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Review

Reviewing resource criticality assessment from a dynamic and technology specific perspective – using the case of direct-drive wind turbines

Komal Habib*, Henrik Wenzel

Department of Chemical Engineering, Biotechnology and Environmental Technology, University of Southern Denmark, Niels Bohrs Alle 1, 5230 Odense M, Denmark

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ABSTRACT

The recent debate on potential resource constraints for the broad scale implementation of clean energy technologies in future has led to wider concern across the board. This concern, among others, lies behind growing research in the field of so-called *resource criticality*. This study is a review of existing resource criticality assessment methodologies. It characterizes and analyses existing methods and identifies aspects of concern for the ability of assessment methods to provide proper guidance for strategy making in the field of energy system development. The validity of the identified concerns is, further, demonstrated by applying a case study of resource criticality assessment of the direct-drive wind turbines technology. Two key concerns are identified. The first is the need for a *dynamic* perspective on the supply risk dimension. This study reveals that the geological reserve estimates and geographical location of supply change significantly over time, implying that the static supply risk assessment provided by many methods gives misleading guidance. The second concern is the ability of methods to properly account for the *vulnerability* of the studied system to a supply disruption of the resource in question. Through the case study, the options for resource substitution are elaborated for wind turbines by applying a holistic design approach looking at all levels of design substitutions from the level of materials and components to subassemblies and whole-product concepts. This approach reveals that the dependence of substances like neodymium and dysprosium is not strong, and that they are not essential to the wider implementation of direct-drive wind turbines in general. This technology specific and product design based approach is new, and questions the ability of existing methods to properly address the impact that the risk of supply disruption of a given resource really has on the technological and economic development of a system or technology under study.

1. Introduction

A transition from the current fossil based society to a future low-carbon society requires a broad scale implementation of clean energy technologies. Many such technologies, like wind turbines, solar cells, and electric vehicles are quite complex and advanced. They often include state-of the-art electronics and complex composite materials and alloys, which in turn contain both precious and scarce resources, like in some cases rare earth elements. This has led to a concern that a successful wider scale implementation of clean energy technologies may be constrained by limitations or disruptions in the supply of key resources. This concern, among others, lies behind growing research in the field of so-called "resource criticality".

The recent debate on critical resources in terms of potential supply constraints of raw materials is not new. The earliest reference to it, to our knowledge, dates back to 1939, just before the World War II, in the context of having a secure and uninterrupted supply of different raw materials for the U.S. military purposes (National Research Council, 2008). More recently, the

List of abbreviations: Dy, Dysprosium; EoL, End-of-Life; HHI, Herfindahl Hirschman Index; Nd, Neodymium; NdFeB, Neodymium-iron-boron; REEs, Rare Earths Elements; Sr, Strontium; WGI, Worldwide Governance Indicators.

* Corresponding author. Tel.: +45 24409707; fax: +45 65507354.
E-mail address: koh@kbm.sdu.dk (K. Habib).

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National Research Council (2008) initiated the whole criticality debate once again by highlighting the issue and coming up with a methodology to assess the critical resources for the U.S. economy. This methodology used a matrix approach assessing resource criticality in two dimensions: a concern for supply risk in the one dimension and a concern for the importance of supply risk in the other dimension. Later, this matrix concept was adapted and used in a number of studies, with varying assessment indicators to explore the criticality of resources at different organizational levels including global, regional and corporate (Bauer et al., 2010, 2011; European Commission, 2010, 2014; Duclos et al., 2010). Graedel et al. (2012) have suggested the most elaborated methodology, so far. By this approach, they assess the criticality of resources in three dimensions, i.e., the supply risk, the vulnerability to supply risk, and the environmental aspects of supply (mining), and in doing so, further target the assessment towards different systemic levels, i.e., global, national and corporate levels.

1.1. Reviewing existing methodological approaches

The concept of *resource criticality assessment*, as it has been used till now, has analogies to the traditionally used concept of *risk assessment*. In the risk assessment of e.g. chemicals or chemical production & storage facilities, the probability or risk of an incident to happen causing releases of hazardous substances and exposure to recipients is assessed (Glöser et al., 2015). The risk assessment, thus, comprise two dimensions, the first being the probability of an incident/release, the second being the consequence such an incident/release can have. The two dimensions of the existing methodological approaches to resource criticality assessment are analogous: the first being the assessment of the probability/risk of a disruption in resource supply, the second being the importance of such a disruption or the vulnerability of affected technologies or systems/economies to such a disruption.

The majority of resource criticality assessment studies have relied on these two main dimensions applying *composite* indicators to each of them, which in turn further consist of a number of sub-indicators. The most commonly used composition of sub-indicators for the two main indicators covers:

i. **Supply Risk**: This indicator is used to identify any potential supply constraints of resources under consideration. Such supply risk of a resource may originate from a number of different underlying constraints such as:
   a) *Geological availability* of a resource is considered, the principal concern being the geological presence and availability of a resource. This indicator is often quantified by calculating the ratio of identified geological reserve[1]/reserve base[2] of a resource to its annual consumption, which results into the lifetime or depletion time of the identified reserve of the resource in question.
   b) *Geopolitical availability* of a resource is considered, the principal concern being geographically related political barriers to supply and availability of the resource in question. This, further, often covers two concerns, the first being the *share of global supply* a given supplying nation represents, the second being the state of political governance and stability of the nation in question.
      - *Global supply share* is an indicator representing the degree of monopoly or oligopoly one or a few nations has/have, i.e. the degree to which one or only few countries dominate the global supply of a resource. This parameter is assessed with the help of the widely used Herfindahl Hirschman Index (HHI) indicator, which shows the risk of potential supply constraints originating from a single or a few countries controlling the global supply of resources. The high HHI score shows highly concentrated supply, few producers and hence the greater supply risk; whereas low HHI score shows less concentrated supply, more producers and hence less supply risk.
      - *Worldwide Governance Indicators (WGI)* – a set of six sub-indicators has been used in a number of studies to assess the supply risk related to politically unstable countries being dominant producers of a resource. This indicator is provided by the World Bank and is aggregated based on a set of sub-indicators such as voice and accountability, political stability and absence of violence etc.

ii. **Importance of Supply Risk**: The importance of supply risk is the second dimension of resource criticality assessment, where the vulnerability of the system under study to potential supply constraints (and resulting price increases/fluctuations) is assessed. Importance of supply risk is also an aggregated indicator, meaning that it consists of a number of concerns specific to the system under consideration such as:
   - *Economic importance*, where the economic importance of a resource is assessed for a company or a geographical region i.e. how large is the impact of a potential shortfall in a given resource supply on the company's overall revenue or on the Gross Domestic Product (GDP) of a country or region.
   - *Substitutability*, where the ease or possibility of substitution is assessed for the resource in question, meaning that high degree of substitutability lowers the vulnerability of a system to the potential supply risk.

Fig. 1 illustrates some typical results of resource criticality assessment shown in the two dimensions.

The choice of sub-indicators and their aggregation into one main indicator/dimension differs from study to study. For example, the substitutability parameter is part of supply risk dimension in the EU methodology whereas it is part of the importance/vulnerability dimension in the methodology proposed by Graedel et al. (2012). Apart from these two most commonly used indicators/dimensions, the methodological approaches also differ on the *modelling assumptions/parameters*, including assumptions on the rate of recycling, the future growth in demand, unexpected demand by future innovations, etc. Further, the applied sub-indicators are often aggregated in an inexplicit and subjective manner.

Recently, Sonnemann et al. (2015) have presented a comprehensive review of resource criticality assessment methodologies. In the present study, we have provided a detailed overview of the assessment methods and indicators of resource criticality studies until now, which is presented in Table 1. In this overview, we have grouped all the indicators into the two main dimensions, i.e. the supply risk and the impact of supply risk. Further, the applied modelling assumptions such as recycling and future growth in demand are shown. As the table shows, most of the studies have incorporated geological availability, geopolitical supply risk (using the global supply share as indicator), and importance of supply risk (including substitutability) parameters.

[1] According to USGS, reserve is that part of reserve base (part of the total geological resource of a metal) which could be extracted or produced economically at the point of determination (Source: http://minerals.usgs.gov/minerals/pubs/mcs/2009/mcsapp2009.pdf).

[2] According to the USGS, reserve base is that part of an identified resource that meets specific minimum physical and chemical criteria related to current mining and production practices (Source: http://minerals.usgs.gov/minerals/pubs/mcs/2009/mcsapp2009.pdf).