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Material Criticality Assessment and Resource Nexus Analysis

Gavin M. Mudd

Introduction and brief background

There has always been basic human needs for reliable water, food, shelter and community – but the past few centuries has seen substantial growth in demands for a range of metals and minerals to meet the demands of new technologies, infrastructure and modern lifestyles, including both civilian and military needs and desires (e.g. Rankin, 2011; von Gleich et al., 2006). Throughout the 20th century the common metals of copper, iron, lead, zinc, nickel, tin, silver and gold found increasingly widespread use in a range of contexts, such as buildings and infrastructure, piping systems for gas, water and sewerage, telecommunications, power transmission systems and electrical wiring, military equipment, munitions and technologies and consumer appliances, among others (e.g. Graedel et al., 2015; Spitz and Trudinger, 2008). The past few decades, however, has seen a major transformation with modern demands now including a considerably wider range of metals for specialty alloys, high-performance electronics (especially mobile phones, flat screens and computers), chemical catalysts, renewable energy technologies (especially wind turbines, solar photovoltaic panels), hybrid electric-petrol or fully electric transport vehicles and military technologies (e.g. NRC, 2008; Skirrow et al., 2013). These new ‘technology’ metals include indium, molybdenum, gallium, germanium, selenium, tellurium, cobalt, rhenium, the six platinum group elements, the family of rare earth elements (REEs) and perhaps a few others. Given that the demands for technology metals include uses such as consumer electronics and renewable energy, uses which are expected to grow considerably in coming decades, these metals are often considered vital to meet the reasonable technological, social and environmental needs of our 21st century global society – hence they are often labelled as ‘critical’ due to their fundamental importance.

These ‘technology’ metals, however, are generally not mined in their own right but are mostly (if not entirely) derived as by-products incidental to the mining of the primary metals – meaning that supply of a particular technology metal is entirely dependent on the host primary metal, a situation often referred to as ‘companion metals’. At present, many technology metals are produced by a small number of countries or companies (or less), meaning any disruption to supplies could have significant consequences for uses such as consumer electronics or renewable energy. For example, rhenium is dominantly sourced from Chile and China has a near
monopoly on rare earths – meaning any changes to export policies or supply potential from these countries would significantly and negatively affect all the technological uses of such metals.

Over the past decade there have been a variety of formal assessments of which metals in particular are critical (e.g. BGS, 2015; EC, 2014; NRC, 2008; Skirrow et al., 2013) – along with important developments and improvements in the methodologies adopted to assess the extent to which an individual element can be regarded as critical. This chapter examines the primary concepts involved in mineral resources, mining and supply, examines the factors used to assess criticality, and discusses the wide variety of complex and often inter-related factors which affect the criticality of numerous metals which are increasingly in demand in the modern world. Finally, these issues are discussed in content of the resource nexus – the relationships between metals supply and other environmental, social and economic factors which will underpin our ongoing ability to meet potential supply scenarios for numerous technology metals.

**Theoretical approaches to assessing criticality**

Over the past decade there has been widespread interest in determining which metals are critical and in improving the methodology used to assess criticality. The most common groups interested in such assessments are government agencies responsible for policy (e.g. US Department of Energy), national or international scientific agencies (e.g. US or British Geological Surveys, US National Academy of Sciences, European Commission), companies (suppliers or consumers) and the industrial ecology research community. In general, there are a range of factors which can be incorporated into criticality assessment, but the fundamental concerns involve the degree of supply risk and the impact of supply disruption to particular uses.

In the US, the National Research Council (NRC, 2008) used a two-axis approach to assessing criticality, involving the importance of use and availability of a given metal or mineral, as shown in Figure 9.1. The first component is focussed on the impacts of possible supply

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**Figure 9.1** US National Research Council framework for assessing criticality

*Source: NRC (2008)*
disruptions and considers the various uses of a particular metal, the ease and relative cost effectiveness of substitution and the scale of its use. The second component addresses where supply is currently sourced from, including geologic or mineable reserves, current production, the ease and degree of recycling, environmental, economic and social constraints on production (especially political stability), as well as the spread of production across countries or regions. Similarly, the European Commission (EC, 2014) uses dimensions of economic importance and supply risk in their assessments of critical metals and minerals, with their most recent assessment shown in Figure 9.2.

More recently, the Centre for Industrial Ecology at Yale University developed a more comprehensive methodology (see Graedel et al., 2012) for quantifying criticality, keeping supply risk and disruption as key elements but also adding a third dimension of the environmental implications. An example of the matrix approach used to quantify supply risk is shown in Figure 9.3, with a similar matrix for the vulnerability to supply risk. The environmental implications are derived from life cycle impact assessment values for human health and ecosystem impacts. By varying the input values and their relative weighting, different perspectives can be adopted (such as corporate, national or international) as well as the sensitivity of criticality to particular factors (also shown in Figure 9.3).

The major challenge with any assessment of the criticality of a particular metal or mineral is the extent and quality of data which underpins it. For some aspects, such as current primary supply, there is reasonably reliable annual production data for many major metals (e.g. copper, iron, gold, zinc, etc.) but not for some of the technology metals (e.g. gallium, scandium) – but for reserves in particular, there are often major gaps in knowledge of global reserves for many technology metals (in contrast to regular assessments for major metals). Furthermore, understanding key issues such as substitution and vulnerability to a supply disruption require extensive

![Image of Figure 9.2](image_url)
investigation to assess and quantify, as well as the environmental implications of metals and minerals extraction.

At heart, there is no criticality methodology which explicitly includes the nexus between energy, food, water, metals and minerals (or even social issues). To an extent they may be able to be included indirectly in some of the factors shown in Figure 9.3 (e.g. higher energy costs as ore grades decline could be included under technological in supply risk), but this leaves such assessments as somewhat subjective. Furthermore, the environmental implications do not directly address the complex relationship between energy and metals and growing impacts as ore grades decline – although they could be indirectly assessed, or values varied for a sensitivity analysis, this is not a satisfactory or comprehensive approach. Recycling can be a key component of current supply (e.g. lead), and it is difficult to address future trends in metals recycling in criticality assessments. Finally, it must be remembered that criticality assessments are a snapshot in time

Figure 9.3  a and b  Factors used to assess and quantify supply risk (left) and visual representation of criticality and sensitivity to input parameters (right)

Source: Graedel et al. (2012)
and are not intended to cover temporal changes in metals supply, vulnerability to supply or the growing environmental implications of mining (e.g. more mine wastes, greater energy and water needs, etc.).

In the remaining parts of this chapter, the focus will be on mineral resources and mine production, as these are generally this most crucial aspects in understanding the criticality of any metal or mineral – that is, a review of the key trends and factors which affect metals supply.

**Essential concepts and issues in metal mining**

**Mineral resources**

In essence, to make a metal worth extracting from the earth’s crust there needs to a sizeable body of enriched rock – that is, rich concentrations in rock from which the metals of interest can be extracted, with typical enrichment factors ranging from tens to thousands of times crustal
abundance. Over the past century, and especially the past few decades, the global mining industry has developed standardised methodologies to conduct such assessments, often embodied in codes, guidelines or standards which are required by industry associations or statutory legislation. For example, Australia uses the JORC Code, Canada uses National Instrument 43–101, South Africa has the SAMREC Code, Europe has PERC and so on. The common elements in these and similar approaches are the concepts of ore reserves and mineral resources, which are crucial in understanding the criticality of all metals (or other resources such as oil, phosphate, etc.).

In simple terms, ore reserves are based upon detailed drilling, geological, metallurgical, mine planning and numerous other studies to demonstrate that mining has a high likelihood to be profitable, whereas mineral resources are less studied and certain than ore reserves but are similar in nature and there are reasonable prospects for eventual economic extraction. Ore reserves consist of proved and probable reserves, while mineral resources include measured, indicated and inferred resources, with the key components being increasing geological confidence in a mineral deposit and the range of modifying factors which can affect the potential to mine a deposit, such as environmental, economic, legal, metallurgical and other factors which facilitate or hinder development, as shown in Figure 9.4.

For many primary metals, it is possible to compile a detailed assessment of reported mineral resources (or ore reserves), to synthesise a regional, national or even global assessment of a particular metal of interest – arriving at an estimate of tonnes of metal ‘X’, which can be compared to current global annual production rates to derive a crude estimate of the years of supply currently estimated to be remaining.

While the primary metals enjoy wide reporting, often due to their widespread nature and large volume and economic importance, almost all technological metals are not the main target during primary mining and there is minimal to negligible data reported for such metals in ore reserves or mineral resources – often related to the lack of value attributed to such metals during primary mining. This paucity of reserves/resources data makes it very difficult to assess the ability to meet potential future demand scenarios – which can often be (easily) confused with a lack of reserves/resources. In other words, although we don’t have extensive data on the reserves/resources of technology metals does not mean we are potentially constrained by geological resources in the ability to meet growing future demands.

**Figure 9.4** Typical conceptual relationship between ore reserves and mineral resources

*Source: AusIMM et al. (2012)*
Current trends in reserves-resources and future potential

The main group which compiles estimates of global reserves of metals and minerals is the US Geological Survey, published annually in their Mineral Commodity Summaries (USGS, 2016) – although they have data for copper, gold, iron, lead, zinc and many other primary metals, they have no current estimates for gallium, germanium, hafnium, indium, scandium and thallium (and incomplete estimates for others such as tantalum, tellurium).

Overall, there is good evidence that global reserves-resources of most major metals continues to grow – as shown for copper (Mudd et al., 2013a), nickel (Mudd and Jowitt, 2014), platinum group elements (Mudd, 2012), cobalt (Mudd et al., 2013b), lithium (Mohr et al., 2012) and more recently indium (Werner et al., 2017). Although the same has yet to be demonstrated for the various technology metals and minerals (excluding the recent indium study), this is largely a function of the fact that these sectors are still relatively minor in value for the global mining industry and the extent of reporting to date for numerous mineral deposits remains minimal (albeit increasing in recent years). That is, based on experience in the major metals sectors, it is reasonable to expect that similar trends will eventually be discernible for the various technology metals – especially since most technology metals depend on primary metal resources in the first place. The reported reserves or resources of copper are shown in Figure 9.5 over time, including both global and selected countries.

Figure 9.5  Historical trends in copper reserves or resources by global or selected countries
Source: data updated from Mudd et al. (2013a)
Table 9.1 Current global production, reserves and/or resources of various primary and technological metals by world or country

<table>
<thead>
<tr>
<th>Primary metals</th>
<th>Copper</th>
<th>Lead</th>
<th>Zinc</th>
<th>Nickel</th>
<th>Iron ore</th>
<th>Gold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global production (2015) [1]</td>
<td>18.7 Mt Cu</td>
<td>4.71 Mt Pb</td>
<td>13.4 Mt Zn</td>
<td>2.53 Mt Ni</td>
<td>3,320 Mt Fe ore</td>
<td>3,000 t Au</td>
</tr>
<tr>
<td>Global reserves (2015) [1]</td>
<td>720 Mt Cu</td>
<td>89 Mt Pb</td>
<td>200 Mt Zn</td>
<td>79 Mt Ni</td>
<td>186,000 Mt Fe ore</td>
<td>56,000 t Au</td>
</tr>
<tr>
<td>Years remaining</td>
<td>~38.5 years</td>
<td>~18.9 years</td>
<td>~14.9 years</td>
<td>~31.2 years</td>
<td>~56.0 years</td>
<td>~18.7 years</td>
</tr>
<tr>
<td>Australia – reserves (2014) [2]</td>
<td>141.0 Mt Cu</td>
<td>50.42 Mt Pb</td>
<td>92.73 Mt Zn</td>
<td>43.1 Mt Ni</td>
<td>139,875 Mt Fe ore</td>
<td>14,013 t Au</td>
</tr>
<tr>
<td>Canada – reserves (2010) [3]</td>
<td>10.75 Mt Cu</td>
<td>0.4 Mt Pb</td>
<td>4.133 Mt Zn</td>
<td>3.07 Mt Ni</td>
<td>no data</td>
<td>1,473 t Au</td>
</tr>
<tr>
<td>South Africa – reserves (2013) [4]</td>
<td>11 Mt Cu</td>
<td>0.3 Mt Pb</td>
<td>14 Mt Zn</td>
<td>3.7 Mt Ni</td>
<td>650 Mt Fe ore</td>
<td>6,000 t Au</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Technology metals</th>
<th>Cobalt</th>
<th>Indium</th>
<th>Gallium</th>
<th>Germanium</th>
<th>Lithium</th>
<th>Platinum</th>
<th>Palladium</th>
<th>Rhenium</th>
<th>Selenium</th>
<th>Tellurium</th>
<th>Rare earths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global production (2015) [1]</td>
<td>124 kt Co</td>
<td>755 t In</td>
<td>~435 t Ga</td>
<td>~165 t Ge</td>
<td>~32.5 kt Li</td>
<td>178 t Pt</td>
<td>208 t Pd</td>
<td>46 t Re</td>
<td>no data</td>
<td>no data</td>
<td>124 kt REOs</td>
</tr>
<tr>
<td>Global reserves (2015) [1]</td>
<td>7,100 kt Co</td>
<td>no data</td>
<td>no data</td>
<td>no data</td>
<td>14 Mt t Li</td>
<td>66,000 t PGEs²</td>
<td>2,500 t Re</td>
<td>120 kt Se</td>
<td>25 kt Te</td>
<td>130 Mt REOs</td>
<td></td>
</tr>
<tr>
<td>Years remaining</td>
<td>~57.3 years</td>
<td>no data</td>
<td>no data</td>
<td>no data</td>
<td>~430 years</td>
<td>~150 years</td>
<td>~54.3 years</td>
<td>no data</td>
<td>no data</td>
<td>~1,048 years</td>
<td></td>
</tr>
<tr>
<td>Australia – reserves (2014) [2]</td>
<td>2,610 kt Co</td>
<td>no data</td>
<td>no data</td>
<td>no data</td>
<td>~1.712 Mt Li</td>
<td>343 t PGEs²</td>
<td>no data</td>
<td>no data</td>
<td>no data</td>
<td>58.1 Mt REOs</td>
<td></td>
</tr>
<tr>
<td>Canada – reserves (2010) [3]</td>
<td>no data</td>
<td>no data</td>
<td>no data</td>
<td>no data</td>
<td>no data</td>
<td>no data</td>
<td>no data</td>
<td>no data</td>
<td>no data</td>
<td>no data</td>
<td></td>
</tr>
<tr>
<td>South Africa – reserves (2013) [4]</td>
<td>no data</td>
<td>no data</td>
<td>no data</td>
<td>no data</td>
<td>no data</td>
<td>66,000 t PGEs²</td>
<td>no data</td>
<td>no data</td>
<td>no data</td>
<td>no data</td>
<td></td>
</tr>
<tr>
<td>Recent detailed global studies</td>
<td>26,793 kt Co [9]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>~23.6 Mt Li [10]</td>
<td>90,783 t PGEs [11]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>619.5 Mt REOs [12]</td>
<td></td>
</tr>
<tr>
<td>Common Source Primary Metals [1]</td>
<td>Ni, Cu</td>
<td>Zn</td>
<td>Al, Zn</td>
<td>Zn</td>
<td>-</td>
<td>Ni-Cu</td>
<td>Cu-Mo</td>
<td>Cu</td>
<td>Cu, Pb</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

A compilation of various sources of global production and reserves-resources data is shown in Table 9.1, along with some estimates at a national level. The first critical aspect to note is whether the estimate is reserves or resources. For example, Canada reports reserves of 10.75 million tonnes (Mt) of copper and 3.07 Mt of nickel – yet detailed assessments of resources shows 54.12 Mt Cu (Mudd et al., 2013a) and 21.92 Mt Ni (Mudd and Jowitt, 2014). Similarly, South Africa’s reserves of PGEs are reported as 63,000 tonnes of PGEs (CMSA, 2014; USGS, 2016) yet when analysing project by project as strictly reported by PGE companies in South Africa, Mudd (2012) estimates reserves of 9,884 tonnes of PGEs with an additional 62,455 t PGEs in resources (i.e. total ~72,339 t PGEs, or more than the global reserves of 66,000 t PGEs from USGS (2016). Although many of the metals display ~20–30 years remaining, this is based on reserves only, and this aligns with the shorter term timeframes for mine planning and not the larger mineral resources – and the value of ~20–30 years of remaining reserves has been maintained for several decades despite growing global production.

Given ongoing mineral exploration, new discoveries, resource expansions, technological improvements in mining and ore processing, favourable economics (especially demand and prices versus input costs), it is reasonable to justify an optimistic view of meeting resource needs for some decades – across both primary metals as well as technology metals. There are several caveats to this, discussed later, as these are crucial in understanding the criticality of different metals.

**Current trends in global metals production**

In general, almost all metals have continued to display long-term growth in annual production globally. The trends are shown for primary and technological metals in Figure 9.6, using production...
Figure 9.6  Continued
### Table 9.2 Global production in 2015, main supplier countries and relative production to 1900 or 2000

<table>
<thead>
<tr>
<th>Metal</th>
<th>Global production 2015</th>
<th>Largest national producer (fraction)</th>
<th>Global production relative to 1900(^a)</th>
<th>Global production relative to 2000(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>18.7 Mt Cu</td>
<td>Chile (30.5%)</td>
<td>37.8</td>
<td>1.42</td>
</tr>
<tr>
<td>Lead</td>
<td>4.71 Mt Pb</td>
<td>China (48.8%)</td>
<td>6.29</td>
<td>1.47</td>
</tr>
<tr>
<td>Zinc</td>
<td>13.4 Mt Zn</td>
<td>China (36.6%)</td>
<td>28.0</td>
<td>1.53</td>
</tr>
<tr>
<td>Nickel</td>
<td>2.53 Mt Ni</td>
<td>Philippines (20.9%)</td>
<td>272</td>
<td>2.15</td>
</tr>
<tr>
<td>Gold</td>
<td>3,000 t Au</td>
<td>China (16.3%)</td>
<td>7.77</td>
<td>1.16</td>
</tr>
<tr>
<td>Silver</td>
<td>27,300 t Ag</td>
<td>Mexico (19.8%)</td>
<td>5.06</td>
<td>1.51</td>
</tr>
<tr>
<td>Iron ore</td>
<td>3,320 Mt Fe ore</td>
<td>China (41.6%)</td>
<td>23.2(^a)</td>
<td>2.06(^a)</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>267 kt Mo</td>
<td>China (37.8%)</td>
<td>26,700</td>
<td>1.98</td>
</tr>
<tr>
<td>Cobalt</td>
<td>124 kt Co</td>
<td>DRC (50.8%)</td>
<td>507(^a),(^b)</td>
<td>2.54(^a)</td>
</tr>
<tr>
<td>Gallium</td>
<td>435 t Ga</td>
<td>China</td>
<td>27.2(^c)</td>
<td>4.83</td>
</tr>
<tr>
<td>Germanium</td>
<td>165 t Ge</td>
<td>China (72.7%)</td>
<td>4.04(^d)</td>
<td>2.36</td>
</tr>
<tr>
<td>Indium</td>
<td>755 t In</td>
<td>China (49.0%)</td>
<td>11.0(^e)</td>
<td>2.25</td>
</tr>
<tr>
<td>Lithium(^f)</td>
<td>590 kt Li(^e)</td>
<td>Australia (41.2%)</td>
<td>158(^e)</td>
<td>2.89(^e)</td>
</tr>
<tr>
<td>Platinum group elements</td>
<td>~460 t PGEs</td>
<td>South Africa (51.3%)</td>
<td>69.4</td>
<td>1.26</td>
</tr>
<tr>
<td>Rare earth elements</td>
<td>124 kt REOs</td>
<td>China (84.7%)</td>
<td>119</td>
<td>1.36</td>
</tr>
<tr>
<td>Rhenium</td>
<td>46 t Re</td>
<td>Chile (56.5%)</td>
<td>7.04(^e)</td>
<td>1.28</td>
</tr>
<tr>
<td>Tantalum</td>
<td>1,200 t Ta</td>
<td>Rwanda (50.0%)</td>
<td>3.09(^b)</td>
<td>1.12</td>
</tr>
</tbody>
</table>

**Source:** USGS (2016)

**Notes:** \(^a\)data for 2014; \(^b\)relative to 1901; \(^c\)relative to 1973; \(^d\)relative to 1957; \(^e\)relative to 1972; \(^f\)data remains inconsistent for lithium production, with some sources appearing to be spodumene concentrate (e.g. 590 kt in 2015) and others containing lithium (e.g. 32.5 kt in 2015); \(^g\)relative to 1925; \(^h\)relative to 1969.
relative to 1900 (or the earliest year of production data). Overall, most metals show strong growth, but some display exceptional growth, such as nickel, molybdenum and cobalt – all alloying metals – or lithium and the rare earths, which are both closely aligned with the rise of modern electronics and allied uses. A summary of 2014 global production and the major supplier countries is shown in Table 9.2, showing the clear dominance of China in particular for numerous metals but also Chile for copper and rhenium, Australia for lithium, Rwanda for tantalum and South Africa for PGEs.

A key aspect in assessing criticality is the supply risk – or in other words, whether a supply is dominated by particular countries (or country) or a small number of supplier companies. As shown by Table 9.2, there is a strong concentration of almost all of the important technology metals in just a few countries (as well as several primary metals such as copper) – meaning any changes to export policies could significantly affect the ability to continue to produce the range of technologies which rely on such metals (e.g. renewable energy, consumer electronics). Another important point to note is that some metals in particular are derived from regions which are perceived to be socially unstable or perhaps somewhat volatile (e.g. Rwanda, DRC, South Africa), highlighting that the rest of the world has a clear economic (let alone humane) interest in seeing real progress on human development in these countries.

Finally, given that many technology metals are extracted as opportunistic by-products from metal refineries, it is important to understand these trends over time. For example, indium is dominantly extracted from zinc refineries, rhenium from molybdenum refineries or tellurium from copper refineries – with the ratio of global refined technology metal to host primary metal for these examples shown in Figure 9.7. Curiously, tellurium shows a gradual decline in apparent
refinery extraction efficiency, while rhenium appears to have plateaued but indium continues to increase. While these collectively may be a reflection of refinery processing technology, especially the growing dominance of solvent extraction-electrowinning technology in copper refineries (meaning tellurium recovery becomes less economic), it is unclear whether this is also a function of declining ore grades in or concentrate grades from source mining projects. Given that current process technology and recovery rates in primary metal refineries are commonly geared towards the primary metal and not the by-product technology metal, this would suggest that it is possible to increase technology metal production (assuming the normal economic factors of demands, prices and costs are aligned).

**Potential constraints to future supply**

The depletion of the world’s endowment of non-renewable mineral, metal and energy resources often focuses on ‘how much is left’ or ‘how many years left’ – yet in reality there are many complex factors at play which will influence how much and at what rate various resources are made available for human use. This is a large area of literature and scholarly debate, and the most important factors are listed and briefly noted herein:

- **Declining ore grades** – As documented in the various global resource studies noted earlier, ore grades of primary mining continue to decline for all metals – meaning that more ore has to be mined and processed and generating more tailings per unit metal, increasing the environmental footprint exponentially. At some point in the distant future (i.e. latter 21st century perhaps), it may be more economic and preferable to mine secondary stocks and wastes for their metal content rather than primary mining;
- **Waste rock (overburden)** – As mining has moved to increasingly large open-cut mine techniques, this has exponentially increased the quantities of waste rock involved, which increases costs during mining as well as rehabilitation needs and long-term environmental liabilities;
- **Life cycle assessment (LCA) studies** – LCA studies show that as ore grades decline, energy, greenhouse gas emissions and other aspects increase exponentially, increasing the environmental footprint of mining substantially;
- **Value proposition for technology/by-product metals** – At present, most of the technology metals with strong growth prospects are all produced as a by-product of a primary metal at a refinery (see Table 9.1) and mines receive negligible to zero value for such metals – thus the economic incentives are not clear and direct for increasing production, especially since technology metals remain dependent on their primary host metal in the first place (i.e. there appears to be a need to increase primary metal production to increase technology metal production);
- **Environmental issues** – A variety of environmental risks and impacts need to be managed pro-actively during mining and refining of all metals, and many communities remain concerned about such risks, especially mine waste management, acid and metalliferous drainage (i.e. acid mine drainage or AMD), tailings management (especially the potential for catastrophic failures), rehabilitation effectiveness and post-mining land use, carbon price and responses to climate change, dust management, ecological and biodiversity changes, surface water and groundwater resources impacts (especially long-term changes to local or regional hydrologic regimes), etc.
- **Role of recycling** – Although metals are in theory recycling, at present many uses are diffuse or in small quantities, making recycling technologically or economically difficult, despite recycling commonly having a lower environmental footprint in the supply of a metal;
• **Social issues** – Concerns over social impacts or risks, especially economic benefit sharing, can lead to significant community opposition to new mining projects.

There are many examples globally where deeply held concerns about existing or proposed mining projects has led to some deposits becoming inaccessible to any development. For example, concerns over AMD and other environmental risks led to the exclusion of any development of the large Windy Craggy deposit in British Columbia, Canada (the area is now a world heritage-listed national park); concerns over extensive environmental and social impacts from the (now-former) substantial Panguna copper-gold-silver mine on Bougainville Island in Papua New Guinea led to its shutdown – the ensuing civil war between locals and the national government led to an estimated death toll of thousands of Bougainvillean people; political, security and social concerns has delayed the development of the sizeable Reko Diq project in Pakistan; deeply held environmental and social concerns appears to have effectively delayed any development of the super-giant Pebble project in Alaska, US. This list could continue, but it is sufficient to show that there are numerous and often complex but well-justified reasons to opposition to new mining projects or the expansions of existing mines.

**Case study: the complex family of the rare earth elements**

**Uses of rare earth elements**

The rare earths family of elements, strictly the lanthanide family of elements plus scandium and yttrium (i.e. 17 elements), are finding increasing uses in a range of modern technologies due to their unique physical and chemical characteristics. These uses include permanent magnets in renewable energy, medical equipment, military technology, consumer electronics, phosphors, alloys and chemical catalysts – almost all of which are expected to grow in demand substantially in coming decades. For example, the development of high-performance neodymium-iron-boron permanent magnets in the 1980s has allowed the rapid evolution and deployment of various consumer electronics using such magnets (especially computers) as well as improving the performance of turbines for electricity generation (especially wind turbines). Overall, there is a strong growth trajectory expected for rare earth elements to meet the demands of an increasingly affluent global population and its increasingly complex technological mix.

The generation of electricity from wind energy has been the fastest growing source of electricity over the past two decades, growing from a cumulative installed capacity of 7.6 GW in 1997 to 369.6 GW in 2014 (GWEC, 2015). Over time, wind turbines have become larger and more efficient, with current designs for onshore and offshore turbines increasingly using rare earths to improve economics and productivity. For example, recent designs by wind turbine manufacturer Vestas include ~0.5 t REOs to reduce the need for steel, aluminium, polymers and other materials in their V112 wind turbine model, leading to an ~15% reduction in lifetime greenhouse gas emissions intensity from these turbines compared to those turbine models which do not use rare earths (D’Souza et al., 2011; Garrett and Ronde, 2014).

Other strong sources of demand growth for rare earths include electric vehicles, solar photovoltaic (PV) panels, batteries for energy storage (especially in consumer electronics), among others. The primary problem, however, is that the uses with the best prospects for demand growth are known as the heavy rare earths (or HREEs) (Jowitt et al., 2013; Zepf, 2016), which constitute only a minor fraction of total rare earths production. There are consistent concerns that to meet future HREE demands, especially from secure and stable suppliers, that total REE production will need to substantially exceed current total production of REEs just to meet an
individual REE need – this is known as the ‘balance’ problem. To solve the balance problem is difficult – it implies the need for massive over-production of all REEs just to meet a single REE demand, or the need to find a substitute material with similar properties or effectiveness which hitherto has not been discovered. But from a mining-refining perspective, the total costs and revenues are not driven by a single element but the whole REE family, as well as potential co/by-products such as phosphate, uranium, niobium, iron, zircon and hafnium – making the economics of REE projects difficult to assess and predict.

Mineral resources of rare earths

A recent study by Weng et al. (2015) examined in detail the currently known global mineral resources of rare earths, which are found in a wide range of mineral deposit types. Despite the name ‘rare’, rare earth deposits are certainly widespread. Although current production is dominated by China due to the super-giant Bayan Obo iron–REE mining complex in Inner Mongolia and the HREE-dominant mines in the Seven Southern Provinces, future production could be sourced from a wide variety of possible projects. Weng et al. (2015) showed that there is at least 619.5 Mt of total rare earths (including REO+Y) known in reported and estimated resources – and given 2015 global production of ~124 kt REOs (see Table 9.1 or 9.2), this means of the order of thousands of years of potential future supply.

Therefore, there is clearly an abundance of already known mineral resources (let alone other potential sources of REOs in poorly quantified mineral resources such as heavy mineral sands, see Mudd and Jowitt, 2016) which can meet optimistic long-term demand scenarios – so the primary issue remains short-to-medium term production and demands and especially the fraction of HREEs.

In the near term, potential REE projects outside of China may need to develop new ore processing technologies, focus on HREE over LREE products, or focus on developing HREE-dominant projects. This is already happening, as the recently approved Dubbo-Toongi project in Australia recently has chosen to stockpile LREE from their proposed process configuration to focus on sales of HREE and other co-products of zirconium, hafnium and ferro-niobium. Of further note is that despite the recent crisis in the rare earths sector (i.e. China’s 2010 export restrictions and the massive spike in prices over 2010–2011), only one new REE mine was developed globally (Mount Weld, Australia with a refinery in Malaysia) – highlighting the particular difficulty in developing REE mines. Overall, there needs to be clarity in understanding the difference between known resources and current and future production, especially the HREE-LREE split for projects (although detailed statistics by individual REE are rarely published, especially on a global basis).

Criticality of rare earths

In reality, despite extensive global mineral resources and the potential for production outside of China, the rare earths will remain labelled as critical due to the ongoing supply dominance of China, the fact that there remain little substitutes for the REE in most of their uses and the balance problem makes the economics of REE production difficult to predict.

Discussion: criticality assessments of metals and the resource nexus

The application of criticality methodologies are intended to help in understanding the dynamics of a particular metal (or mineral, or any other resource) – to explore where bottlenecks
may exist (e.g. technology metals dependent on primary metals), where opportunities are (e.g. new sources of supply, new process technology), or to investigate policy options (e.g. conflict minerals). At heart, criticality allows the assessment and management of risk (e.g. prices, policy changes, social unrest, etc.). With respect to the resources nexus, however, a variety of aspects remain which current criticality methodology does not address directly (or at least could be addressed indirectly but not clearly), and these are discussed below in sections 5.1 to 5.4.

**Water resources and impacts from mining**

As mines grow in scale and ore grades decline (e.g. Mudd, 2007; Mudd et al., 2013a), so too does the need for water to supply mines as well as their footprint in catchments (see Northey et al., 2013). That is, bigger mines consume more water but can also present significant risks to water resources (both quantity and quality), as evidenced by recent major tailings dam failures (e.g. Mount Polley, Canada; Samarco, Brazil) or ongoing acid mine drainage (e.g. the Tinto region of southern Spain, Witwatersrand Basin, South Africa), among others. Although the mining industry recognises water as a strategic sustainability issue (e.g. IIED and WBCSD, 2002), with considerable work done by many companies, water-related risks will grow continue to grow in importance and drive a greater nexus between metals supply and water issues. For example, concerns over potential impacts to water resources and associated biodiversity and ecosystems can drive significant social opposition to mining projects (e.g. Windy Craggy, Canada, now stopped; Pebble, Alaska, US, where development is delayed). Although a recent study (Sonderegger et al., 2015) adapted criticality methodology for water, it was intended for water quantity only and does not account for water quality. Therefore, at present, criticality assessments do not address the metals–water nexus.

**Energy sources and consumption**

Similarly to water, as mines grow in scale and ore grades decline (or if the ore becomes more refractory and difficult to process), they require exponentially more energy (both diesel for machinery and electricity). This represents not only a direct operating cost to mines, but also magnifies the environmental impacts due to the additional impacts from this higher energy consumption (especially if the energy sources are carbon based, such as diesel and coal, which give rise to significant greenhouse gas emissions linked to climate change risks). In theory, increasing energy costs could be quantified using LCA studies and included in the ‘geological, technological and economic’ component of criticality (see Figure 9.3), but this is currently not done and it would require a comprehensive assessment of all existing mines and mineral resources for their energy intensity – clearly outside the scope of a standard criticality assessment.

The energy needs for the mining of metals could be met with renewable energy sources, such as biodiesel (for machinery), wind turbines, solar photovoltaic panels or solar thermal with heat storage (or a myriad of other options which be present locally), and this could also accommodate greater energy needs – it depends on economics, local renewable energy resources, and ultimately whether the focus is on energy security, capital and operating costs or climate change adaptation.

A related issue is that as the energy intensity of metals increases (assuming no improvements in technology and/or energy efficiency during mining), this will increase the embodied energy of any product using that metal. For example, a wind turbine uses a range of metals (e.g. copper, iron, neodymium, etc.) and as the energy costs increase for these metals, the embodied energy of the wind turbine increases, meaning the energy return on energy invested, declines also. This
leads to a greater need for energy productivity in the wind turbine, which given the rapid evolution of wind technology in recent decades, shows that there is certainly room for optimism on this front. There are similar arguments which could also be presented for other technologies used in energy systems, such as solar panels (especially the wide array of possible metals which can be used in various designs), lithium-based batteries or even geothermal or solar thermal systems, but there is a strong need for considerable research in this area.

In the end, although criticality assessments may conduct sensitivity analyses to address the energy issues for metals supply (and use for energy supply), they cannot explicitly capture the complex relationships and issues which link the supply of metals and energy.

Metals required to supply metals

A rarely examined issue is the metals required to mine and produce metals (e.g. t Cu input per t Cu supply). As ore grades decline, the size of mineral deposits often increases (see Mudd et al., 2017; Mudd et al., 2013a), meaning that larger project scales are possible and economic and they can therefore produce greater amounts of metals over a mine’s life. The larger processing plants and bigger excavators and haul trucks clearly require more metals to manufacture, but whether this is offset by the larger size of the project and greater amounts of metals produced is unclear. While it can reasonably be expected not to be a significant issue, especially in comparison to energy and water nexus issues, it is one which remains poorly addressed.

Social and economic aspects

Social and economic issues, perhaps unsurprisingly, can be especially difficult to address well in criticality assessments (as noted with some examples previously).

The current Yale-led methodology includes components of social, regulatory and geopolitical factors (see Figure 9.3), using data from regular surveys such as the Fraser Institute’s annual survey of the mining industry’s perception of investment in a particular country or jurisdiction or the United Nation’s Human Development Index (UNHDI). While these are useful, they are surveys conducted external to communities and do not necessarily represent a local community’s views towards mining – and therefore supply risk may be incorrect and often overly optimistic (e.g. numerous mining-related social conflicts across the breadth of the Americas; e.g. Tambogrande, Pebble, Famatina, Pascua Lama, Mount Tolman, Crandon, Marlin, etc.). The Fraser Institute is an industry body and certainly does not represent community views. To address this, community surveys could be undertaken or literature analysed to explore sources of conflict (e.g. Davis and Franks, 2014), but this requires extensive work – although it may deliver very different results to those suggested by the Fraser Institute survey or the UNHDI on their own. The common themes in community concerns with respect to mining projects include environmental risks (e.g. water depletion, water quality impacts from AMD, landscape change), economic impacts (e.g. benefits go to multinational companies and not locally compared to the level of negative impacts received, such as higher costs of living, no investment in education by government, etc.) or cultural issues and sacred sites (i.e. sites fundamental to local culture and need protection; e.g. former Coronation Hill Au-Pd-Pt-U project in Australia). Another area of great social complexity is the issue of conflict minerals in central Africa – although the US included sections in the Dodd-Frank Act to address this issue, with some of the most critical metals emanating from this region, it remains controversial as to whether policy intervention in this way has helped or hindered the negative impacts on the ground. In reality, the incorporation of social aspects into criticality assessments will always be constrained by the methodology.
adopted, and especially victim to the sources of data used (and their independence and relevance to the communities involved), but it remains fundamental that such issues be acknowledged and considered.

Economic (or in reality, more socio-economic) issues are another area of great difficulty for criticality assessments. While standards measures for different regions have readily available metrics, such as income per capita or level of education, these are not necessarily indicative of social concerns with respect to mining and therefore supply risk. To a limited extent, they can be included in the Fraser Institute survey results, as opinions by mining company management on social risks are implied in their results, but this is far from a satisfactory basis upon which to explore such factors which could affect supply risk. In addition, costs of labour, energy, chemicals, infrastructure and taxation regimes may also affect economic risks of mining projects, especially in some countries perceived to be more volatile politically.

Overall, it is possible to conceive of a variety of ways to add several axes for criticality assessment to the current three-axis approach (perhaps leading to a matrix-based assessment) – such as social, economic, energy, water and so on. In the end, the level of detail is up to the user of such assessments, and in particular their purpose – for example, a corporation sourcing metals, a government managing high-technology industry sectors, military defence procurement strategies, individuals concerned about the supply of the metals used in goods and services they consume, or similar.

**Summary: insights into the criticality assessments of metals and the resource nexus**

Criticality assessments provide a methodology or framework to understand the current supply and uses of metals and minerals (or other materials or resources), and allow deeper insights into the dynamics of a particular metal and its applications. A wide variety of metals, especially important technology metals, are currently labelled as critical due to the supply dominance of a few countries (or less) and the lack of their substitutability for crucial applications. However, the labelling of such metals as critical has often led to confusion that we are ‘running out’ – despite strong evidence that there are still abundant mineral resources to meet current and future demands for some decades. Furthermore, there is little recognition that such criticality assessments are based on a wide array of data and assumptions, and that often there is a major lack of data to underpin the detail required for a thorough criticality assessment. There is clearly a need to consider a variety of nexus-related issues in criticality, as they can indeed be important and even affect supply – the extent of analysis can be widened, deepened and expanded in scope to include a wide array of factors and issues (e.g. social, economic, energy, water), but this also makes the assessment more difficult to complete. Ultimately, it depends on your purpose as to what level of detail one works towards – it remains fundamental to acknowledge that the criticality of a particular metal is dependent on a considerably more complex array of factors than those currently addressed in criticality assessments.

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**References**

AusIMM, MCA, and AIG. (2012). *Australasian code for reporting of exploration results, mineral resources and ore reserves: The JORC code*. Parkville, VIC: Joint Ore Reserves Committee (JORC) of The Australasian Institute of Mining and Metallurgy (AusIMM), Minerals Council of Australia (MCA) and Australian Institute of Geoscientists (AIG), December, 44 p.


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