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Limits to the critical raw materials approach

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The issue of a secure supply of raw materials has regained importance in recent years. A prominent feature of the current discussion has been the identification of 'critical raw materials' and of adequate measures to reduce their 'criticality'. This paper explores the definition, uses and limitations of lists of critical raw materials as a policy tool today and in a historical perspective. It becomes clear that the underlying issues affecting security of supply tend to persist while the identity of the 'critical' raw materials changes due to changing market conditions. The usefulness of shortlists of critical raw materials as a policy instrument therefore depends not only on the degree to which a particular methodology reflects the underlying issues but also on the timeframe chosen for the analysis.

1. Historical perspective

The recent explosion of interest in the topic of non-energy raw material supply may persuade observers that this is a fundamentally new concern. It is not. In the Bronze Age, metals were transported over long distances from mining areas to demand centres (e.g. gold, tin and copper from the British Isles to mainland Europe), effectively creating a situation of dependence on foreign resources (Troitzsch and Weber, 1982). Because our supply of metals and minerals is largely met by mining, and mining is tied to particular geological formations that are generally unevenly distributed around the globe, the dependence of some countries and regions on foreign resources remains to this day, albeit with different actors and more varied resources. Depending on the prevailing political and economic environment, this is sometimes considered a vital problem and sometimes not (e.g. Dannreuther, 2010; Humphreys, 2010). Currently, the strong economic development of China and other emerging economies has contributed to a rapidly increasing demand for metals and minerals, in many cases leading to large price increases and fears of physical scarcity. This, in turn, has brought the issue of securing supply at 'reasonable' prices back to the fore.

Regarding mineral resources, concerns about specific raw materials have fluctuated very much with market circumstances and have seen changing sets of raw materials that were considered critical at certain times in the past, by certain countries or regions. An interesting observation is that, although these historical criticality studies follow basically the same questions as recent studies, the resulting selection of 'critical minerals' is different from current ones. The raw materials regarded as critical have changed depending on the global political environment at the time of analysis and on the state of technological development and degree of industrialisation, but the way of looking at the problem has remained the same over the last decades. Therefore, it is instructive to review a few historical studies on the possible impact of supply disruptions for minerals.

In 1974, under the Nixon administration, the report *Critical Imported Materials* (US DoS, 2012) examined 19 major industrial raw materials. The report assessed the risks of price gouging and supply interruption for each of these materials, as well as the potential impact of such events upon the US economy and national security, and found bauxite, platinum and chromium should be considered critical. Yet overall, it concluded the following.

> Some risk exists with regard to a few of the other 16 materials examined. Under currently foreseeable circumstances, however, market forces, with all their imperfections, appear adequate to deter price gouging or cartel-like action for all 16 materials.

A contemporary communication by the Commission of the European Communities (CEC, 1975) on the raw materials supply of the community identified tungsten, manganese, chromium, phosphate and platinum as being of concern, based upon a qualitative evaluation of supply and demand trends, substitutability, producer concentration and estimated political risk. A later report by the US Congressional Budget Office (CBO, 1983) focused on similar risk factors and identified chromium, cobalt, manganese and platinum-group metals (PGMs) as critical materials.

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An important observation is that, although the identified raw materials vary, not only are the fundamental concerns discussed in these historic studies the same as today, but also, to a large extent, so are the subsequent analysis and proposed solutions. The 1975 CEC report is an excellent example of this. It states that, though geological scarcity is not foreseeable, the supply of raw materials is of high importance for the future. Risks for supply bottlenecks were seen in Europe's import dependence, the concentration of production in unstable countries, the nationalisation of mining companies and the increasing tendency to process raw materials in producer countries. Several measures were proposed to counteract possible supply shortages: stockpiling of raw materials, long-term supply contracts and the exploitation of European resources. Recycling, substitution, efficiency, longer product lifetime and supporting research activities are also mentioned as supporting measures. The document (CEC, 1975) furthermore states that the problem exceeds the national frame of the member states and that a common solution for all European states should be aimed at. It suggests creating a body within the European Community that pools knowledge and information on raw materials. Furthermore, it emphasises that only with a systematically organised, close collaboration of all relevant disciplines can the knowledge base be created, which is needed to shape a European resource policy. These conclusions are very similar to recent policy statements.

The historical criticality studies briefly described here relied mostly on qualitative assessments by experts. In recent years, there has been an increasing trend towards trying to quantify the supply risks and (economic) impact of supply disruptions of certain materials. This has led to the use of indicators (e.g. the human development index and World Bank worldwide governance indicators (World Bank, 2011)) as a measure of political stability and the potential for supply disruptions. To identify the economic impact of a supply disruption of certain minerals, estimates are often made by means of calculating the value of the products or overall industry sectors dependent upon a certain material, adjusting for the potential of substitution or increased resource efficiency. These efforts have contributed to increased transparency and ease in assessing the results of criticality exercises but are burdened by the fact that most of the indicators used were developed for purposes other than assessing risks to the supply of metals and minerals or potential impacts of supply shortages. Further issues related to the selection of indicators are discussed later.

2. Defining critical raw materials

In the context of this discussion, the term 'critical raw materials' has recently re-emerged to denote mineral, non-energy raw materials that combine a comparatively high economic importance with a comparatively high risk of supply disruptions. While these two dimensions have been considered in discussions of raw materials supply dating back to at least the 1970s, it is only recently that mostly two-dimensional (2D) graphical depictions have gained popularity as a communication tool (e.g. CCMI *et al.*, 2008). The concept of this 2D representation is shown in Figure 1.

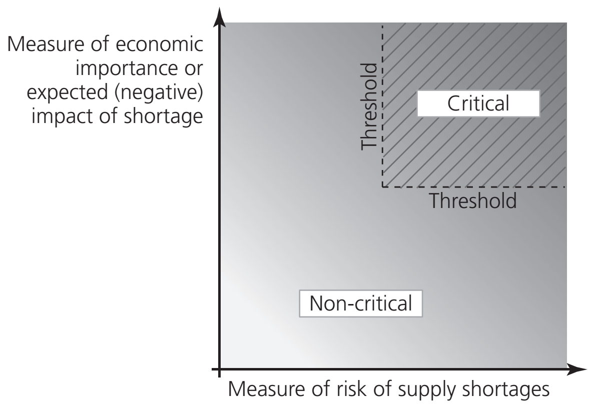

Figure 1. Representation of the criticality concept: both a high potential impact of a shortage (economic importance) and a comparatively high probability of such a shortage must be present for a material to be considered critical. Thus, criticality is a matter of degree (as illustrated by the gradient) but thresholds may be defined in both dimensions to distinguish between those raw materials considered critical and those that are not (CCMI *et al.*, 2008; European Commission, 2010). A third dimension considering environmental issues (related to environmental policy as in European Commission (2010) and related to environmental impact as in Graedel *et al.* (2012)) may be added, but the illustration here is kept 2D for the sake of simplicity

Within the conceptual framework provided by Figure 1, the difficulty in defining a set of critical raw materials emerges in the definition of suitable indicators to reflect their economic importance and supply risks. This has led to different sets of indicators and methodologies to produce shortlists of raw materials on which to focus (CCMI *et al.*, 2008; European Commission, 2010; IZT and Adelphi, 2011; REKTN, 2008). These shortlists of critical raw materials are generally meant to highlight the underlying issues accounted for in the respective methodologies, and serve as a focus point for concrete actions of policy makers (e.g. devoting research funding to the search for substitutes as in the European Union (EU) Seventh Framework Programme or initiating raw material partnerships with producing countries as done by the German government). Selected studies identifying critical raw materials at the national level (including groups of nations like the EU) are listed in Table 1.

Common to all methodologies is that they must have a basis of comparison for all candidate raw materials. This basis is defined as more or less measurable indicators reflecting the issues considered important by the authors of each study. For example, the degree of dependence on foreign sources may be seen as a

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Study	Criteria	Critical minerals
CCMI *et al.* (2008)	■ US consumption (value) ■ Substitutability ■ Emerging uses ■ US import dependence ■ Ratio of world reserves to production ■ Ratio of world reserve base to production ■ World by-product production compared with total primary production ■ US secondary production from old scrap compared with consumption	Indium, manganese, niobium, PGMs, rare earths
REKTN (2008)	■ Global consumption levels ■ Lack of substitutability ■ Global warming potential ■ Total material/environmental requirement ■ Physical scarcity ■ Monopoly supply ■ Political instability ■ Climate change vulnerability	Gold, rhodium, platinum, strontium, silver, antimony, tin
US DoE (2010)	■ Basic availability ■ Competing technology demand ■ Political, regulatory and social factors ■ Co-dependence on other markets ■ Producer diversity ■ Demand for clean energy ■ Substitutability	Dysprosium, neodymium, terbium, europium, yttrium, indium
European Commission (2010)	■ Concentration of supply ■ Governance rating of producing countries (alternatively environmental performance) ■ Substitutability ■ Recycling rate ■ Value added of end use sectors	Antimony, beryllium, cobalt, fluorspar, gallium, germanium, graphite, indium, magnesium, niobium, PGMs, rare earths, tantalum, tungsten
IZT and Adelphi (2011)	■ Share of Germany in world consumption ■ Change in the share of Germany in world consumption ■ Change in imports ■ Sensitivity of the relevant value chains in Germany ■ Demand from emerging technologies ■ Substitutability ■ Governance of producing countries ■ Governance of countries selling to Germany ■ Country concentration of reserves ■ Company concentration of production ■ Ratio of reserves to production ■ Share of by-product production in world production ■ Recyclability	Germanium, rhenium, antimony (highest criticality), tungsten, rare earths, gallium, palladium, silver, indium, tin, niobium, chromium, bismuth (high criticality)

Table 1. Selection of recent studies identifying critical non-energy raw materials for different countries and regions

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Study	Criteria	Critical minerals
Graedel *et al.* (2012)	■ Depletion times (reserves) ■ Companion metal fraction ■ Policy potential index ■ Human development index ■ Worldwide governance indicators: political stability ■ Global supply concentration ■ National economic importance ■ Percentage of population utilising ■ Substitute performance ■ Substitute availability ■ Environmental impact ratio ■ Net import reliance ratio ■ Net import reliance ■ Global innovation index ■ Lifecycle assessment cradle-to-gate: 'human health' ■ Lifecycle assessment cradle-to-gate: 'ecosystems'	Example ranking for the 'copper family' to the USA: arsenic = gold > silver > selenium ≈ copper > tellurium

Table 1. Continued

risk factor for which the ratio of imports to total raw material needs may serve as an indicator (e.g. CBO, 1983; CEC, 1975; Graedel *et al.*, 2012; IZT and Adelphi, 2011; Nassar *et al.*, 2012). Other authors focus on the diversity of possible sources (i.e. are we dealing with a monopoly/oligopoly?) and assign a higher supply risk to highly concentrated markets (e.g. European Commission, 2010; Graedel *et al.*, 2012; Nassar *et al.*, 2012). Environmental concerns may be taken into account separately (e.g. European Commission, 2010; Graedel *et al.*, 2012; Nassar *et al.*, 2012), into a combined risk assessment (e.g. REKTN, 2008) or not at all (e.g. IZT and Adelphi, 2011). The focus of the analysis presented here is on security of supply.

All indicators mentioned above share a common feature: they have to be measured or estimated at one point in time to fit into the methodologies used to define critical raw materials. Thus, evaluations of the criticality of mineral raw materials have mostly been inherently backward-looking and can at best reflect the current situation and the near-future situation as far as this does not prove different than the status quo. It is also worth noting that some studies (e.g. IZT and Adelphi, 2011; US DoE, 2010) explicitly use projections while others (e.g. CCMI *et al.*, 2008; European Commission, 2010; Graedel *et al.*, 2012) are limited to the speed at which the indicators used may change. It has been pointed out that the pace of change of different indicators is also different (Graedel *et al.*, 2012); this issue is explored further below.

Some efforts have been made to give a dynamic character to criticality assessments. To date, these efforts are mostly based on different assessments of the same indicator for the short/medium/long term or through a combination of current risk and future expected demand/impact (IZT and Adelphi, 2011; US DoE, 2010). An example of combining current assessments with expectations for the future is shown in Figure 2 (see also Tercero Espinoza, 2011). More recently, a report combined projections for the supply of rare earths to 2017 with demand scenarios based on projections for green energy technologies to provide a sense of the time dimension in possible supply restrictions (Hatch, 2011).

3. Interpreting criticality studies: limits to the critical minerals approach

Criticality studies should be seen as an attempt to highlight issues related to secure access to (mostly) imported mineral resources of comparatively high economic importance. Different aspects in these considerations (such as the 'political risk' or 'accident risk' of supply disruptions as well as the economic impact of such an event) are, however, inherently difficult to quantify. Furthermore, the resource markets that are analysed can be quite dynamic – something that holds in particular for the smaller resource markets such as 'technology metals'. In such markets, the situation in terms of balance between supply and demand and the sources of supply can change relatively quickly when contrasted to the much larger markets of base metals or energy resources. This becomes apparent, for example, when reviewing the changes in country concentration of primary production and the corresponding governance ratings, as shown for selected raw materials in Figure 3.

Based on analysis carried out within the Polinares project (e.g. Buijs and Sievers, 2011a, 2011b), the following limitations of

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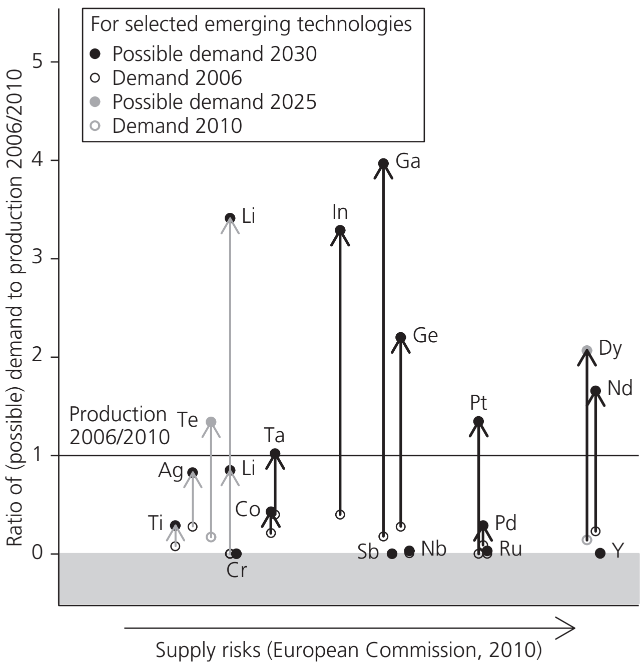

Figure 2. Combining current risk assessments with expected demand due to emerging technologies provides insights as to where action is needed more urgently but cannot fully capture the dynamic nature of both supply and demand. The horizontal axis was taken from the EU assessment and thicker arrows denote raw materials classified as critical in that assessment (European Commission, 2010). The vertical axis is based on different recent studies (Angerer *et al*., 2009a, 2009b; Elsner *et al*., 2010; US DoE, 2010). The arrows denote the magnitude of the expected demand increase (normalised to recent global production), with the black arrows denoting raw materials identified as critical by the European Commission (2010)

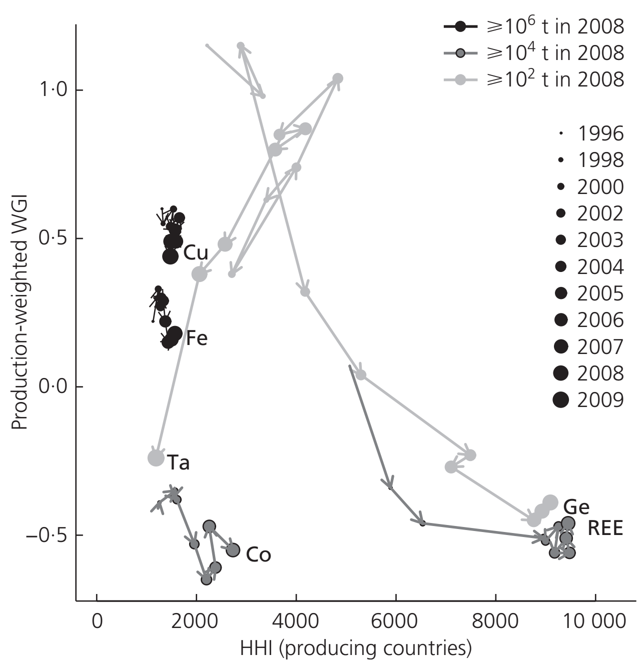

Figure 3. Changes in the concentration of supply at the level of producing countries (BGR, 2011) and corresponding worldwide governance indicator (WGI) (World Bank, 2011) between 1996 and 2009 for selected metals in three different market sizes. Notice that it is the smaller markets that are more prone to large changes over short periods of time. The Herfindahl–Hirschmann index (HHI) is a measure of concentration calculated by $\mathrm{HHI} = \sum (\text{Market share}_{\text{country}})^2$; thus, a HHI of zero corresponds to an infinite number of very small producers while a HHI of 10 000 represents a monopoly

current criticality studies (which will be elaborated upon in this paper) can be listed.

- The studies show a bias towards technology minerals by emphasising high-tech applications and the role of market power of producers in small markets.
- They lack predictive power beyond the short term.
- They have a tendency to overstate the economic impact of a possible supply disruption of ‘critical’ minerals.
- They often fail to distinguish between short-term and long-term problems.
- They take insufficient account of the diversity and particular characteristics of the resource markets that are analysed.
- They focus exclusively on risks related to the mining and export of raw materials but disregard the larger production chain (e.g. refining, transport and trade in semi-products).

As discussed in Section 1, the sets of minerals that have been identified as ‘critical’ have changed over time, depending upon the situation of the countries concerned and the state of global resource markets at the time of study. Most of the minerals that have historically been classified as ‘critical’ have in fact never caused significant problems. Some of these minerals, for instance bauxite, which was classified as potentially problematic in the 1970s by the USA, have disappeared from the list. Other minerals, such as the PGMs used in automotive catalysts, have remained on criticality lists for the past few decades but no severe market disruptions have actually occurred. This is not to say that criticality studies had no use in avoiding problems in these resource markets, but it should be acknowledged that in many instances criticality studies have not been able to capture the dynamics of resources markets.

Examining the (recent) shortlists of critical raw materials, we can distinguish a bias towards so-called technology metals/minerals: metals or minerals that are only used in small quantities for very specific applications. These technology minerals are often only mined in small volumes, which makes price volatility and producer dominance much more likely. New sources of demand arising from newly developed applications can cause demand to outstrip supply in the short term (or an

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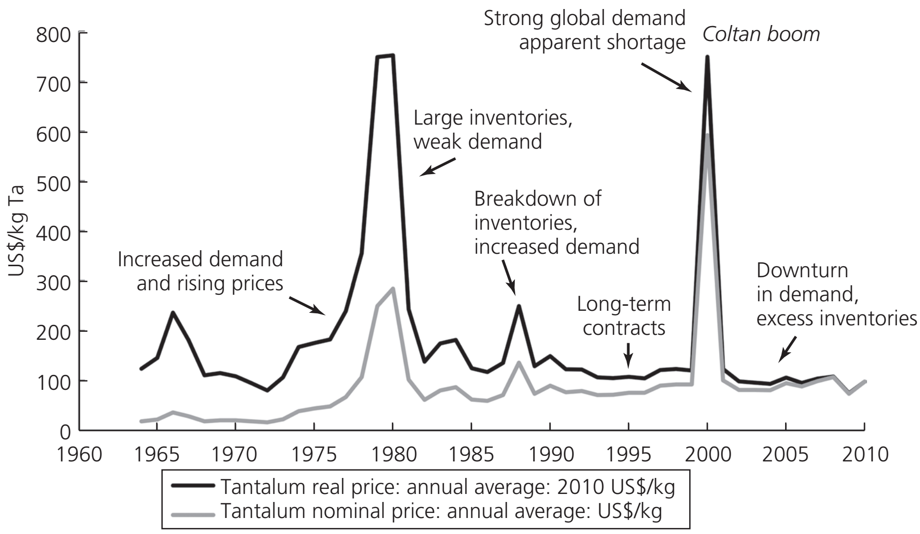

Figure 4. Tantalum published spot prices (Papp, 2010; USGS, 2009). The long-term annual spot price has shown long-term stability, interrupted by very sharp price jumps due to concerns in the tantalum industry and based on strong demand and fears about shortage

expectation that this will be so), causing price spikes and a pressure for substitution. On the supply side, there is sometimes only a limited number of producing mines, leading to producer concentration levels that appear to be very alarming but are in fact not fundamental. In this case, just one or a few new large mines coming on-stream might change the picture entirely (see also Figure 3). In terms of resources – rather than reserves or production – the dominance of some producers (such as China for the rare earths) is not so definite and in itself not necessarily always a problem. This is very different from the oil market, for instance, where the dominance of the Middle East as a source of cost-competitive oil reserves and resources is very pronounced and has remained so even though oil has been sought for all around the globe.

Having a much smaller market also means that there is less flexibility on the supply side to adjust to an increase in demand. Instead of many mines that only have to increase production marginally, for smaller markets maximum production capacity might be more easily reached causing severe market tightness. As a consequence, price spikes are a fairly common phenomenon for smaller specialised resource markets (see Figure 4). Four to eightfold price increases in the time span of a few years might sound dramatic, but the effects of such price spikes are not as devastating as they might appear.

In fact, the economic impact of a potential supply disruption of technology minerals seems to be overemphasised. Although their use in various electronic components might be very widespread, the fact that usually only small quantities are used implies that the impact of any price hike will be limited. The costs of such technology minerals as a percentage of the overall product costs will remain small, thus mitigating the impact of a price increase and allowing producers to pay a much higher price for the specific minerals they need. The situation is different if physical scarcity actually leads to a no-build situation in which manufacturers are unable to purchase the raw materials they need (and are therefore temporarily unable to manufacture their products) despite willingness to pay high prices. In other words, availability is a much stronger concern than price.

The key issue, therefore, is to retain a functioning market even in tight market situations, where consumers that are willing to pay the highest price can still obtain the resources they require. Such severe supply disruptions that might actually lead to physical shortages and a lack of supplies even for those consumers that are willing to pay very high prices are, however, quite rare. In many cases, a strong price increase will cause all kinds of counter-reactions and provide an incentive for more resource efficiency (of the required material inside the end product), more efficient use of the end product, substitution with other materials or of the end product itself and an incentive to bring more supplies to the market, whether from primary or secondary sources (i.e. new mines or increasing recycling activity).

In the very capital-intensive mining industry, bringing new supplies online can be a protracted process, requiring long lead times of 5–10 years. Yet the strong incentives of high prices in a tight market can lead to unexpected technological progress in order to cope with the situation: an instructive example is

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the historical cobalt crisis of the late 1970s. During this time, two-thirds of the world's supply of cobalt was taken off the market due to a civil war in the Shaba region of Zaire (now Democratic Republic of Congo). Despite the fact that few substitutes were known for the use of cobalt in high-tech applications like gas turbines and jet engines, strong R&D efforts initiated after the start of the crisis led to the development of several alternatives in the following years. Looking back on the crisis in 1983, the US CBO concluded that although the crisis had been harsh for individual cobalt-using sectors, the overall impact on the economy had remained very limited and new efforts into resource efficiency and substitution were already paying off. A comparison to the rare earths case shows strong similarities: perceived market tightness has spurred research efforts into permanent magnets and batteries that do not use rare earths or use them in smaller quantities. Additional sources of supply, both from new mines and mines that were previously in use but not able to compete with Chinese supplies, are being brought into production again and this will likely resolve the situation in the short to medium term. The irony is that simple economics actually gave China its current dominant position in the rare earths market: China was able to produce at much lower prices, given the country's access to cheap labour and lax environmental regulation. Although most reports now focus on the price increases caused by Chinese export restrictions, prices actually dropped significantly during the 1990s, which made some applications of rare earths possible that had previously been too costly. The main reason for the closure of the Mountain Pass mine in California in the USA, which provided 70% of the global supply of rare earths in the 1970s, was that it could no longer compete against such cheap Chinese supplies.

The above discussion should be taken as a pointer as to how to interpret the outcome of criticality studies and putting these results in an appropriate perspective: some of the minerals identified as 'critical' might only pose a temporary problem and other more long-term problems might not be highlighted enough by these studies. Thus, although shortlists of critical raw materials are well suited for focusing the attention of policy makers and highlighting many current issues, the lumping together of a variety of very different factors (e.g. short-term supply–demand imbalances against long-term producer dominance and political risks) can in fact obscure the nature of the underlying challenges. Moreover, the necessity of a common database for the comparison of different raw materials prevents or limits the extent to which some relevant issues (e.g. influence of emerging uses, recycling potential, influence of resource nationalism on supply trends, cradle-to-grave environmental impacts) can be considered in the analyses because data or assessments of comparable quality are not always available for all raw materials included in the analysis. Finally, the heavy reliance on historical data and the dynamic nature of raw material markets make criticality studies less suitable to guide long-term policy. Instead, when thinking about a timeframe of several decades, it is argued that it is more useful to step back and separately consider the different aspects that are hidden behind the lists or ranking of critical raw materials. This should include an analysis of (historical) trends and the way they are related to each other, an improvement of the quality of data required for criticality assessments as well as a move towards a more systemic and dynamic interpretation of the concept of criticality.

4. Relevance to civil engineering and related practice

The discussion around critical raw materials affects policy related to the supply of both primary (mining and related infrastructure) and secondary (recycling and urban mining) raw materials. Secondary raw materials are generally regarded as more secure than primary because they are locally available.

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