Materials Availability:

Comparison of material criticality studies – methodologies and results

Working Paper III

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Preface

This report has been produced by the UK Energy Research Centre's Technology and Policy Assessment (TPA) function. The TPA was set up to address key controversies in the energy field through comprehensive assessments of the current state of knowledge. It aims to provide authoritative reports that set high standards for rigour and transparency, while explaining results in a way that is useful to policymakers.

This working paper addresses some of the issues arising in the contemporary debate on materials availability, specifically examining metals critical to the development of low carbon technologies. The subject of this assessment was indicated as of importance independent experts from government, academia and the private sector.

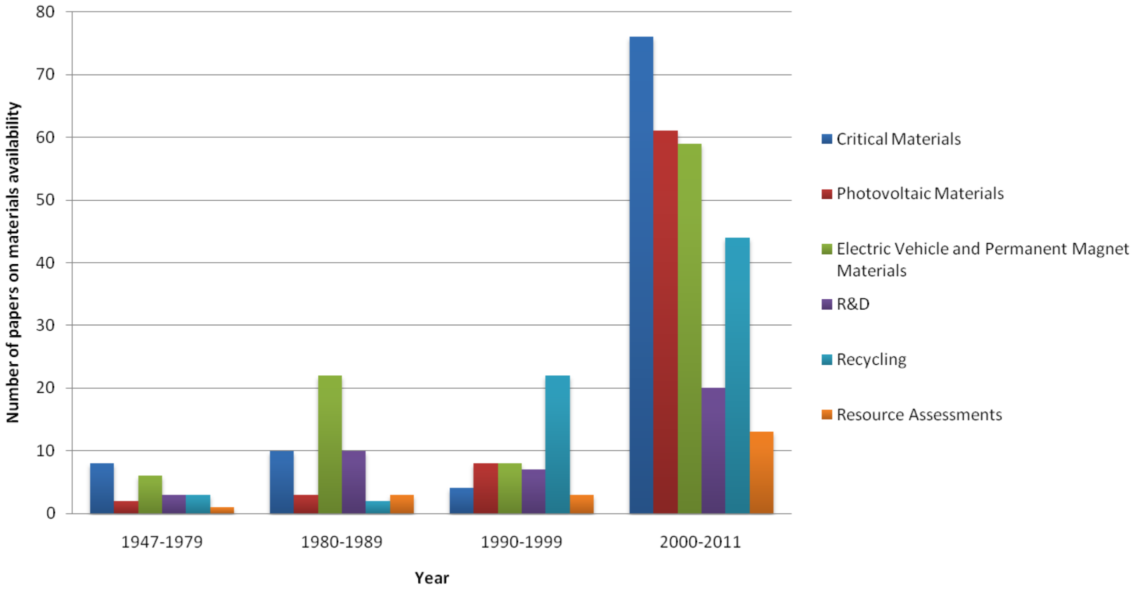
Abstract

Policy makers and industry are increasingly concerned over the availability of certain materials key to the manufacture of low carbon technologies. The literature addressing this topic includes reports termed ‘criticality assessment’ that aim to quantify the relative criticality of a range of materials. In this study we examine the methodologies underpinning these criticality assessments, and attempt to normalise and compare their results. This process identified a list of 10 metals or metal groups for which average normalised scores are presented, along with maximum and minimum scores to indicate the range of uncertainty. We find that criticality assessment methodologies diverge significantly, making comparison difficult. This leads to apparently wide uncertainty in results. We also find that in order to achieve comparability within studies, authors typically rely on simple metrics for which data is available for all metals considered. This leads to some compromises which affect results. Finally we suggest that, given these uncertainties and methodological difficulties, criticality assessments are best used to highlight materials or technologies of particular interest, which should then be further examined in isolation, to improve insight and accuracy.

1 Introduction

The availability of the more exotic metals has increasingly concerned the manufacturers of low carbon technologies. While only a few decades ago, energy technologies were made of the more common metals—iron, nickel, aluminium, cobalt—today their 'materials palette' has expanded dramatically (Graedel 2011), and now over 70 different metals are commonly utilised in manufacturing (Duclos *et al.* 2010). The availability of some of these metals is now uncertain given significant price increases and export quotas, and concerns have been raised over the implications for manufacturing low carbon technologies and the resulting impact on the achievability of decarbonisation goals. In addition, governments, corporations and research institutes have increasingly published articles, assessments and analyses of these so-called 'Critical Metals', building an important body of literature that has grown significantly in the last decade (Figure 1).

Figure 1. Number of published papers on materials availability by topic, 1947-2011.



Note: Results obtained based on a systematic review of the available literature on materials availability, following the systematic review process utilised by the UK Energy Research Centre (UKERC) Technology and Policy Assessment (TPA) theme. See http://www.ukerc.ac.uk/support/TPA+Overview

This paper conducts a review of the 'assessments of metal criticality', comparing their methodologies and results in an attempt to characterise the evidence base and examine the criteria on which metal criticality is assessed. This review includes reports focussed on metals used in low carbon technologies, and those examining criticality of materials from a wider manufacturing perspective, often referred to as *material* criticality assessments. After examining the different assumptions and levels of sophistication in various studies, we expose the divergence in results and comment on the most useful aspects of metal criticality assessments, focusing on metals used in low carbon energy technologies.

Recent literature reviews the existing criticality assessment studies. Most notably, a review by Erdmann and Graedel (Erdmann and Graedel 2011) examines 10 criticality studies. The review highlights the impact on results of metric choice, weighting, scope, study focus or perspective (i.e. metals critical to the globe, an individual country or an industry etc.) and the number of materials analysed. In addition to this paper, recent criticality assessments (DOE 2011; Moss *et al.* 2011) and discussion papers (Schüler *et al.* 2011; Peiro *et al.* 2012) review previous methodologies, listing the methods used and the materials designated critical. This study focuses on metals used in low carbon energy technologies such as wind turbines, thin-film photovoltaics and electric vehicles, and builds on previous work by providing a comparison of results based on normalised scores, allowing for measurement of the uncertainty surrounding the assessments of certain metals, and incorporates a number of recently published criticality studies that have not appeared in previous comparisons (Achzet *et al.* 2011; BGS 2011a; DOE 2011; Moss *et al.* 2011; SEPA 2011; Graedel *et al.* 2012; Nassar *et al.* 2012).

We identify 15 studies (National Research Council (NRC) 2007; Morley and Eatherley 2008; Angerer *et al.* 2009; Buchert *et al.* 2009; Rosenau-Tornow *et al.* 2009; AEA Technology 2010; Duclos *et al.* 2010; EC 2010; Achzet *et al.* 2011; BGS 2011a; DOE 2011; Moss *et al.* 2011; SEPA 2011; Graedel *et al.* 2012; Nassar *et al.* 2012) with sufficient methodological detail which we discuss below (Annex 1). From this initial comparison a number of key differences can be seen in scope, technological focus, timeframe and number of materials analysed. These all contribute to the difficulty in normalisation and comparison.

Excluded from this comparison are studies which have no mention of low carbon energy technologies, such as defence-focused criticality assessments (Thomason *et al.* 2008), studies which discuss critical materials but do not clearly define and apply a criticality assessment methodology (OECD 2010; Parthemore 2011) and studies that are specific to a certain metal or technology (Feltrin and Freundlich 2008; Fthenakis 2009; Wadia *et al.* 2009; Yaksic and Tilton 2009; Kara *et al.* 2010; Gruber *et al.* 2011; Wadia *et al.* 2011).

In Section 2 we discuss and compare the different methodologies used in assessing metals criticality, breaking down this analysis to examine each of the criteria in turn. In Section 3 we present the results of a normalization process designed to create some level of comparability between studies. In Section 4 we discuss these results before concluding in Section 5.

2 Methodological Comparison

In the assessment of metal criticality authors typically gather together a range of metrics or ‘factors’ representing important variables determining the future availability of metals. A range of metals or other materials are then assessed and scored against these factors before aggregating scores (with weighting in some cases) to provide a relative measure of criticality. While methodologies developed to assess metal criticality vary widely, there are some commonly assessed factors. These factors are listed in Annex 2 alongside the 15 studies considered here. They are:

- Supply factors, including
    - Geological availability, economic availability and recycling
- Geopolitical factors, including
    - Policy and regulation, geopolitical risk, and supply concentration
- Demand factors, including
    - Future demand projections, and substitutability
- Other factors, including
    - Cost-reduction via technology and innovation, environmental issues, economic importance/ impact, and media coverage.

All studies reviewed here consider geological and economic availability and the concentration of material supply (i.e. how many countries or companies can supply a material). Most of the studies include a measure of recycling, substitutability and geopolitical risk, although the measure may be qualitative or subjective. A number of other factors—policy and regulation, cost reduction, environmental issues, economic importance and media coverage—are used in some studies. In this section, we discuss the main methods used in these studies to quantify or assess these common factors.

There are two issues associated with assessing the methodologies used in the studies in Annex 2. First, there are some studies which appear to discuss issues surrounding a particular factor, without including that factor in final scoring. Though these discussions highlight a level of understanding, this does not translate to the criticality score, and is therefore not reflected in any comparison made. Criticality studies can also be ambiguous, and it is not always easy to interpret the method used to derive a criticality score, or identify the factors included. In comparing the methodologies of these studies, we attempt to identify only the factors that are directly included in the assessment, which can be difficult due to issues discussed above.

2.1 Supply Factors

Supply factors, those factors associated with the physical availability of a metal or material, are the principal factors in a criticality assessment, and are considered in a number of forms and with varying complexity in all studies presented in Annex 2. Supply factors are usually presented as three components:

- geological availability, a measure of what is physically present;
- economic availability, a measure of what can be economically accessed; and
- recycling, a measure of the availability of metal recovery from end-of-life products.

Social and environmental concerns may also form part of supply risk in some studies (National Research Council (NRC) 2007; Graedel *et al.* 2012) but in this comparison we consider these as separate criteria in Annex 2.

The 15 studies considered here use similar methods to measure geological availability. Its evaluation involves examining data on the global resource of a particular metal, and the global annual production and demand for it. This data can be found in various sources but is overwhelmingly sourced from the *Mineral Commodity Summaries* and *Minerals Yearbook*, two annual reports published by the U.S. Geological Survey (USGS) (USGS 2008; USGS 2012), based on data reported by resource-endowed countries. For many metals, the USGS publish the only up-to-date and continuous data on world reserves, resources and production. The USGS divides its total resources by level of uncertainty: *reserves* are those quantities of the resource that can be recovered with proven technology and current economics while the *reserve base* encompasses parts of the resource that have a reasonable potential for becoming economically available within planning horizons beyond those considered reserves.[1] Other commonly used sources include national geological surveys (BGR 2011; BGS 2011b) and independent consultants such as Roskill (Chegwidden and Kingsnorth 2011) and Industrial Minerals Company of Australia (IMCOA) (Kingsnorth 2010). In the studies considered here, however, these are mostly used as supplements to the USGS data.

In order to quantitatively assess the geological availability of a metal or classify it in terms of supply risk, studies often employ a multiplying factor or ratio. Examples of this can be found in a number of studies (Morley and Eatherley 2008; Angerer *et al.* 2009; EC 2010; Moss *et al.* 2011) where estimated future demand for a metal is compared with current global production. The factor or ratio reflects the relative difference between current production and estimated future demand.

Another, more commonly used ratio is the *reserves-to-production* (R:P) ratio, used in seven studies as shown in Table 1[2]. The R:P ratio is used by BP in its annual publication *Statistical Review of World Energy* (BP 2011) to express the number of years remaining until resources such as coal, oil, and natural gas are depleted assuming static reserves and static global production. While it is a simple and recognised metric, both the reserves and the production of any resource are highly dynamic and the R:P ratio gives very little information regarding future supply concerns. A discussion of the inadequacy of R:P ratios for the assessment of future availability of a resource can be found in (Sorrell *et al.* 2009).

An alternative to R:P ratios is presented by Graedel *et al* (2012) to evaluate the so-called 'geological, technical and economic' (GTE) component of supply risk. This metric is called the *Depletion Time* (DT) and also measures the number of years before a metal resource is depleted. However, depletion time is not simply the ratio of reserves to production but is

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[1] Definitions of resources and reserves can be found in Appendix C of the USGS Mineral Commodity Summaries (USGS 2012)

[2] An analogous metric, the reserves-to-consumption ratio, is used in the Öko Institut and UNEP study (Buchert *et al.* 2009)

calculated based on an iterative spreadsheet model and incorporates recycled metal resources by modelling end-of-use lifetimes. This is further discussed below. The equation for DT also allows for more sophisticated evaluation using future scenarios for world demand, recycling rate and lifetime of end-use products. However, in the application of this methodology to the 'copper geological family'[3] (Nassar *et al.* 2012), demand, recycling rate and lifetime were assumed constant for simplicity. Moreover, for metals estimated by UNEP(2011a) to have zero recycling rates, the equation was reduced to an R:P ratio. The authors noted that a more sophisticated analysis is in development and is to be published in future papers. The DT calculation also lacks a form of geological constraint. The calculation contains an inherent assumption that future production (minus any losses) is equal to future demand minus end-of-life recycling i.e. future supply always meets future demand.

Not all resources are cost effective to produce and this is acknowledged in the *economic availability* component of 14 studies. The acknowledgement and inclusion of economic availability is usually implicit in the use of USGS data, most commonly reserve and reserve base data, as defined above. Economic availability is also discussed and explained in these studies, although no study identified here undertakes modelling of economic availability over time. Metal price fluctuation can be considered part of economic availability, and is quantitatively incorporated in the assessments of three studies (AEA Technology 2010; Duclos *et al.* 2010; SEPA 2011).

Recycling is a key factor in calculating future supply, but is not always included in criticality assessments. Key recycling variables include the average lifetime of products (end-of-life (EOL)); and the future recycling rate. Recycling rates vary and at present a significant portion of the energy metals have very low recycling rates (UNEP 2011a). Increasing these rates will depend on the resource economics over time—a high metal price incentivises more recycling—although this is not modelled in any criticality assessment. Graedel *et al* (2012) provide the most sophisticated modelling of recycling, using a Weibull distribution to estimate the useful lifetime of products, but assuming present-day recycling rates, presented in a recent UNEP study (UNEP 2011a).

2.2 Geopolitical factors

Geopolitical factors can be used to describe three supply criteria linked to national policies and global markets (as opposed to mining and extraction or 'below ground' factors). These three criteria are:

- policy and regulatory risk; a measure of risks domestic policies and public opposition pose to mining industries;
- geopolitical risk; a measure of the risks posed by political instability and policy actions to global material trade and supply; and

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[3] The 'copper geological family' (Nassar *et al.* 2012) consists of copper and its by- and co-products: arsenic, selenium, silver, tellurium and gold.

- supply concentration; a measure of the number of different countries producing a material.

These factors may limit the availability of certain metals that are not geologically scarce, and are often included in criticality assessments either qualitatively or quantitatively. These factors also inter-relate, with policy and regulatory risk representing the domestic implications, geopolitical risk representing the global implications, and supply concentration representing the relative impact of domestic or global policy implications on material availability. Quantification of geopolitical factors, and other factors discussed below, often employs indices compiled by third party organisations. The list of indices and the studies using them is shown in Table 1.

2.2.1 Policy and regulation

Policy and regulation is a factor used in some studies to assess the risk that existing national policies may pose to the mining industry, as well as public opposition to mining projects due to perceived negative environmental or socio-economic effects. This factor is considered qualitatively in a number of studies (DOE 2010; DOE 2011) while it is quantified in others (National Research Council (NRC) 2007; Graedel *et al.* 2012). Quantification of this factor usually employs the Policy Potential Index (PPI), a metric produced by the Fraser Institute and serving as “a ‘report card’ to governments on the attractiveness of their mining policies” (McMahon and Cervantes 2011). The PPI takes into account taxation and regulation that affect exploration and mining investments. Two other metrics produced by the Fraser Institute as complements to the PPI are the Current Mineral Potential Index (CMPI), a measure of the resource endowment of a certain region at present, and the Best Practices Mineral Potential Index (BPMPI) a measure of the theoretical resource endowment assuming ‘best practice’ policy measures (McMahon and Cervantes 2011); these are used in the NRC study (National Research Council (NRC) 2007) to quantify the policy and regulation factor, but their weighting and importance in determining the final criticality score is unclear. Graedel *et al* (2012) use the PPI along with the Human Development Index (HDI), a metric reported annually by the United Nations Development Programme (UNDP) that measures human development according to country statistics on health (e.g. life expectancy), education (e.g. years of schooling) and living standards (e.g. income per capita) (UNDP 2011). PPI and HDI are weighted equally to give a score of 0-100 for the ‘Social and Regulatory’ component of supply risk (Graedel *et al.* 2012).

2.2.2 Geopolitical risk

Geopolitical risk measures the risk of political instability or policy actions that may limit the global availability of a particular material. Examples of this risk are the high level of historical political instability in the Democratic Republic of Congo, which is a key supplier of cobalt, or the export quotas for rare earth metals applied by China, which currently supplies over 95% of world production (USGS 2012).

Geopolitical risk can be considered in combination with one or both of the other geopolitical factors (Rosenau-Tornow *et al.* 2009; DOE 2010; Duclos *et al.* 2010; EC 2010; DOE 2011) or as a separate criterion (Morley and Eatherley 2008; AEA Technology 2010; Moss *et al.* 2011; SEPA 2011). When it is considered as a separate criterion it is worth noting that geopolitical risk is only important if the supply of a particular material is judged to be geographically concentrated (see section 2.2.3). A number of metrics are used to quantify political instability and overall geopolitical risk: the World Governance Indicators (WGI) and a subset, the Political Stability and Absence of Violence/Terrorism (WGI-PV), both developed by the World Bank (Kaufmann *et al.* 2010); as well as the Fund for Peace's Failed States Index (FSI) (Fund for Peace 2011). The WGI measures cross-country governance using six 'dimensions': Voice and Accountability, Political Stability and Absence of Violence/Terrorism, Government Effectiveness, Regulatory Quality, Rule of Law, and Control of Corruption (Kaufmann *et al.* 2010). The FSI in turn measures geopolitical risk using 12 indicators across social, economic, political and military aspects: 1) Mounting Demographic Pressures; 2) Massive Movement of Refugees or Internally-Displaced Persons; 3) Vengeance-Seeking Group Grievance; 4) Chronic and Sustained Human Flight; 5) Uneven Economic Development; 6) Poverty and Sharp or Severe Economic Decline; 7) Legitimacy of the State; 8) Progressive Deterioration of Public Services; 9) Violation of Human Rights and Rule of Law; 10) Security Apparatus; 11) Rise of Factionalized Elites; and 12) Intervention of External Actors (Fund for Peace 2011).

Both indicators use freely available data yet aggregate them differently, resulting in sometimes varying results; the JRC study (Moss *et al.* 2011) examines both the WGI and FSI scores of key suppliers in order to assign a qualitative (High-Mid-Low) score for a metal's political risk. The inclusion of geopolitical risk is essential in assessing supply risk, although its consideration and usage of the WGI may not capture all of the more sensitive effects such as sudden political shifts, and is not particularly effective in longer-term assessments.

2.2.3 Supply concentration

The geographical concentration of supply is another important geopolitical factor, as the production of many of the metals used in low carbon energy technologies is concentrated in a small number of countries and regions (Moss *et al.* 2011). The likely impact of a policy or geopolitical risk is dependent of the proportion of global supply coming from the countries where these risks arise. The supply concentration is considered in all 15 studies in different ways. Most studies (National Research Council (NRC) 2007; Morley and Eatherley 2008; AEA Technology 2010; DOE 2010; DOE 2011; SEPA 2011) simply assign a score based on the number of supplying countries reported by the USGS (USGS 2012). Other studies (Rosenau-Tornow *et al.* 2009; EC 2010; Graedel *et al.* 2012) use the Herfindahl-Hirschman index (HHI), a commonly used measure of market concentration (DOJ 2010). The HHI is calculated using the squares of the market shares of different suppliers, so a higher HHI indicates a more concentrated market.

Inclusion of the supply concentration factor in a metal criticality assessment should take into account the fact that production concentration may change over time, particularly if the distribution of reserves of a metal differs from its production distribution. In the case of materials for low-carbon energy technologies, lithium and the rare earth elements are examples of metals with reserves more widely distributed than their production (Kara *et al.* 2010; Clarke 2011; Parthemore 2011). It is therefore likely that supply concentration of these metals will change in the future. The overall risk due to supply concentration for such metals should be adjusted for any foreseeable future changes, and an assessment of short- and medium-term mining projects in planning should be undertaken in order to assist this adjustment. This is done in varying depth in a number of studies (Rosenau-Tornow *et al.* 2009; DOE 2010; EC 2010; DOE 2011; Moss *et al.* 2011) but it is omitted in others (AEA Technology 2010; SEPA 2011; Graedel *et al.* 2012), resulting in an arguably pessimistic bias on geopolitical factors.

2.3 Demand Factors

Future demand for a metal is a key determinant of its future availability. Two factors commonly used in criticality assessment to capture demand are:

- Future demand projections; an estimate of the likely development of demand in the future; and
- Substitutability; a measure of the potential for reduction in future demand through substitution for other metals or technologies.

These factors are discussed in more detail below.

2.3.1 Future demand projections

Current global demand for many materials is published by trade journals, the USGS *Minerals Yearbook* (USGS 2010) or consultancy reports (Chegwidden and Kingsnorth 2011). Future demand is projected in a number of ways in different studies.

Morley and Eatherley (2008) and Rosenau-Tornow *et al.* (2009) use exogenous assumptions for future demand, citing consultancy and market analyst forecasts (e.g. Chegwidden and Kingsnorth (2011)). Graedel *et al.* (2012) allow for demand projections in their methodology, although these have not yet been applied (Nassar *et al.* 2012). Other studies incorporating future demand projections (see Annex 2) produce their own projections, often using expert opinion, based on assumed annual growth rates related to economic growth (Angerer *et al.* 2009; Buchert *et al.* 2009; EC 2010) or material intensity (the amount of metal demanded per unit of final product) (Angerer *et al.* 2009; DOE 2010; DOE 2011; Moss *et al.* 2011). Some of these studies assume current demand obtained from industry sources, while others attempt to provide results from mass analyses or adjusted theoretical intensity. Excluding selected cases (Angerer *et al.* 2009), no other criticality assessment makes adjustments for future reduction in material intensity which may arise through improved manufacturing techniques or partial substitution. A more sophisticated treatment of material intensity can be found in studies that are metal or technology specific (Feltrin and Freundlich 2008; Fthenakis 2009; Wadia *et al.* 2009; Yaksic and Tilton 2009; Kara *et al.* 2010; Gruber *et al.* 2011; Wadia *et al.* 2011). As a result, projections of future demand in criticality assessment studies often remain subjective.

2.3.2 Substitutability

Material substitution can be driven by material cost and can have a transformative effect on demand. Although all but 3 studies consider substitutability in their analyses, measuring this factor is difficult. One option is to use expert elicitation to decide which technologies are more inherently substitutable than others. This is done in many studies, although in some of these the source of expert opinion is not made clear (Morley and Eatherley 2008; AEA Technology 2010; SEPA 2011). Where expert opinion is not available or substitutes have not yet been fully developed then this factor becomes of limited use to the assessment, as substitutes can still arrive unforeseen. For most of the metals in energy applications, substitutes are either known or in development (USGS 2012), with the main exceptions to this being batteries using lithium, whose energy density is yet unparalleled (Armand and Tarascon 2008; Väyrynen and Salminen 2011), and rare earth permanent magnets for which there appears to be a consensus that their total substitution is very difficult (Jones 2011). However, for both these cases technological solutions exist. Induction motors which use no magnets can be substituted for permanent magnet motors in many applications, and vehicle designs less reliant on battery based energy storage such as fuel cell vehicles may substitute for battery electric vehicles.

2.4 Other factors

A group of other factors are used in some reports, though their use is less common than other factors:

- Cost reduction effects; representing supply or demand side effects associated with the reduction of technology costs associated with innovation and learning;
- Environmental issues; a measure of the potential for environmental impacts of material production to become an influence on future production through regulation ; and
- Economic importance; which measures how critical a material is to a particular economy.

The final criterion in Annex 2 is media coverage. This is used only in two studies, both by AEA Technology and both following the same methodology. Media coverage is assessed using the average number of press articles on the availability of each metal on the BBC website between 2007 and 2010. While media coverage may indicate public awareness of the supply risks of certain metals it remains a largely subjective factor which may not be useful in a criticality assessment. These three other factors are discussed in turn below.

2.4.1 Cost reduction via technology and innovation

Cost-reducing effects can be both demand and supply-related. The demand side includes reduction in the costs of technologies due to innovation and learning effects, or in material intensity. The supply side includes reductions in the cost of metal extraction, production, refining and recycling. Cost reduction effects are considered only in some studies (see Annex 2), and mainly include assumptions about future reductions in material intensity

(DOE 2010; DOE 2011) and assumptions that production costs will fall or remain the same (Rosenau-Tornow *et al.* 2009). Achzet *et al.* (2011) do not consider cost reduction via technology innovation, but account for the effects of more complex extraction and processing techniques on supply and price. As mentioned above, no study undertakes dynamic modelling in which certain resources such as recycled metal or currently sub-economic deposits become gradually profitable and accessible.

Graedel *et al.* (2012) conduct the only study to consider innovation directly in their methodology. For corporations, a qualitative indicator is assigned while for nations, the Global Innovation Index (GII) from the INSEAD Business School is used. The GII provides a score from 1-7 for 125 nations, with a higher score indicating a more innovative nation. The index is based on seven ‘pillars’: Institutions, Human capital and research, Infrastructure, Market sophistication, Business sophistication, Scientific outputs and Creative outputs. Other innovation scales exist (e.g. Porter and Stern (2002)) but are not used in any other studies.

2.4.2 Environmental Issues

Environmental issues or implications is a factor used in several studies, although the method and objective varies significantly between studies. The NRC (National Research Council (NRC) 2007), Volkswagen AG and Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) (Rosenau-Tornow *et al.* 2009) and DOE (DOE 2010; DOE 2011) studies consider this factor qualitatively, including it as a regulatory restriction to expanding supply. Morley and Eatherley (2008) include a score for three environmental factors: global warming potential, or the amount of CO_2 equivalent generated per kilogram of material extracted over 100 years; total material requirement, a measure of the amount of rock and substrate displaced by mining; and the vulnerability of key supplying regions to climate change. The environmental implications metric used by Graedel *et al.* (2012) indicates the potential environmental issues of using a particular metal, based on data from the Ecoinvent life cycle analysis (LCA) tool (Hischier *et al.* 2010).

By contrast, the European Commission (EC 2010) uses the Environmental Performance Index (EPI) to measure the risk that an important supplying country may take measures to protect its domestic environment and by doing so limit the supply of raw materials to the EU. This measure is also assessed explicitly by Graedel *et al.* (2012) in the social and regulatory component of their methodology, and it is possible, though unclear, that other studies implicitly assess this risk in their social, political and regulatory risk factors.

In general, however, environmental issues are only explicitly included in the methodologies of eight studies and their inclusion is sometimes qualitative or unclear. The importance of environmental implications also varies widely: while it is included in Graedel *et al.* (2012), it is not directly included in other studies using a criticality matrix (National Research Council (NRC) 2007; DOE 2010; EC 2010; DOE 2011) and thus does not form part of their pre-selection of critical metals.

2.4.3 Economic Importance

Economic importance is a factor inherent to any study with a national or corporate scope; in the latter case it is often termed ‘impact on revenue’ (Duclos *et al.* 2010; Graedel *et al.* 2012). Economic importance or impact on revenue often forms one axis of a criticality matrix (Duclos *et al.* 2010; EC 2010) or is incorporated into another axis metric such as impact of or vulnerability to supply restriction (National Research Council (NRC) 2007; Graedel *et al.* 2012). Economic importance is quantified in various ways in the literature. In the EC study (EC 2010) gross domestic product (GDP) and gross value added (GVA) are used to calculate economic importance, while the Yale University study (Graedel *et al.* 2012) assess this either quantitatively where possible on a scale of 0–100, or where qualitative assessment is more practical, a low, medium, high, or very high label is applied, and a score of either 12.5 (low) 37.5 (medium) 62.5 (high) 87.5 (very high) is applied. These scores are used to maintain quantitative comparability between factors. The scores are chosen by dividing the scoring range into 4 ‘bins’, each bin representing 25 points. The middle score for each bin is assigned to the qualitative labels, with the range surrounding these scores representing the apparent uncertainty associated with qualitative metrics.

2.5 Factors summary

The discussion above highlights the key factors in metal criticality assessment, the wide range of different methodological approaches, and some of the limitations of these approaches. Some factors, such as Geological Availability or Supply Concentration, are common to most studies, while other factors, such as Environmental Issues or Economic Importance, are used in a minority of studies. The choice and design of factors is dictated, to an extent, by the availability of data, leading to some compromises in methodology.

Table 1: List of common metrics and their issuing organisations (where applicable) used in criticality assessment methodologies of 15 studies.

Study	Year	Common metrics included in criticality assessment									
			UNDP	World Bank	Fraser Institute			Fund for Peace		INSEAD	Yale
		R:P	*HDI*	*WGI*	*PPI*	*CMP*	*BPMI*	*FSI*	*HHI*	*GII*	*EPI*
National Research Council	2007	✓			✓	✓	✓				
Oakdene Hollins	2008			✓							
Volkswagen AG & BGR	2009	✓		✓					✓		
Öko Institut and UNEP	2009	✓[a]									
Fraunhofer ISI	2009										
European Commission	2010			✓					✓		✓
US Dept. of Energy	2010			✓							
General Electric	2010										
AEA Technology	2010	✓									
US Dept. of Energy	2011										
SEPA	2011	✓									
EC Joint Research Centre	2011							✓			
British Geological Survey	2011			✓							
University of Augsburg	2011	✓									
Yale University	2012	✓[b]	✓	✓	✓				✓	✓	

Notes: a) Öko Institut and UNEP use a reserves to consumption ratio, which is a notable analogue to R:P. b) Yale University use a so-called '*depletion time*' metric which also includes in-use stocks, the availability of in-use stocks and estimated recovery rates; however, this metric also employs reserves or reserve base (the latter used in the longer term criticality assessment), and present global demand, and equally results in a number of years until depletion.

3 Normalisation of criticality scores

In this section we normalise the criticality 'scores' of a number of studies in an attempt to systematically compare them and to expose the range of conclusions for each metal. A number of caveats apply for this normalisation process, and these are detailed below.

The criticality 'scores' for all studies in Annex 1 were transformed to a uniform numerical scale. In order to limit the number of metals considered we selected only those metals judged critical in the studies themselves. Notable exceptions are Angerer *et al.* (2009) and the British Geological Survey (BGS 2011a), where metals are ranked by an indicator rather than classified critical. These studies were used to supplement the criticality range for metals designated critical in other studies.

This normalisation was possible for a number of studies (National Research Council (NRC) 2007; Morley and Eatherley 2008; Angerer *et al.* 2009; AEA Technology 2010; DOE 2010; EC 2010; BGS 2011a; DOE 2011; Moss *et al.* 2011; SEPA 2011; Nassar *et al.* 2012) which provided clear classifications of critical metals. Rosenau-Tornow et al (2009) only applied their methodologies to the case of copper thus not giving sufficient results for comparison. Duclos *et al.* (2010) disclose only one of their seven critical metals, giving insufficient information on results, and thus were also excluded. The US Department of Energy studies (DOE 2010; DOE 2011) provide short- and medium-term scores, both of which were included. The Graedel *et al.* (2012) methodology has so far been applied only to copper and its five by-products in a separate paper (Nassar *et al.* 2012); the scores for these six metals have been included, although it has not been possible to compare this methodology with the others for all metals. Buchert *et al.* (2009) could not be included because it did not report actual scores but 'prioritised' metals based on a number of criteria regarding demand growth, supply risk and recycling limitations using a plus (+) or minus (-) scale with unclear weighting. Finally Achzet *et al.* (Achzet *et al.* 2011) was not included because it did not include aggregate scores or ranking for the 19 metals considered.

The scores for critical metals in the literature are reported in a number of ways including: an explicit numerical scale, a criticality matrix with two coordinates for the two axes, or a qualitative low-mid-high scale[4]. In the criticality matrix case, the two coordinates were simply summed to give a total score. In the qualitative case, the low-mid-high scale was replaced with a 1-3 scale. All of these numerical scales were then transformed to give a scale of 0 to 10, and this allowed for comparison and display in Figure 2.

Using this normalisation procedure resulted in a list of 38 metals found in 11 of the 15 studies listed in Annex 1. This list reflects the various end-uses and technological sectors considered in the studies. Since this paper is primarily focused on the materials critical to

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[4] In the case of the JRC study (Moss *et al.* 2011), a weighting system is used in combining the four factors into an 'overall criticality' score. However, the details of this weighting are not made clear in the report, and we have assumed no weighting for the factors when normalising the scores. This did not alter the original ranking of critical metals reported in the study.

low-carbon energy technologies, we extracted from the overall list a subset of ten materials most relevant to clean energy technologies, shown in Table 2, and present their normalised criticality ranges in Figure 2. Copper and Tin also appear in many criticality assessments and could arguably be included here based on their extensive use in a number of low-carbon technologies. However, they have been excluded on the basis that they are base metals, are the subject of a much more extensive literature, and are therefore better served in a separate discussion.

The average criticality of a metal is indicated by the blue circle, while the range of scores is shown by the vertical bar. Not all metals are considered in all 11 studies, and the number in parentheses on the horizontal axis indicates the number of studies in which the metal is analysed. Consequently, the graph does not provide a perfectly balanced picture of a metal's criticality, but indicates the range of uncertainty and the placement of critical metals within the existing literature.

Table 2. Clean energy applications of the 10 metals or metal groups selected for normalisation.

Material	Symbol	Clean Energy Technology Applications
Silver	Ag	Photovoltaics (c-Si), Concentrated Solar Power (CSP), Nuclear
Cobalt	Co	Electric vehicle batteries, Biofuels (Fischer-Tropsch process)
Gallium	Ga	Photovoltaics (CIGS)
Germanium	Ge	Photovoltaics (a-SiGe)
Indium	In	Photovoltaics (CIGS, Transparent Conductive Oxide)
Lithium	Li	Electric vehicle batteries
Platinum Group Metals	PGMs	Fuel Cells, Catalytic Converters
Rare Earth Elements	REE	Electric vehicle batteries and motors, wind turbine generators, efficient lighting (phosphors)
Selenium	Se	Photovoltaics (CIGS)
Tellurium	Te	Photovoltaics (CdTe)

In this comparison of ten metals or metal groups used in low carbon energy technologies, the uncertainty ranges surrounding each metal appear to be largest for gallium, cobalt and silver, while the lower uncertainty ranges are for germanium, lithium and tellurium. The rare earth elements (REE) [5] and indium (In) are considered in the largest number of studies, while

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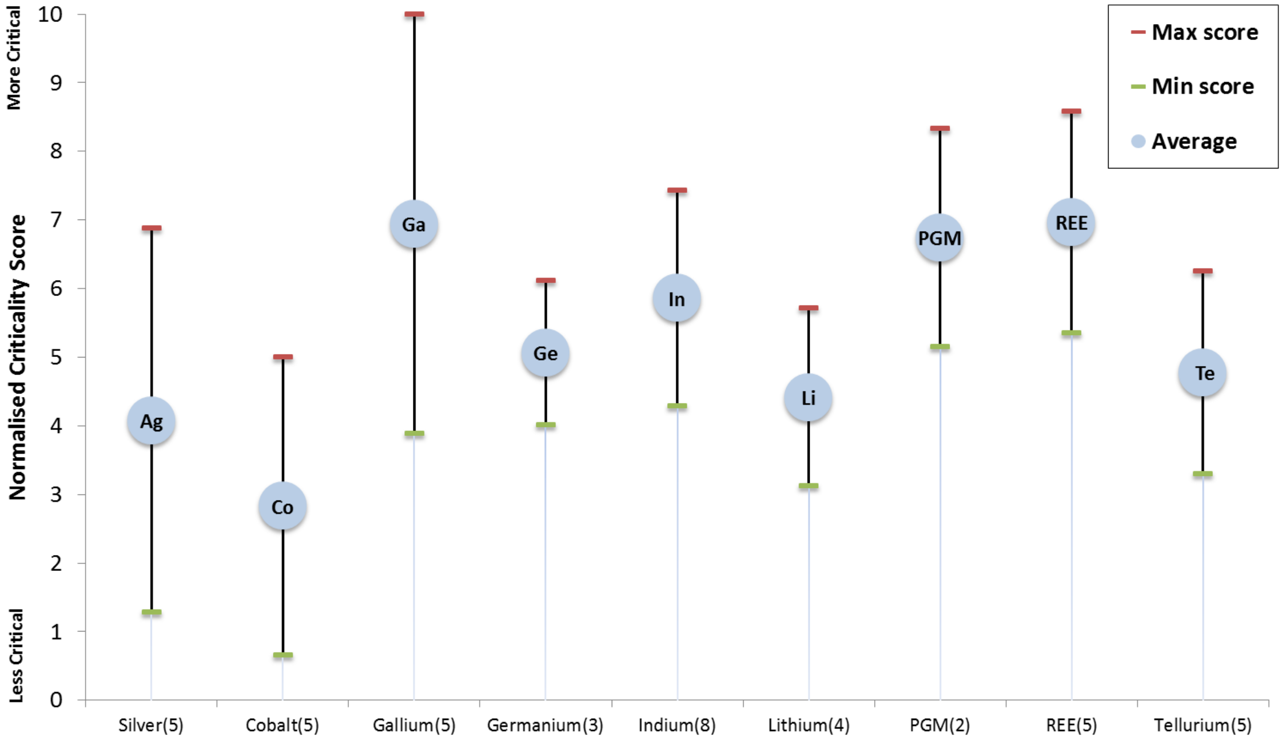
[5] It is worth noting that the range of uncertainty around REE in Figure 2 includes estimates for individual rare earths (Nd, Dy, Eu, Tb, Y) given in certain studies (Angerer *et al.* 2009; DOE 2010; DOE 2011; Moss *et al.* 2011). The Fraunhofer ISI (Angerer *et al.* 2009) indicator for yttrium is not incorporated in this range, because the end-uses based on which the indicator is calculated do not include any low carbon energy technologies.

tellurium is only included in two studies; the latter element is often excluded due to lack of information on its worldwide supply (BGS 2011b), since the USGS (USGS 2012) do not currently publish worldwide production estimates. There does not appear to be any correlation between the number of studies and a higher criticality score; PGMs for example are evaluated in only 2 studies yet have one of the highest criticality scores.

A number of limitations to this normalised comparison must be addressed. The 11 studies represented in Figure 2 do not all focus solely on the clean energy sector, and this may affect the score assigned to a particular metal. For example, the highest score for Gallium is found in the Fraunhofer ISI report (Angerer *et al.* 2009), which considers the use of Ga in photovoltaics and a number of non-energy applications. The British Geological Survey report (BGS 2011a) judges supply risk (one dimension), studies using criticality matrices (National Research Council (NRC) 2007; EC 2010; APS and MRS 2011; DOE 2011) judge supply risk and 'importance' or equivalent (two dimensions) and the most recent study (Graedel *et al.* 2012) adds a third dimension, environmental implications. For these reasons, the comparison cannot be interpreted as one between equivalent studies, or as leading to a conclusion on which materials are most critical and which are least critical. However, it provides an overview of the conclusions found in recent literature regarding the broad criticality of these eleven metals, selected here for their use in clean energy technologies, but considered in some studies for other uses as well.

Figure 2. Normalised criticality range of 11 materials for low carbon energy technologies found in 11 studies.



4 Discussion

The normalisation process above compares the relative criticality and the range of variation around certain metals discussed in a number of recent assessments from governments, corporations and research institutions. As shown in Figure 2, the range of uncertainty is high, and can be explained by a number of crucial differences as well as methodological compromises that are discussed here.

The most evident source of variation is due to the scope and technological focus of the study. This is acknowledged in Erdmann and Graedel (2011), and consequently Graedel *et al.* (2012) explicitly differentiates between corporate, national and global foci. This differentiation is not done in the other studies listed in Annex 1. In particular, studies with only a global scope (Buchert *et al.* 2009; Achzet *et al.* 2011; APS and MRS 2011; BGS 2011a; DOE 2011) carry larger uncertainty in the attempt to generalise results: the resources critical to one nation, region or even the Western hemisphere cannot apply uniformly, as a resource is most often only critical to nations not endowed with reserves. Additionally, with technological improvements bringing currently sub-economic resources on-stream, it is difficult to apply criticality measures with certainty at a global level, even in the short term.

Another factor accounting for the large uncertainty presented here is the number of methodological limitations. First, some sources of information are repeatedly used throughout the literature, including USGS reserve data and the metrics included in Table 1. These are updated annually and are thus unable to capture sudden events such as geopolitical instability or sudden and significant shifts in reserves or resources estimates (USGS 2006) giving rise to the potential for significant variation between assessments performed only a few years apart. The use of these commonly recognised metrics and data provides a consistent basis for the comparison of multiple materials using the same methodology, but exposes the methodology to the limitations discussed above.

The assessment of supply risk is complex and expressing or judging it using the number of years of remaining resources via an R:P ratio or equivalent is likely to be insufficient. The time till depletion of a given resource is highly dynamic, and includes non-linear production, non-linear resource discovery and reserve growth, non-linear availability of recycled resources, technology improvements through gradual learning as well as sudden and unforeseeable breakthroughs that may improve availability. The R:P ratio has been used very often in criticality assessments[6] despite its issues, since it provides a commonly available metric which can be compared across all metals. Using geochemical scarcity is not an alternative for R:P ratios since it provides no inherent assumptions regarding economic availability. On the other hand, the depletion time (DT) metric proposed by Graedel *et al.* (2012) could potentially improve the supply risk assessment if used in its expanded form, though the practicalities of its application are yet to be proved.

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[6] sometimes replacing reserves with reserve base to allow for a more long-term outlook (National Research Council (NRC) 2007; Graedel *et al.* 2012)

An important variation in results can be caused by the weighting used (if any) to aggregate separate metrics into a single criticality score for one metal. This issue and its important effect on rankings and criticality scores in a number of studies is discussed extensively in Erdmann and Graedel (2011). An important observation is the variation in results assuming different methods of aggregating the metrics (usually supply risk and vulnerability or importance, the axes of a criticality matrix). This can be done with either: a) no weighting; b) a 'linear adjustment' using coefficients to weight the two metrics; or c) a square root adjustment to calculate the distance of a point from the origin. An additional point to note is that a single criticality index or score allows for materials to be critical if they have a high supply risk score *or* a high vulnerability or importance score, while a criticality matrix requires critical materials to have both a high supply risk *and* a high vulnerability or importance score. These two points may affect the comparability of metals in different studies.

As a result of the lack of data, subjective criteria are often used in studies, particularly for factors such as: future cost-reduction due to technology improvements; future demand projections; substitutability; and media coverage (see Annex 2). Converting subjective criteria to quantitative measures should be avoided where possible, and this is acknowledged in some studies (National Research Council (NRC) 2007; Morley and Eatherley 2008; DOE 2010; Duclos *et al.* 2010; DOE 2011; Moss *et al.* 2011). Purely subjective criteria are sometimes replaced with expert elicitation (Angerer *et al.* 2009; EC 2010; Moss *et al.* 2011), and where this is done, more detail should be provided than at present in order to improve comparability. However, this is in many cases not possible due to proprietary knowledge or unpublished forward-looking statements.

Finally, in order to maintain comparability between metals, simple metrics such as R:P ratios are often applied since the data requirements of this metric are easily satisfied for most metals. However, this approach leaves many metal criticality assessments exposed to the limitations of these simple metrics. As a result many assessments overlook important factors determining future availability of metals. To improve understanding of the full range of issues associated with metal availability in the future, studies that focus on specific metals or technologies may provide researchers the freedom to explore all aspects of metal availability applying techniques to the analysis that would otherwise be impossible in a comparative metals criticality assessment (Candelise *et al.* 2011; Speirs *et al.* 2011).

5 Conclusions

This paper compares the various methodologies used to determine material criticality in recent studies and normalises their results for comparison. It also updates previous work and provides new analysis of the factors affecting criticality assessment. The normalisation process highlights a number of key points. The range of criticality scores for many metals used in low carbon energy technologies is extremely wide. The large uncertainty associated with these scores is driven primarily by methodological issues, scope and technological focus, and there appears to be no correlation between an increasing number of studies in which a metal is analysed and a decreasing uncertainty range. Overall, the ranking and ultimate criticality of any particular material used in low carbon energy technologies is difficult to deduce from a comparison of existing criticality assessments, and it is likely that improvements in data availability and assessment methodology will reduce the uncertainty range presented here. Harmonisation of methodological approaches could improve the comparability of studies, and may decrease uncertainty, though steps should be taken to avoid compromising methodological rigour for the sake of comparability.

The range of uncertainty in the findings of this comparison appears too wide to make conclusions on which metals are most critical and which are least critical. It is evident that those metals with larger uncertainty ranges should be subject to more rigorous analysis. This suggests that data availability and consistency across materials should be improved before any single methodology may be able to reduce uncertainty, particularly at a global level. A number of initiatives are now targeting this issue for those metals with poor data availability (BGS 2011b; Goonan 2011; Du and Graedel 2011a; Du and Graedel 2011b; Du and Graedel 2011c; Goonan 2012).

The broad focus of criticality assessments does not allow for sophisticated or dynamic assessment of future availability, particularly due to the availability of common and consistent data on all metals. Therefore it is likely that studies specific to a metal or technology can provide more insight than multi-material criticality assessment. While recent reviews (Candelise *et al.* 2011; Speirs *et al.* 2011) have also shown wide disagreement among the technology or metal-specific studies, the case remains that a thorough understanding of all the risks surrounding a particular resource may be more useful to stakeholders than a simpler prioritisation or classification of materials. Criticality assessments can, however, help prioritise those materials that require further investigation.

6 References

Achzet, B., A. Reller and V. Zepf (2011). Materials critical to the energy industry: An introduction. Augsburg, Germany, University of Augsburg report for the BP Energy Sustainability Challenge.

AEA Technology (2010). Review of the Future Resource Risks Faced by UK Business and an Assessment of Future Viability. London, UK, Report for the Department for Environment, Food and Rural Affairs (Defra).

Angerer, G., L. Erdmann, F. Marscheider-Weidemann, A. Lullmann, M. Scharp, V. Handke and M. Marwede. (2009). "Raw materials for emerging technologies: A report commissioned by the German Federal Ministry of Economics and Technology (English Summary)." Fraunhofer ISI Retrieved 31/10/2011, from http://www.isi.fraunhofer.de/isi-en/service/presseinfos/2009/pri09-02.php.

APS and MRS. (2011). "Energy critical Elements: Securing materials for emerging technologies." American Physical Society and Materials Research Society Retrieved 15/10/2011, from http://www.aps.org/policy/reports/popa-reports/loader.cfm?csModule=security/getfile&PageID=236337.

Armand, M. and J. M. Tarascon (2008). "Building better batteries." Nature **451**(7179): 652-657.

BGR (2011). Biennial Report 2009/2010. Hanover, Germany, German Federal Institute for Geosciences and Natural Resources (BGR).

BGS (2011a). Risk List 2011. Nottingham, UK, British Geological Survey.

BGS (2011b). World Mineral Production 2006-2010. Nottingham, UK, British Geological Survey.

BP. (2011). "Statistical Review of World Energy - June 2011." British Petroleum Retrieved 10/2/2012, from http://www.bp.com/assets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2011/STAGING/local_assets/pdf/statistical_review_of_world_energy_full_report_2011.pdf.

Buchert, M., D. Schüler and D. Bleher (2009). Critical Metals for Sustainable technologies and Their Recycling Potential. Nairobi, Kenya, United Nations Environment Programme (UNEP) and Oko-Institut.

Candelise, C., J. Speirs and R. Gross (2011). "Materials availability for thin film (TF) PV technologies development: a real concern?" Renewable and Sustainable Energy Reviews **15**(9): 4972-4981.

Chegwidden, J. and D. J. Kingsnorth. (2011). "Rare earths - an evaluation of current and future supply." Roskill and IMCOA Retrieved 15/7/2011, from http://www.slideshare.net/RareEarthsRareMetals/rare-earths-an-evaluation-of-current-and-future-supply.

Clarke, G. (2011). Lithium Availability WallMap (LAWM) - June 2011.

DOE (2010). Critical Materials Strategy. Washington, D.C; Oak Ridge, Tenn., United States Department of Energy

DOE (2011). Critical Materials Strategy 2011. Washington, DC, US Department of Energy.

DOJ (2010). Horizontal Merger Guidelines. Washington D.C., USA, United States Department of Justice.

Du, X. and T. E. Graedel (2011a). "Global In-Use Stocks of the Rare Earth Elements: A First Estimate." Environmental science & technology **45**(9): 4096-4101.

Du, X. and T. E. Graedel (2011b). "Global Rare Earth In-Use Stocks in NdFeB Permanent Magnets." Journal of Industrial Ecology **15**(6): 836-843.

Du, X. and T. E. Graedel (2011c). "Uncovering the Global Life Cycles of the Rare Earth Elements." Nature Scientific Reports **1**(145).

Duclos, S. J., J. P. Otto and G. K. Konitzer (2010). "Design in an era of constrained resources." Mechanical Engineering **132**(9): 36-40.

EC (2010). Report of the Ad-hoc Working Group on defining critical raw materials. Critical Raw Materials for the EU. Brussels, European Commission.

Erdmann, L. K. and T. E. Graedel (2011). "The Criticality of Non-Fuel Minerals: A Review of Major Approaches and Analyses." Environmental Science & Technology **45**(18): 7620-7630.

Feltrin, A. and A. Freundlich (2008). "Material considerations for terawatt level deployment of photovoltaics." Renewable Energy **33**(2): 180-185.

Fthenakis, V. (2009). "Sustainability of photovoltaics: The case for thin-film solar cells." Renewable and Sustainable Energy Reviews **13**(9): 2746-2750.

Fund for Peace. (2011). "Failed State Index 2011." Retrieved 15/2/2012, from http://www.fundforpeace.org/global/?q=fsi-grid2011.

Goonan, T. G. (2011). Rare Earth Elements - End Use and Recyclability. Reston, VA, USA, US Geological Survey. **Scientific Investigations Report 2011-5094**.

Goonan, T. G. (2012). Lithium use in batteries. Circular 1371. Reston, VA, US Geological Survey

Graedel, T. E. (2011). "On the Future Availability of the Energy Metals." Annual Review of Materials Research **41**: 323-335.

Graedel, T. E., R. Barr, C. Chandler, T. Chase, J. Choi, L. Christoffersen, E. Friedlander, C. Henly, C. Jun, N. T. Nassar, D. Schechner, S. Warren, M.-y. Yang and C. Zhu (2012). "Methodology of Metal Criticality Determination." Environmental science & technology **46**(2): 1063-1070.

Gruber, P. W., P. A. Medina, G. A. Keoleian, S. E. Kesler, M. P. Everson and T. J. Wallington (2011). "Global Lithium Availability: A Constraint for Electric Vehicles?" Journal of Industrial Ecology **15**(5): 760-775.

Hischier, R., B. Weidema, H. J. Althaus, C. Bauer, G. Doka, R. Dones, R. Frischknecht, S. Hellweg, S. Humbert, N. Jungbluth, T. Köllner, Y. Loerincik, M. Margni and T. Nemecek (2010). Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent v2.2 No. 3. . Dübendorf, Switzerland, Swiss Centre for Life Cycle Inventories.

Jones, N. (2011). "Materials Science: The pull of stronger magnets." Nature **472**: 22-23.

Kara, H., A. Chapman, T. Crichton and P. Willis (2010). Lanthanide Resources and Alternatives: A report for Department for Transport and Department for Business, Innovation and Skills. Aylesbury, UK, Oakdene Hollins.

Kaufmann, D., A. Kraay and M. Mastruzzi (2010). The Worldwide Governance Indicators: Methodology and Analytical Issues. Policy Research Working Paper 5430. Washington DC, World Bank.

Kingsnorth, D. J. (2010). Rare earths: facing new challenges in the new decade. SME Annual Meeting, Phoenix, Arizona.

McMahon, F. and M. A. Cervantes (2011). Fraser Institute Survey of Mining Companies 2010/2011. Vancouver, BC, Canada, Fraser Institute.

Morley, N. and D. Eatherley (2008). Material Security: Ensuring resource availability to the UK economy. Chester, UK, Resource Efficiency KTN, Oakdene Hollins and C-Tech Innovation.

Moss, R. L., E. Tzimas, H. Kara, P. Willis and J. Kooroshy (2011). Critical Metals in Strategic Energy Technologies. Brussels, Belgium, European Commission Joint Research Centre (EC JRC). **EUR 24884 EN - 2011**.

Nassar, N. T., R. Barr, M. Browning, Z. Diao, E. Friedlander, E. M. Harper, C. Henly, G. Kavlak, S. Kwatra, C. Jun, S. Warren, M.-Y. Yang and T. E. Graedel (2012). "Criticality of the Geological Copper Family." Environmental science & technology **46**(2): 1071-1078.

National Research Council (NRC) (2007). Minerals, critical minerals, and the US economy. Washington, DC, National Academies Press.

OECD (2010). A sustainable materials management case study : Critical metals and mobile device. Paris, France, Organisation for Economic Co-operation and Development: Working Group on Waste Prevention and Recycling (WGWPR).

Parthemore, C. (2011). Elements of Security: Managing the Risks of US Dependence on Critical Minerals. Washington, D.C., USA, Centre for a New American Security (CNAS).

Peiro, L. T., G. V. Mendez and R. U. Ayres (2012). Rare and Critical Metals as By-Products and the Implications for Future Supply. Faculty & Research Working Paper. Fontainebleau Cedex, France, INSEAD. **2011/129/EPS/TOM/ISIC**.

Porter, M. and S. Stern (2002). National Innovative Capacity. The Global Competitiveness Report 2001-2002. M. E. Porter, Sachs, J. D., Cornelius, P. K., McArthur, J. W., Schwab, K. New York, Oxford University Press: 102-118.

Rosenau-Tornow, D., P. Buchholz, A. Riemann and M. Wagner (2009). "Assessing the long-term supply risks for mineral raw materials—a combined evaluation of past and future trends." Resources Policy **34**(4): 161-175.

Schüler, D., M. Buchert, D. I. R. Liu, D. G. S. Dittrich and D. I. C. Merz (2011). Study on Rare Earths and Their Recycling. Final Report for The Greens/EFA Group in the European Parliament Darmstadt, Germany, Öko-Institut.

SEPA (2011). Raw materials critical to the Scottish economy. Edinburgh, Scotland, A report by AEA Technology for the Scottish Environmental Protection Agency (SEPA) and the Scotland and Northern Ireland Forum For Environmental Research (SNIFFER).

Sorrell, S., J. Speirs, R. Bentley, A. Brandt and R. Miller (2009). Global Oil Depletion: An assessment of the evidence for a near-term peak in global oil production. London, UK Energy Research Centre.

Speirs, J. F., R. Gross, C. Candelise and B. Gross (2011). Materials Availability: Potential constraints to the future low-carbon economy - Working Paper, UK Energy Research Centre. **REF UKERC/WP/TPA/2011/002**.

Thomason, J. S., R. J. Atwell, Y. Bajraktari, J. P. Bell, D. S. Barnett, N. S. J. Karvonides, M. F. Niles and E. L. Scwartz (2008). From National Defense Stockpile (NDS) to Strategic Materials Security Programme (SMSP): Evidence and Analytic Support, . Volume I. Alexandria, VA, 2008, Institute for Defense Analyses (IDA).

UNDP (2011). Human Development Report 2011. New York, NY, USA, United Nations Development Programme.

UNEP (2011a). Recycling Rates of Metals: A Status Report. Report of the Working Group on the Global Metal Flows to the International Resource Panel, United Nations Environment Programme.

USGS (2006). Mineral Commodity Summaries. Reston, VA, U.S. Geological Survey.

USGS (2008). Minerals Yearbook: Rare Earths. Reston, VA, U.S. Geological Survey.

USGS. (2010). "Minerals yearbook." from http://minerals.usgs.gov/minerals/pubs/commodity/myb/.

USGS (2012). Mineral Commodity Summaries 2012. Reston, VA, US Geological Survey.

Väyrynen, A. and J. Salminen (2011). "Lithium ion battery production." The Journal of Chemical Thermodynamics **In Press**(Corrected Proof).

Wadia, C., P. Albertus and V. Srinivasan (2011). "Resource constraints on the battery energy storage potential for grid and transportation applications." Journal of Power Sources **196**(3): 1593-1598.

Wadia, C., P. A. Alivisatos and D. M. Kammen (2009). "Materials Availability Expands the Opportunity for Large-Scale Photovoltaics Deployment." Environmental Science & Technology **43**(6): 2072-2077.

Yaksic, A. and J. E. Tilton (2009). "Using the cumulative availability curve to assess the threat of mineral depletion: The case of lithium." Resources Policy **34**(4): 185-194.

7 Annexes

Annex 1: List of criticality assessment studies considered in this comparison paper.

Study	Scope	Timeframe	Materials analysed (initial list)	Technology focus
National Research Council 2007 (National Research Council (NRC) 2007)	National (US)	Short-term	11	US Industries
Oakdene Hollins 2008 (Morley and Eatherley 2008)	National (UK)	to 2050	69 [a]	UK Industries
Volkswagen AG and BGR 2009 (Rosenau-Tornow *et al.* 2009)	Corporate + National	2004 – 2020	1 [b]	NA
Oko-Institut and UNEP 2009 (Buchert *et al.* 2009)	Global	Short term (next 5 years); Medium term (to 2020); Long term (to 2050)	26	Sustainable technologies
Fraunhofer ISI 2009 (Angerer *et al.* 2009)	National (Germany)	2006-2030	22	EU Emerging technologies
AEA Technology 2010 report for Defra (AEA Technology 2010)	National (UK)	Short term (5 years); Medium term (5-20 years); Long-term (20+ years)	6 (27) [c]	UK Industries
European Commission 2010 (EC 2010)	European	10 year time horizon (2010 – 2020)	41	15 European "megasectors"
General Electric 2010 (Duclos *et al.* 2010)	Corporate	NA	11 (70)	GE Products
US Dept of Energy 2010 (DOE 2010)	Global	Short term (0-5 years); Medium term (5-15 years)	14	Clean energy

US Dept of Energy 2011 (DOE 2011)	Global	Short term (0-5 years); Medium term (5-15 years)	16	Clean energy
Joint Research Centre 2011 (Moss *et al.* 2011)	European	2010 – 2030	14 (60)	EU SET-Plan Energy technologies
Scottish Environmental Protection Agency (SEPA 2011)	National (Scotland)	Short term and long term (not specified)	12 (27) [c]	7 Scottish industries
British Geological Survey (BGS 2011a)	Global	2011	52	NA
Resource Strategy, University of Augsburg (Achzet *et al.* 2011)	Global	Not specified	19[d]	Energy industry
Centre for Industrial Ecology, Yale University (Graedel *et al.* 2012; Nassar *et al.* 2012)	Global + National (US) + Corporate	Corporate (1-5 yr); National (5-10 yr); Global (10-100 yr)	6 [e]	All

Notes: a) Oakdene Hollins identifies 8 most at risk metals out of the ranking of 69. b) The Volkswagen AG and BGR paper define their methodology as one applicable to all materials, but only apply it to the case of copper. c) Includes non-mineral resources such as fish, algae, coral and aggregates. d) This becomes 35 materials if the group rare earth elements (REE) are considered separately. e) The Yale University methodology has so far only been applied to copper and its by-products, although forthcoming publications will apply it to more materials.

Annex 2: List of the factors included in the criticality assessment of 15 studies.

Study	Year	Factors included in criticality assessment											
		Supply Factors			**Geopolitical factors**			**Demand Factors**		**Other**			
		Geological Availability	*Economic Availability*	*Recycling*	*Policy and Regulation*	*Geopolitical Risk*	*Supply concentration*	*Future demand projections*	*Substitutability*	*Cost–reduction via Technology & Innovation*	*Environmental issues*	*Economic Importance / Impact*	*Media coverage*
National Research Council (National Research Council (NRC) 2007)	2007	✓	✓	✓	✓	✓	✓		✓		✓	✓	
Oakdene Hollins (Morley and Eatherley 2008)	2008	✓	✓	✓		✓	✓	✓	✓		✓x3		
Volkswagen AG & BGR (Rosenau-Tornow *et al.* 2009)	2009	✓	✓	✓		✓	✓	✓	✓	✓	✓		
Öko Institut and UNEP (Buchert *et al.* 2009)	2009	✓	✓	✓x3			✓	✓					
Fraunhofer ISI (Angerer *et al.* 2009)	2009	✓	✓	✓		✓	✓	✓				✓	
European Commission (EC 2010)	2010	✓	✓	✓		✓	✓		✓		✓	✓	
US Dept. of Energy (DOE 2010)	2010	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
General Electric (Duclos *et al.* 2010)	2010	✓	✓	✓		✓	✓	✓	✓x2			✓	
AEA Technology (AEA	201	✓	✓			✓	✓x2	✓	✓				✓

Technology 2010)	0												
US Dept. of Energy (DOE 2011)	2011	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
SEPA (SEPA 2011)	2011	✓	✓			✓	✓x2	✓	✓				✓
EC Joint Research Centre (Moss *et al.* 2011)	2011	✓	✓			✓	✓	✓	✓		✓		
British Geological Survey (BGS 2011a)	2011	✓				✓	✓x2						
University of Augsburg (Achzet *et al.* 2011)	2011	✓	✓	✓		✓	✓		✓		✓		
Yale University (Graedel *et al.* 2012; Nassar *et al.* 2012)	2012	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	

Notes: A multiplier (x2, x3) indicates that more than one indicator is used to quantify the relevant factor.