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Circular economy strategies for mitigating critical material supply issues

Gabrielle Gaustad[a,b,*], Mark Krystofik[a,b], Michele Bustamante[c], Kedar Badami[a,b]

[a] *Golisano Institute for Sustainability, Rochester Institute of Technology, United States*
[b] *Center of Excellence, Advanced and Sustainable Manufacturing, 190 Lomb Memorial Drive, Rochester, NY 14623, United States*
[c] *Materials Systems Lab, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, United States*

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ABSTRACT

Raw materials deemed critical are defined as having potential issues in their supply, limited substitutes, and applications of importance, namely in clean energy, defense, healthcare, and electronics. Disruptions in supply of critical materials can have serious negative repercussions for firms, consumers, and economies. One potential set of mitigation strategies for firms dealing with criticality issues is the implementation of circular economy principles in their supply chain, operations, and end-of-life management. This work conducts a literature review combined with case study analysis to examine how certain firms assess and monitor their vulnerability to critical material supply chain issues and provides specific business examples for integrating circularity strategies. Results indicate the potential for risk reduction that could be gained from implementation of these strategies; specifically recycling, for example, can provide an in-house source (for prompt or fabrication scrap) or at least domestic source (for post-consumer scrap) for critical materials; up to 24% for the case of indium usage in China. Just in time manufacturing techniques have the potential to both exacerbate supply issues (by encouraging low inventory or needed resources for manufacturing) and improve supply issues by introducing resiliency in the supply chain indicating that approach of firms in undertaking these strategies is important. Many cases reviewed show other quantifiable secondary benefits beyond risk reduction, such as economic savings, reduction in energy consumption, and improved corporate social responsibility via enhanced supply chain oversight.

1. Introduction: what are critical materials and why should firms care?

In recent years, there has been growing interest in assessing materials availability due to increased use of materials, and particularly scarce materials in important technologies, creating growing risk of supply disruptions. Supply disruptions have the potential to occur via two distinct mechanisms: actual physical scarcity of a raw material or short-term shortages caused by rapid demand intensification, political unrest and instability, natural disasters, etc (Alonso et al., 2007a, 2007b). These risks are generally referred to as factors of material or resource criticality; however, what makes a material critical varies somewhat depending upon who is asked. For example, the US Department of Energy (DOE) considers material criticality as a measure that combines two dimensions: importance to clean energy and risk of supply disruption (Bauer et al., 2011). The European Commission defines critical raw materials as having high supply risk combined with economic importance to the European Union (Commission, 2014). The US Defense Logistics Agency (DLA, a part of the Department of Defense) uses the words “strategic and critical” in considering materials that “would be needed to supply the military, industrial, and essential civilian needs of the United States during a national emergency” (Critical Materials Stockpiling Act, 2014) and are likely to experience supply disruptions or stockpile shortfalls. The challenge in creating a current list of critical materials lies in the stakeholder-specific nature of criticality assessments. An excellent overview in creating a multi-stakeholder criticality perspective is available in (Graedel et al., 2012); this work explores several important metric approaches to criticality determination. Materials that are of concern for the US energy sector may not be of concern for the EU or even the US manufacturing or defense sector and vice versa. As shown in Fig. 1, there are significant areas of overlap and several materials considered critical (and strategic by DLA) by all three of these groups for their most recent reporting year. However, it should be noted that criticality is a dynamic property of materials. As products continue to utilize more and more elements from the periodic table and the demand for these products continues to increase; increased competition between sectors for the same materials will shift their criticality status. Concurrently, supply continues to become less diverse for many of these materials and socio-political issues may arise that could disrupt supply. Therefore, Fig. 1 is really only a

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[*] Corresponding author at: Golisano Institute for Sustainability, Rochester Institute of Technology, 190 Lomb Memorial Drive, 81-2175, Rochester, NY 14623, United States.
E-mail address: gabrielle.gaustad@rit.edu (G. Gaustad).

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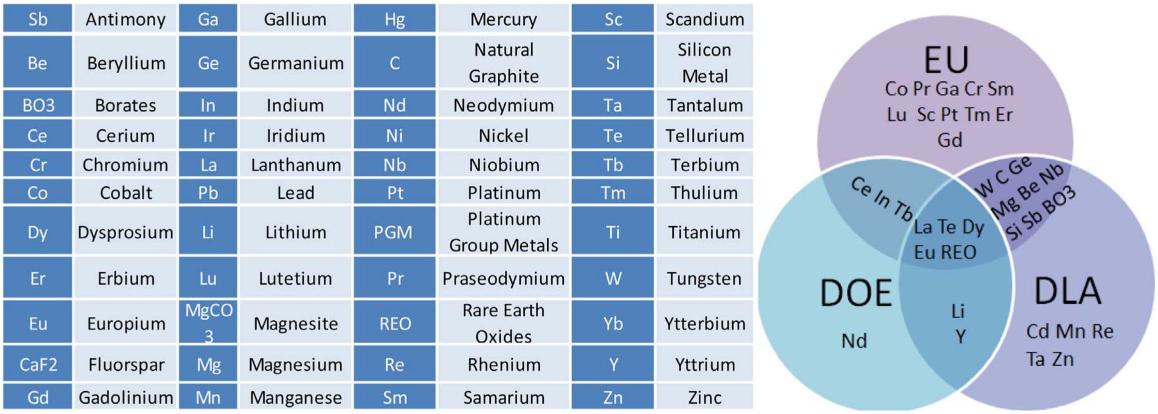

Sb	Antimony	Ga	Gallium	Hg	Mercury	Sc	Scandium
Be	Beryllium	Ge	Germanium	C	Natural Graphite	Si	Silicon Metal
BO3	Borates	In	Indium	Nd	Neodymium	Ta	Tantalum
Ce	Cerium	Ir	Iridium	Ni	Nickel	Te	Tellurium
Cr	Chromium	La	Lanthanum	Nb	Niobium	Tb	Terbium
Co	Cobalt	Pb	Lead	Pt	Platinum	Tm	Thulium
Dy	Dysprosium	Li	Lithium	PGM	Platinum Group Metals	Ti	Titanium
Er	Erbium	Lu	Lutetium	Pr	Praseodymium	W	Tungsten
Eu	Europium	MgCO3	Magnesite	REO	Rare Earth Oxides	Yb	Ytterbium
CaF2	Fluorspar	Mg	Magnesium	Re	Rhenium	Y	Yttrium
Gd	Gadolinium	Mn	Manganese	Sm	Samarium	Zn	Zinc

Fig. 1. Materials deemed critical by various groups including the US Department of Energy (DOE), the US Defense Logistics Agency (DLA), and the European Union (EU). Some groups call out specific REEs (eg. Ce, Er, etc) in addition to all listing REOs in general. (Romans 2008; Bauer et al., 2010; Commission, 2014; Thomason et al., 2015).

Table 1
Sectors of relevance for selected critical and near-critical materials (Dresselhaus et al., 2001; DoE, 2005; Bauer et al., 2010; Chu, 2011).

	Clean Energy	Defense Applications	Electric Vehicles	Electronics	Lighting
Cerium		X	X	X	X
Dysprosium	X	X	X		
Europium		X	X	X	
Gallium	X	X		X	X
Germanium	X	X			
Indium	X	X			X
Lithium		X	X	X	
Neodymium	X	X	X	X	
Praseodymium	X	X	X	X	
Tellurium	X	X		X	
Yttrium		X	X	X	X

static snapshot and example of critical materials. Table 1 shows some of the relevant industrial sectors that have demand for these critical materials including clean energy, defense applications (which include essential civilian and industrial sectors according to DLA), electric vehicles, electronics, and lighting. Many other sectors make use of critical and strategic materials as well including metal processing, healthcare, information and communication services, and chemical production.

The high-level perspective taken by most assessments (global or national) makes it difficult and potentially inappropriate for firms to directly apply the findings to inform their supply-chain management strategies. As a result, recent work has been undertaken to develop and quantify metrics for assessing criticality of materials as these metrics are key indicators of supply risks for firms within the technology lifecycle (Erdmann and Graedel 2011; Chu and Majumdar, 2012). Large-scale national (Japan, US) and multi-national (EU) efforts are currently underway to systematically assess criticality for specific sectors of interest to a variety of stakeholder groups (Matsumura 2001; Bauer et al., 2011; Pacheco-Torgal 2014). Supply gaps, even short-term, have the potential to create significant price volatility and commodity price uncertainty (Alonso et al., 2007a, 2007b; Craighead et al., 2007). For example, in the 1970's, a small scale uprising in Zaire (now the Democratic Republic of the Congo) created a short-term cobalt supply shortage as 40% of global production was mined in that geographic area. This caused massive spikes in the commodity price of cobalt, as shown in Fig. 2, which resulted in speculation, government stockpiling, and massive disruption to firms in the semiconductor industry (Alonso et al., 2007a, 2007b). Anywhere from 30%–60% of the cost of a semiconductor chip manufactured in the 1980's was materials costs, with cobalt being a significant contributor (Peters et al., 1995). Now, lithium ion batteries which also rely heavily on cobalt, face a similar vulnerability as, cathode materials make up 25% of the total cost with cobalt being the largest contributor to cost by far (Henriksen et al., 2002). Fig. 2 also shows the recent spike in rare earth oxide prices for comparison. A massive price spike would not be able to be passed on to consumers in these two case examples as well. Assessment of import reliance shows that even today the US may be quite vulnerable to similar supply disruption events for a number of other materials, including bismuth, germanium and rare earths, for which it is even more heavily reliant upon supply from a single country:, China (see Fig. 3).

Beyond severe price volatility, even temporary supply shortages can cause a variety of other challenges for firms, including production bottle-necks, long lead times, and failure to deliver on-time products. The further downstream firms are from material suppliers, the more severe these impacts can be; a phenomenon often referred to as the bull-whip effect (Lee et al., 1997). These effects will only magnify as firms continue to move toward just-in-time manufacturing (aka Toyota production system, short-cycle manufacturing, lean, etc.). Industries where materials make up a large portion of the total product by weight or by value are particularly at risk. A recent survey of industry executives revealed that many firms feature products containing at least 1/4 of components with scarce minerals and metals by weight and by value, including the automotive sector, energy and utilities, infrastructure, and the renewable energy sector (Fig. 4A) (Schoolderman and Mathlener, 2011). The automotive sector particularly has concerns with platinum group metals used in catalytic convertors and for rare earth metals used in alloying specialty steels (Nansai et al., 2014). The renewable energy sector relies on rare earth magnetics for rotors in wind turbines, tellurium, gallium, indium, and selenium in thin-film solar cell technologies (Alonso et al., 2012). Wide electric vehicle adoption relies on a growing supply of lithium, cobalt, nickel, and natural graphite. Within the automotive sector specifically, raw materials have been estimated to constitute nearly half of the cost of a vehicle (see Fig. 4B) (Kallstrom, 2015), suggesting economic impact vulnerability to material supply disruptions due to this heavy reliance upon materials.

The present work provides a brief overview of how some firms are currently assessing and monitoring their vulnerability to critical material supply chain issues and uses a case study analysis approach to propose strategies based on a combination of circular economy principles and supply chain management practice for mitigating their risks.

2. Methods: circular economy principles for criticality mitigation

Information from academic literature as well as firm and business case studies available in the literature and, miwere combined with original insight gathered by the authors via industry contact to first report on how companies frame and quantify material criticality internally. Firm cases were selected based mainly on quantified data availability or contacts willingness to share unpublished quantified