Resources Policy 44 (2015) 35–46

Contents lists available at ScienceDirect

Resources Policy

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

Raw material criticality in the context of classical risk assessment

Simon Glöser [a,*], Luis Tercero Espinoza [a], Carsten Gandenberger [a], Martin Faulstich [b]

[a] Competence Center Sustainability, Business Unit Systemic Risks, Fraunhofer Institute for Systems and Innovation Research ISI, Breslauer Str. 48, 76139 Karlsruhe, Germany

[b] CUTEC Institute, Chair of Environmental and Energy Technology, Clausthal University of Technology, Leibnizstraße 21 + 23, 38678 Clausthal-Zellerfeld, Germany

ARTICLE INFO

Article history:
Received 18 September 2014
Received in revised form
23 December 2014
Accepted 31 December 2014

Keywords:
Critical raw materials
Criticality assessment
Criticality matrix
Risk matrix
Supply risks

ABSTRACT

The rapid economic development of emerging countries in combination with an accelerating spread of new technologies has led to a strongly increasing demand for industrial metals and minerals regarding both the total material requirement and the diversity of elements used for the production of specific high-tech applications. Several minor metal markets which are often characterized by high market concentrations of raw material production at the country and the company level have shown high turbulences since the beginning of the 21st century. This has led to growing concerns about the security of raw material supply, particularly in established western economies. As a result, numerous studies on supply risks and raw material criticality for different countries and regions were carried out recently. In this paper, we discuss the methodology of raw material criticality assessment within a criticality matrix which is a modification of a classical risk matrix. Therefore, we first provide an overview of the approaches and results of major studies quantifying raw material criticality by means of a criticality matrix. By applying a uniform scaling to the matrices of different recent studies, a direct comparison of results and data interpretation was enabled. As shown in this paper, the close relation between the criticality matrix and classical risk analysis within a risk matrix was overlooked in most studies which may lead to misunderstanding and misinterpretation of the results. We posit that the interpretation of the coordinates within the criticality matrix and the thresholds separating critical and non-critical raw materials need to be revised by means of general risk definitions.

Introduction

A basic requirement for sustainable economic development and the successful production of high technology applications is the secure supply with raw materials, free from disruptions, disturbances and bottlenecks leading to high commodity pricing and market volatility. Most industrialized countries strongly depend on raw material imports, as their domestic raw material deposits and exploitation activities are small (Behrens et al., 2007). Forced by the rapid growth of emerging markets, particularly China, the increasing dynamics in the development of new technologies and the increasing diversification of metals with very specific properties needed for these high-tech applications, the raw material supply situation has strongly deteriorated in the previous decade (Rosenau-Tornow et al., 2009).

Current supplies of raw materials are often characterized by high concentrations of production both on the country and the company level (Sievers and Tercero, 2012). This means mining activities are limited to a few countries and basic raw material processing is carried out by several large mining corporations with significant power in oligopolistic markets. In this context, the distortion of competition caused by export restrictions and the taxation of specific high-tech metals in several emerging countries are a serious threat to different industries as both higher prices and the limited availability of essential raw materials compromise their competitiveness (e.g. Parthemore, 2011; Campbell, 2014; Massari and Ruberti, 2013).

Furthermore, several mining countries are suffering from political instability and inadequate economic and social conditions. The potential for political conflicts in these countries is high and poses a latent threat to raw material supplies (Le Billon, 2001).

Regarding geology, different minor metals only occur within the ores of major carrier metals and are therefore mainly jointly extracted and refined as the separate production of these side-product or companion metals is usually economically not feasible (Verhoef et al., 2004). This is of particular relevance if the demand of the byproduct materials increases faster than the demand of the main metal, for instance due to the non-substitutable use within an emerging technology. In this case, supply cannot be independently increased and will not be able to meet demand which can lead to

* Corresponding author. Tel.: +49 721 6809 387; fax: +49 721 6809 135.
E-mail address: simon.gloeser@isi.fraunhofer.de (S. Glöser).
URL: http://www.r-cubed-research.eu (S. Glöser).

http://dx.doi.org/10.1016/j.resourpol.2014.12.003
0301-4207/

disproportionately high market prices and raw material scarcity (Fizaine, 2013; Tercero, 2012).

Beside social, economic and political aspects of primary raw material production, the ecologic implications of mining and material processing are gaining increasing public attention which could also affect supply security due to regulations and restrictions in mining countries or potential environmental regulations and strong certification requirements in raw material consuming countries (Bleischwitz et al., 2012; Norgate et al., 2007).

Finally, the market dynamics are increasingly forced by speculation on raw material pricing and raw material related commodity derivatives as financial markets and raw material markets move closer together (Humphreys, 2010a; Tilton et al., 2011).

Hence, there is mounting anxiety that the development, the commercialization and the use of new innovative technologies might be negatively affected or prevented due to shortages and high pricing in raw material markets (e.g. Hoenderdaal et al., 2013; Novinsky et al., 2014). Therefore, the systematic evaluation of supply risks, vulnerabilities and economic consequences of supply restriction form scientific challenges at present. In this context, the determination of raw material criticality is a key element in quantifying and communicating economic vulnerabilities due to insecure material supplies.

Supply risks or criticality may be assessed for an enterprise (e.g. Duclos et al., 2008), a country (e.g. Erdmann et al., 2011), a region (e.g. European Commission, 2010, 2014) or for the world (e.g. Graedel and Nassar, 2013). Apart from the spatial dimension, several studies particularly focus on raw material supply for specific emerging technologies, with particular emphasis on energy technologies (e.g. APS, 2011; Moss et al., 2011, 2013; U.S. DoE, 2010, 2011). Based on the methods used, Erdmann and Graedel (2011) classified major studies dealing with the quantification of raw material criticality and supply risks into three categories:

1. Studies using the principle of a criticality matrix as a modification of a classical risk matrix in order to assess raw material criticality.
2. Studies quantifying a single risk index which is calculated from different sub indicators.
3. Studies working with scenario analysis and time series analysis in order to forecast demand (and supply) side developments.

An overview of different publications based on the concepts described in items 1–3 is provided in the accompanying supplementary information. In this paper, we focus on the concept of criticality determination within a criticality matrix (item 1 above). While recent publications in this field analyzed and discussed the choice and weighting of underlying indicators used for the quantification of a material's supply risk or its economic importance (Achzet and Helbig, 2013; Erdmann and Graedel, 2011), herein, we focus on the interpretation of a material's position within the criticality matrix in the context of general risk analysis—the original inspiration for the criticality matrix. As described in the following sections, the close link between a classical risk matrix and the criticality matrix has been at least partly overlooked in several previous studies. This can potentially lead to misinterpretations which we intend to clarify in this paper.

After a short review of the historic debate about critical raw materials, we provide a detailed quantitative derivation of the criticality matrix approach as a modification of a classical risk matrix. Then we present the matrices of different criticality studies from recent years and we compare the interpretation of the results from different studies by projecting the materials' coordinates into a matrix with uniform scaling of the axes and contour lines representing the criticality level.

Current and historic debate about critical raw materials

Despite the recently increasing interest in critical metals and minerals, the topic of raw material supply security goes back to early human civilizations (Buijs et al., 2012) and whole periods of human history were named after the metals or alloys that dominated anthropogenic use like the "Copper Age", the "Bronze Age" or the "Iron Age" (NRC, 2008).

Regarding the 20th century, which is most relevant for current supply aspects, the debate about the security of raw material supplies was dominated by political conflicts such as the two World Wars or the Cold War (Gandenberger et al., 2012). The term "critical raw material" was first introduced in the "Strategic and Critical Materials Stock Piling Act" from 1939 (Legislative Councel, 1939). The "President's Materials Policy Commission" was appointed by President Truman in the early 1950s due to fears of raw material shortages not only for the United States but for the whole western world (Mason, 1952). In the 1970s and 1980s, due to relatively high commodity prices (Humphreys, 2010a), the two oil crises in 1973 and 1979 (Kesicki, 2010), the cobalt crisis in 1978 (Alonso et al., 2007) and not least because of the Cold War, the awareness of import dependencies and vulnerabilities was high (Humphreys, 2010b). This is evident from several publications about strategic and critical raw materials from that time (Haglund, 1984; Jacobson et al., 1988; Leamy, 1985; Robinson, 1986) and official reports from governmental institutions such as the U.S. Council on International Economic Policy (1974), the Commission of the European Communities (1975) or the U.S. Congressional Budget Office (1983). Furthermore, the issue of raw material criticality was part of political initiatives like "The National Critical Materials Act of 1984" (Committee on Science, 1984). However, after the collapse of the Soviet Union and due to continuously decreasing commodity prices in the 1990s, the topic of non-fuel minerals and metals supply security lost attention for more than a decade (Humphreys, 1995).

This has substantially changed over the past years. Due to the aforementioned current tensions in raw material markets, numerous studies about the quantification of supply risks of mineral and metallic raw materials have been carried out in the past 10 years. A literature review recently published by the UK Energy Research Centre (Speirs et al., 2013) quantifies the number of publications on materials availability over the previous decades and confirms the aforementioned relations as illustrated in Fig. 1.

In addition to research work, several concepts of national resource strategies such as the "EU Raw Materials Initiative" from 2008 (European Commission, 2008) which was integrated into national research strategies of EU member states (defra, 2012; Tiess, 2010) have been published in recent years. In 2013 alone, the "National Strategic and Critical Minerals Production Act" and the "National Strategic and Critical Minerals Policy Act" have been presented to the U.S. House of Representatives. These are two bills that seek to expedite the development of strategic and critical

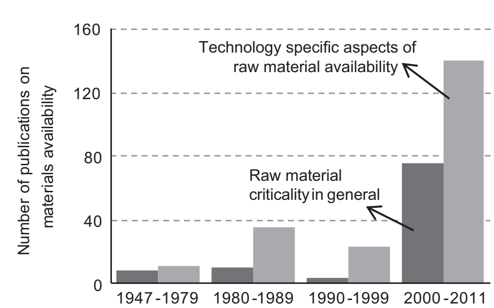

Fig. 1. Number of publications on materials availability since 1947 based on Speirs et al. (2013). Note that the publications for specific technologies were summarized.