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A report for UKERC by
UKERC Technology & Policy Assessment Function

Materials availability for low-carbon technologies: An assessment of the evidence

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Preface

This report was produced by the UK Energy Research Centre's (UKERC) Technology and Policy Assessment (TPA) function.

The TPA was set up to inform decision-making processes and address key controversies in the energy field. It aims to provide authoritative and accessible reports that set very high standards for rigour and transparency. The subject of this report was chosen after extensive consultation with energy sector stakeholders and upon the recommendation of the TPA Advisory Group, which is comprised of independent experts from government, academia and the private sector.

The primary objective of the TPA, reflected in this report, is to provide a thorough review of the current state of knowledge. New research, such as modelling or primary data gathering may be carried out when essential. It also aims to explain its findings in a way that is accessible to non-technical readers and is useful to policymakers.

The TPA uses protocols based upon best practice in evidence-based policy, and UKERC undertook systematic and targeted searches for reports and papers related to this report's key question. Experts and stakeholders were invited to comment and contribute through an expert group. The project scoping note and related materials are available from the UKERC website, together with more details about the TPA and UKERC.

About UKERC

The UK Energy Research Centre is the focal point for UK research on sustainable energy. It takes a whole systems approach to energy research, drawing on engineering, economics and the physical, environmental and social sciences.

The Centre's role is to promote cohesion within the overall UK energy research effort. It acts as a bridge between the UK energy research community and the wider world, including business, policymakers and the international energy research community and is the centrepiece of the Research Councils Energy Programme.

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Supporting Documents

This Synthesis Report presents the main findings of this assessment. More detailed analyses are contained in the supporting Working Papers, which are available to download from the UKERC website:

- Working Paper I: Materials availability in the Thin-Film Photovoltaics sector
- Working Paper II: Potential constraints to the future low-carbon economy: Batteries, Magnets and Materials
- Working Paper III: Comparison of material criticality studies
- Energy Materials Availability Handbook

The TPA report on Materials Availability was conducted in co-operation with the Energy Research Partnership's (ERP) Mineral Resources project. The ERP conducted a review of the issues surrounding resource availability for UK interests. Given the similar nature of these two projects the authors co-operated with each other by sharing emerging findings, bilateral meetings, and through ERP participation in the TPA Expert Group process.

The ERP brings together key funders of energy research, development, demonstration and deployment (RDD&D) in Government, industry and academia, plus other interested bodies, to provide high-level leadership for, and to enhance the coherence of, energy research and innovation activities in the UK, set within an international context.

The ERP Mineral Resources project can be found at www.energyresearchpartnership.org.uk

Executive Summary

There is increasing concern that future supply of some lesser known 'critical metals' will not be sufficient to meet rising demand in the low-carbon technology sector. A rising global population, significant economic growth in the developing world, and increasing technological sophistication have all contributed to a surge in demand for a broad range of metal resources. In the future, this trend is expected to continue as the growth in low-carbon technologies compounds these other drivers of demand. This report examines the issues surrounding future supply and demand for critical metals.

While the list of critical metals is not fixed, several metals commonly considered critical and the low-carbon technologies they are used in are listed below.

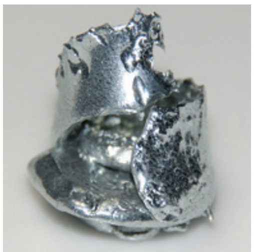
Metal	Low-carbon technology
Cobalt	Lithium-ion batteries
Gallium	Thin-film photovoltaics (PV), Light emitting diodes (LED lighting)
Germanium	Thin-film PV, LED lighting
Indium	Thin-film PV, LED lighting
Lithium	Lithium-ion batteries
Platinum group metals (PGMs)	Hydrogen fuel cells
Rare earth elements (REEs)	Electric vehicles and wind turbines
Selenium	Thin-film PV
Silver	PV (c-Si), concentrating solar and nuclear
Tellurium	Thin-film PV

The main conclusions of the report are as follows:

- Demand for critical metals is expected to grow significantly in the future given the forecast rates of growth in the low-carbon technology sector. This creates a sizeable challenge for future supply. In several cases this would require a several-fold increase in production to meet rising demand from the low-carbon sector alone.
- For many metals data on current production, existing reserves and estimates of reserve growth/future supply are subject to a range of problems and limitations. Improving this situation through further research and support for data-gathering activities is important to improve the evidence base.
- There is little evidence to suggest that resource availability or depletion is affecting production growth now and/or in the short term. If economic incentives persist then more reserves are likely to be found and production is likely to increase. However, exponential production growth cannot be maintained indefinitely, and it is not clear how far into the future rapid rates of production rate growth can be maintained.
- The availability and economics of several critical metals are complicated by the fact that they are secondary metals found in ores such as bauxite, zinc, or copper for which a primary metal accounts for the principal economic value. In some cases it is possible to extract a higher proportion of the secondary material available – as the value of the secondary metal increases so the incentive increases to refine a higher proportion of the material available, for example in in tailings and refinery wastes.
- In many cases alternative low-carbon technologies can substitute for technologies containing particular critical metals. In the event that critical metals availability and price influences the manufacture of low-carbon technologies, these substitutes are likely to be favoured.

- Recycling of critical metals from end-of-life products can augment supply in the future. However, recycling is unlikely to be sufficient to overcome all future availability issues while demand is increasing significantly.
- There are a number of policy responses that have historically been used in response to metal availability concerns. Countries with domestic mining potential may be able to provide policy incentives to increase domestic production. Other options include facilitating recycling, supporting R&D into substitute technologies, and trade and foreign policy interventions to secure imports.

Cobalt



Gallium

Germanium

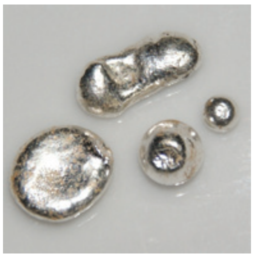
Indium

Lithium

Platinum Group Metals (PGMs)

Rare Earth Elements (REEs)

Selenium



Silver

Tellurium

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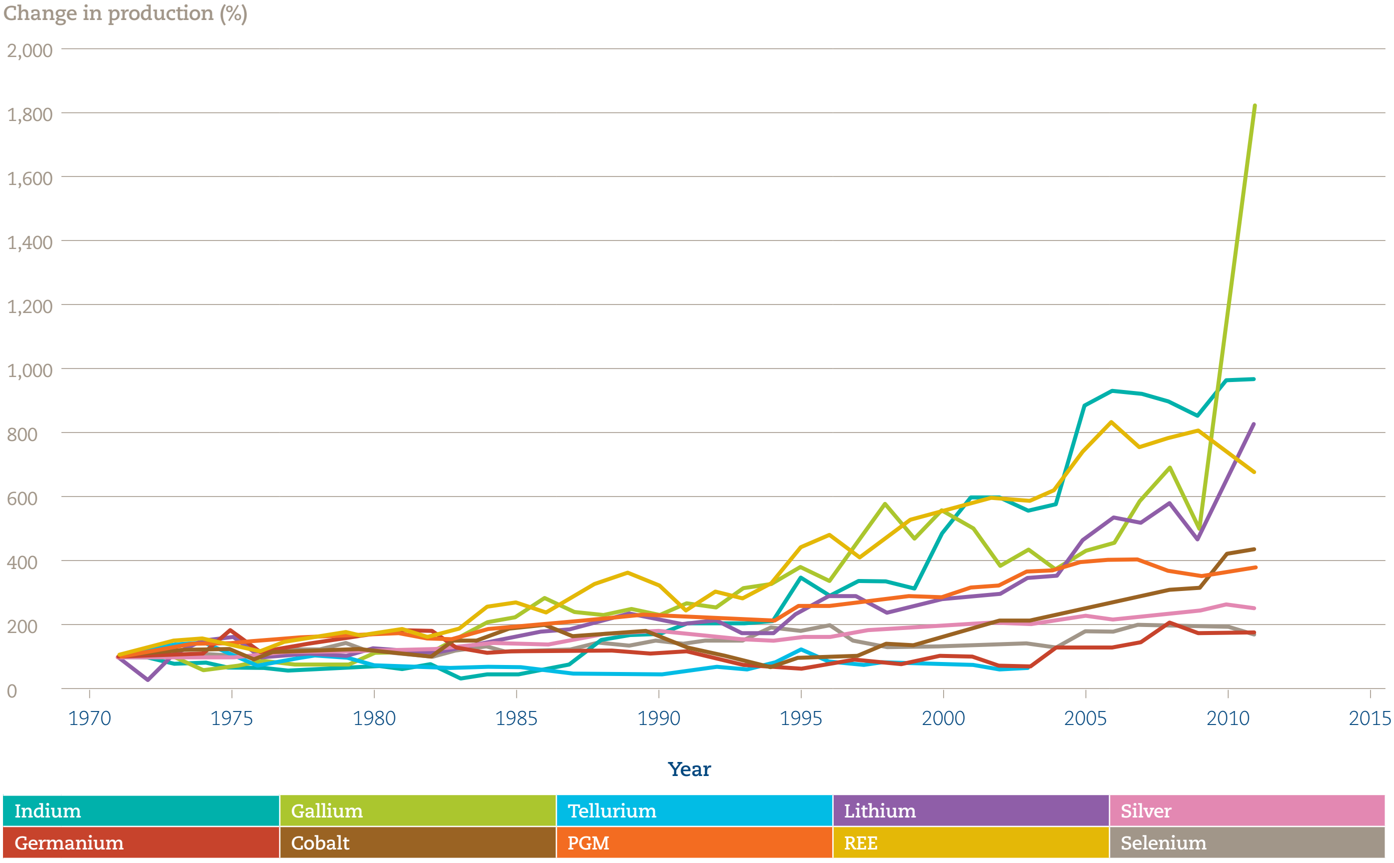
What's critical about metals

Critical metals in context

For over two centuries man has debated whether the availability of natural resources could place a constraint on development. Thomas Malthus questioned the availability of food to sustain the growing population (Malthus 1798), Jevons and Hubbert questioned the availability of fossil fuels to sustain growing industrial economies (Jevons 1865; Hubbert 1956), and The Club of Rome questioned the global 'Limits to Growth' associated with a range of natural resources (Meadows 1972).

Perhaps ironically, a new dimension to this debate is around the demand for metals that may arise from the expansion of some low-carbon technologies (Angerer *et al*. 2009a; Moss *et al*. 2011). While technologies, such as solar photovoltaics (PV) or wind power, address some environmental and resource concerns, they may also create others. Global population growth, significant economic growth in the developing world, and increasing technological sophistication have all contributed to growth in demand for a broad range of metal resources (Figure 1). In the future, this trend is expected to continue as the growth in low-carbon technologies compounds these other drivers of demand.

Figure 1: Growth in critical metals production from 1971-2011



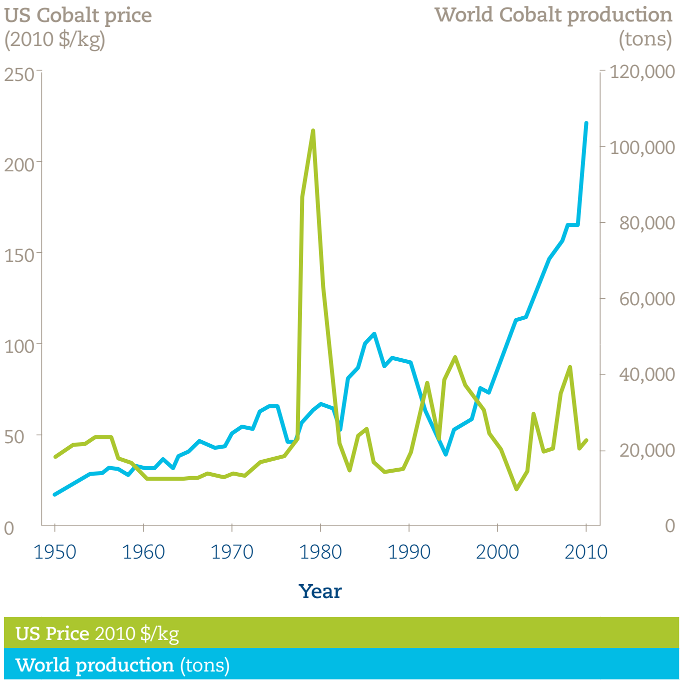
Source: USGS

Note: This figure presents the ten metals or metal groups covered in the UKERC Energy Materials Availability Handbook (Speirs *et al*. 2013a). This does not represent all the metals that have previously been considered in critical metals studies.

As demand for critical metals has increased, the debate has risen swiftly up the academic, political and industrial agenda (Speirs *et al.* 2013c). In the last decade the number of academic papers, government reports and grey literature discussing the availability of critical metals has increased severalfold (Figure 3). Some of these studies discuss the physical limits to availability, and are concerned with maximum production rates and estimates of the available resource (Tilton 1999; Andersson 2000; Wadia *et al.* 2009). Other studies focus on the economic, social and geopolitical influences on resource availability, the so-called above ground factors (Lee *et al.* 2012; Lehner *et al.* 2012). While demand for these metals has been increasing, demand in the future is still uncertain, and many of these studies make efforts to examine the drivers of future metal demand in order to inform their assessments of future availability (Fthenakis 2009; Houari *et al.* 2013).

Regardless of the underlying nature of potential constraints history has shown that metal supply can be interrupted. In the late 1970s conflict in the Democratic Republic of Congo (Zaire) and neighbouring countries first interrupted mining supply routes and then directly affected mine production (Westing *et al.* 1986). During the 1970s, Zaire was responsible for approximately half of global cobalt production, and supply disruptions precipitated a number of responses, including a significant price increase (Figure 2), strategic stockpiling (Guttman *et al.* 1983), and concerted effort towards developing substitute materials (Sichel 2008).

Figure 2: US cobalt price and world mine production showing significant price spike between 1978 and 1980 and more recent increase in production



Source: Bureau of Labour Statistics (2013) and U.S Geological Survey (USGS 2013b; USGS 2013a)

The critical metals debate is ultimately concerned with identifying the main drivers of future metal supply and future metal demand, and whether the former can keep pace with the latter. However, significant uncertainty surrounds each of the factors that contribute to future availability and addressing these uncertainties is a significant challenge.

Conducting this assessment

The focus of this report, and the wider supporting research, is to address the research question:

What is the evidence that the transition to a low-carbon economy may be influenced by access to critical metals?

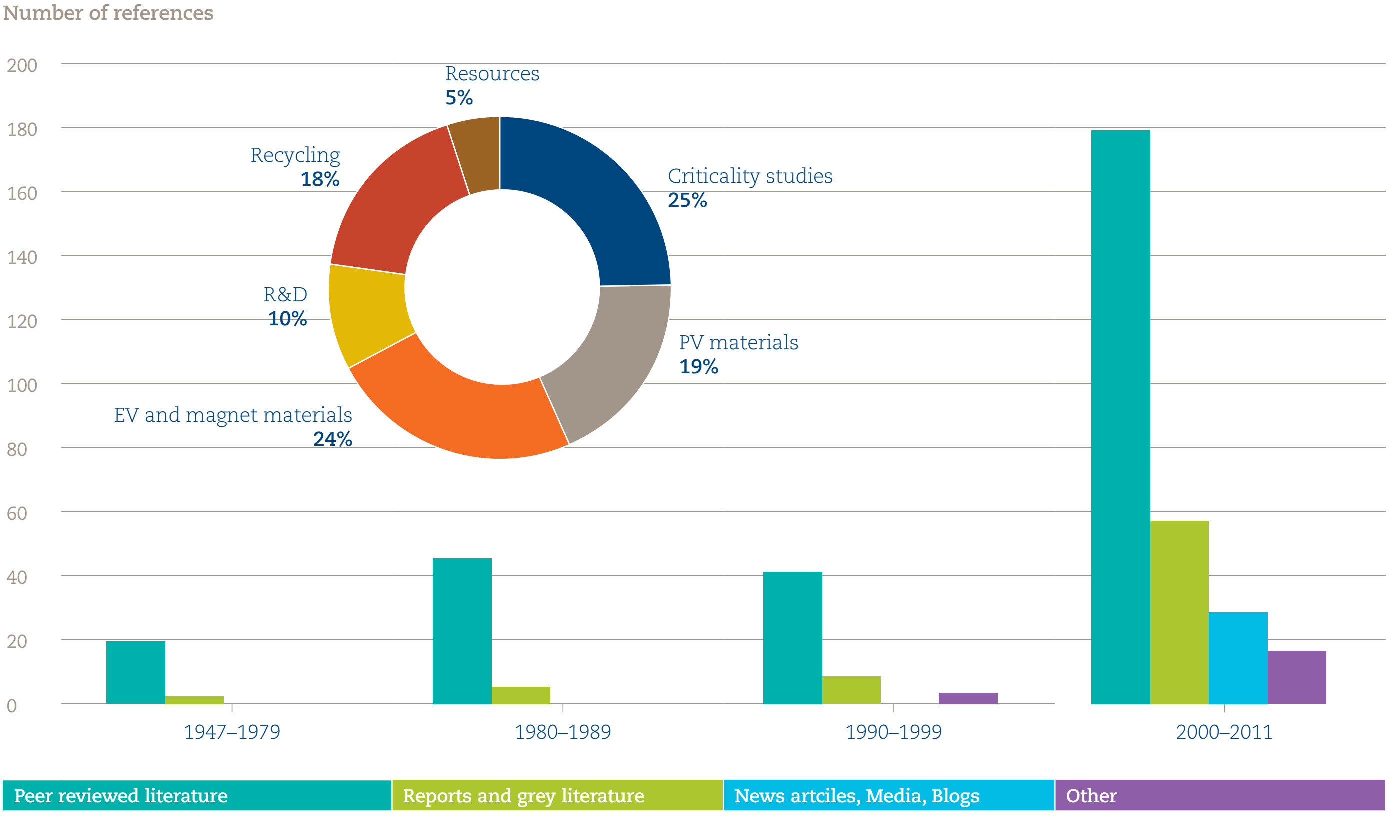
The research was conducted using the UKERC Technology and Policy Assessment (TPA) approach, which has at its centre the process of systematic review. A brief synopsis of this approach is provided in Box 1.

Box 1: Overview of the TPA approach

The TPA approach is informed by a range of techniques referred to as ‘evidence-based policy and practice’ (EBPP), including the practice of systematic review. This aspires to provide more robust evidence for policymakers and practitioners, avoid duplication of research, encourage higher research standards and identify research gaps. Core features of this approach include exhaustive searching of the available literature and greater reliance upon high quality studies when drawing conclusions. Energy policy presents a number of challenges for the application of systematic review and the approach has been criticised for excessive methodological rigidity in some policy areas (Sorrell 2007). UKERC has therefore set up a process that is inspired by this approach, but is not bound to any narrowly defined method or technique. The process carried out for each assessment includes the following components:

- Publication of Scoping Note and Assessment Protocol.
- Establishment of a project team with a diversity of expertise.
- Convening an Expert Group with a diversity of opinions and perspectives.
- Stakeholder consultation.
- Systematic searches of clearly defined evidence base using keywords.
- Categorisation and assessment of evidence.
- Review and drafting of technical reports.
- Expert feedback on technical reports.
- Drafting of synthesis report.
- Peer review of final draft.

Figure 3: Analysis of the results of a systematic review of the evidence surrounding critical metals for low-carbon technologies



Note: 'Other' includes patents, theses, corporate presentations and webpages. Pie chart depicts distribution of literature by topic.

In the course of this review over 300 references were catalogued, including journal articles, reports and grey literature, and a range of materials topics were addressed, including resource assessment, electric vehicle (EV) and photo-voltaic (PV) materials, criticality assessment, and recycling (Figure 3).

As with all TPA assessments the purpose is not to conduct new research on the availability of critical metals, but instead to provide a thorough review of the current state of the evidence. This began with a *scoping note*, which outlines the key areas where the TPA approach can make a contribution. An expert group was then convened to provide guidance and insight, helping to inform the research. Three working papers were then produced, representing key topics within the research question which warranted more detailed research than could be fully replicated in this report. These are:

- *Working Paper I*: Material availability in the thin-film photovoltaic sector;
- *Working paper II*: Potential constraints to the future low-carbon economy - Batteries, Magnets and Materials; and
- *Working paper III*: Comparison of material criticality assessments

In addition the *Energy Materials Availability Handbook* was created, providing a guide to 10 metals or metal groups that feature prominently in the critical metals literature, and presenting the pertinent facts regarding their production, resources, and other issues surrounding their availability.

The scoping note, working papers and handbook are available online at www.ukerc.ac.uk.

What is in this report

The remainder of this report is structured as follows:

In Part I we examine a number of key conceptual issues and definitions central to the critical metals debate. This includes discussion of the relevant data sources and the differing methodologies used to examine availability of metals.

In Part II we examine the issues surrounding future supply of metals. This includes both physical issues such as the estimates of available reserves and production rates, and above-ground factors such as the economic and geopolitical issues influencing metals supply.

In Part III we examine the issues of metal demand, focusing on the drivers of low-carbon technology demand, and covering the potential for substitution and efficiency improvements to reduce demand.

In Part IV we compare findings for both supply and demand in order to illustrate the scale of the challenge facing critical metals in the future.

In Part V we present some conclusions based on the findings of this research, and highlight the implications for policy.

What is availability?

1

Concern over the future availability of critical metals raises the question, how should availability be measured? This in turn elicits a number of subsequent questions: what do we mean by availability; what data should we use to measure availability; and does availability vary depending on national, industrial or political perspective? However the answers to these questions are not simple, and there remains significant disagreement, uncertainty and confusion.

The following sections address a range of these issues, beginning with a discussion of common definitions. A number of different definitions exist in the current literature, often describing the same or similar concepts, and contributing in some way to ongoing confusion. Next is a discussion of the types of data typically used in the assessment of availability, and the data sources commonly used in the current literature. Numerous issues surround the availability and quality of these data, affecting the robustness of resulting conclusions. Finally the types of methodological approach to assessing availability are discussed.

The key concepts

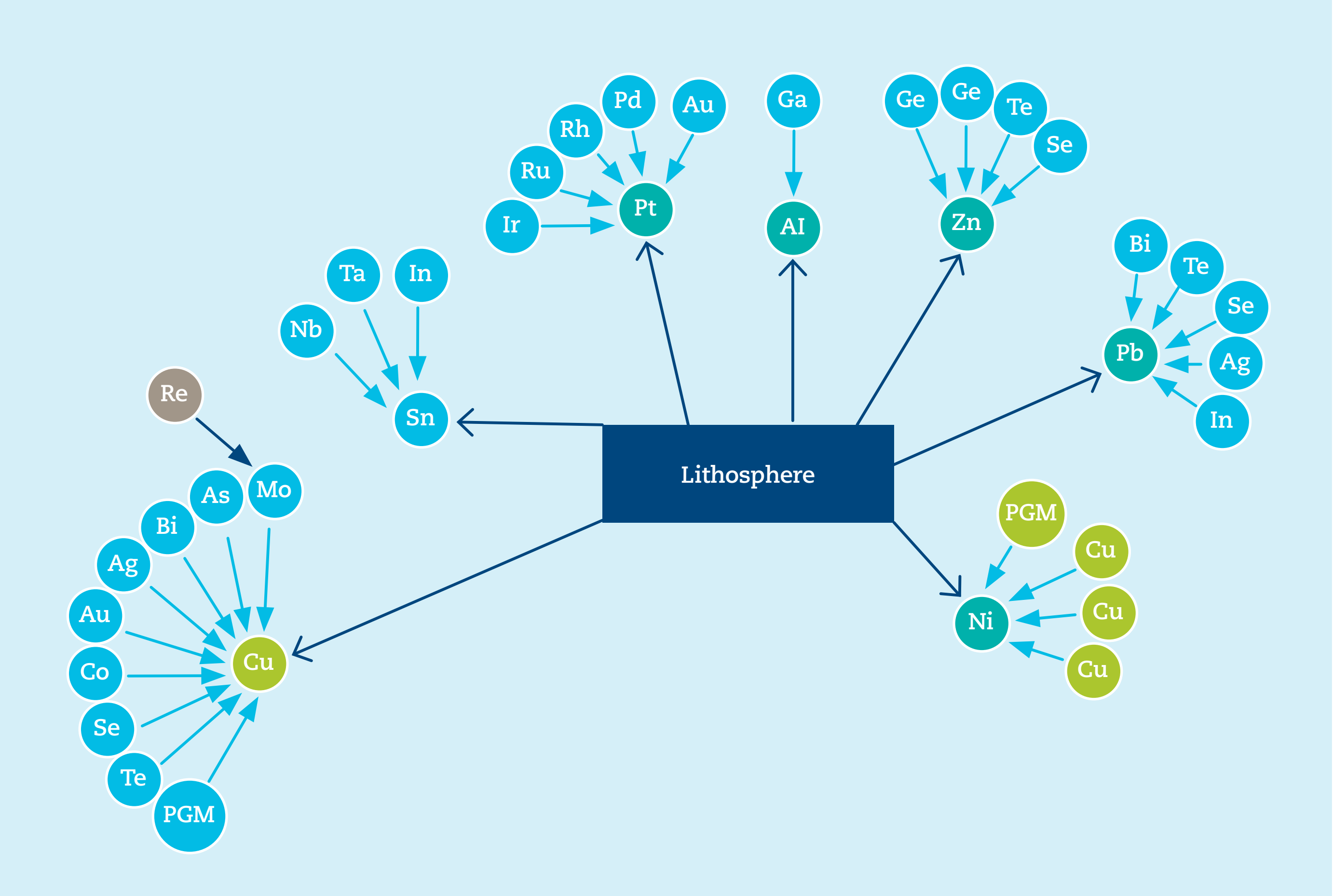
The concept of future availability of a non-fuel mineral resource is referred to by various names in the literature. Critical metals is a commonly used phrase, referring to metals deemed of most availability concern (Buchert *et al*. 2009; Moss *et al*. 2011), though sometimes the phrases *critical materials* or *minerals* are employed to include non-metals such as feldspar or graphite (EC 2010; BGS 2014). The word *critical* generally denotes the idea that these materials have economic importance, with the relative *criticality* measured in multi-criteria analyses referred to as *criticality assessments* (see below).

The literature also refers to *strategic metals* or *materials* (Hocquard & Deschamps 2008; Science and Technology Committee 2011). Historically the word strategic has been used to denote resources perceived to be vital from a military or political perspective, or to maintain some industrial or economic strength (Westing *et al*. 1986). The European Commission (EC 2010) define the use of the word strategic to denote military concerns exclusively, and the word critical to denote aspects of concern for national economies. The military perspective is the focus in some studies (Guttman *et al*. 1983; Albritton *et al*. 2010), but economic or industrial concerns are a more prevalent focus in much of the literature.

The phrase *technology metal* or *low-carbon technology metal* may be used to indicate a specific group of metals used in modern technologies such as smart phones, solar panels and electric vehicles. This recognises the fact that many of the metals considered of most concern from an availability perspective have uses in these types of technologies, and demand for these technologies is expected to increase significantly in the future.

The well-known metals, such as copper, lead, nickel and zinc, are often referred to as the *base metals*. This refers to the fact that they all oxidise reasonably easily, though it is also used to refer to the low value of these metals in comparison to less abundant *precious metals*. Though future availability of *base metals* is sometimes discussed (Falconer 2009) the *critical metal* debate is largely focused on the less abundant metals. However, many of the *critical metals* are produced as *by-products* of base metal refining (Figure 4). For example, a typical copper ore may also contain a number of other metals at much lower concentrations, such as selenium, tellurium and precious metals (silver, gold, and platinum group metals (PGMs)). In the course of copper refining these metals may be recovered if economically viable. In some instances this type of *by-product* recovery accounts for the vast majority of a metal's production (e.g. tellurium). Metal groups such as the rare earth elements (REEs) or PGMs are usually produced together as *co-products* from one ore body. These types of production often complicate the typical economic responses to fluctuating metal price, which we discuss in Part II.

Figure 4: By-product metals and their respective host metals



Source: Adapted from Hageluken and Meskers (2010)

There are several different terms used in the literature to refer to *by-product* recovery of critical metals. Some authors refer to these critical metals as *secondary metals* though this phrase is also used to refer to metals produced through recycling, creating confusion (Candelise *et al*. 2011). Other authors refer to these critical metals as *daughter metals*, with the phrase *parent metals* referring to the originating base metal (Graedel 2011). The phrase *hitch-hiker* is also used in some literature (Peiró *et al*. 2011). In this document we use the phrase *by-product* to refer to metals produced as a by-product of the refining of a more abundant *host* metal.

The *critical metals* are not a fixed or consistent group, and different authors include different metals. Table 1 presents some examples of the groups of metals considered and highlights the variation found between studies. However, a number of 'usual suspects' are commonly included, indicated by the traffic lights.

The variation in metals considered between different studies is a function of the different methodologies used and the different perspectives from which these studies view the problem. These points are discussed below.

Table 1: Comparison of critical metal lists from five studies

Metal	NRC	EC	JRC	AEA	Fraunhofer
Indium	✓	✓	✓	✓	✓
Gallium	✓	✓	✓		✓
Rare Earth Elements	✓	✓	✓		✓
Platinum Group	✓	✓	✓		✓
Germanium		✓	✓		✓
Cobalt		✓		✓	✓
Niobium	✓	✓			✓
Copper	✓			✓	✓
Tantalum	✓				✓
Antimony		✓			✓
Lithium	✓			✓	
Titanium	✓				✓
Tin				✓	✓
Lead				✓	
Silver					✓
Selenium					✓
Tellurium			✓		
Magnesium		✓			
Magnesite		✓			
Tungsten		✓			
Manganese	✓				
Vanadium	✓				
Beryllium		✓			
Borates		✓			
Chromium		✓			
Silicon metal		✓			
Hafnium			✓		
Rhenium			✓		

Source: NRC (2008) EC (2014b), JRC (Moss *et al*. 2013), AEA (2010) and Fraunhofer (Angerer *et al*. 2009a)

Notes: Metals are ranked by the number of critical metals studies they appear in, with metals appearing in all five studies listed first. PGMs and REEs grouped together. Non-metals fluorspar, phosphate rock, coking coal and graphite excluded from EC (2014b). Non-metal graphite excluded from JRC (Moss *et al*. 2013) Non-metal phosphorous excluded from AEA (2010). JRC (Moss *et al*. 2013) includes metals in the 'critical' and 'near-critical' categories as defined in their report.

How reliable are the data?

Studies assessing the availability of critical metals typically rely on a range of published data to inform their analysis. However, the quality of these data sources has been questioned, potentially affecting the robustness of any analysis relying on them (Willis *et al*. 2012).

Many studies examining critical metals availability studies begin by analysing the historical geological data. Two types of data are typically included:

- historical production data; and
- reserve and resource data[1].

These types of data are collected and published by a number of institutions, though three main international sources of this data are commonly used. The British Geological Survey has published global metal production statistics for a century, and an archive of all previous publications can be found online (BGS 2014). Crowson's (2001) Minerals Handbook, published between the 1980s and early 2000s, is another source of metals production and reserves data used in availability assessments (Andersson 2000). By far the most often cited geological data source is the US Geological Survey (USGS). The USGS maintain several publications, and archive these online (USGS 2013d). The most cited of these, the Minerals Commodity Summaries (MCS), present annual production and estimated reserve data for most metals[2].

The USGS is a popular source for geological data because it has among the widest coverage of metals, and its data are freely available online. However, there are limitations to this data. First, there are certain *data omissions* that have implications for critical metals analysis. The USGS MCS for gallium, for example, has not reported production, reserves or reserve base data since the beginning of its online archive, citing the proprietary nature of producer data. The US proportion of production is also omitted for many of the metals covered in the USGS MCS publication, again citing issues of data ownership. Specialist studies can be used to cover some of these omissions, such as International Study Groups (Willis *et al*. 2012) or consultancy reports (Chegwidden & Kingsnorth 2011).

Comparing USGS data for different metals can also be challenging. The rare earth elements (REE), for example, are a group of 17 different elements that the USGS report in aggregate. It is not therefore possible to accurately compare the production or reserves of any of the individual metals included, nor is it possible to accurately compare any REE with any other metal[3]. The REEs are also reported as oxide, where most other metals are reported by 'metal content'. Oxide contains the additional weight of oxygen atoms while data reported as metal content includes only the weight of the metal. For the by-product metals the data quality are particularly poor, reflecting in part the complexities associated with the economics of extracting these metals (Speirs *et al*. 2011). This must be corrected for when comparing metal reserve, resource and production data with expected metal demand.

While reserve estimates are dynamic in nature and subject to change, very large revisions are also found in the data, suggesting uncertainty in data reporting. For example, indium reserve estimates were revised upward in 2008 to ~390% of their pre-2008 estimate (Figure 5). This is attributed to a significant revision in China's reserve estimates. It is noteworthy that China's estimated production and estimated reserves were approximately equal in the 2007 edition of the USGS MCS, which is geologically unlikely. Since 2009 the USGS has omitted indium reserve data, stating that *"quantitative estimates of reserves are not available"*. The changes in USGS indium reserve data are therefore likely to reflect difficulty in obtaining accurate information, rather than a reflection of real changes in economically recoverable indium. These data issues highlight the fact that reserve estimates are often not a good reflection of future availability.

The availability of data tends to be greatest for metals produced in the greatest quantity, and for metals produced in smaller quantities this data availability generally decreases (Willis *et al*. 2012). This is largely a function of the economic incentive to understand the geology of metals most in demand. In order to improve the quality and availability of data for the critical metals it may be necessary to increase the funding of public bodies such as the national geological surveys or provide other incentives to the extractive industries to provide publically available information on resource and reserve estimates. Efforts such as the EC Raw Materials Initiative (EC 2014a) are a significant step in this regard and should be maintained in the future to respond to the dynamic nature of future critical materials availability.

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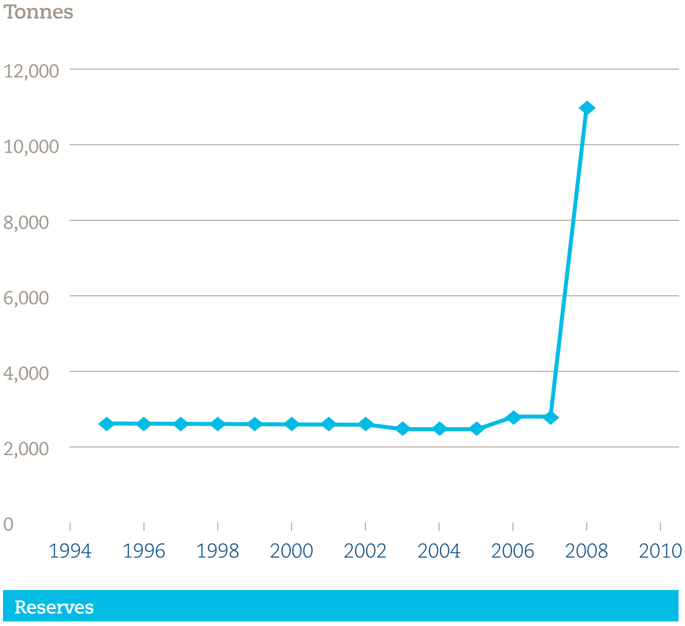
[1] Precise definitions of these terms are provided in Box 2

[2] USGS data is published early in the calendar year, and are therefore subject to revisions in the short term as information for that year improves.

[3] Some reports are beginning to provided REE data disaggregated by individual metal, though this development is not replicated in most publically available metals data (EC 2014b).

Figure 5: USGS estimates of global indium reserves from 1995 to 2008



Source: USGS (2013d)

Measuring availability

Critical metals availability is measured in two ways: high level comparative multi-criteria analyses, referred to as *criticality assessments*; and material or technology specific assessments. While the former provides a way to compare the criticality for a range of metals, the latter provides a greater level of analytical depth.

Criticality assessment

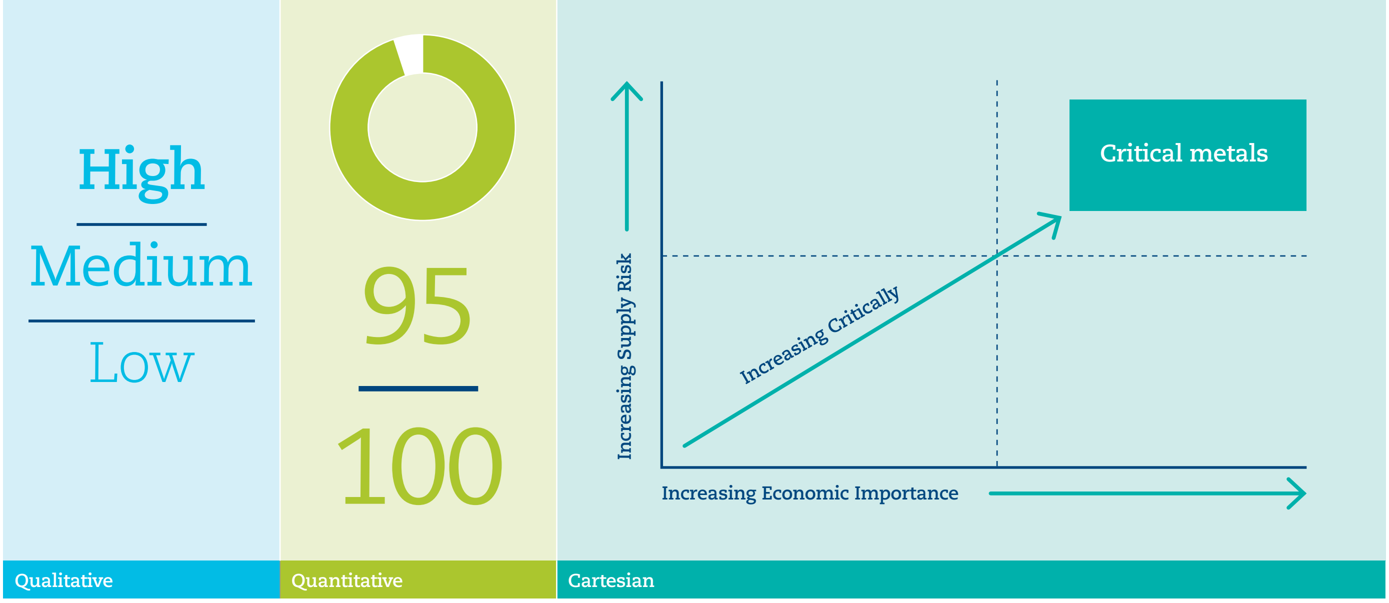
Criticality assessment has become a popular methodology in the past decade as concerns over the availability of critical metals increase, and governments and companies seek ways to identify the particular metals most at risk of availability constraints in the future. Given the diversity of audiences for such reports – companies, regions, and countries – it is perhaps not surprising that many different approaches have been applied. However, there is a degree of agreement in the general methodology for criticality assessments. Authors typically gather together a range of metrics or 'factors' representing important determinants of future metal availability. 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. Some commonly assessed factors 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.

Though there are several commonly included factors, the exact mix of factors and form criticality assessment takes varies significantly between studies. A comprehensive comparison of the factors included in different assessments is presented in Working Paper III (Speirs *et al*. 2013c).

Assessments also vary in the way they score metals against the assessed factors including: qualitative low-mid-high scales; explicit numerical scales; or criticality matrices with two coordinates for the two axes (Figure 6). Where criticality matrices are used the assessed factors are generally split into two groups and expressed on two separate axes. Supply factors and geopolitical factors are commonly grouped together, referred to as *supply risk*, while the demand factors and other factors are grouped together as *economic importance* (Angerer *et al*. 2009a; EC 2010) or *vulnerability* (Erdmann & Graedel 2011). In more sophisticated methodologies the matrix can be represented by three separate axes. For example, Graedel *et al*. (2012) present a three axes matrix, with *environmental implications* represented on the third axis, capturing the environmental implications of using a particular metal, including human health and ecosystem impacts.

Figure 6: Examples of types of criticality scoring used in the criticality assessment literature



Studies also vary in the weighting and aggregation of criticality scores. When aggregating scores for multiple factors in a criticality assessment some authors choose to give extra weight to particular factors judged to be more important, while other authors judge all factors equal (Erdmann & Graedel 2011). The ways in which weighting is applied may also vary, between and within studies. Though aggregation methodologies appear to be largely subjective the impact of different weighting can significantly alter the outcome of criticality assessment. Erdmann and Graedel (2011) demonstrate the impact of varying aggregation method on the criticality scores in the EC study 'Critical raw materials for the EU'. By comparing scores using different weighting methods it is apparent that the classification and ranking of critical metals may be significantly affected by the aggregation methodology used.

The perspective or focus of the criticality assessment also influences findings. Some assessments may be conducted from the perspective of a national economy (Morley & Eatherley 2008; NRC 2008), some from the perspective of private company (Duclos 2010b), and some from a specific political goal, such as defence capability (Thomason *et al.* 2010) or low-carbon technology development (Buchert *et al.* 2009; DOE 2010). Geographical scope may provide further variation in results and studies with a global scope typically produce more uncertain results (Buchert *et al.* 2009; Achzet *et al.* 2011; APS & MRS 2011; BGS 2011; DOE 2011). Since resources critical to one nation or region may not be critical to another, aggregating this variation can create significant uncertainty.

A limitation of criticality assessment methodologies is that they are not designed to capture the impacts of changes in criticality over time. This is a particular problem for the calculation of supply risk where contributory factors, such as metal supply or geopolitical factors, may change significantly in the medium or long term. For example, several criticality studies include geological data as a supply risk factor by calculating the ratio of reserves to production in the most recent year (R/P ratio) (NRC 2008; Buchert *et al.* 2009; Rosenau-Tornow *et al.* 2009; AEA 2010; Achzet *et al.* 2011; SEPA 2011; Graedel *et al.* 2012). However, R/P ratios should not be considered a good measure of future availability, as discussed in Part II. Alternatives to the R/P ratio have been proposed[4] (Graedel *et al.* 2012) but have seldom been applied in criticality assessment.

Attempts to assess and compare a large number of metals, as criticality assessments do, creates its own difficulties. First, it limits the types of metrics that can be included since necessary data may not always be available for all metals. This is one reason why many assessments use metrics such as R/P ratios which may have inadequacies, but for which data is freely availability for the majority of metals. Second, though data may be available for all metals, the data for different metals may not have the same level of confidence or certainty. Resources data, for example, may be based on extensive geological evidence for some metals, and limited evidence for others. Without incorporating ranges of uncertainty a criticality assessment gives all data equal certainty, masking the variation in quality of data sources. A range of issues associated with reserve estimates is discussed in Part II.

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[4] An alternative to the R/P ratio, called the Depletion Time (DT) (Graedel *et al.* 2012), is calculated based on an iterative spreadsheet model and incorporates recycled metal resources by modelling end-of-use lifetimes. DT also allows for more sophisticated evaluation using future scenarios for world demand, recycling rate and lifetime of end-use products.

Technology- or metal-specific analyses

An alternative to criticality assessment is to examine the specific availability issues associated with a particular metal, or end-use demand (e.g. a low-carbon technology such as an electric vehicle). A number of studies take this approach, allowing for a more detailed and inclusive analysis of the evidence (Andersson 2000; Fthenakis 2009; Yaksic & Tilton 2009). Metal or end-use specific studies tend to be less methodologically driven than criticality assessment and. the range of variation in approaches reflects the different conditions surrounding each of the critical metals.

Some of these assessments have a supply perspective, working towards an estimate of available metal, and calculating a quantity of technology that can be manufactured. For example, Andersson (2000) calculates the capacity of thin-film PV that could be manufactured using the total reserve estimate for metals typically used in thin-film PV cells[5]. However, as with criticality assessment, this approach does not capture the changes in reserve estimates or metal demand over time. This can be addressed by estimating scenarios for annual production of metals over several decades and calculating the annual thin-film PV capacity that could be manufactured from the available quantity of metal (Fthenakis 2009; Moss *et al*. 2013)

The demand side perspective can also be addressed in more detail in metal or end-use specific assessments. The technological drivers of demand, for example, are critical variables and are likely to vary over time. Variables like the thickness of active layer in thin-film PV or the size of batteries in electric vehicles impact significantly on total metal demand, are both likely to change over time, and are difficult to predict. A number of assessments include static assumptions on these technological variables (Andersson 2000; Keshner & Arya 2004; Wadia *et al*. 2009) and others include scenarios for the change in these technological variables over time (Fthenakis 2009; Houari *et al*. 2013) (see Part III).

More complex modelling methodologies can be applied to incorporate all of the changes in demand side and supply side variables over time, and the dynamic interactions between them (Houari *et al*. 2013). However, few assessments employ these types of techniques, and the evidence base is largely limited to more static forms of assessment.

Summary

A number of issues are worth addressing when considering the literature on future availability of critical metals. First, the range of different terms, often used interchangeably, can create some confusion, and defining these clearly is important. For various reasons the available data on both reserves and production is relatively poor for a number of lesser-known metals. This is in part a function of the relatively low economic importance of these commodities historically.

Two different approaches are applied to the assessment of future availability of critical metals:

- Criticality assessments, using a multi-criteria approach to assessing the relative availability of metals in the future; and
- Technology- or metal-specific analyses, using a more focussed in-depth approach to examine the issues specific to particular metals and the technologies/end-uses they used in.

While the former can provide high level signposting of the important issues facing critical metals, the latter can provide greater detail in the analysis if particular metals. The following sections of this report examine in more detail some of the important issues of supply of, and demand for, critical metals now and in the future.

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[5] Andersson (2000) examined several thin-film technologies and some of their associated metals: Cadmium Telluride (CdTe), containing cadmium and tellurium; Copper Indium Gallium (di)Selenide (CIGS) containing indium gallium and selenium; amorphous silicon (aSi) containing germanium; and dye-sensitised nano-crystalline cells, containing ruthenium.

Estimating future supply

2

The quantity of metal available to global markets in the future is an important aspect of the critical metals debate and is influenced by a number of factors. First, physical and economic factors contribute to define the quantity of metal recoverable at any moment in time. The physical recoverability of a metal resource is influenced by technological capability, and the incentive to produce resources is a function of the economic factors of production; cost of extraction and market price of commodity. In addition to these physical and economic factors, a host of other factors relating to geopolitics and policy may influence the supply chain for these metals, limiting the quantity of metal available to global metal markets. In this section we discuss these issues, beginning with the physical resource and its extraction, and concluding with an examination of the geopolitical and policy influences on metals supply.

Resources and their extraction

The first issues influencing the future supply of metals are those of physical availability: the quantity of the recoverable resource and the rate at which it can be extracted. These are difficult to estimate and subject to uncertainty, as with many of the variables affecting future metals availability. In some assessments resource estimates are used as a proxy for future cumulative production (Andersson & Jacobsson 2000; Feltrin & Freundlich 2008; Wadia *et al.* 2009). In other assessments future production estimates are developed using a variety of approaches, providing annual metal production over a given time period (Andersson & Jacobsson 2000; Keshner & Arya 2004; Fthenakis 2009; Moss *et al.* 2013). Both approaches have their benefits, and their limitations. We now look at these approaches in more detail.

Reserves and resources

There are several different categories of resource estimate, with estimates of reserves most often used to estimate future metal availability. Where these estimates are used authors typically compare reserves to estimates of demand or material intensity[6] to provide some comparative metric for their relative availability. For example, Andersson calculates that 300GW of Cadmium Telluride (CdTe) thin-film PV could be manufactured using the 1998 tellurium reserve estimate (20,000 tonnes) published by the USGS[7]. This is compared to other PV technologies including Copper Indium Gallium (di) Selenide (CIGS), of which 90GW could be manufactured using the 2,600 tonnes of indium reserves estimated in 1998[8]. However, the reserves category is typically a conservative figure with a high probability of being exceeded in the future, and any estimates of future low-carbon technology manufacture based on reserve estimates are likely to be similarly conservative.

Box 2: Reserve and resource definitions

The USGS define the terms ‘reserves’ and ‘resources’ as follows:

”Reserves - That part of the [resource] that could be economically extracted or produced at the time of determination. The term reserves need not signify that extraction facilities are in place and operative. Reserves include only recoverable materials; thus, terms such as “extractable reserves” and “recoverable reserves” are redundant ....”

“Resources - A concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth’s crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible.”

The different categories of resource estimate are commonly classified in a form similar to Figure 7[9]. The total area of the box represents all resources of metal in the Earth’s crust, of which only a proportion will be recovered in the future due to physical, technological, economic and socio-political constraints. *Reserves* represent those resources of metal that can currently be extracted given available technology and current economic conditions (costs of extraction and market price of metal) (USGS 2013c). The final category, *Unidentified resources*, represents quantities of metal that are currently unknown or uncharacterised, but are likely to be in the future.

Reserve estimates are available for many metals and published by the USGS (2013c), while estimates of identified resources or undiscovered resources are not generally available. The resources are not necessarily fixed to any one classification, and move depending on changing economic conditions, development in extraction technologies, and the results of exploration. While these boundaries can move in either direction it is more common for the quantities of metal considered in each category to grow over time.

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[6] Material intensity is the weight of metal per unit of low-carbon technology (e.g. weight of lithium per vehicle or weight of indium per 100 watts peak of solar panel capacity).

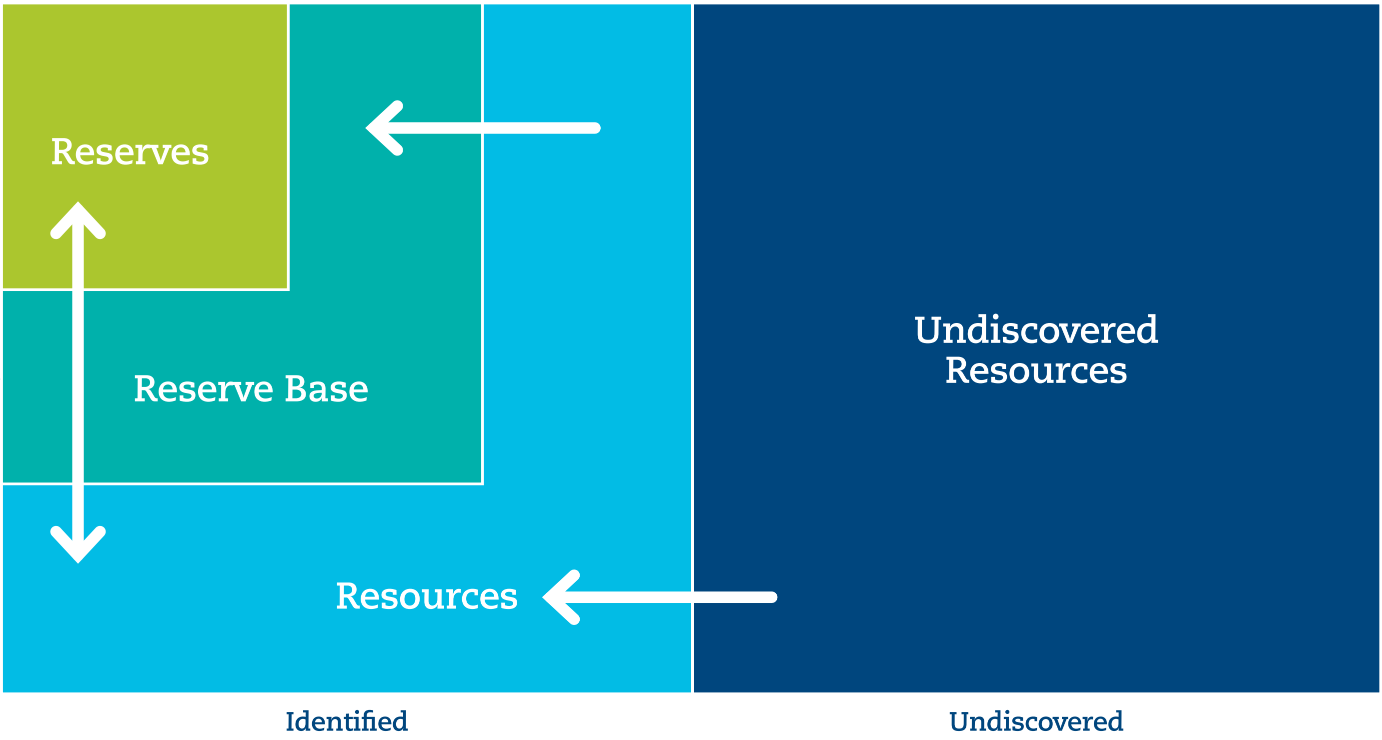
[7] Based on a material intensity of 6.5 grams per 100Wp.

[8] Based on a material intensity of 2.9 grams per 100Wp.

[9] Other classification schemes exist, most notable the CRIRSCO Template. This is a comprehensive classification scheme with extensive accompanying documentation, designed to help standardise the reporting of reserve and resource estimates by the minerals extraction industry.

Over time, regional estimates of reserves are likely to grow more than other resource categories, given their conservative nature. Ideally, the total resource recoverable over all time should be estimated, including the recoverable fractions of all categories of resource and future discoveries. This concept exists in oil resource classification, and is referred to as the ultimately recoverable resource (URR) (Sorrell *et al*. 2009). However, estimating the URR is time consuming, reliant on significant quantities of data, and can be highly uncertain. It is unclear whether URR estimates are feasible for critical metals given the lack of available data and the large number of metals for which estimates are needed.

Figure 7: Simplified classification of metal resources



Source: Adapted from EC (2010)

Table 2 presents available reserve estimates and production data for ten critical metals used in low-carbon technologies. Annual production is included to provide context for the reserve estimates. However, as discussed above, the ratio of reserves to production should not be considered a good indicator of future availability of a commodity.

Table 2: Reserve estimates and production data for ten metals commonly considered critical to low-carbon technology manufacture (tonnes)

Metal	Primary Production	Reserves
Cobalt	120,000	7,200,000
Gallium	280	>1,000,000[1]
Germanium	155	-
Indium	770	6,000[2]
Lithium metal	35,000	13,000,000
Platinum Group Metals	Pt 192 Pd 211	66,000
Rare Earth Elements[3]	110,000	140,000,000
Selenium	3,000-3,500[4]	120,000
Silver	26,000	520,000
Tellurium	500[5]	24,000

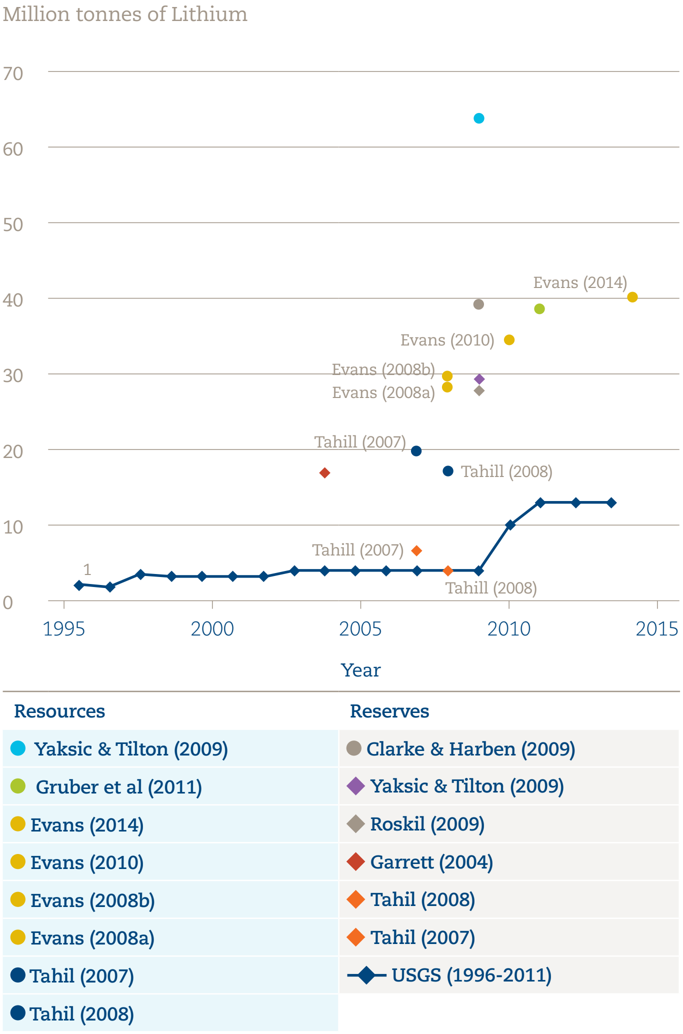
Source: Data from USGS (2014) unless otherwise stated

Notes:

1 USGS (2006)
2 USGS (2007)
3 Rare Earth Oxide and not metal
4 Based on estimate in USGS (2011b)
5 Speirs *et al.* (2011)

As mentioned above, one significant issue associated with reserve and resource estimates is that they are a function of current conditions, such as current economic conditions, current technological expertise or cumulative exploratory effort to date. Therefore, as these conditions change over time so to do these estimates. The nature of the 'moving target' of reserve and resource estimates, means that it is difficult to use them when estimating the future availability of a resource. Figure 8 highlights this problem for lithium reserve and resource estimates. First, it highlights the differences between categories of resource estimate. Second, it highlights the general trend of resource estimate growth over time.

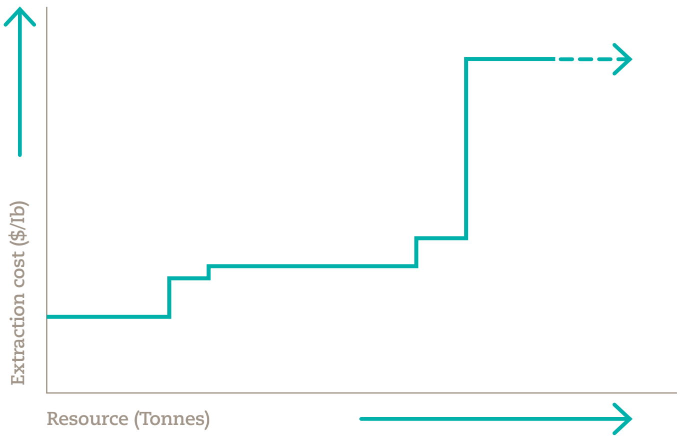
Figure 8: Range of historical reserve and resource estimates for lithium, presented in the year in which the estimate was made



Source: Yaksic and Tilton (2009) Gruber *et al.* (2011) Evans (2014) Evans (2010) Evans (2008b) Evans (2008a) Tahil (2007) Tahil (2008) Clarke and Harben (2009) Yaksic and Tilton (2009) Garrett (2004) USGS (2014) (Chegwidden & Kingsnorth 2011)

The cumulative availability curve provides an alternative approach to calculating the future availability of resources. In this approach the geological sources of extractable metal are presented on two axes, with the quantity of the resource along the x axis and the cost at which the resource can be produced on the y axis (Figure 9). Different sources are presented in order of cost, with the cheapest sources on the left and the most expensive on the right. This approach provides an idea of the increased cost associated with producing the marginal tonne of metal. Where the cumulative availability curve of a metal is relatively flat, the cost of expanding future production is relatively low, indicating that future metal production might be relatively unconstrained by economic factors. Where the curve is steep, however, future metal production may be constrained by the rate at which extraction costs increase in the future.

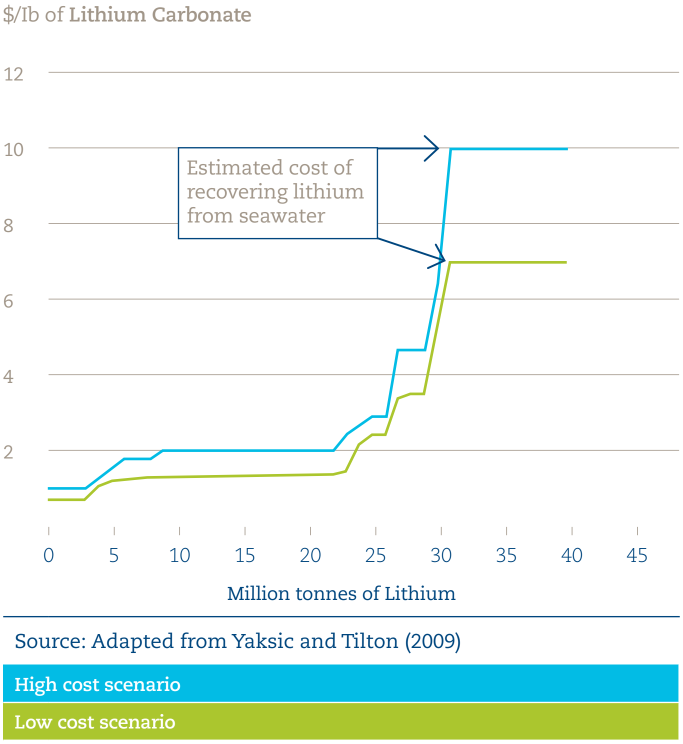
Figure 9: Generic representation of a cumulative resource availability curve, with the quantity of resource on the x axis and the cost of extraction on the y axis



Yaksic and Tilton (2009) present a cumulative availability curve for lithium, highlighting the very large quantities of resource available if consumers are willing to pay the high cost of extracting lithium from sea water (Figure 10). This indicates the physical challenges associated with extracting metals from geological sources with ever-decreasing metal concentrations, and the ever-increasing costs associated with recovering these metals. Being able to compare resource-cost curves like this for several metals could be a valuable means by which to assess the relative ease with which future production can be increased. However, very few studies employ this approach and cumulative availability curves are not available for most metals. These analyses would need to be updated regularly, with costs likely to change over time as the technology develops; lowering the cost of extraction for a given geological source. Creating and maintaining cumulative availability curves is also subject to the transparency of extraction costs, which operators may have commercial incentives to keep confidential. All of these factors are likely to impact on the accuracy of these curves, both immediately and over time. In addition, future availability of by-product metals is very difficult to measure using cumulative availability curves due to their reliance on the economics of their host metals. The economics of host metal recovery could also be incorporated into the cumulative availability curves of by-product metals. However, partly due to the impracticality of this type of analysis, by-product metal cumulative availability curves do not appear often in the available literature.

The USGS calculate the reserves of by-product materials by estimating the quantity of metal know to occur in their host metals. For example, estimates of tellurium reserves are based on the known quantities of tellurium found in the anode slimes of copper production (USGS 2011a). However, tellurium also exists in association with other metals and in some instances is recovered on its own and not in association with a host metal (Houari *et al.* 2013). These sources are not currently considered in USGS estimates[10].

Figure 10: Cumulative availability curve for lithium carbonate



Source: Adapted from Yaksic and Tilton (2009)

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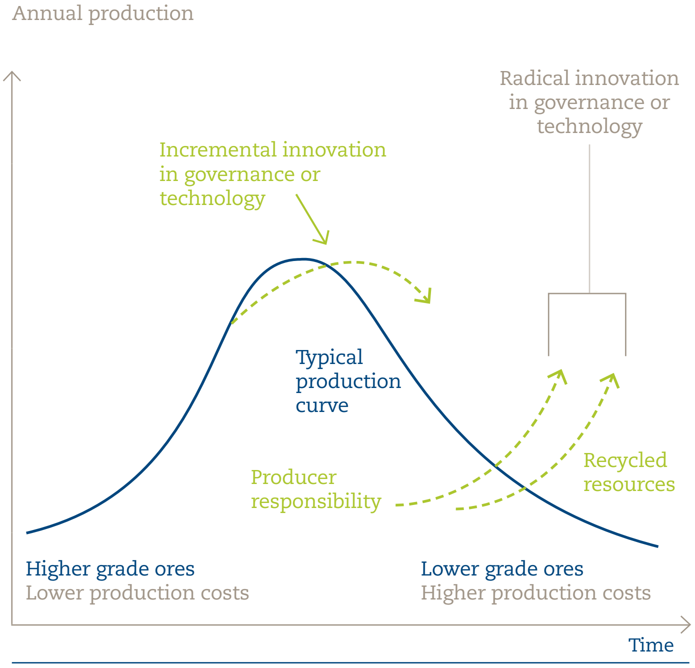
[10] Working paper I (Speirs *et al.* 2011) discusses issues of by-product metal recovery in more detail.

Production rates

While estimates of recoverable resources may provide an indication of potential cumulative production, it is also important to understand the rate at which a resource can be produced year on year. Though data on historical production is commonly available for most metals, estimates of future production rates are less common.

The generic production profile for a given mine or discrete metal deposit can be assumed to follow a roughly bell shaped curve, with various factors capable of modifying the exact shape of the curve (Figure 11). In the initial phase there is significant potential to increase production, though production increases become harder as mining companies move towards the marginal resource. As discussed in Part 1 the aggregate data are subject to considerable uncertainty, both in terms of production growth and reserves. However, based on the apparent exponential rate of increase in production (Figure 1), and the rate of increase in reserve estimates over time (Figure 8), many of the critical metals appear to have significant potential to increase rapidly in the immediate future. There is little evidence to suggest that resource availability or depletion is affecting production growth now and/or in the short term. If economic incentives persist and prices remain high then exploration activity will increase, more reserves will likely be found and production will rise. However, exponential production growth cannot be maintained indefinitely, and it is not clear how far into the future rapid production rate growth can be maintained.

Figure 11: Typical resource exploitation profile for a given mine or deposit, with annotation indicating where events may modify this profile



Source: adapted from Prior *et al.* (2012)

Production rate is considered in criticality assessment in two ways. Estimates of current production are often used in indicative metrics, such as reserve to production ratios (R/P) (NRC 2008; Buchert *et al.* 2009; Rosenau-Tornow *et al.* 2009; AEA 2010; Achzet *et al.* 2011; SEPA 2011; Graedel *et al.* 2012), or future demand to production ratios (Angerer *et al.* 2009a; EC 2010). The R/P ratio is a common metric used in many extractive industries, including the oil and gas industry, and simply calculates a quantity of reserves for a given company, country or region divided by the annual production from that reserve. From an investor perspective the R/P ratio can provide a useful indication of the relative endowment of an extractive company's projects, and provide a way to measure companies against each other.

However, since both production and reserves estimates are likely to change over time, this metric gives little indication of the likely trend in metal availability in the future (Speirs *et al.* 2013c); the usefulness of the R/P ratio for indicating the future availability of resources at regional or global scale is therefore questionable, with studies examining regional R/P ratios for oil finding them to be a poor indicator of future availability (Bentley *et al.* 2007; Sorrell *et al.* 2009).

Alternatively, current production can be measured against an estimate of demand in a given future year. This provides an indication of the increases in production needed to meet increasing uses of critical metals. However, estimates of future demand are difficult, and subject to significant uncertainty, with no standardised methodology. For example, Angerer *et al.* (2009a) selects 15 metals or metal groups, and 32 associated emerging technologies assumed to drive the demand for these metals in the future. A range of technical and economic factors are then considered for each technology, and global economic conditions accounted for, in order to estimate the increased metal demand between 2006 and 2030. The estimate of future demand is then divided by current production. This kind of supply indicator can convey the relative difference between current production and future demand, but provides no indication of the scale of the challenge associated with increasing production in the future. For some metals, future supply increases may come at a low cost, while for others future production may be more economically and technically challenging. The metric is also highly sensitive to the assumptions regarding future demand. The European Commission (EC 2010) followed a similar methodology to generate indicators of relative future demand. However, given differences in assumptions the resulting factor estimates are significantly different than those derived by Angerer *et al.* (2009a) highlighting the sensitivity of these factors to the uncertainty in future demand estimates (Table 1).

Table 3: Estimated future demand from emerging technologies in 2030 over current production for 10 metals included in both Angerer et al. (2009a) and EC (2010)

Metal	Angerer *et al.*	EC
Gallium	6.09	3.97
Neodymium	3.82	1.66
Indium	3.29	3.29
Platinum	1.56	1.35
Tantalum	1.01	1.02
Silver	0.78	0.83
Cobalt	0.40	0.43
Palladium	0.34	0.29
Titanium	0.29	0.29
Copper	0.24	0.24

Modelling future supply prospects on an annual basis provides a more sophisticated alternative to the simple supply indicators discussed above. However, typically only the material or technology specific studies take this approach and very few critical metals have been examined in this way (Moss *et al*. 2013).

By-product metals create an additional level of complexity, which is demonstrated in some efforts to model their future production. Fthenakis (2009), for example, estimates the annual production rate of indium and tellurium based on third party projections of the future recovery of their host metals, zinc and copper, respectively. Two different host metal case studies are defined for each metal, based on the literature. From these cases, the quantity of indium or tellurium associated with host metal production is calculated, and a recovery rate assumed, which varies over time. Fthenakis (2009) then estimates the quantity of metal available to thin-film photovoltaic manufacturing by subtracting an estimate of the material demanded for all other uses.

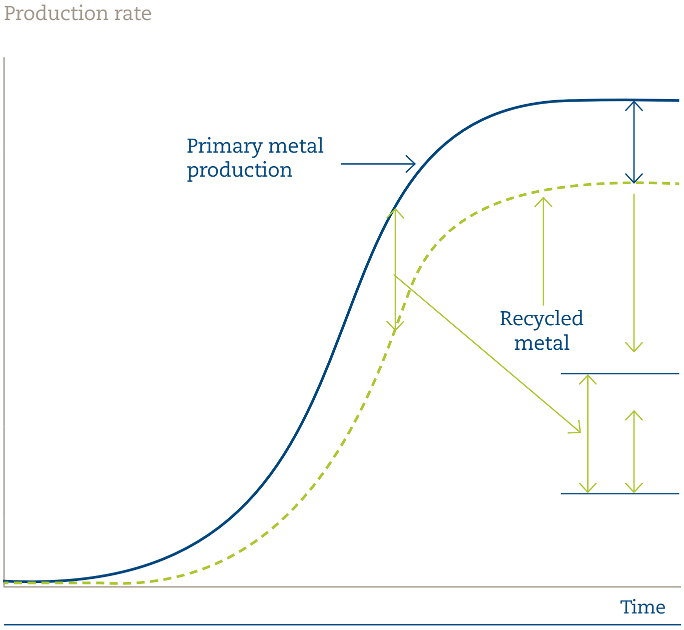
In an alternative approach, Houari *et al*. (2013) use a system dynamics modelling approach to perform a calculation that places more emphasis on the dynamic variability of the key variables over time, and the sensitivity of model outcomes to these dynamic variables.

Recycling

Recycling of metals from products at their end-of-life is often highlighted as a way in which future metal supply may be supplemented, reducing the reliance on mine production. However, the impact of recycling on future metal availability is subject to a number of factors. First, the lifetime of a product delays the availability of its components to the recycling market. In thin-film solar PV for example, modules may be expected to last for up to 30 years. Access to the recycled critical metals, contained within those modules, is therefore delayed by the same period of time. In most cases the recyclable quantity of this metal will be less than 100%, and estimating the future recovery rate[11] is difficult given that it is likely to be a function of technical capability and economic factors many years in the future. The relative contribution of recycling during different phases of the production cycle is also important. While production is growing, the quantity of recyclable material is always a fraction of what is produced from mines in any given year. This is due to the recovery rate, and the product lifetime delay. Where the rate of production growth is steep, the relative proportion of recyclable material is likely to be smaller than periods where the production rate plateaus. This means that periods where demand is growing most quickly coincide with periods where recycling can contribute a smaller proportion relative to primary production. Of course the issues for recycling are specific to individual metals, and when examining the potential for future recycling of any one of the critical metals care must be taken to understand these specific issues (EPOW 2011; UNEP 2011; Parker & Arendorf 2012).

Despite these limitations, countries or regions that are net importers of critical metals, seeking to protect themselves from metal supply chain constraints, may want to encourage recycling as a means to reduce the relative level of imports. This may mean incentivising the design of products to be easily recycled, and policy support and regulation for recycling capability.

Figure 12: The relative contribution to supply of recycling during exponential growth and plateau phases of metal production



Note: The difference between primary production and recycled production, as indicated by the double-headed arrows, changes over time, and is greatest when production rates are increasing rapidly

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[11] The recovery rate is defined as the percentage of a metal that can be recycled from the total metal container in end-of-life products.

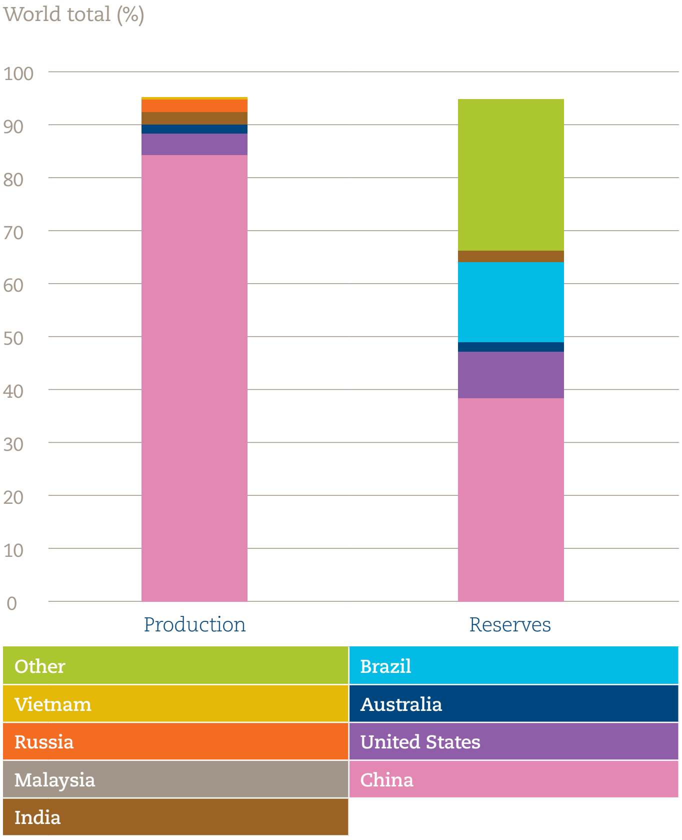
Geopolitics and policy

Geopolitical concerns and wider policy decisions can have a substantial impact on the availability and price of critical metals in global markets. These concerns are highly context/metal specific and vary through time. Geopolitical issues can be grouped into industrial policy issues, and conflict issues, with several high profile instances having received recent media and political attention (Blas 2013; Hornby & Donnan 2013).

In order to analyse the vulnerability of a metal's supply chain to geopolitical concerns it is first necessary to understand the geographical distribution of the reserves and production of that metal. Where a small number of countries are responsible for a large proportion of a metals production, then any policies and events in those countries that affect metal supply and export are likely to have a significant impact on global availability. Conversely, if the production and reserves of a metal are evenly distributed across a larger number of countries, then any potential geopolitical factors or single country political events will likely have less impact on the availability of metal globally. This assumes no coordination between countries such as a cartel.

To measure supply concentration most studies simply assign a score based on the number of supplying countries reported by the USGS (NRC 2008; Morley & Eatherley 2008; AEA 2010; DOE 2010; DOE 2011; SEPA 2011; USGS 2012). Other studies use the Herfindahl-Hirschman index (HHI), a commonly used measure of market concentration (Rosenau-Tornow *et al.* 2009; DOJ 2010; EC 2010; Graedel *et al.* 2012). The HHI is calculated using the squares of the market shares of different suppliers, so a higher HHI indicates a more concentrated market. However, it is important to also be aware of the geographical distribution of reserves. In some cases, while production may be concentrated in a small number of countries, reserves may be more evenly distributed. This may be the case where the cost of production in some countries is slightly higher than the current price. These reserves will become accessible if fears of supply concentration drive the price higher, and therefore situations like these are less influential on future availability. The rare earth elements (REE) market is a good example of this, where China was responsible for over 85% of global production in 2012, but only held 50% of global reserves (Figure 13).

Figure 13: Geographical distribution of global rare earth metal production and reserves as a percentage of the world total



Source: USGS (2014)

Notes: Reserves for Russia and Vietnam included in 'Other'.
No production data for 'Other'

If supply concentration is an issue, then a number of different events may impact on global metal supply. The first group of impacts relates to industrial policy decisions. A country responsible for a large proportion of global supply of a metal, may use that dominant position to its advantage by seeking to control the quantity of metal available to the global market. This can be achieved by instituting embargoes on trade with specific countries, or quotas to limit global exports. The goal may be to support or increase the global price of that commodity by creating an imbalance between supply and demand. Alternatively, some wider industrial policy goal may be sought, such as to encourage manufacturers to build products within the country, rather than importing components and materials to some other country which therefore benefits from the high-value end of the supply chain.

Issues of industrial policy have been of particular interest in recent years. For example, China has limited its exports of metals such as REEs and indium through a combination of export quotas, environmental regulation and domestic consumption (USGS 2013c). This has had significant impacts on certain importing countries such as Japan, whose 2012 imports of indium from China were reduced by almost 70% on the previous year (USGS 2013c).

Conflict and civil unrest in regions of metal supply concentration can also have a significant impact on global metal availability. The 'Shaba' conflicts in Zaire in the late 1970's have already been discussed as an example of metals availability being impacted by conflict (Westing *et al.* 1986). Other domestic conflicts, such as the miners' strikes and resulting civil unrest in the South African platinum mining industry, have had a much more muted impact on availability and price. The South African example is particularly counter-intuitive given that South African platinum production represents 70% of global platinum supply. This muted response to strike action is likely a result of both weak demand from main end-uses such as vehicle manufacturing, and the buffering effect of above ground stockpiles (Harvey 2013)

A number of policy options were highlighted in a report by the US Congressional Budget Office (CBO) in response to cobalt supply disruption associated with the Shaba conflicts. These include options to manage mineral availability, such as stockpiling, subsidising domestic production, and developing novel mineral resources, such as ocean-based resources. Policy options to reduce future cobalt demand include R&D funding for development and supply of substitute materials (CBO 1982). However, while these responses may be appropriate for the US context, many countries will not have all these options. In particular, many countries will not have domestic resources which can be supported through subsidy.

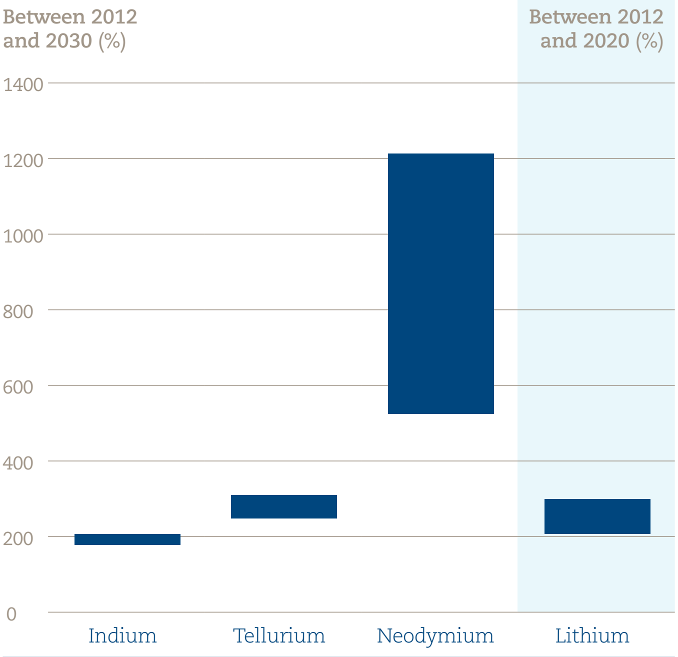
Criticality assessments tend to deal with the potential impact of conflict on future availability by scoring the perceived stability of the countries in question. This perceived stability can be measured qualitatively, or through indicators. These include the UN Human Development Index (HDI) (Graedel *et al.* 2012), the World Bank's World Governance Indicators (WGI) (Moss *et al.* 2011) and Fund for Peace's Failed States Index (FSI) (Morley & Eatherley 2008; EC 2010; DOE 2011; Graedel *et al.* 2012). The attractiveness of investment from an industrial policy perspective can be measured by the Fraser Institute's Policy Potential Index (PPI) and related metrics (McMahon & Cervantes 2011).

Finally, environmental concerns may result in policy decisions that impact on global metal supply. For example, China outlawed artisanal rare earth production due to its environmental impact (Els 2012), and have restricted export of critical metals in the past to minimise environmental harm (BBC 2014). Environmental constraints can be measured using qualitative scoring, Life Cycle Analysis (LCA) analysis or the Environmental Performance Index (EPI) (Speirs *et al.* 2013c; Yale 2014).

The range of future supply estimates

To illustrate the kinds of supply growth forecast found in the literature Figure 14 presents estimates of future supply in 2030 (Fthenakis 2009; Kara *et al.* 2010) (or 2020 for lithium (Tahil 2008; DCM 2009; Anderson 2011) for four critical metals as a percentage of supply in 2012 (USGS 2013c). Supply of all four of these metals is expected to grow in the coming years.

Figure 14: Estimated supply growth by 2030 for indium, tellurium, neodymium and lithium as a percentage of supply in 2012



Source: Speirs *et al.* (2013b) & Speirs *et al.* (2011)

Note: Neodymium supply range based on forcast rare earth oxide supply scenarios (Kara *et al.* 2010). Kara *et al.* (2010) assume Nd production is 16.2% of total REO production. This value was used to adjust the scenarios for neodymium content. Oakdene Hollins data was extracted from graphs using Engauge Digitizer. This creates a very wide range for neodymium supply. Lithium forecast only presented to 2020 due to lack of scenario evidence past this time horizon.

Summary

The future supply prospects for critical metals are dependent on a number of factors. First, issues related to the physical nature of resources should be considered. Estimates of reserves are inherently uncertain, but are likely to increase over time due to their conservative nature. Methods to estimate future production range from simple and potentially misleading R/P ratios, to more sophisticated and robust future production scenarios. The future rate of recycling has the potential to contribute to future supply, but access to metal is delayed by the lifetime of the products containing those metals. Countries that control large proportions of global supply can significantly influence the availability of metals through industrial policy decisions such as export tariffs, quotas and embargoes.

Existing estimates suggest that supply of some critical metals, such as indium, tellurium, lithium and neodymium, are likely to rise in the future, in some cases significantly. However, the range of uncertainty in those future supply estimates is large, and efforts to reduce this uncertainty should be pursued.

In the following section the issues related to estimating future metal demand are explored.

Estimating future demand

3

If availability of critical metals is defined as the ability of future supply to meet future demand then it is important to understand the likely range of future demand estimates for these metals. As with the estimation of future supply, discussed above, future demand depends on a large number of factors, all of which are likely to change over time. Future metal demand is estimated in a number of different ways in the literature, from simple use of assumptions to more sophisticated scenario-based estimates. At the centre of these scenario-based estimates is a range of variables including market growth of low-carbon products using critical metals, factors that influence the quantity of metal used in manufactured goods, known as the material intensity, and the change in that material intensity over time. The following discussion examines the range of approaches used in the literature before examining in more detail the variables driving metal demand over time.

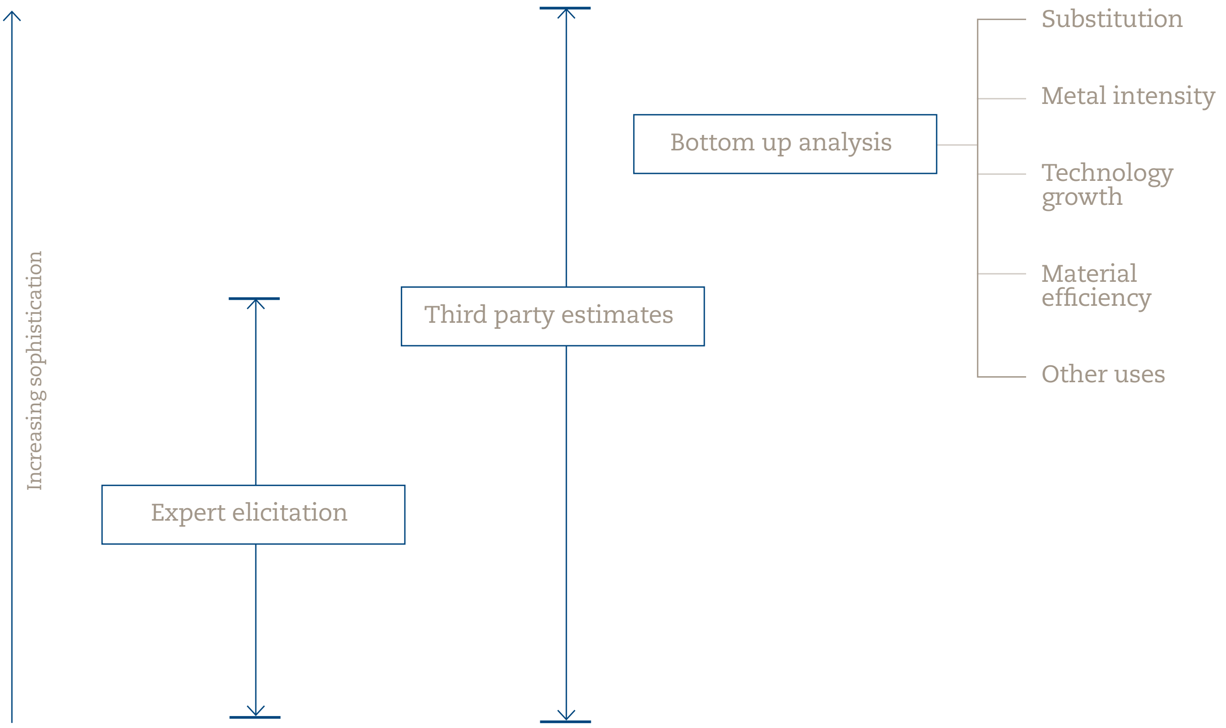
Approaches to estimating future metal demand

One approach to providing estimates of future demand for metals is to conduct expert elicitation (Angerer *et al.* 2009a; EC 2010; Moss *et al.* 2011). This may be conducted in various ways but typically involves asking a group of structured questions to selected individuals who have expertise in areas relevant to the future demand for critical metals. However, this process can be compromised by difficulties in posing appropriate questions for the technology specific aspects affecting demand, or gathering a sufficient number of responses, given the highly specialised nature of these technological issues (Angerer *et al.* 2009a). It may also suffer as a result of the proprietary nature of much data and the fact that many experts are employed by companies for whom data are commercially sensitive.

Some studies use third party estimates of future metal demand. Morley and Eatherley (2008) and Rosenau-Tornow *et al.* (2009) cite consultancy and market analyst forecasts, such as Roskill (Chegwidden and Kingsnorth, 2011). However, without full knowledge of the methodology used, it is difficult to assess whether it is any more or less robust for analysing critical metals availability than any other approach.

Finally, studies may conduct bottom-up scenario-based assessments of future metal demand. This approach is typically applied in material or technology specific studies (Speirs *et al.* 2011; Speirs *et al.* 2013b), though some criticality assessments also apply bottom-up approaches to future demand estimation (Angerer *et al.* 2009a; Graedel *et al.* 2012). A number of important variables can be incorporated into these bottom-up approaches, as discussed below (Figure 15).

Figure 15: Sources of future metal demand estimates in the literature and their relative sophistication



Key variables influencing future metal demand

Market growth in end-use technologies

Future demand for critical metals may arise from a number of end-uses. However, end-uses in low-carbon technologies have the potential to increase demand for many critical metals in the coming decades. For example, cadmium telluride photovoltaic cells are expected to be the fastest growing and major end-use for tellurium in the coming decades, playing a more significant role in future tellurium demand than all other uses combined. Table 4 lists a number of critical metals and the low-carbon technologies in which they are used.

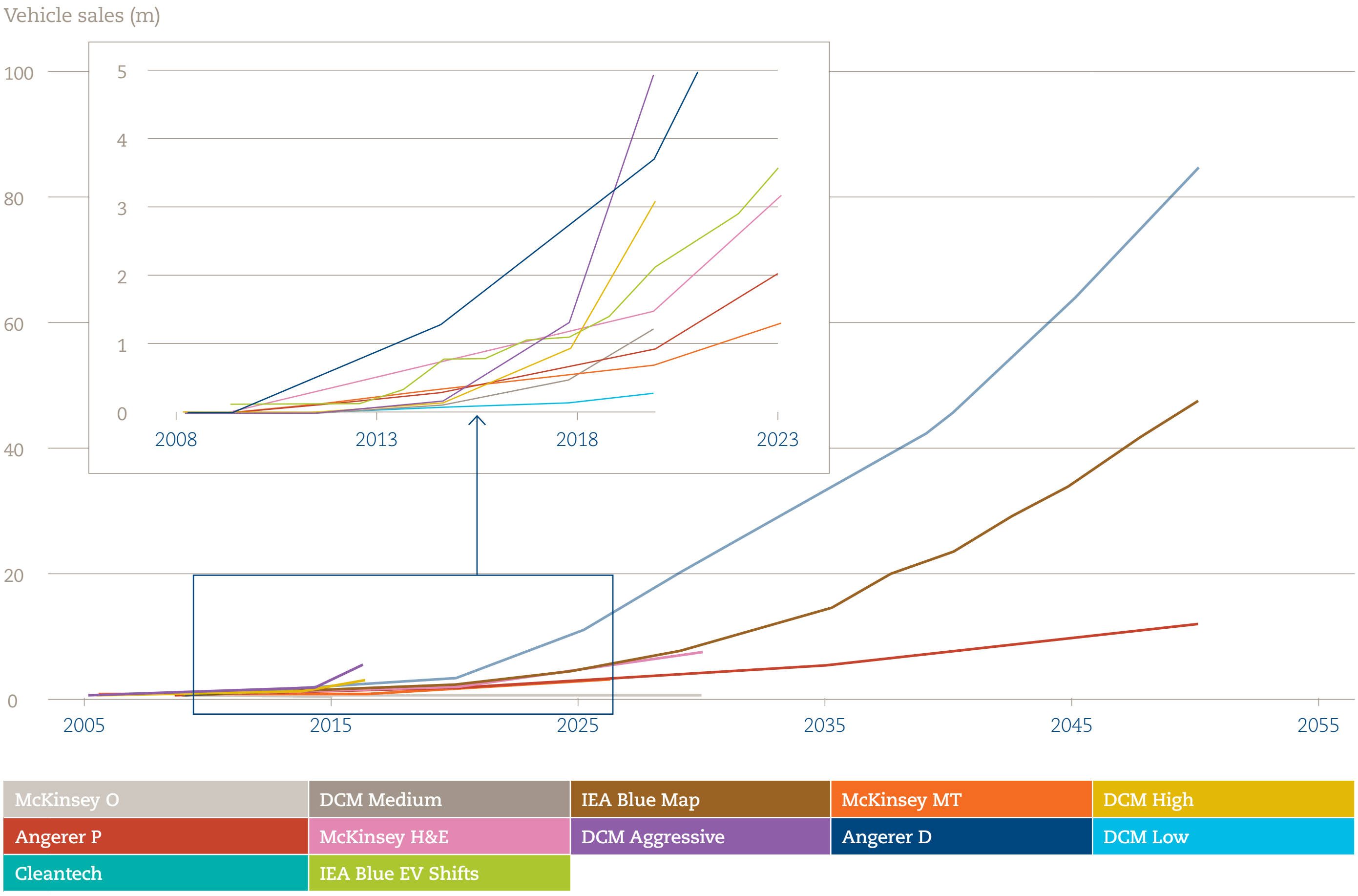
Table 4: List of ten critical metals and the low-carbon technologies in which they are used

Metal	Low-carbon technology
Cobalt	Lithium-ion batteries
Gallium	Thin-film photovoltaics (PV), Light emitting diodes (LED lighting)
Germanium	Thin-film PV, LED lighting
Indium	Thin-film PV, LED lighting
Lithium	Lithium-ion batteries
Platinum group metals (PGMs)	Hydrogen fuel cells
Rare earth elements (REEs)	Electric vehicles and wind turbines
Selenium	Thin-film PV
Silver	PV (c-Si), concentrating solar and nuclear
Tellurium	Thin-film PV

Notes: The selection of critical metals is based on the metals analysed in Speirs *et al.* (2013a)

Having established these key technological uses, plausible scenarios for the *growth* of these technologies must be established. Useful scenarios are often found in the academic literature, though studies apply different methodologies and assumptions, developing a wide range of scenario outcomes (Figure 16). Choosing a scenario on which to base estimates of future demand is therefore difficult. In the case of metals critical to electric vehicle manufacture, such as lithium or neodymium, a wide range of different vehicle manufacturing scenarios are available, including a range of different electric vehicle types (Speirs *et al.* 2013b). These scenarios are conducted over different time frames, include varying types of low-carbon vehicle, and may or may not be consistent with global greenhouse gas emissions targets. These differences, coupled with the array of methodological approaches used, leads to a significant range of estimates of low-carbon vehicle manufacture in any given year. Figure 16 presents a number of scenarios of future battery electric vehicle sales. This wide range of outcomes is common across many low-carbon technologies.

Figure 16: Comparison of scenarios of future annual battery electric vehicle (BEV) production



Source: IEA (2010); Angerer *et al* (2009b); DCM (2009); Marcus (2010); McKinsey (2009)

Note: McKinsey (2009) present three scenarios: the Optimised Internal Combustion Engine scenario (ICE); the Mixed Technology scenario, which includes a mix of efficient ICEs and electric vehicles; and the Hybrid and Electric scenario, which focuses on electric vehicles. DCM (2009) present four scenarios representing increasingly optimistic penetrations of electric vehicles: a low case; a medium case; a high case; and an aggressive case. Angerer *et al.* (2009b) presents two scenarios with the P scenario focusing on hybrid vehicles while the D scenario focuses on battery electric vehicles (BEVs). The IEA (2010) Bluemap Scenario is the central decarbonisation scenario commensurate with a 2 degree future, while the IEA Blue EV Shifts scenario is a more aggressive electric vehicle scenario.

Material intensity

Once the low-carbon technology demand scenario is established, the *material intensity* or metal demand per unit of these manufactured products is estimated. Material intensity is dependent on several factors and those factors are often technology specific. While individual manufacturers know the quantity of metal used in their products, they seldom divulge this information. There is also likely to be variation in the material intensity of products from different manufacturers. Even if the material intensity of all manufacturers' products was known, the variation in the average material intensity over time is not known and must be estimated. This variation over time is not always incorporated in critical metals studies and the impact of this omission should be acknowledged when comparing studies.

Thin-film PV provides an illustrative example of the issues associated with calculating material intensity. Thin-film PV consists of three main technologies: amorphous silicon (a-Si); CIGS; and CdTe. Silicon is relatively abundant and not generally considered 'critical' to the future of the technology. However, CIGS and CdTe are both subject to concern, due to speculation about future availability of indium[12] and tellurium, respectively. These two types of thin-film PV are therefore often examined in critical metals studies.

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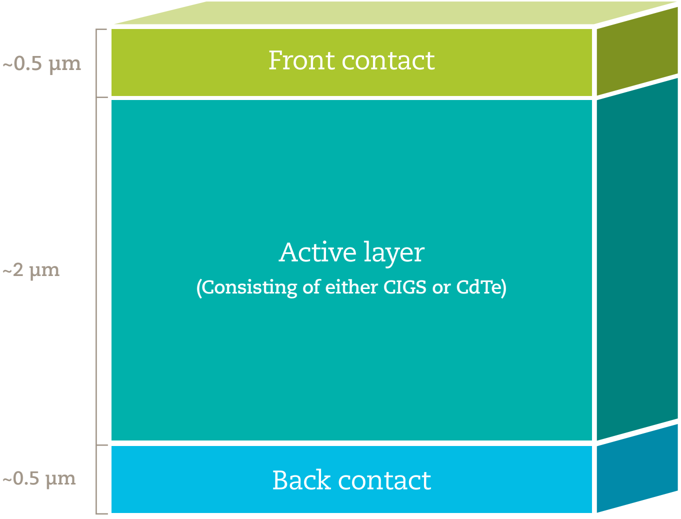
[12] Selenium and gallium also occur often in lists of critical metals, though indium is typically assumed to be the most critical for thin-film PV.

Figure 17: A simplified diagram of a generic thin-film layer structure



Thin-film PV cells consist of an active layer of photoelectrical semiconductor, sandwiched between further layers that make up the conductive front and back contacts (Figure 17). The active layer, consisting of either CIGS or CdTe, constitutes the majority of the thickness of the cell, and is where the critical metal is found. The weight of critical metal per unit area of the cell can be calculated from three factors:

1. the thickness of the layer;
2. the density of the active layer material; and
3. the proportion of critical metal in the active layer material.

The *thickness of active layers* in thin-film PV is often stated by manufacturers or analysts. The density of the active layer material is also available in published literature, or in industrial chemistry reference literature (Ullmann & Bohnet 2012). The proportion of critical metal in the active layer can again be taken from the literature, or calculated where the material has a fixed chemical relationship (stoichiometry). For example, CIGS is referred to as a solid solution of copper indium selenide (CIS) and copper gallium selenide (CGS). The relative proportion of these can vary and is not widely given by manufacturers. CdTe on the other hand has a stoichiometric proportionality, and the weight of tellurium in CdTe can be calculated from its chemistry.

The manufacturing processes for depositing these layers of active layer material varies and there is invariably some wasted material that is not properly deposited. Some of this waste material can be collected and recycled, but the rest is lost. The efficiency of metal deposition, sometimes referred to as the *utilisation rate*, must be factored into the calculation of material intensity, to capture the total weight of metal used to manufacture a unit of final thin-film PV.

The quantity of critical metal per unit area can be calculated from these factors, but to calculate the material intensity per unit of electricity generating capacity, the *efficiency* of electricity conversion must be considered. This is usually expressed as a percentage of energy captured per square metre under standard test conditions[13]. Current commercial thin-film PV efficiencies are in the order of 10-12%.

These variables can be combined in the following mathematical relationship:

$$M_R = \frac{\rho F \mu}{U S \eta}$$

Where M_R is the material requirement in tonnes per gigawatt peak (t/GWp), ρ is the density of the active layer material, F is the % of material in layer, µ is the thickness of the layer in microns (µm), U is the utilisation rate, η is the electrical conversion efficiency of the PV cell and S is solar insolation under standard conditions (1000W per m2) needed to calculate efficiency.

While all these variables can measured or estimated to reasonable degrees of accuracy, when estimating their impact on future demand for critical metal over several decades, the rate at which these variables might change is also important. Variables such as efficiency, layer thickness and utilisation rate are all likely to change as manufacturers seek to reduce the cost of PV modules through efficiency improvements, reduction in layer thickness, and improvements in manufacturing processes. The rate at which these variables might change in the future can be informed by examining the historical rate of improvements in these variables and extrapolating into the future, while being bounded by known theoretical limits (Wadia *et al.* 2011; Houari *et al.* 2013). However, much of the literature assumes static values for each of these variables, the impact of which is often not acknowledged. Those who do account for these dynamics over time, tend to estimate more optimistic outcomes for the future of PV manufacturing in the face of critical metals availability.

The case of thin-film PV illustrates the challenges associated with estimating material intensity, although it should be noted that values assigned to each variable are specific to a technology or manufacturing process.

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[13] Standard Test Conditions (STC) assumes a solar insolation of 1000 watts per square meter

Lithium intensity in electric vehicles (EVs), for example, is determined by the average capacity in kWh of lithium ion batteries, and is less sensitive to the efficiencies of manufacturing or other performance characteristics. It is also very difficult to calculate the lithium intensity per kWh of battery capacity, estimates of which are typically taken from the published literature. This highlights some of the technology specific issues that are important to consider and are difficult to incorporate into criticality assessment.

Substitutes

In response to concerns over the availability of a critical metal, or to increasing metal prices due to scarcity, manufacturers may change to a *substitute metal* that provides the same function. The market may also respond to similar pressures by choosing a *substitute technology* that provides the same utility. For example, as one of the responses to disruptions in the supply of cobalt in the late 1970s, the magnet industry began developing permanent magnets with non-cobalt chemistries to substitute for the incumbent samarium-cobalt magnets of the time. Through this effort neodymium-iron-boron magnets were developed, which have been the most powerful magnets ever since.

However, estimating the impact of metal or technology substitution is difficult. In criticality assessments expert elicitation is used to estimate the relative substitutability of technologies using critical metals (Morley & Eatherley 2008; AEA 2010; SEPA 2011). Substitute materials exist for most of the critical metals used in low-carbon technologies (USGS 2013c), however, lithium chemistry batteries and permanent magnet motors are notable exceptions. There is currently no efficient substitute for lithium-based EV batteries given the unparalleled energy density delivered by this chemistry (Armand & Tarascon 2008; Väyrynen & Salminen 2011)[14] and no other chemistry provides magnets of the power achievable with neodymium magnets used in permanent magnet motors (Jones 2011).

Although these metals are hard to substitute, there are technological substitutes. Electric vehicles could be substituted for low-carbon vehicles with less reliance on batteries, such as fuel cell vehicles, and induction motors can substitute for permanent magnet motors, eliminating the need for magnets containing neodymium. There are also a range of technological thin-film PV substitutes, for example, both crystalline silicon and amorphous silicon thin-film technologies can substitute for CdTe and CIGS. The silicon PV supply chain has recently been reorganised, making it more robust to future supply bottlenecks (Hoggett 2014). Furthermore, crystalline silicon PV has continued to experience price reductions over recent years and it remains a cost-competitive substitute for other PV technologies (Gross *et al*. 2013). There are also a number of other PV technologies in a pre-commercial phase of development, which may in the future provide suitable alternatives to critical metal-containing PV technologies (Speirs *et al*. 2011).

Other uses

The published literature suggests that these low-carbon drivers of critical metal demand account for a significant proportion of expected future demand for some critical metals. However, low-carbon technologies are not the only uses of these metals, and the impact of other competing end-uses will not be uniform across all critical metals. In some instances these impacts may be significant, and discounting them may significantly affect critical metals analysis. The critical metals tellurium and indium provide two contrasting examples.

- Tellurium has traditionally been used in three different types of end-use: as an alloy additive to improve machinability or fatigue resistance; chemical uses such as to vulcanize rubber, colour glass and ceramic, or as a catalyst; and as a component of electrical applications such as thermal imaging or PV. PV is now the largest end-use of tellurium, and is expected to account for almost all future demand increases (Fthenakis 2009). Therefore studies that pay little attention to other end-uses of tellurium in their future demand forecasts are unlikely to be significantly affected by this omission.
- Indium on the other hand, has several significant and relatively new uses, all of which are likely to drive future demand. Indium use is growing in CIGS PV modules and in LED lighting. Indium is also used in the manufacture of flat panel displays, due to the transparent and conductive properties of indium tin oxide (ITO). Flat panel displays are likely to significantly increase demand for indium in the future (Schwarz-Schampera 2014). These competing demands have helped support the price of indium, helping in turn to support the indium supply chain.

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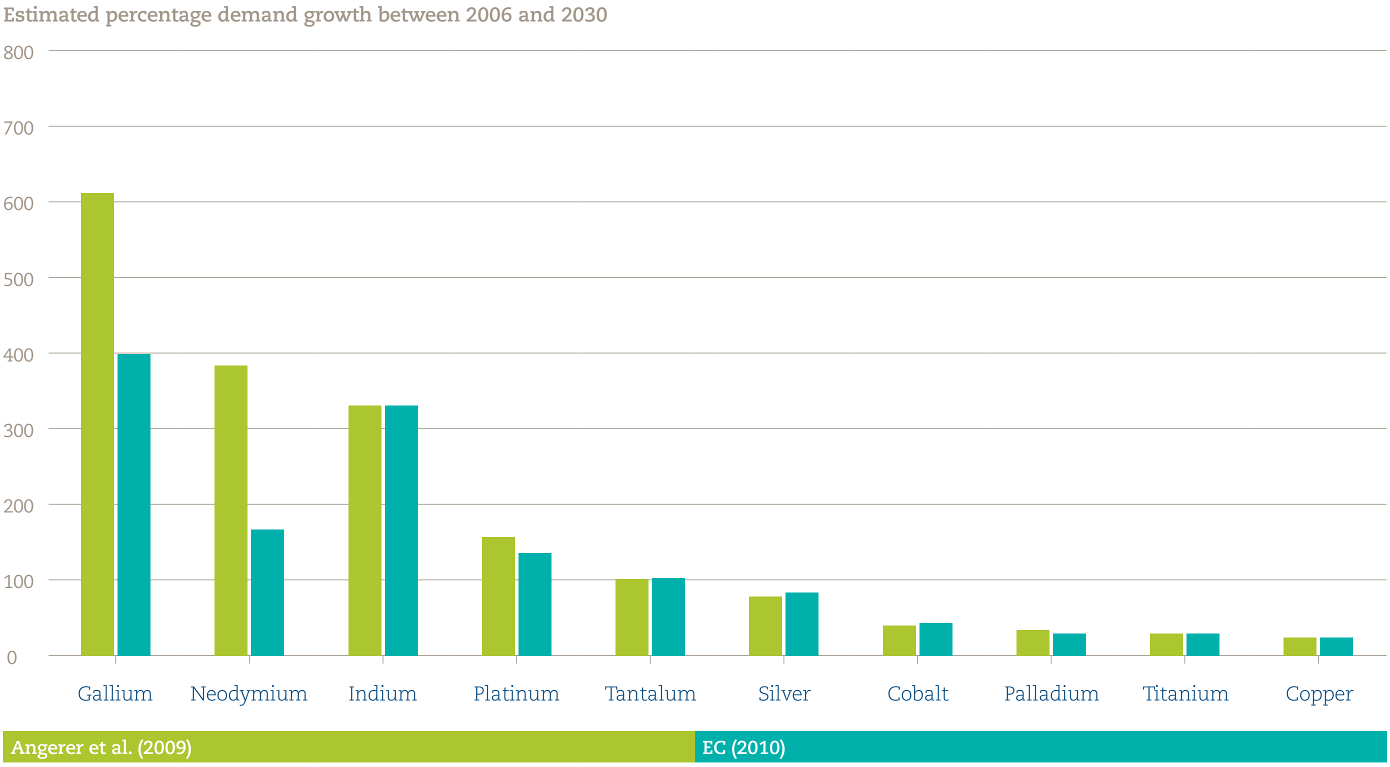
[14] A number of alternative lithium battery chemistries are under development but these technologies are unlikely to significantly reduce the lithium intensity of electric vehicle batteries.

Figure 18: Estimated percentage demand growth from emerging technologies between 2006 and 2030 for a range of critical metals analysed in European criticality assessments.



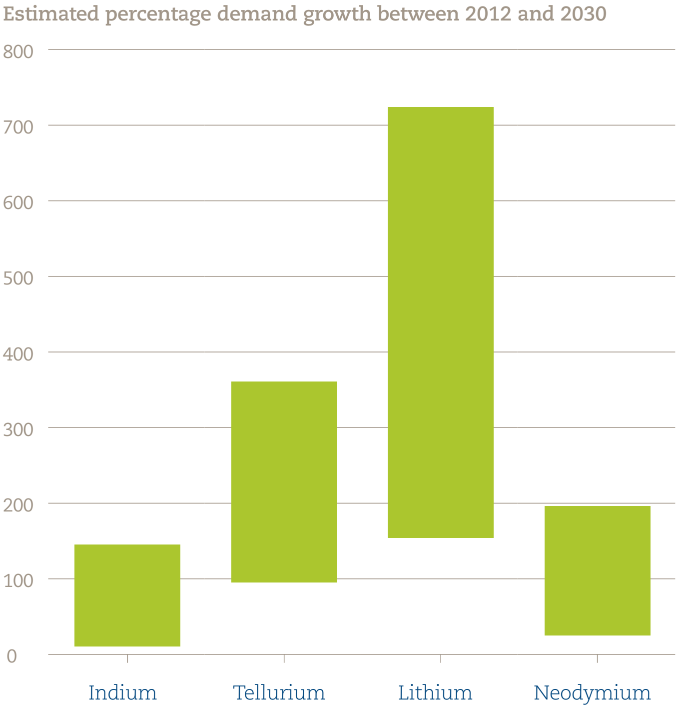
Source: Angerer et al. (2009a) and EC (2010)

Illustrative future demand estimates

The product of these demand side issues is a range of different estimates of emerging technology demand for critical metals. However, not all of the critical metals are expected to experience significant demand growth from emerging technologies in the coming decades. While demand for some metals such as indium, gallium and neodymium, is expected to grow, some analysis suggests that emerging technology demand for other critical metals, such as cobalt or palladium, might actually decrease (Figure 18). In some cases this may be driven by substitution in low-carbon technologies. For example, cobalt-chemistry lithium-ion batteries are unlikely to be the battery technology of choice for electric vehicle manufacturers as they move towards battery chemistries that are safer and better optimised for automotive applications (Armand & Tarascon 2008).

Given the range of variables contributing to estimates such as those in Figure 18, and the uncertainty associated with each of these variables, it may be more appropriate to present results as a range of possible outcomes, rather than a deterministic estimate. However, few assessments take this approach. Figure 19 presents the ranges of estimated future demand growth by 2030 for indium, tellurium, lithium and neodymium (Speirs *et al.* 2011; Speirs *et al.* 2013b). These ranges are the result of applying a range of plausible assumptions to each of the key variables determining demand. For these metals, the challenge in meeting future demand appears significant, particularly in the case of lithium. In the following section these results are compared to the findings in Speirs *et al.* (2013c), in order to assess how challenging these future demand estimates are in practice.

Figure 19: The range of estimates of future demand in 2030 as a percentage of supply in 2012 for indium, tellurium, lithium and neodymium



Source: Speirs et al. (2011) and Speirs et al. (2013b)

Notes: Production in 2012 taken from (USGS 2013c). Tellurium production assumed to be 500 tonnes as USGS estimate omits some countries production and some literature suggests that annual tellurium production could be up to this quantity (Speirs et al. 2011). Reducing this assumption leads to a greater range of estimates.

Summary

It is important to understand the prospects for future critical metals demand in order to quantify the scale of the future availability challenge. A number of techniques are applied to the estimation of future critical metal demand, based on either expert elicitation methods or bottom-up demand analysis. However, there is not enough evidence to provide a strong consensus.

A large proportion of future critical metal demand is expected to come from low-carbon technologies. Examining the factors influencing low-carbon demand for critical metals can help inform bottom-up assessments. These factors include; the market growth of low-carbon technologies; the intensity of critical metals in those technologies; and the impacts of substitutes. By calculating a range of assumptions for these factors, illustrative future demand estimates can be derived. The resulting estimates show wide ranges of future demand, highlighting the uncertainty in these estimates. However, they suggest that future demand will grow significantly from current demand in many cases.

Putting supply and demand together

4

This section briefly presents future critical metals supply and demand estimates together, giving a perspective on the scale of the challenge faced by low-carbon technology manufacturers and critical metals suppliers in the decades leading to 2050. While the narrative in this report is generic, and can be applied to a range of critical metals, the detailed analysis in the supporting working papers (Speirs *et al*. 2011; Speirs *et al*. 2013b) focuses on two technologies and four metals. Findings for those technologies and metals are presented below by comparing the future demand ranges estimated for each metal with the historical production data, and the short term future supply estimates.

Lithium, neodymium and electric vehicles

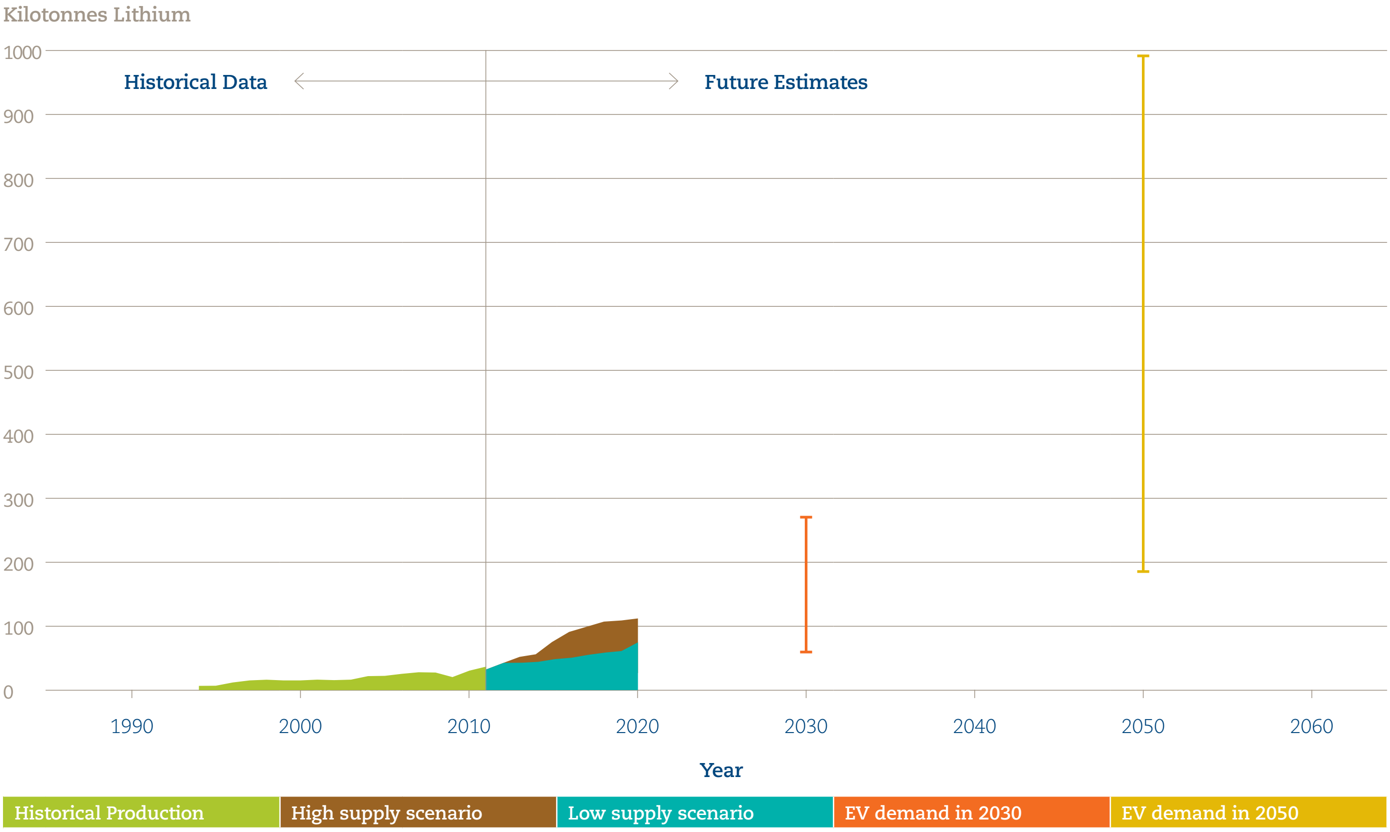
Electric vehicle manufacturing is forecast to grow rapidly in most published scenarios, with the IEA estimating over 40 million battery electric vehicle sales per year by 2050, from current annual battery electric vehicle sales of around 150,000 (ABI Research 2013). Supply of the critical metals lithium and neodymium, both used in the manufacture of electric vehicles, is constrained by several factors including physical constraints on the rate of production growth, competing uses in other technologies and export restrictions from major exporting countries. Despite these challenges, the comparison between estimates of future supply and future demand suggest that meeting expected demand for electric vehicle critical metals is achievable.

Lithium, used in electric vehicle batteries, has the most challenging outlook, based on the comparison between future supply and demand estimates (Figure 20). However, if the rate of growth forecast in the most optimistic estimates of future production can be maintained, then even the most extreme estimates of future demand are potentially achievable. The lack of long-term supply forecast evidence significantly limits the robustness of any conclusions about future availability, and growing production to this extent will clearly be a significant challenge. Reducing the material intensity of lithium-containing products, and developing and deploying substitute technologies, is likely to help reduce the magnitude of the future supply challenge.

Neodymium, used in electric vehicle motors and wind turbines, appears far less challenging when comparing future supply and demand estimates (Figure 21). Recent price inflation for neodymium and other rare earth elements has led to a flurry of exploration and production activity, which has in turn generated optimism in estimates of future supply. If these future supply estimates are achieved then future demand for low-carbon uses of neodymium are likely to be met.

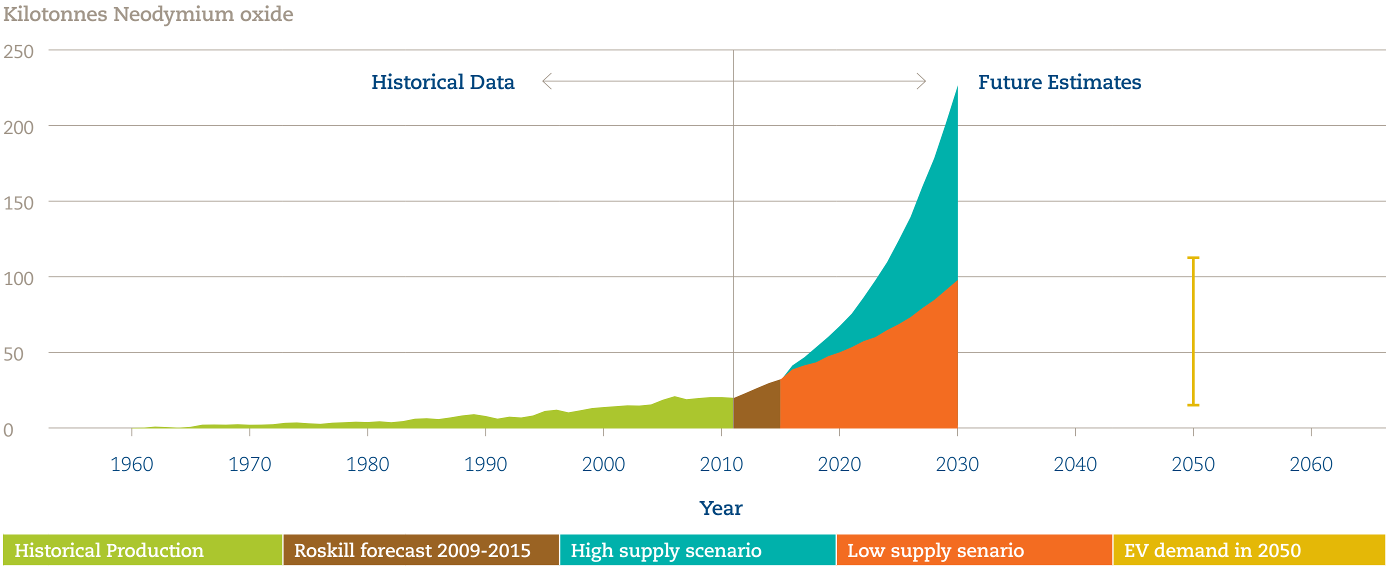
The supply and demand ranges, presented in Figure 20 and Figure 21, are large and reflect the wide range of assumptions in the literature and the uncertainty in estimates of critical metals futures. This is therefore an illustration of the implications of assumptions in the literature, rather than a useful forecast of critical metals availability.

Figure 20: A comparison of historical lithium production, future supply estimates and future demand estimates (kilotonnes)



Source: Historical production from USGS (2013c). Supply forecast range from Tahil (2008) and DCM (2009). Demand range resulting from multiplying the 2030 and 2050 IEA BLUE Map scenario for PHEV and BEV (IEA 2010) by the range of material intensities and battery size in kWh found in the literature. The material intensity assumptions are described in (Speirs et al. 2013b).

Figure 21: A comparison of historical neodymium oxide production, future supply estimates and future demand estimates (kilotonnes)



Source: Historical production from USGS (2013c). Supply forecast range from Chegwidden and Kingsnorth (2010) and Kara et al. (2010). Demand range resulting from multiplying the 2030 and 2050 IEA BLUE Map scenario for PHEV and BEV (IEA 2010) by the range of material intensities and battery size in kWh found in the literature. The material intensity assumptions are described in Speirs et al. (2013b). Note: Demand range based on 50% PM magnets in EV vehicle fleet.

Indium, tellurium and thin-film photovoltaics

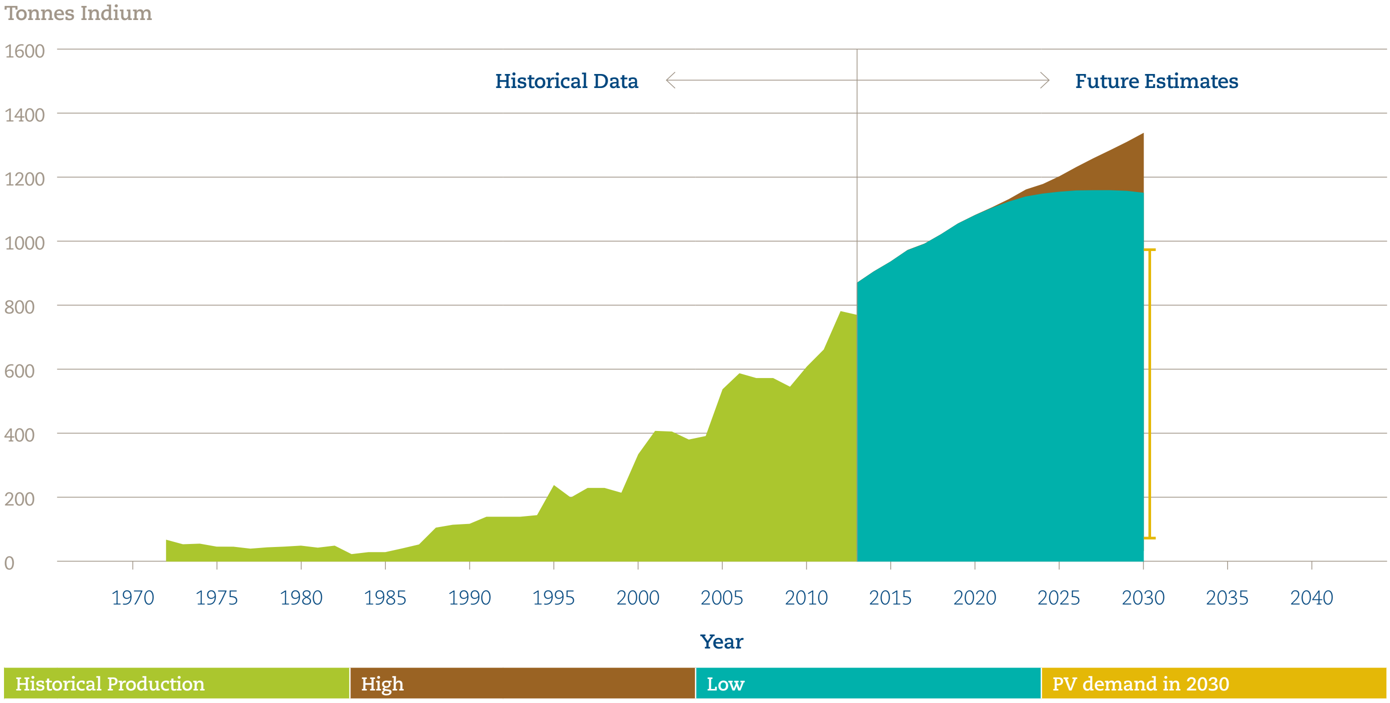
Solar PV electricity generation is one of the fastest growing renewable energy technologies globally. This growth is expected to continue until 2050, where the IEA forecasts global PV manufacturing of 140 gigawatts per year, from a total installed capacity of ~100GW in 2012 (Prabhu 2013). As with electric vehicles, supply of the critical metals indium and tellurium, used in some types of thin-film photovoltaic technologies, is constrained by issues such as physical constraints, trade restrictions and competing uses. Despite these challenges, comparing future supply and demand estimates suggests that meeting future indium and tellurium demand is achievable.

Indium, used in copper indium gallium diselenide solar cells, has future supply and demand estimates that appear relatively comparable (Figure 22). Future supply of indium is expected to increase significantly in response to high prices, brought about by demand for indium in both PV and flat panel display applications. The data in Figure 22 therefore suggests that future availability of indium for thin-film PV manufacturing is not challenging if future supply estimates are achieved. This is of course subject to developments in other uses of indium, such as ITO in flat panel displays, and the developments in zinc production, which is the host metal responsible for the majority of indium production. These issues are discussed in more detail in Speirs *et al.* (2011).

Tellurium, used in cadmium telluride solar cells, appears significantly less available than indium in the comparison of its future supply and demand estimates (Figure 23). This is in part due to the relatively slow growth in supply over the last four decades, due to the decreasing demand in traditional uses of tellurium. This gives tellurium a low base from which to grow from. It is also a function of the very broad range of assumptions used to generate the demand range in 2030. Therefore, as with lithium, it is important to pursue any demand reduction opportunities, and recycling opportunities, in order to lower the upper end of the estimated demand range.

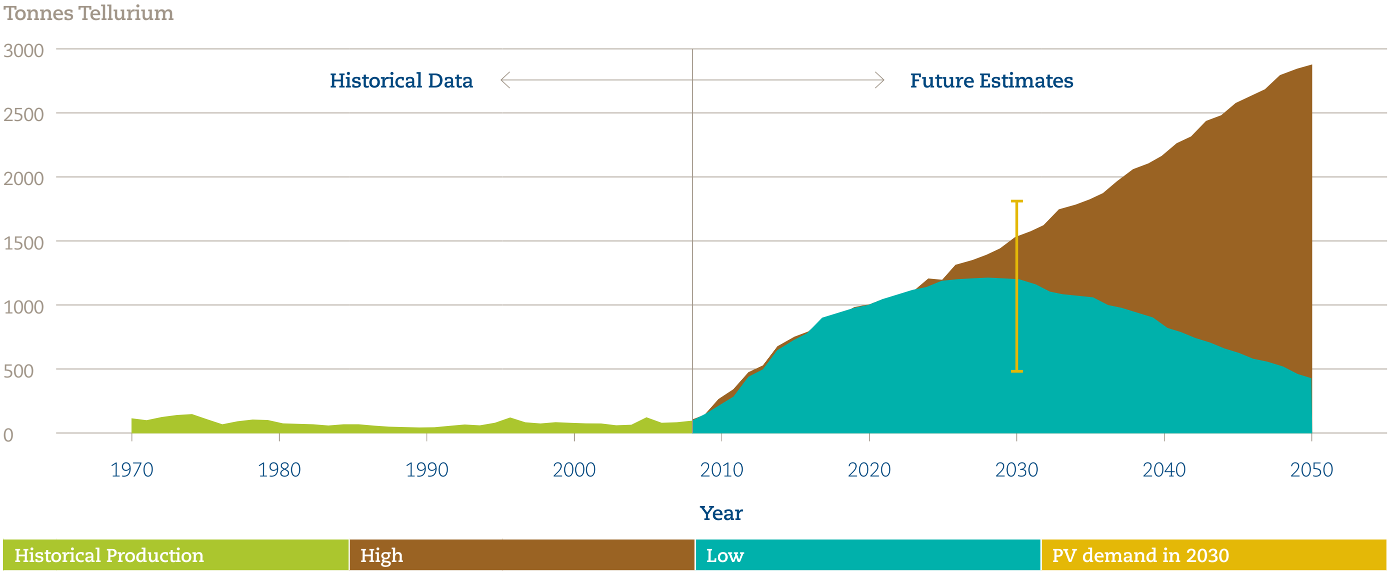
As above, the supply and demand ranges presented in Figure 22 and Figure 23 are wide and reflect the wide range of assumptions in the literature and the uncertainty in estimates of critical metals futures. This is therefore an illustration of the implications of assumptions in the literature, rather than useful forecast of critical metals availability.

Figure 22: A comparison of historical indium production, future supply estimates and future demand estimates



Source: Historical production from USGS (2013c). Demand range based on the PV scenarios in the IEA bluemap scenario (IEA 2010), and the range of material intensity variables in the literature multiplied by a scenario for thin-film PV uptake as described in Speirs et al. (2011). This includes (Andersson 2000; Keshner & Arya 2004; Fthenakis 2009; Wadia et al. 2009). Supply forecast from Fthenakis (2009).

Figure 23: A comparison of historical tellurium production, future supply estimates and future demand estimates



Source: Historical production from USGS (2013c). Demand range based on the PV scenarios in the IEA bluemap scenario (IEA 2010), and the range of material intensity variables in the literature multiplied by a scenario for thin-film PV uptake as described in Speirs et al. (2011). This includes (Andersson 2000; Keshner & Arya 2004; Fthenakis 2009; Wadia et al. 2009). Supply forecast from Fthenakis (2009).

Note: Historical production likely to be underestimated as USGS data excludes a number of undisclosed producing countries.

What does it all mean?

5

This report has examined the myriad of issues associated with estimating future availability of critical metals and measured this in terms of the demand resulting from future decarbonisation ambitions. The following sections present the report's conclusions, beginning with the report's main findings, and then presenting the issues that are unresolved or need further attention, before finally presenting the implications of these findings for policymakers.

Findings: What are the prospects for future materials availability?

The high levels of future estimates of critical metal demand and associated estimates of future supply present a significant challenge. The dramatic rate at which deployment of low-carbon technologies is expected to grow will see a significant increase in demand for critical metals, and it will be challenging for future supply to meet this demand. However, there are some reasons for supply optimism suggesting that meeting this demand may be possible.

The very high rate of production growth and the rate of increase in reserve estimates in the past, suggest that many of the critical metals appear to have significant potential to increase production rapidly in the future. There is little evidence to suggest that resource availability or depletion is affecting production growth or will do so in the short-term. If economic incentives persist then more reserves are likely to be proven and production is likely to increase.

Rising demand is likely to provide that incentive, as it drives up prices, encouraging exploration and production companies to find and produce increasing quantities of metal. The existing estimates of future supply for many of the critical metals agree with this assessment, presenting various degrees of production growth in the future. However, such increases to production cannot be maintained indefinitely, and it is not clear how long such high levels of production rate growth can be maintained.

Recycling of metals from end-of-life products can augment supply in the future, given a sufficient price incentive and/or regulation. While recycling is not sufficient to mitigate all of the challenges associated with dramatic demand growth, it can play a valuable role in improving the security of metal supply, particularly for countries or regions that rely on imports as their primary source of critical metals.

While future critical metal demand is likely to grow quickly, substitution is one mitigating factor which might ease future demand. While the options for material substitution for some technologies appear to be limited, there are several technologies which can substitute for those containing critical metals. For example, while some thin-film PV technologies rely on critical metals, others, such as amorphous silicon, do not. Crystalline silicon solar cells are also a substitute for these technologies, as they continue to experience price reduction and have well developed material supply chains. Electric vehicles have similar technological substitutes, with fuel cells, hybridisation and electric induction motors helping to reduce the demand for lithium and neodymium in future designs.

Unresolved issues

There are a number of issues that make estimating the future availability of critical metals a significant challenge. The resulting uncertainty is therefore problematic from a policy perspective given the resulting wide range of future estimates.

First, the availability of data on production and reserves of critical metals is incomplete. The USGS publishes the most widely cited data for most critical metals, and is an extremely useful source of production and reserves data. However, USGS data is subject to a number of omissions, particularly for the lesser known metals, which is a challenge for critical metals. For example, the USGS gallium data does not include estimates of reserves, indium reserves have not been reported since 2007 when China's stated reserves doubled and tellurium production is only reported for selected countries due to inadequate availability of information (Speirs *et al.* 2013a; USGS 2013c). In addition, US production data for many metals is withheld, citing the protection of companies' proprietary data (Speirs *et al.* 2013a; USGS 2013c). Other sources are available but suffer from significant omissions themselves (Speirs *et al.* 2011; BGS 2014).

The estimation of future supply is highly uncertain, creating problems for estimating future availability. Forecasting future supply is difficult for other commodities such as oil or gas (Sorrell *et al.* 2009; Pearson *et al.* 2012). However, this is particularly the case for critical metals, where relatively little effort and expertise has been applied to refining future supply estimates. The sophistication of future supply estimates is likely to improve over time, though as with many commodities, some level of uncertainty is likely to remain.

One significant reason that supply side data is currently poor is the relatively low economic incentives associated with critical metals in comparison to base metals (Moss *et al.* 2011). However, this is likely to change as demand increases in response to low-carbon technology growth. As things improve it is important to maintain surveillance of critical metals issues and identify developing issues as they arise.

Estimates of future demand are similarly constrained by significant uncertainty, applying generally to all end-uses and more specifically to low-carbon technology deployment and material intensity. Uncertainty around low-carbon technology deployment is largely a function of the lack of clear signals from international climate policy. Uncertainty surrounding estimates of material intensity are likely to improve over time, through examination of learning rates and substitution effects. However, it is unlikely that all uncertainty in future demand estimates will be resolved completely.

Implications for policy

A number of policy issues arise in response to the analysis in this report. The traditional policy responses to metal supply chain concerns include: public support for domestic exploration and mining; strategic stockpiling of selected metals; international diplomacy; financial support and bilateral agreement with foreign exporters; and funding for the research and development of viable substitute technologies. While larger countries, such as the US, may have capacity to engage with all of these responses, smaller countries may not have that capacity independently. For these countries, engagement in policy responses through larger international collaboration is likely to be most efficacious.

Whether policy responses are unilateral, or coordinated, it is important that countries concerned about critical metals intimately understand which, and how much, critical metals they might need in the future. This knowledge will facilitate policy making for unilateral actors, and inform negotiating positions where a country's policies are formed at a regional level. In order to maintain this critical metals intelligence, policy-makers may need to support the capacity of national geological surveys, or other suitably equipped institutions. These institutions are best placed to compile and analyse geological data, and have traditionally made such information publicly available. However, in order to fill the gaps in current data sources, additional resources and closer cooperation with industry are needed.

Support for research into future technological needs, required by the transition to a low-carbon economy, is also important to maintaining an evidence-base around which to create policy. For a given country two questions can be asked: to what extent is the country's future energy system reliant on specific metals; and, to what extent does the country's expertise in substitute technologies provide a useful advantage in a metal constrained future?

It is also important to understand the issue of international relations in critical metals markets. The geopolitical issues associated with some critical metals mean that foreign diplomacy is likely to become an important aspect of any industrial policy making. In the first instance, it is important to understand the potential constraints where supply of a critical metal is concentrated in a small number of countries with restrictive export policies. In addition, it may be beneficial to understand the diplomatic policy options that can be brought to bear on these geopolitical constraints. Maintaining a capacity in terms of analysis and foreign diplomacy is therefore important.

Finally, the contribution of recycling of end-of-life products to supply is currently limited while demand for mined metal is growing rapidly. However, the value of improving recycling rates within net-importing countries, where relatively few resources are located, is significant. Encouraging recycling in regions with low levels of critical metal resources, including incentivising the design of recycling processes and maintaining recycling capacity, is a sensible goal to pursue through policy. For by-product metals, policy to encourage production is limited given the economic link between the by-product and its host metal. Policy focused on demand reduction or recycling is therefore likely to be more effective.

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