous approaches. Apart from the two-axis as key element of criticality assessment, the scope of the materials, the role of substitution, the delineation of the supply chain and data, and indicator selection are addressed as key elements. The abovementioned criticality assessment practice is approached in function of the upcoming international debate on criticality. The paper tackles the role of criticality assessment in the context of the sustainability assessment toolbox and it proposes a clear distinction between criticality assessment and resilience to criticality. The insights offered in the paper may feed the international discussion in the identification of elements that may be harmonized and elements that may be better left open in function of the particular application.

1. Introduction

The criticality concept for raw materials has seen a growing interest in the last decade, with the majority of studies carried out in Europe and the United States (Erdmann and Graedel, 2011; Buijs et al., 2012; Sonnemann et al., 2015; Graedel and Reck, 2016). Much of the work deals with metals and metalloids. However, non-food and non-energy bio-based raw materials have also been included, e.g., by the assessments of the European Commission (EC, 2010, 2014) and recently even water (Sonderegger et al., 2015). Criticality as concept for raw materials has been interpreted differently. Erdmann and Graedel (2011) state that "raw material criticality seeks to capture both the supply risks on the one hand and the vulnerability of a system to a potential supply disruption on the other". Looking across the different approaches, the largest divergence seems in the definition of the economic system (both geographically and user-specifically) for which a stable and secure supply of raw materials is to be assured. Here, the economic systems to protect ranges from a single corporation (Duclos et al., 2010), to a sector or a few selected technologies of strategic importance (sector-specific criticality assessment) (Moss et al., 2013a , 2013b; USDOE, 2010, 2011), to entire national/regional economies (economy-wide criticality assessment) (EC, 2010, 2014; NRC, 2008; Graedel et al., 2015; BGS, 2012; Achzet et al., 2011; Coulomb et al., 2015; NSTC, 2016; Skirrow et al., 2013), and the world (global criticality assessment) (Graedel et al., 2015). Furthermore, the number of materials covered in criticality assessments ranges in scope from a single element (Rosenau-Tornow et al., 2009), to less than 5 metals belonging to the same geological family (Nassar et al., 2012; 2015a, , 2015) or used in similar end-use applications (Nuss et al., 2014; Harper et al., 2015b), to more than sixty raw materials, embracing and tying to encompass a large and diverse number of non-fuel, non-food mineral and biotic raw materials (EC, 2010, 2014). While the materials of interest are determined by the goal and scope of the assessment, we note that a desirable aspect of criticality determinations includes the applicability of the methodology to a wide range of materials (Graedel and Reck, 2016).

Criticality assessments have been around for a while, e.g. the term "critical and strategic material" has been in use in the US since 1939 as part of the original stockpile legislation and further reported in the 1950–1980s (Charles River Associates, 1982; Committee on the Technical Aspects of Critical and Strategic Materials, 1977; Paley et al., 1952). But the current approaches of criticality assessment in the last decade and the growing international attention lack an international forum that specifically intends to converge the criticality

* Corresponding author at: Research Group ENVOC, Ghent University, Coupure Links 653, B-9000 Ghent, Belgium.
E-mail addresses: jo.dewulf@ugent.be (J. Dewulf), gianandrea.blengini@jrc.ec.europa.eu (G.A. Blengini), david.pennington@jrc.ec.europa.eu (D. Pennington), philip@nuss.me (P. Nuss), nnassar@usgs.gov (N.T. Nassar).

http://dx.doi.org/10.1016/j.resourpol.2016.09.008
Received 13 June 2016; Received in revised form 21 September 2016; Accepted 21 September 2016
Available online 13 October 2016

praxis, as is taking place for other assessment tools, e.g. Life Cycle Assessment (LCA) with activities by UNEP (United Nations Environmental Program), SETAC (Society of Environmental Toxicology and Chemistry), and ISO (International Organization for Standardization). The goal of this paper is to provide some perspective on the current state of practice in order to determine where there is convergence and divergence in criticality assessment methods. This paper may in the long-run serve as input to the international scene to discuss if international convergence to a uniform methodology is feasible and, if so, to identify which aspects may be harmonized and which may better be left open in function of the particular application.

In the next section convergence and divergence on the various aspects of the generally practiced two-axis approach are discussed. Subsequently, both axes (i.e. risk or likelihood of supply disruption and economic importance or vulnerability to disruptions) are discussed where there are clearly different practices in elaboration and quantification. In the subsequent section, some particular attributes (e.g. scope of materials covered, the role of substitution and recycling, the modeling of the supply chain, and indicators and data) are discussed. Finally, some considerations on future directions in the international context are presented. The positioning of criticality assessment in the sustainability assessment toolbox is also discussed. Equally the paper addresses the distinction between criticality calculations of raw materials for a certain entity and the way the entity is able to respond to this criticality, i.e., its resilience.

2. The criticality concept and the predominant two-axis approach

2.1. More convergence than divergence: a concept with two axes

A review of recent international approaches reveals a general consensus that criticality is comprised of two main dimensions (Fig. 1): supply risk, graphically represented on a horizontal axis, and the impact of or vulnerability/exposure to that supply risk, graphically represented on the vertical axis. While there is general consensus on the intentions of the supply risk dimension, there are notable differences in its underlying components and computation among the various approaches. In contrast, there is little consensus regarding the vertical axis aside from the overall theme of attempting to quantify the impact or vulnerability that may arise from the supply risk. Indeed, the variations in the vertical axis highlight the general differences in intentions and the targeted beneficiaries or scope of the various approaches. Some studies, like those of the European Commission (EC, 2010, 2014), examine the potential economic impact on a region (i.e., the European Union) or the vulnerability of a specific country (NRC, 2008; Graedel et al., 2015; BGS, 2012). Others examine the impact of specific sectors (Moss et al., 2013; USDOE, 2010, 2011) or a specific company (Duclos et al., 2010). In general, however, the different interpretations typically tend to quantify the potential impact that supply disruption may have on the system under study. Glöser et al. (2015) bring the two approaches mathematically together based on the reasoning that raw material criticality equals the product of supply risk and vulnerability, but at the same time also that it is the result of the multiplication of likelihood of supply disruptions and economic consequences. Roelich et al. (2014) take a similar, albeit more dynamic approach, by suggesting that material criticality is the product of supply disruption potential and exposure to disruption.

2.2. Convergence and divergence: the two axes approach as a basis for quantifying criticality

The two dimensions are typically kept separate, a reflection of the idea that the two dimensions are independent. A raw material is thus only considered critical if it is found to have both a high supply risk (x-axis) and a high importance/vulnerability (y-axis). The aggregation of the criticality axes into one single criticality indicator is seldom done. A notable exception is Graedel et al. (2012) who use a criticality vector magnitude (i.e., the distance from the origin to a metal's location in criticality space) as the basis for aggregation. Based on classical risk assessment, Glöser et al. (2015) also explored some potential paths for providing a single criticality indicator by multiplying the two factors resulting in convex contour lines in the two dimensional plot and by defining the vector length resulting in concave contour lines. However, there are multiple ways to combine the two axes; in case the criticality is defined as an abstraction of classical risk assessment, i.e., a simple multiplication of the two axes, one ends up with convex contour lines – see Paley et al. (1952) for a further discussion.

A remarkable divergence in approach on levels of criticality is to be mentioned. The quantification of criticality often leads to a relative ranking of raw materials along the scale and, eventually, a categorization of the raw materials as being either critical or not. In the 2014 The EC study (EC, 2010, 2014), for example, twenty raw materials are considered to be critical: Antimony, Beryllium, Borates, Chromium, Cobalt, Coking coal, Fluorspar, Gallium, Germanium, Indium, Magnesite, Magnesium, Natural Graphite, Niobium, Platinum Group Metals (PGMs), heavy Rare Earth Elements (REEs), light REEs, Silicon metal, and Tungsten. From an overview of criticality studies, Erdmann and Graedel (2011) distinguish three levels of criticality for all materials where sufficient studies are available. In the highest level of criticality, Scandium, Yttrium, Niobium, Tungsten, PGMs (Ru, Rh, Pt) and REEs (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) are listed. The methods used to perform this categorization are often somewhat arbitrary, which draws criticism and concern regarding the raw materials close to the thresholds. One exception is the recent criticality methodology presented by the U.S. President's National Science and Technology Council, which uses a hierarchical cluster analysis as the basis for the categorization of the raw materials as critical or not. Graedel and Reck (2016) emphasize that criticality is rather a matter of degree, not a state of being. Presenting criticality as a state of being has clearly the advantage of easier communication to a broader audience. Apart from the (absolute) degree, important is that criticality calculations lead to a relative ranking: certain raw materials are "less secure" and/or "more important" than others.

2.3. Mostly divergence: the role of environmental issues

Some studies include environmental issues into the assessment of criticality, but there is very little consensus regarding the purpose and method used for its inclusion (Achzet and Helbig, 2013). In certain assessments (EC, 2010) environmental issues are considered to be an extension of issues related to ensuring supply and is thus included as a component in the supply risk dimensions (e.g., using the environmental performance index at country-level; www.epi.yale.edu). Despite the relevance of environmental impacts as an issue in the sustainable supply of materials, it is questionable if it is inherent to criticality either as an immediate supply risk factor or in terms of immediate (economic) importance.

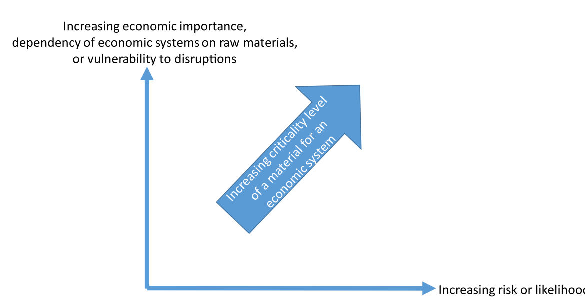

Fig. 1. Illustration of the two main dimensions in the assessment of the criticality of materials.