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Metals in a Low-Carbon Economy: Resource Scarcity, Climate Change and Business in a Finite World

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EXECUTIVE SUMMARY

In the last two decades there has been rapid growth in the development and installation of low-carbon technologies to reduce greenhouse gas emissions to mitigate climate change, as well as to secure energy supplies. However, interest in these technologies has been matched by concern that potential bottlenecks in the supply chains for various metals that are critical for low-carbon technologies could hinder the deployment of these technologies on a substantial scale.

A range of metals are essential for manufacturing and operating low-carbon technologies, and the majority of companies and governments supporting their development depend on imports for many of them. As demand grows and competition over resources intensifies, concerns have arisen that limited metal availability might slow deployment of the technologies.

This report, written as part of the partnership programme between the business leaders' initiative 3C (Combat Climate Change) and the Stockholm Environment Institute, examines the use of five metals in low-carbon technologies: **cobalt, lithium, neodymium, indium** and **tellurium.**

Our analysis uses scenarios to explore the impacts of the significant uncertainty in potential supply, and a rapid growth in demand, for these materials. The outcomes of the scenario analysis were shared with businesses, and their responses and insights on these issues are also presented in this report.

The scenarios we applied are from the International Energy Agency (IEA) *World Energy Outlook 2010* and the World Economic Forum (WEF) *Mining and Minerals Scenarios 2010*. The IEA scenarios show the potential energy demand and emissions profiles under three different trajectories, based on a comprehensive bottom-up assessment of the demand and a large-scale mathematical construct designed to replicate how energy systems function. However, the IEA scenarios do not evaluate how the availability of metals needed for low-carbon technologies may change, so to fill this gap, we used the WEF scenarios. Using a structured scenario planning method, the WEF identified social, technological, economic, environmental and geo-political drivers that were shaping the metals and minerals markets. The WEF scenarios were developed through a year-long, qualitative process, which brought together the private sector, government, academia and international NGOs.

These scenarios were used to assess the scale of metal supply under an established and comprehensive assessment of potential demand- and supply-side futures. Amongst other factors, technology development, growth in mining, efficiency of use, innovation, metal uptake and recycling could affect future demand and supply. These and other variables were explored under the framework of the two groups of scenarios (see Box 1).

All of WEF scenarios involved social economic, environmental and geo-political drivers which were translated into variables that would affect the metal supply.

To quantify the implications of the scenarios on metal supply and metal demand, a scenario calculator was developed. This is a custom tool that allows the user to estimate the quantity of metal available under each scenario in 2008, 2020 and 2035. These dates correspond to the available years from the IEA analysis. The calculator was created in the open-source scenario modelling software IPAT-S, which was designed by SEI to develop a variety of sustainability scenarios. The tool provides an output of the metal surplus or deficit at each year and calculates the cumulative results over the time period.

The scenario calculator output suggested that there would be:

- Severe risk of medium and long term CSD (cumulative supply deficits) of **indium** and **tellurium**;
- Moderate risk of medium term and severe risk of long term CSD of **neodymium**; and
- Limited risk of long term CSD of **cobalt** and **lithium.**

These results are in accord with the findings of another recent study, by the Institute for Energy and Transport of the Joint Research Centre of the European Commission (Moss *et al*. 2011).

The risks pose a challenge to nations' efforts to transition to a low-carbon global economy. In an effort to help identify possible solutions, our study explored how "green energy" businesses that rely on these metals might respond. Some of the options identified include exploring alternatives to the metals required (substitution), adopting new technologies that do not

Box 1: Scenarios

The following three energy demand scenarios are applied:

- **IEA Current Policies Scenario**: A baseline scenario in which only policies already formally adopted and implemented are taken into account.
- **IEA New Policies Scenario**: This scenario assumes that existing policy commitments and plans for environmental protection or energy security are carried out, although in a cautious manner. This includes the commitments under the Copenhagen Accord and agreements to phase out fossil-fuel subsidies.
- **IEA 450 Scenario**: In this scenario, energy-related emissions follow a trajectory that keeps CO_2 concentrations below 450 parts per million (ppm) in the long run, but only after an initial overshoot. Thus this scenario fits our definition of a "low-carbon economy", but not very robustly, since it postpones aggressive action to reduce emissions, and implies substantial carbon sequestration after 2035.

These scenarios are used in conjunction with metal supply variables. The changes in these variables were framed by three WEF scenarios:

- **Green Trade Alliance**: The world is divided and countries are defined economically by whether they belong to the Green Trade Alliance (GTA), formed in 2016 to promote "environmental sustainability without compromising competitiveness."
- **Rebased Globalism**: The world is committed to realising the benefits of global interconnection but has become far more complex and multipolar. Power comes from control of resources as well as possession of capital, with resource-rich countries playing by their own rules.
- **Resource Security**: The era of globalisation is a distant memory as nations prioritise narrow self-interest. They hoard domestic resources, enter cartels based on regional and ideological alliances and resource blocs, and engage in neo-colonialism and import substitution strategies.

require these metals, and increasing recycling and the use of recycled materials.

Interviews with business executives show that some companies are indeed taking (or preparing to take) steps to address supply-side risks through recycling activities, vertical integration (e.g. acquiring or merging with mining companies) and material substitution.

Of all the low-carbon technologies affected by the metals focused on in the study, the photovoltaic industry appears to be the one that may be most impacted by metals scarcity. The scarcity issue is directly relevant to second-generation thin-film photovoltaic (TF PV) technologies, Copper Indium (Gallium) (di) Selenide (CIGS) and Cadmium Telluride (CdTe). In relation to these technologies, indium and tellurium availability is already considered a bottleneck to TF PV expansion, with tellurium being of greatest concern. Recycling was seen as the dominant mitigation strategy amongst those involved with the technology in our rapid assessment. This is primarily because CdTe modules are already recycled due to the toxicity of cadmium.

Policy initiatives can help address the challenges outlined above, and provide the right incentives for appropriate business and consumer responses. On the other hand, some policies, such as those that might be taken under the Resource Security scenario, may exacerbate problems of global scarcity.

Recent research on national minerals policies and trends suggests that governments view scarcity primarily as a technological issue and see technological innovation as the key response. Consequently, many policies do not focus scarcity and security of supplies, but rather concentrate on technological advancement and environmental sustainability. However, the analysis here suggests that economic and political risks are also likely to contribute significantly to medium- to long-term management difficulties. In fact, these issues are already arising, as evidenced by a complaint filed with the World Trade Organisation (WTO) by the EU, US and Japan in March 2012, challenging China's restrictions on exports of rare-earth metals.[1]

The WTO complaints are among the more extreme actions to resolve potential scarcity. More commonly, policies will focus on either securing mineral supplies at the national level or increasing domestic capacity. In addition, nations may want to establish

1 See Palmer, D. and Durfee, D. (2012) 'U.S., EU, Japan take on China at WTO over rare earths'. Reuters, 14 March. Washington, DC, US, and Beijing, China. http://www.reuters.com/article/2012/03/14/us-china-trade-eu-idUSBRE82D07Q20120314.

international strategic partnerships (trade agreements, support in international forums, sharing of technology and development aid programmes) to secure metal supplies at the international level.

Yet not all businesses want government intervention. Many companies, especially the larger multinationals, say they would rather see only a carbon pricing system that does not favour any specific technologies for investment. Moreover, the geopolitical issues that often stimulate government responses such as domestic stockpiling do not apply to businesses that operate internationally and have access to supplies in countries of concern, such as China. It is these multi-national-businesses that tend to favour only a liberal market system response. However, policy-makers should be mindful of the risks that may follow from the unhindered application of free-trade principles.

1 INTRODUCTION

THE PROJECT

This study is an effort to comprehensively assess the potential effect of material scarcity on low-carbon energy technologies, taking into account the significant uncertainty in potential future supply. The research was conducted as part of the partnership programme between the business leaders' initiative 3C (Combat Climate Change) and the Stockholm Environment Institute.

This report, one of three studies focused on resource scarcity, explores how constraints on the availability of certain metals might affect the growth of new technologies such as photovoltaics, wind turbines, and electric vehicles that currently depend on these metals in their construction, which will then affect the ability to transition to a low-carbon economy.

Specifically, the study seeks to:

- Assess the state of knowledge about the resources that would underlie a low-carbon economy, focusing on metals;
- Explore the possible interactions between activities utilising finite or limited resources; and
- Identify strategies for businesses and governments to respond to the challenges created by relying on finite or limited resources in the transition to a low-carbon economy.

The project considers aspects of low-carbon energy systems, including energy production and collection, transmission and end use, and focuses on five metals identified as critical to these systems: **cobalt, lithium, neodymium, indium and tellurium.**

THE ISSUES

Most minerals of economic importance are relatively abundant in the earth's crust, but increasing worldwide demand is raising concerns about their prices, potential scarcity, and the environmental impacts of mining and processing the materials. Scarcity arises when finite mineral reserves are gradually depleted, and some of those materials cannot be substituted. Materials can also become effectively (although temporarily) scarce if they are present, but not accessible due to technological, economic, or political constraints.

There has been a great deal of debate about the availability of materials critical to advanced low-carbon technologies, many of which depend on metals that are becoming scarce (Fthenakis 2009; Kara *et al*. 2010; Macfarlane and Miller 2007; Yang 2009). Consequently, there is a growing concern that in trying to deal with one problem – rising greenhouse gas emissions – we are inadvertently creating another, or trying to deliver a solution that may not be viable in the long term.

However, understanding the risks posed by the potential scarcity of materials required for a low-carbon economy is made difficult by a number of factors:

- Reserves of these materials are difficult to estimate, which leads to a lack of confidence in assessments of supply (European Commission 2010).
- Price is not an effective indicator of long-term availability, and price volatility may prevent effective management of supply and demand.
- Reserves of particular materials tend to be concentrated in a small number of countries that are often politically insecure, which means that quantity of supply does not guarantee access to that supply.
- The rate of expansion of these technologies is uncertain.

It is important to acknowledge that there are other environmental implications of metal extraction, which are described briefly in Section 4. While they are not the primary focus of this report, they may not only affect the environmental merits of a given technology that relies on such metals, but also the future cost and availability of the metals. It is important to consider those impacts when looking at future supplies and at the business practices, regulations and policies governing this sector.

THE RESEARCH PROCESS

The analysis and scenarios described in this report have been informed in part through engagement with stakeholders, including multi-national energy-sector executives, policy makers, mining companies and economists in academia. The research was conducted in multiple stages, including a stakeholder workshop and stakeholder interviews. The process is described in more detail in Figure 1.

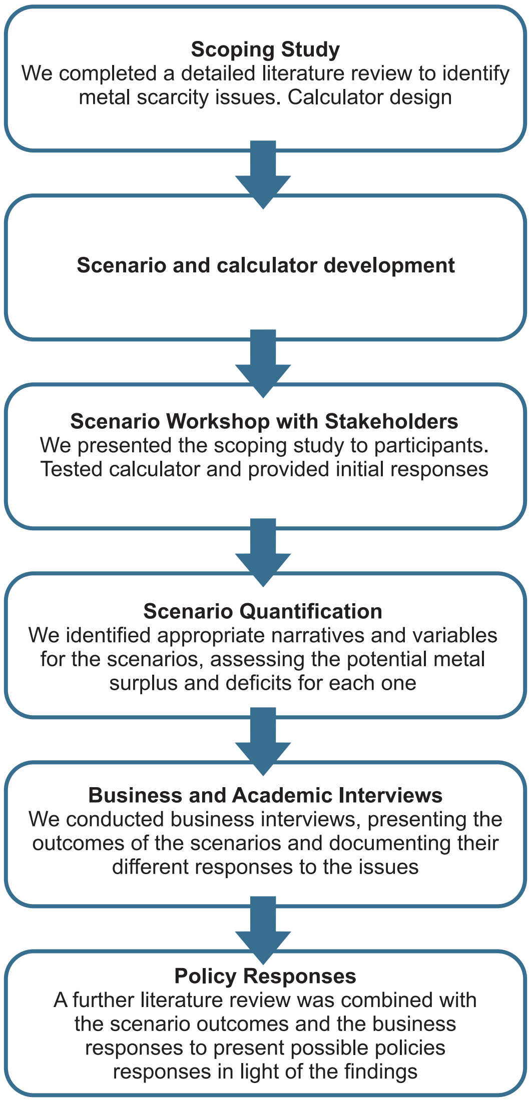


Figure 1: Summary of research process and stakeholder engagement

2 SCARCE METALS IN A LOW-CARBON ECONOMY

The deployment of low-carbon energy technologies to help mitigate climate change builds demand for the scarce metals that are integral to those technologies. Demand growth will depend on the level at which the technology is presently employed and the rate at which it expands. The global demand will also be affected by the degree to which recycling occurs, the availability of substitute materials, and efficiency improvements.

THE LOW-CARBON ECONOMY

Responding to scientific assessments of the risk of dangerous climate change, the 3C initiative recommends in its Roadmap that governments set emission targets consistent with a global temperature increase of less than 2°C above pre-industrial levels by the end of the century (3C 2007). The Copenhagen Accord, endorses this goal, and many countries have placed it at the centre of their national climate change mitigation policies (UNEP 2010).

Estimating the level of emissions reductions required to achieve this goal is a complex task, and there is no unique emissions pathway set out that will achieve this. However, the final global temperature will be determined primarily by the total amount of carbon dioxide (CO_2) released into the atmosphere since industrialisation (Allen *et al*. 2009; Zickfeld *et al*. 2009; Matthews *et al*. 2009; IPCC 2007). This suggests that placing a cap on the cumulative emissions released between now and 2050 is "an essential prerequisite for ensuring, with a certain level of probability, that the 2°C guardrail will be obeyed", as the German Advisory Council on Climate Change has put it (WBGU 2009, p.23).

A recent assessment suggests that cumulative carbon emissions between 2000 and 2049 of either 1,000 gigatonnes (Gt CO_2) or the equivalent of 1,500 Gt CO_2e from all greenhouse gases, presents a 75 per cent probability of staying below 2°C warming (Meinshausen *et al*. 2009). Between 2000 and 2010, around 350 Gt CO_2 were released, leaving a budget of 650 Gt CO_2 for 2010-2050, which will be exceeded in less than 20 years if current emissions rates persist (*ibid*.). To put this into context, in the International Energy Agency's Current Policies (business-as-usual) scenario, in the *World Energy Outlook 2010* (IEA 2010), global emissions are close to 55 Gt CO_2e per year in 2030. This indicates that dramatic emission reductions are urgently required.

Several authors argue that this goal is achievable, although challenging (3C 2007; IEA 2010; Lynas 2011). It will require systemic change, including extensive refurbishment and replacement of energy systems, transformation of supply chains, and far-reaching demand reduction. The necessary technologies exist today, but the rate of technology transformation required would be unprecedented.

IMPLICATIONS FOR POTENTIALLY SCARCE METALS

A number of the technologies that are central to a low-carbon shift currently depend on metals that are becoming increasingly scarce and have limited opportunity for substitution. A number of these technologies, and the scarce metals on which they rely, are presented in Table 1.

Table 1: Low carbon technologies reliant on metals

Technology	Component	Metals
Photovoltaics	Thin film	Indium, tellurium
Wind power	Permanent magnets	Neodymium
Plug in Hybrid and Electric Vehicles	Batteries	Lithium, cobalt
	Permanent magnets	Neodymium

This is not a comprehensive list. These metals have been selected on the basis of a review of a range of publications investigating the risk posed by metals scarcity (USDOE 2010; AEA Technology plc 2010; European Commission 2010; Speirs *et al*. 2011; Fthenakis 2009; Kara *et al*. 2010; Kleijn and van der Voet 2010).[2]

Emphasis is placed here on the technologies that are most likely to be globally relevant and significant in the scale of change described above. The technologies and metals identified in Table 1 will be considered in more detail in the remaining sections of this report.

[2] The work by the European Commission's Joint Research Centre (Moss *et al*. 2011) presents an easily accessible run-down of technologies and the metals of significant involvement

3 DEFINING METAL SCARCITY

Material scarcity arises from a combination of declining, finite mineral reserves and limited options to substitute other materials. There is debate as to whether sources of some scarce materials will ever become exhausted (Tilton 2002). However, even available materials can become effectively scarce, at least temporarily, due to technological, economic, or political constraints.

Recently many reports and articles have attempted to assess the risk posed by material scarcity to national economies (USDOE 2010; AEA Technology plc 2010; European Commission 2010) and to low-carbon technologies (Speirs *et al*. 2011; Fthenakis 2009; Kara *et al*. 2010; Kleijn and van der Voet 2010). These assessments have used a variety of approaches to identify and quantify the risks posed by the scarcity of metals classified as critical to an economy or to future deployment of particular low-carbon technologies. Most have considered not just geological scarcity, but also factors such as geopolitical risks and environmental risks (USDOE 2010; AEA Technology plc 2010; European Commission 2010). Below we discuss in detail the parameters that affect metals supply and demand.

PARAMETERS DETERMINING POTENTIAL SUPPLY

Metals can come from two sources: primary supply, which is produced from mining virgin materials from environmental stocks, and secondary supply, which is produced from recycling metal from end-of life products. The factors that affect these two source types are described below.

Primary production

The rate of production of metals from mining is affected by the absolute availability of the metal in the environment, the economics of production, access to reserves and produced material and the environmental and social impacts associated with production.

Geological availability

The U.S. Geological Survey (USGS) has historically reported estimates for the geological availability for a wide range of metals. Availability is reported as “reserves”, which are the part of the reserve base that can be extracted cost-effectively, plus the “reserve base”, which are resources that could be extracted in the future if production costs decrease or processing increases. Both measures change over time as the costs of extraction and price of metal change. For example, if metal price increases, reserve figures are likely to increase. This is demonstrated for indium in Figure 2: a price increase resulted in a significant increase in the estimates of indium reserves and reserve base.

Neither measure captures the ultimately recoverable resource or quantifies the probability that all reported material will be produced, as is the case with other estimates for other resources, such as oil (Sorrell *et al*. 2010). This is particularly pertinent in relation to metals that are mined as by-products of more abundant metals, such as cobalt, which is mined as a by-product of copper and nickel. With such metals, the economics of resource extraction and probability of reserve extraction are currently driven by the economics of the principal metal.

In short, reserves and reserve base do not provide a reliable indicator of future production. In the absence of estimates of the ultimately recoverable resource for any of the metals of interest, we cannot effectively gauge the limitations of geological availability. Still, another measure –the balance between cumulative production (anthropogenic stocks) and reserve base (an estimate of environmental stocks) – provides some indication of the relative potential to increase production in the future.

Economics of production

There are several factors that can create economic incentives to increase or decrease metals production. These drivers are conditions that can cause producers to act in a particular way. Price is an example of an economic driver because, as traditional economics state, the expansion of demand for a particular material will lead to higher prices, which will lead to an expansion of supply in the material of interest; supply and demand are in equilibrium. Price is a particularly important driver because many of the other economic drives such as production costs or globalisation ultimately influence the price. The following charts show the long-term historical production levels and prices of a number of the scarce metals of interest (USGS 2012).

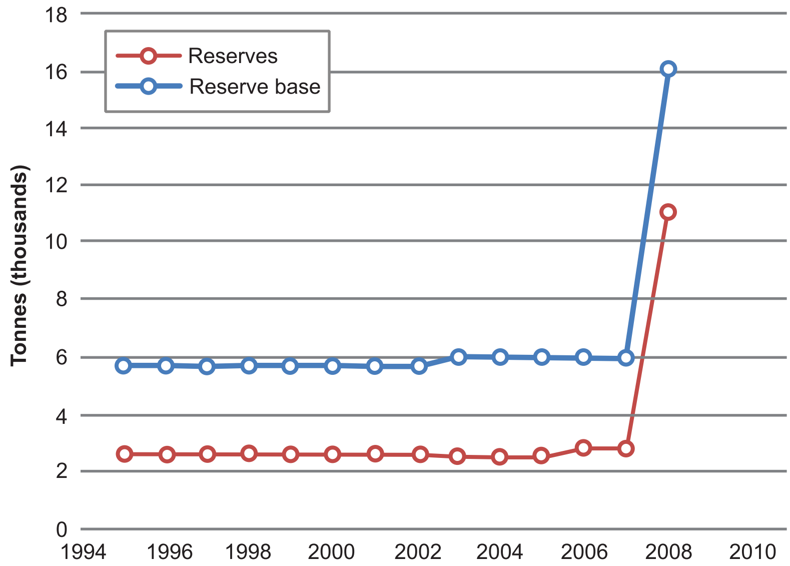


Figure 2: Historical indium reserve and reserve base

Source: Speirs *et al*. (2011), based on U.S. Geological Survey data

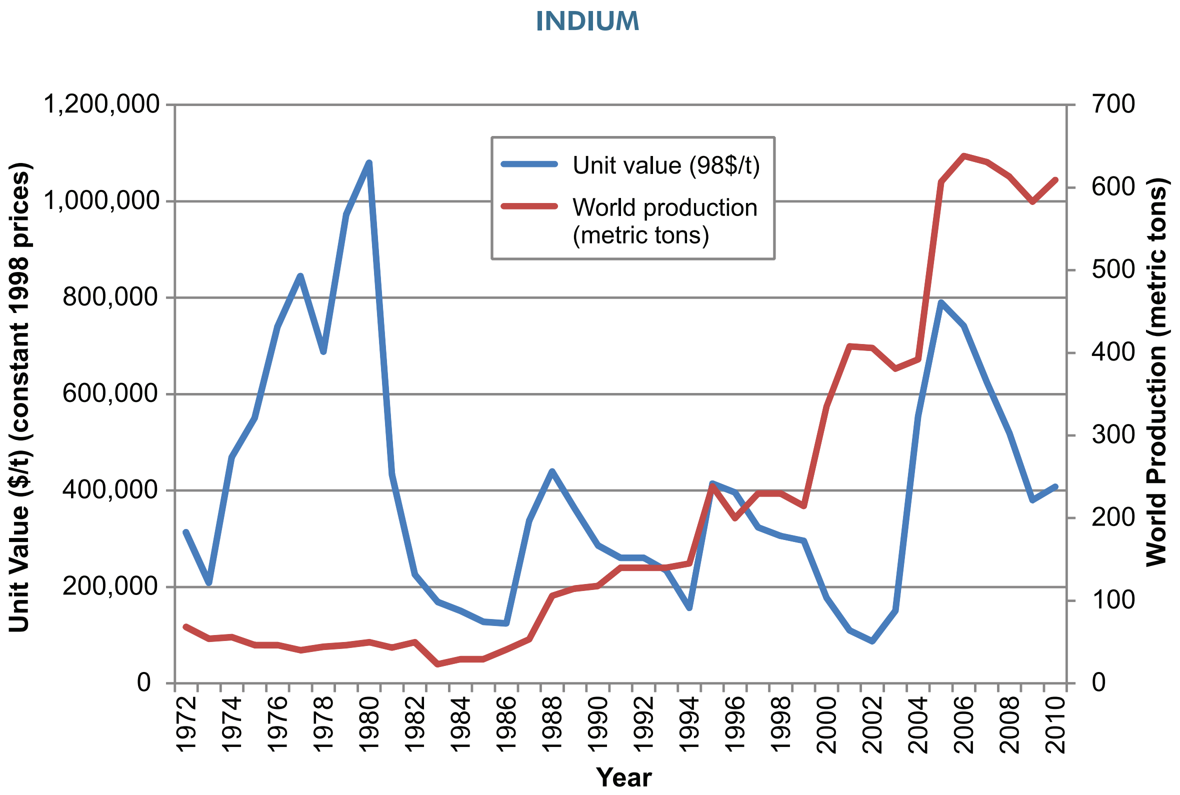
As Figures 3a to 3e indicate, there are numerous factors that could be considered economic drivers due to their impact on the supply-demand curves. They range from political and current events, population, perceptions of the economy, taxes, or government spending and regulations. These can all influence decisions that producers make regarding the amount of material supplied to the market. These factors are complex, take place simultaneously, and interact with one another (Wagner *et al*. 1997).

In the case of the metals of interest, increasing supply can be constrained by a number of factors:

- Depletion of reserves may mean that there are no new (economically viable) sources to exploit.
- High costs of production and infrastructure may restrict investment in exploitation of new reserves at current prices.
- The metals are extracted as by-products of other primary metals, meaning that production will not be increased if it is not cost-effective to increase production of the primary metal and it is not economically viable to mine for them independently.
- Producing countries may pursue industrial strategies to reserve resources for their exclusive use though trade restrictions, taxations and investment policies.
- Access to new reserves may be restricted as a result of regulation and objection to the high environmental and social impacts of mining.

Mine production cannot adapt quickly to meet structural changes in demand patterns; the metals market is more characterised by disequilibrium than equilibrium, and demand for and prices of metals are characteristically highly volatile (Morley and Eatherley 2008). In economic theory, a demand change would affect price levels, and this would immediately cause the quantity supplied to change in response. Therefore, shortage and surpluses (and the associated price fluctuations) should be short-lived features. The scarce metals market exhibits four major economic imperfections which inhibit quick market response and hence a more stable price level:

- It takes a minimum of four years (sometimes up to 25 years) to bring new supply or capacity on stream, so shortages can persist and lead to large price rises.
- Once capacity is in place and fixed costs are paid, producers are reluctant to curb output in response to lower prices, as long as they are still maintaining overhead contributions.



Source: USGS 1999

Indium is produced mainly from residues generated during zinc ore processing. Prior to 1940, indium was used almost entirely for experimental purposes, although domestic production had begun in 1926.

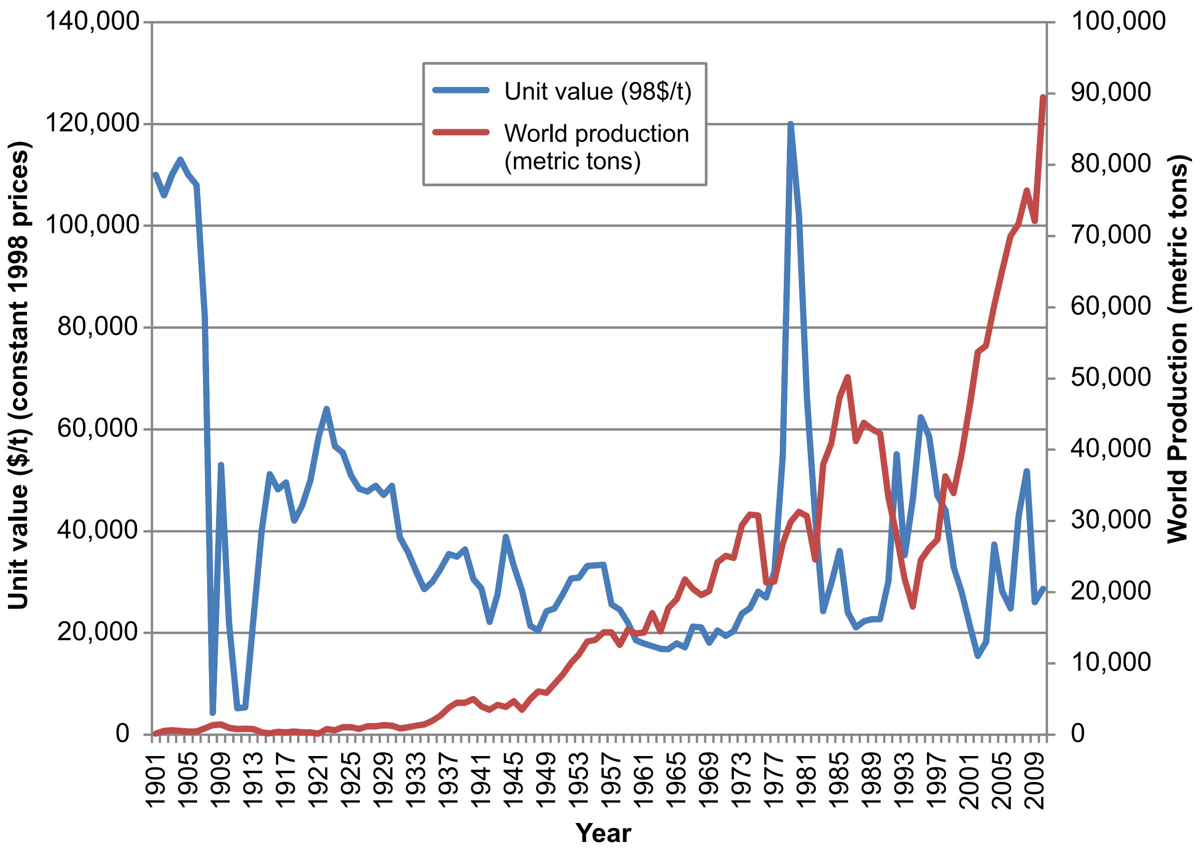
Factors affecting indium prices:

- 1973-80: Period of high demand, significant increase for nuclear control rods
- 1979: Lower demand after nuclear power plant accident at Three Mile Island
- 1980-82: Economic recessions
- 1985: Development of indium phosphide semiconductors and indium-tin-oxide thin films
- 1989: Indium added to National Defence Stockpile (NDS) acquisition plan
- 1992-94: NDS acquisition of indium
- 1995: Steady price increase owing to tight supply and strong demand
- 1996: Steady price decline owing to greater supply and significant recycling
- 1997: Release of more than half of NDS holdings
- 1997-98: Reduced demand owing to decrease in production of liquid crystal displays (LCD's) and to shift to more-efficient thin-film technology

Figure 3a: Historical production and prices of indium

USGS (2012)

COBALT



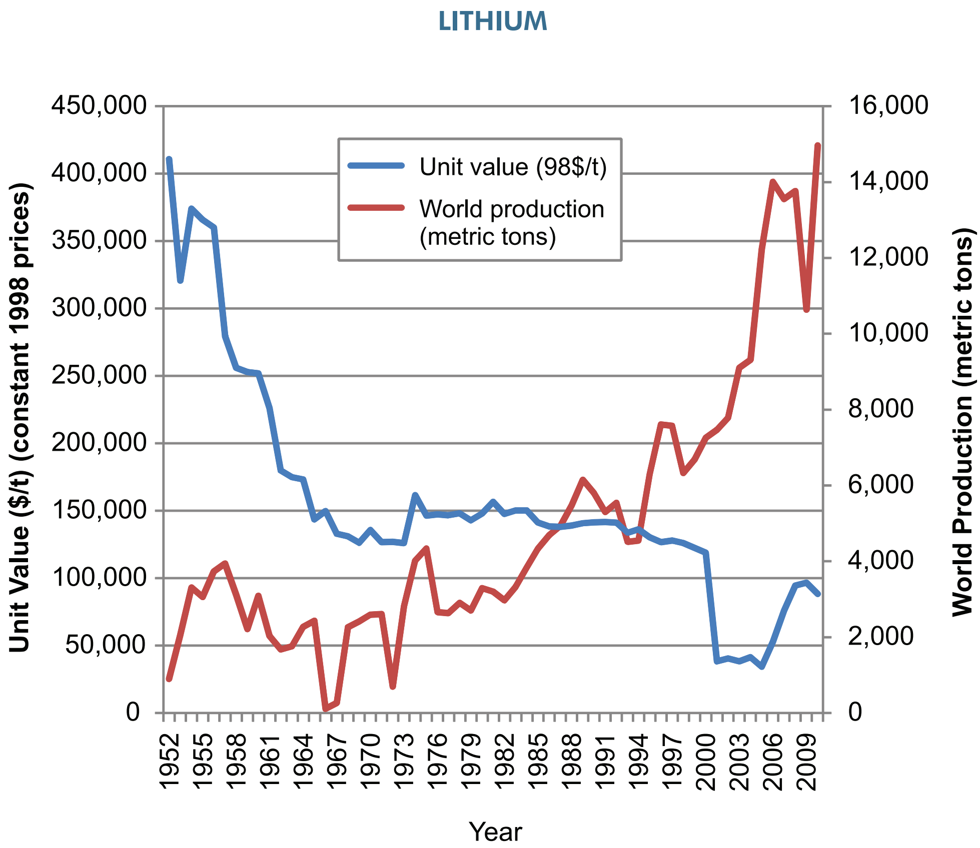
Source: USGS 1999

Significant events affecting **cobalt** prices:

- 1967-1976 Sales of significant quantities of cobalt from U.S. Government stockpile
- 1978 Strong cobalt demand, Zaire's copper-cobalt mining region invaded, and free market developed
- 1981-1982 Sharp recession
- 1984 Zaire and Zambia announce a joint producer price
- 1990-1991 Recession
- 1990 Strikes in Zaire and political unrest in Zambia, cave-in at Zaire's Kamoto copper-cobalt mine, and Russia began exporting cobalt to Western markets
- 1991 Unrest in Zaire and dissolution of the Soviet Union
- 1992-1993 Economic downturn and decrease in U.S. defence spending
- 1993-1998 Sales of cobalt from the U.S. Government stockpile

Figure 3b: Historical production and prices of cobalt

USGS (2012)

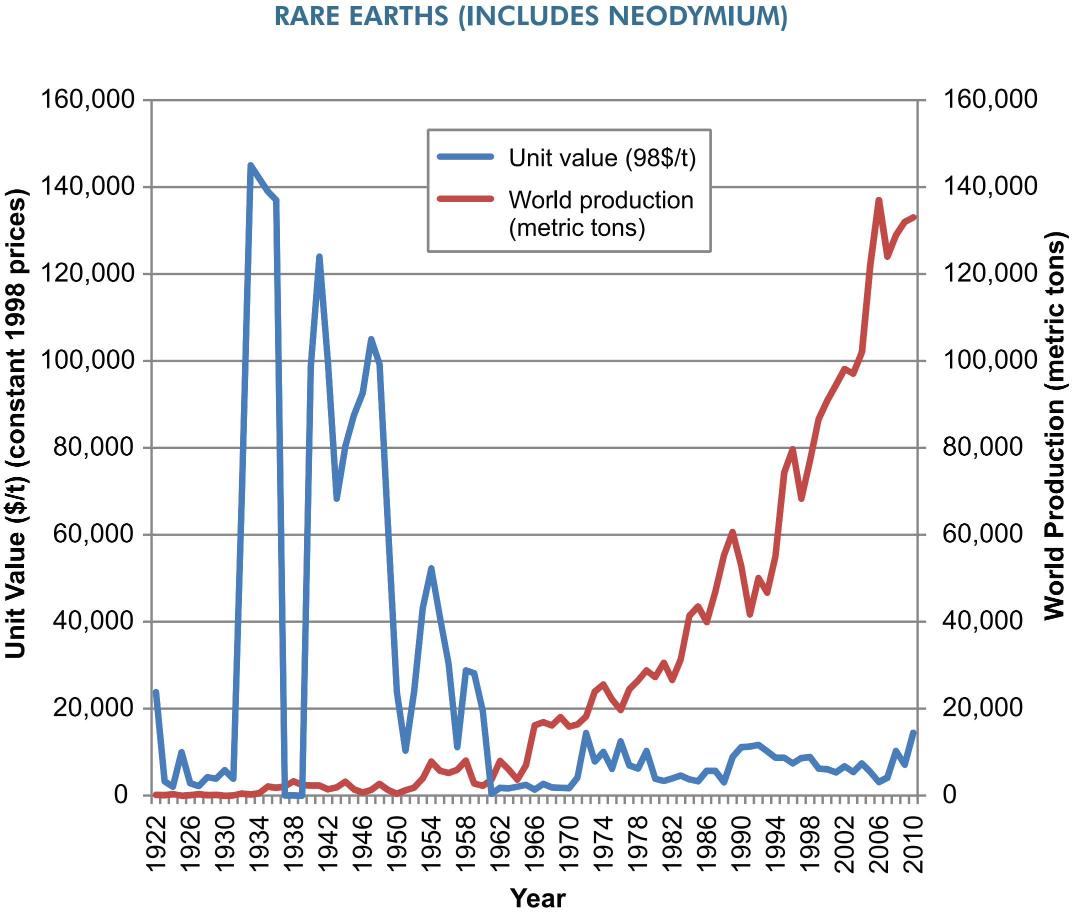


Source: USGS 1999

The changes in **lithium** metal prices appear to be independent of any significant events. Although lithium metal prices were first reported in trade publications in 1952, demand was very low. Small quantities were used as scavengers in the production of low-oxygen copper alloys, but other uses were just beginning to be investigated.

From 1952 to 1974 prices decreased. The potential use of lithium in batteries for electric vehicles was first discussed in the Minerals Yearbook in 1972. The downward trend in lithium metal prices reversed in 1974

Figure 3c: Historical production and prices of lithium
USGS (2012)



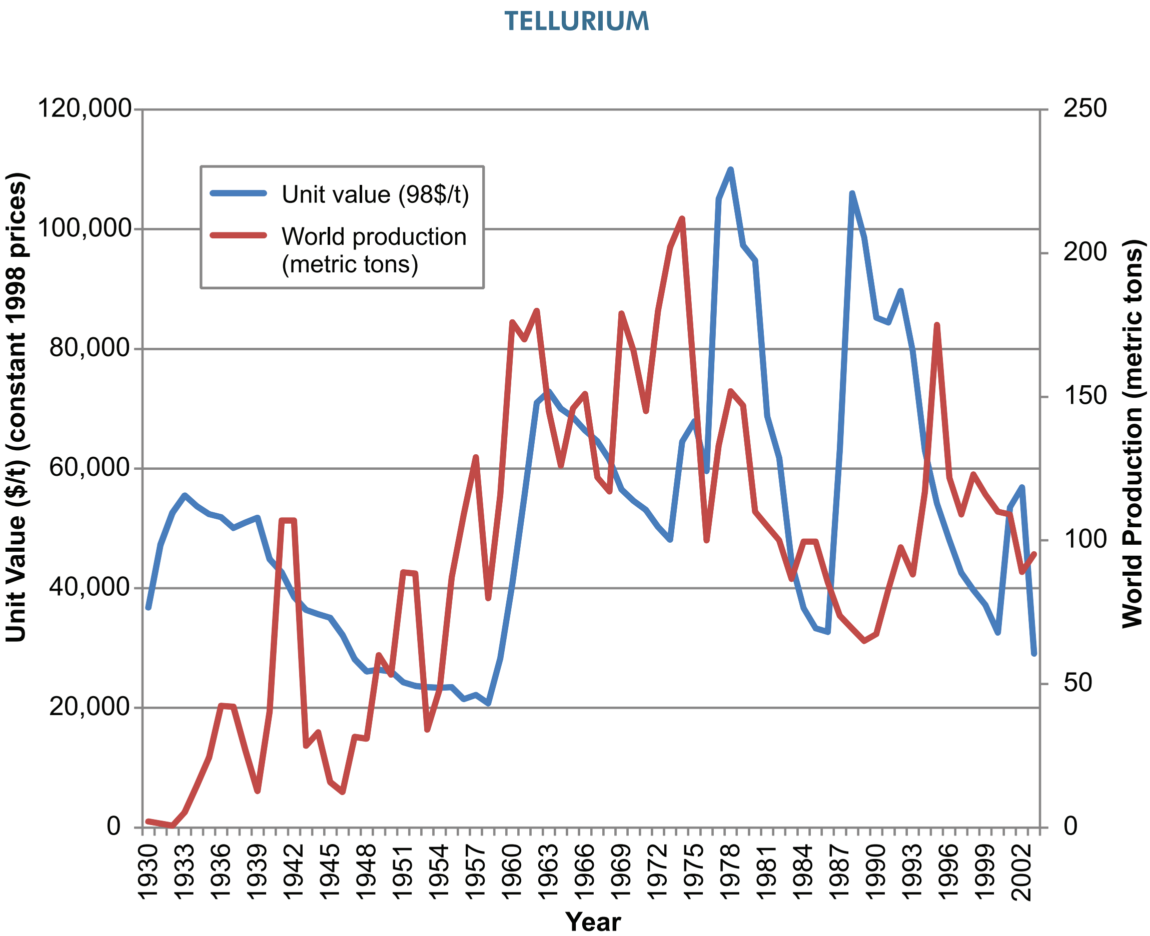
Source: USGS 1999

Rare-earth metal prices vary considerably depending on purity and quantity. Price fluctuations in the late 1950s to 1998 were affected primarily by supply and demand, environmental legislation, and economic factors, especially inflation and energy costs.

Growth in the rare-earth industry between 1986 and 1998 was primarily in the markets for individual high-purity products. Rare-earth metal demand in this period was greatest for neodymium metal used in high-strength neodymium-iron-boron (NIB) permanent magnet alloys. Prices for neodymium and the NIB alloying agent, dysprosium, increased in the mid-1980's as demand increased. As a result of the increased NIB magnet demand, demand and price decreased for samarium metal used in the higher cost samarium-cobalt magnets.

Figure 3d: Historical production and prices of rare earths (inc. neodymium)

USGS (2012)



Source: USGS 1999

Significant events affecting **tellurium** prices:

- 1959-62 Price rise coincides with growth in demand for thermoelectric devices
- 1962-73 Price remains invariant, high inventories, demand averages about 200,000 pounds per year, free-machining steel becomes dominant use
- 1973-80 Price controls during 1973 lifted in December, annual demand doubles stimulated by catalytic uses, reduced production from fall-off in copper production and tellurium content of ores, speculation affects prices
- 1980-86 Demand plummets, major catalytic use ends and consumer inventories return to marketplace, depressed domestic steel industry
- 1987-88 Demand for free-machining steel increases, reduced tellurium production, inventory depletion, price doubles
- 1989-93 Domestic and world demand weakens; production declines faster than consumption, resulting in a moderate fall-off in stocks and sustained high prices
- 1993-98 Oversupply situation develops as demand decreases faster than production, high-efficiency cadmium telluride solar cells fail to increase demand significantly

Figure 3e: Historical production and prices of tellurium

USGS (2012)

- The major end-user markets (e.g. construction, machinery) are also volatile, with many of them heavily affected by recessions and business cycles.

- The nature of the open or auction markets for mineral is strictly marginal, which means that they deal with only a fraction of total production and sales (Wagner *et al*. 1997).

The effective scarcity that this disequilibrium causes could have serious implications for the success of low-carbon strategies.

Geopolitics
Potential supply-demand scarcity is not the only aspect of material availability that determines our vulnerability to scarcity (particularly considering how difficult this is to define). The geographic concentration of scarce materials can also act as a barrier to supply. There are a number of examples of materials whose production is concentrated in a small number of countries (European Commission 2010; Candelise *et al*. 2011; Wray 2010), such as:

- More than 95 per cent of rare earth metals and antimony and over 75 per cent of germanium and tungsten production is concentrated in China;

- 90 per cent of niobium is produced in Brazil; and

- 77 per cent of platinum is produced in South Africa.

Supply can be affected by political instability in the country of production. For example, over 40 per cent of cobalt is mined in the Democratic Republic of Congo, which is viewed as extremely politically unstable, placing the supply of this material at risk (European Commission 2010).

The EU, US and Mexico have previously raised concerns about similar restrictions and requested formal WTO consultation in 2009 (European Commission 2010). The parties argued that the measures in place (quotas, export duties and minimum export prices) violated both general WTO rules and specific commitments that China had made as part of its WTO accession protocol. Export quotas are prohibited without justification and, where they are justified, quotas must be reported to the WTO. There has been no conclusion to this issue thus far, and in March 2012 the US announced that it was filing a further complaint with the WTO, in conjunction with Japan and the EU, about Chinese limits on exports of rare earths used in high-tech products.

It is important to take into account the potential for geo-political issues to restrict supply when making supply assessments. The level of concentration of worldwide production is often used in combination with a measure of political and economic stability to assess risks from geo-politics.

Technology
Technology and productivity can greatly influence the amount of mineral materials that are supplied to the market. Technological improvements such as new machinery, improved processes and the use of computer control systems may all help increase productivity. New technologies are often readily available and it is their application, as opposed to availability, which is commonly the limiting factor for productivity (Wagner *et al*. 1997). Technological progress can provide access to materials and mines that were not previously accessible or economically viable to extract. It can also significantly reduce the costs of production. Labour productivity can have the same effect, reducing the labour inputs required to generate the same level of output and labour costs per unit to the industry.

Secondary production (Recycling)

Metals are never totally consumed, just transferred between forms. In theory, they should continue to provide their desired function indefinitely. However, metals are lost from the system throughout the life-cycle of a product (shown in Figure 4). The nature of the loss and the recovery mechanism differ significantly between the production and use/end-of-life stages.

Losses during raw material production and product manufacture can be significant, particularly where high purities are required or where inherently inefficient techniques are used. These losses can be reduced through more efficient production. However, it is unlikely that all losses can be prevented. Where loss cannot be prevented, the residual material could be recovered back into the production process. In some circumstances (particularly early in the production process, when the metal has not been altered significantly) it is possible to use the recovered material directly (Hagelüken and Meskers 2010). However, if the metal has become contaminated or combined with another material, some form of processing will be required to render it suitable for reuse in the manufacturing process. This is often called recycling of “pre-consumer” scrap.

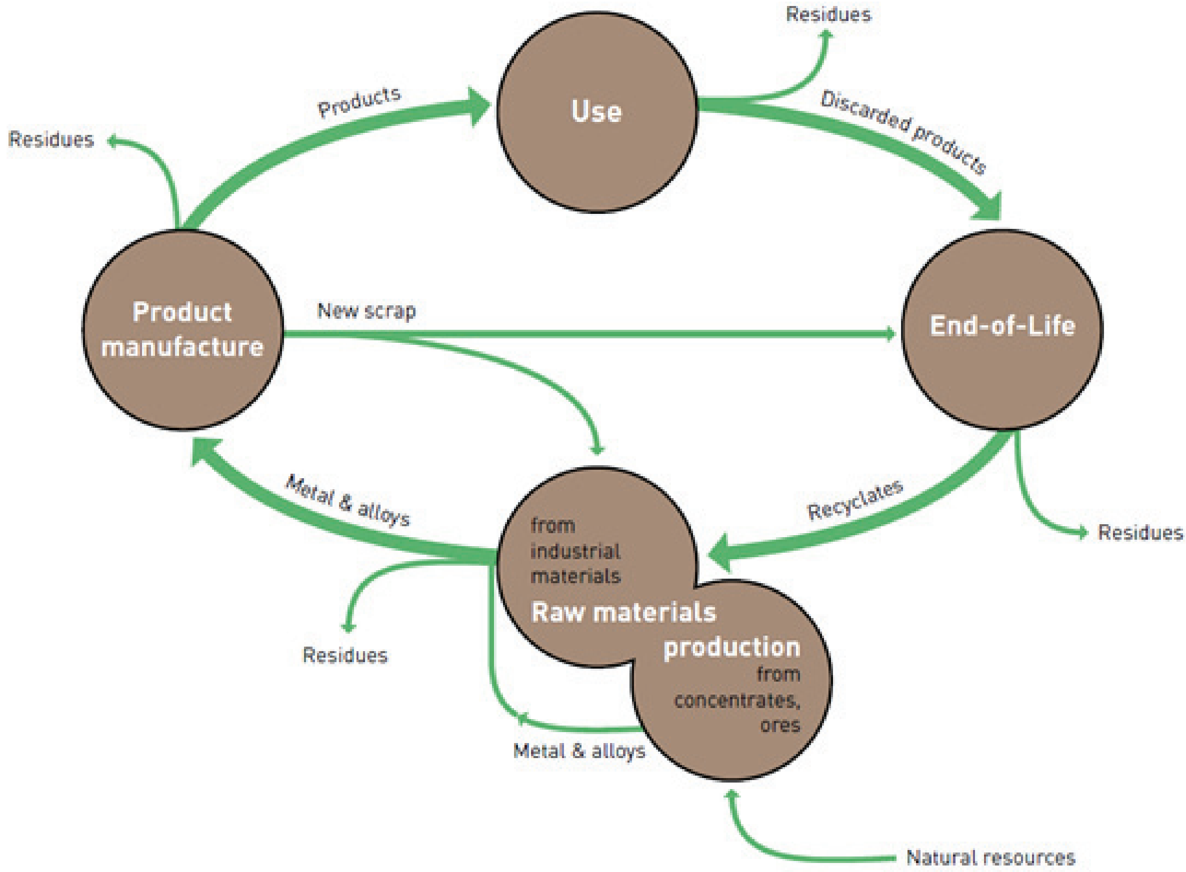


Figure 4: Metal losses through a product lifecycle
(Source: UNEP 2011)

Once a product has moved into the use phase, recovery of metals from "post-consumer" scrap is possible but challenging. Recycling of post-consumer scrap consists of three principal stages:

- Collection of end-of-life products;
- Dismantling/pre-processing of products and components; and
- Recovery of metal from product or component.

Each stage presents a variety of challenges; these are discussed in Box 2.

The economics of recycling is highly dependent on the cost of processing and the price of virgin metals. There have been a number of examples of effective recycling strategies, but these are only successful once prices for raw materials have risen enough to make the costly recovery process economically viable. It is often cheaper to use virgin materials if recycling is left to the market (Morley and Eatherley 2008). This coupled to the down-cycling effect; many recycling processes convert waste materials and discarded items into materials or products of lesser quality and reduced functionality. This can hinder the development of recycling infrastructure, limiting its role in substituting for primary material. However, the European Commission has recently called for industry to play a much greater role in recycling scarce metals (European Commission 2011), indicating that this issue is rapidly moving up the political agenda.

PARAMETERS OF POTENTIAL DEMAND

Efficiency of use

The potential to reduce consumption of scarce materials in existing production processes through waste management or lean production is minimal. The scarcity and price of these materials has already led companies to develop production processes that are designed to maximise efficiency and minimise waste production. However, there are some examples of where the use of scarce materials has been removed

Box 2: Challenges in recycling metals

Collection
- Metals are used in extremely small quantities in a large number of products, which means that collection systems are dispersed and inefficient.
- Users of the goods need to engage in collection systems – this is not a solely technical system.

Dismantling/pre-processing
- Products and components are variable, and feedstocks will change over time, so developing an effective dismantling process is extremely difficult.
- Pre-processing may need to be specific to the metal and where it is hosted (for example, whether it is on ceramics, plastics or other metals).
- Mechanical pre-processing can increase the losses in the recovery phase.

Recovery
- Complex products have a number of complex components that are difficult to separate.
- Each product has a very small amount of metal, which is harder to recover than if it was used in a concentrated form.
- It may be difficult to recover metals when they are coupled with another metal, particularly when the recovery processes for coupled metals are substantially different, or when the coupled material is hazardous. Processes are well established to separate metals that are commonly coupled in nature, but different couplings are used in products, which cannot be separated using traditional processes or technology (Hagelueken and Meskers 2010).
- Product design might make access to metals or metal separation difficult.

from the production process. For example, current industrial cobalt-carbide catalysts require platinum, ruthenium or rhenium promoters to function effectively, all of which are very scarce materials. Oxford Catalysts, a UK-based firm that specialises in technology for synthetic fuel production, has adapted its catalysts to work with fewer precious-metal promoters, removing the need for scarce materials.[3]

There is more potential to reduce consumption through technology development. For example, copper indium gallium (di)selenide (CIGS) and cadmium telluride (CdTe) photovoltaics use absorber layer thickness of around 2µm and 3-8µm respectively. Research is under way to reduce thicknesses to below 1µm, which would dramatically reduce demand for indium and tellurium.

Proportion of technologies using the metal of interest

The low-carbon technologies considered in this report do not all use the same scarce metals. Indium, for example, is only used in around 15 to 20 per cent of thin film PV cells (Speirs *et al*. 2011). Some technologies may apply alternative, cheaper or more readily available materials, depending on manufacturers' production methods and markets.

The proportion of technologies using specific metals may change over time. Lithium use in hybrid electric vehicles has grown over recent years, with some manufacturers reporting a switch to lithium ion batteries as an alternative to the more common nickel metal hydride (NiMH) batteries. The use of the lithium across this market will vary over time, with other manufacturers remaining committed to the NiMH battery, citing ease of management, low cost and durability. Deutsche Bank has forecast that lithium ion batteries will rise to 70 per cent of the hybrid market between 2015 and 2020 (Oakdene Hollins, 2010).

Growth in other demand

The use of the scarce metals explored in these scenarios is not confined to the low-carbon technology sector; there are a number of other sources of demand, such as monitors and displays, microchips or laser and medical technologies, for example, which would compete for the same resources.

3 For a description of the company's patented Fischer-Tropsch process, see http://www.oxfordcatalysts.com/ocge03.php.

4 ENVIRONMENTAL IMPACT OF PRODUCTION

The production of metals from metalliferous minerals typically involves a number of stages, including mining, mineral processing/concentrating, metal extraction and refining (Moriguchi 2010). Each can have significant environmental impacts, including:

- Mine drainage water can be acidic and can be hazardous to the receiving environment, and can also contain heavy-metal contamination.
- Metals and sediments may contaminate ground or surface water.
- Toxic substances used during processing, extraction or refining (for example, cyanide for leaching or mercury for amalgamation), may be released.
- There may be air emissions and deposition (for example, suspended particulate matter from mechanised open-cut mining).
- Waste is produced from overburden (rocks removed to access reserves) and benefaction (mine tailings produced during extraction and processing).
- Pollutants may be discharged from abandoned mines.
- There may be land degradation and deforestation.

In addition to these impacts, production processes consume a great deal of energy and water. Energy is consumed by the equipment used to construct mines, extract ores, and crush or grind ores following extraction. Ground ores can be processed using either pyrometallurgical (smelting metal concentrates at high temperature) or hydrometallurgical (leaching ores and concentrates into aqueous solutions). These process used can have a significant effect on the consumption of energy and water; pyrometallurgical processes are more energy-intensive; hydrometallurgical processes are more water-intensive.

The predominant source of energy for mining processes is fossil fuels, which creates greenhouse gas emissions. Mining and processing of minerals contributes over 3 per cent[4] of global greenhouse gas emissions. Table 2 shows the estimated emissions from mining of a number of critical metals.

Future energy requirements for primary metal production from ores are likely to increase significantly, and associated greenhouse gas emissions will rise (Norgate 2010). The scale of increase will depend on a number of factors, including:

- A decline in ore grades will require more energy to extract the same amount of metal from a larger amount of ore;
- Smaller metal seams and higher overburden layers will require more energy to extract, since they are harder to reach;
- Finer-grained ores will require more energy to extract, since they will have to ground, rather than crushed; and
- Improvements in technology will decrease energy requirements.

For example, the current copper ore grade (0.8 per cent) requires 95MJ/kg copper for primary production. If the ore grade declined to 0.1 per cent, the energy required would increase to 600MJ/kg assuming there is no advancement in technology (MacLean *et al*. 2010).

These environmental impacts are rarely incorporated into the internal costs of production, either by compulsory or voluntary schemes. This means that in some circumstances, there is no financial incentive to reduce the environmental burden of mining.

However, environmental regulation is becoming increasingly strong as a result of international treaties. Management of environmental impact is also improving dramatically as a result of corporate recognition of social and environmental responsibility. Increasing environmental impacts, coupled with improvements in environmental performance and regulation, are likely to increase the cost of production of materials. This will further affect the price of scarce materials and the viability of reserves. It should be taken into account when considering access to geological supplies.

4 Based on GTAP data.

Table 2: Estimated global greenhouse gas emissions from mining

Material	Carbon emissions incurred in mining 1kg of material (kg CO_2 eq)
Indium	156
Cobalt	9
Tellurium	8
Copper	3

Source: Ecoinvent database, http://www.ecoinvent.org/database/

5 FUTURE SCARCITY

In order to build a low-carbon future within the timescales required, we need to be certain about the future security of the supply of particular scarce metals, and ensure that it can meet additional demand resulting from widespread uptake of low-carbon technologies. However, as previously noted, multiple factors make forecasts complex and unreliable, which pose a significant challenge to policy-makers and technology providers.

Some recent studies have made assessments of metal scarcity in the future (European Commission 2010; Speirs *et al*. 2011). However, none has comprehensively assessed the increased need for materials to achieve a low-carbon future and compared this with the projected supply over an equivalent period.

In assessments of future scarcity and future risk, current mine production is often used as an indicator of future production (European Commission 2010). Access to and reliability of current mineral production data may encourage this approach, but over the long time periods used for scenarios of the low-carbon economy, historical production is unlikely to be an effective indicator of future production and material availability. Thus, assessments of future potential production should consider a range of estimates to capture the considerable uncertainty about long-term production.

Estimates of future production should also take into account the production of secondary metals from recycling, which is excluded from the majority of assessments completed to date. Future recycling will depend on the availability of suitable treatment processes, development of treatment infrastructure, and viability of collection logistics, which need to be taken into account when making forecasts.

SCENARIO DEVELOPMENT

The particular scenarios assessed for their impacts on metals are the International Energy Agency *World Energy Outlook 2010* (IEA 2010) and the World Economic Forum *Mining and Minerals Scenarios 2010* (WEF 2010). The IEA scenarios indicate the potential energy demand and emissions profiles under three different trajectories, using a comprehensive bottom-up assessment of the demand and a large-scale mathematical construct designed to replicate how energy systems function. The WEF scenarios were developed through a year-long, qualitative process, which brought together the private sector, government, academia and international NGOs.

These scenarios were used to gauge the scale and uncertainty of metal supply under an established and comprehensive assessment of potential demand and supply-side futures. Technology development, growth in mining, efficiency of use, innovation, metal uptake and recycling were all seen as affecting future demand and supply, and these and other variables were explored within the framework of the two sets of scenarios.

Technology uptake (demand-side) scenarios

The *World Energy Outlook 2010* scenarios were used to create a number of uptake profiles. The IEA sets out long-term projections of energy demand and supply, related CO_2 emissions, and investment requirements for three scenarios to 2035. The scenarios are quantitative and have been developed using the IEA's World Energy Model (WEM) a large-scale mathematical construct designed to replicate how energy systems function. The scenarios used here are:

- **Current Policies:** A baseline scenario in which only policies already formally adopted and implemented as of 2010 are taken into account.

- **New Policies:** This scenario assumes that existing policy commitments and plans for environmental protection or energy security are carried out, although in a cautious manner. This includes the commitments under the Copenhagen Accord and agreements to phase out fossil-fuel subsidies.

- **450:** In this scenario, energy-related emissions follow a trajectory that keeps CO_2 concentrations below 450 parts per million (ppm) in the long run, but only after an initial overshoot. Thus this scenario fits our definition of a "low-carbon economy", but not very robustly, since it postpones aggressive action to reduce emissions, and implies substantial carbon sequestration after 2035.

It is important to note that these scenarios, in particular the 450 scenario, are pragmatic scenarios with a mix of technologies. They do not assume any major change in technologies or new technologies so form a reasonable basis for this kind of analysis. The assumptions used to determine carbon emissions appropriate to avoid dangerous climate change are conservative; there is a possibility that a larger-scale adoption of low-carbon technologies may be needed. Thus, the actual material demand estimates could be significantly greater.

Resource supply and resource efficiency (supply-side) scenarios

The energy demand scenarios do not evaluate how the availability of supply of metals needed for low-carbon technologies may change, so to fill this gap, we relied on the WEF scenarios. Using a structured scenario planning method, the WEF identified social, technological, economic, environmental and geo-political drivers that were shaping the metals and minerals markets, then selected those it deemed to have the biggest potential impact and the highest level of uncertainty. These were identified as the "critical uncertainties" and defined the four dimensions of the scenario framework:

- **Geo-economic landscape:** from free markets and open borders, to controlled markets and closed borders.
- **Geo-political landscape:** from stable and ideologically convergent, to unstable and ideologically divergent.
- **Economic outlook:** from strong, cyclical growth, to stagnation and volatility.
- **Environmental outlook:** from decisive and ambitious, to reactive and incremental.

Table 3 describes in detail the three supply scenarios that the WEF built using that framework.

For the analysis presented here, the following variables were adjusted to reflect the nature of each of the resource supply scenarios:

- Growth in demand from other sources;
- Technology efficiency improvements;
- Growth in mine production;
- Proportion of technology using each metal;
- Growth in metal recycling.

Table 4 shows how each of these factors might vary under each scenario. These assumptions were taken and combined with data on the upper and lower limits of each variable for each metal. In reality, these variables could evolve in a variety of ways in the different scenarios, and there are different potentials for improvement for different metals and technologies. The range of the effects quantified was based on literature review and the best available evidence in each case. A full table of the assumptions taken, with references, is provided in Appendix A.

Each of the three IEA energy demand scenarios was applied to each of the resource supply scenarios.

Table 3: Supply scenario summary (reproduced from GEF 2010)

	Summary	Geo-economics	Geo-politics	Economics	Environmental
Green Trade Alliance	In 2030, the world is divided and countries are defined economically by whether they belong to the Green Trade Alliance (GTA), formed in 2016 to promote "environmental sustainability without compromising competitiveness." GTA countries, including some industrialised, resource-rich and developing countries, have experienced a period of accelerating innovation and lifestyle changes. While there is strong alignment among GTA countries, non-GTA countries operate independently.	Environmental standards are used as the basis for protectionist measures by GTA countries. Limited cross-border flows between GTA and non-GTA countries	World tense relations between GTA and non-GTA countries as they use different approaches to compete for resources Emergence of a Sustainable Trade Organisation to facilitate and enforce GTA trade agreements Transfer of knowledge and technology is encouraged	Global GDP growth averages around 2% annually, as a result of shifting trade patterns In the GTA, an important new metric called GDP+ incorporates environmental and social indicators Investment capital comes with "green ties" Tariffs on imports from countries with poor environmental and social performance Reallocation of subsidies to environmental technologies and developments	In GTA countries, decisive and radical environmental policies (including advanced "cradle to cradle" metals and minerals stewardship) encourage efficiency and re-use of materials and reduce environmental impact throughout supply chain In some non-GTA countries, action is motivated by the desire to overcome impediments to economic growth, and in others, there is no effort to address environmental concerns
Rebased Globalism	In 2030, the world is committed to realising the benefits of global interconnection but has become far more complex and multipolar. Power comes from control of resources as well as possession of capital, with resource-rich countries playing by their own rules. Civil society has gained influence, resulting in various local laws that affect global corporations.	Economic power is held both by markets where there is strong demand – such as the EU, US, China, Brazil and India – and by countries that control strategically important resources Cross-border flows are very open Free-market principles dominate, favouring privatisation and financial liberation Some states set out to capture more social value from their commodities through in-country processing and manufacturing and social taxes on exports	Multipolar world with broad commitment to reaping the benefits of globalisation and interconnectedness International decision-making becomes cumbersome, with numerous players included in the process; agreements are reached bilaterally or among smaller groups of countries Proliferation of local regulations which are strongly enforced Community engagement and civil society organisations have a significant role in decision-making	Global GDP growth averages around 4% annually High levels of investment capital are available, but there are often strict conditions on how investments will affect social development Job creation in resource-producing nations is prioritised Demand for commodities is high, as are most prices Most of the largest companies in the industry come from emerging economies	Strong environmental laws are developed and enforced to protect local environments Limited international agreements to tackle global environmental issues

Table 3: Supply scenario summary (reproduced from GEF 2010) (continued)

Resource Security	In 2030, the era of globalisation is a distant memory, as nations prioritise narrow self-interest. They hoard domestic resources, enter cartels based on regional and ideological alliances and resource blocs, and engage in neo-colonialism and import substitution strategies.	Markets are shaped by state interventionism Trade is defined by a complex web of protectionist barriers and preferential agreements Limited cross-border flows of products, labour and capital Heavy taxation or bans on exports of resources	Globalisation stalls amid geopolitical instability and an emphasis on national self-interests International institutions fade into irrelevance Ideology increasingly plays a role in the choice of allies	Global GDP growth averages around 1.5% Many countries revert to some form of import substitution Limited capital available for mining sector Country risks limit private sector capital for overseas investment Sudden and unpredictable resource constraints lead to extremely volatile prices	Resources and technologies that are most readily available domestically are favoured, irrespective of impact on environment Environmental and social impacts come second place to considerations of national interest

Table 4: Impact of scenarios on variables

Scenario	Summary	Growth in demand from other sources	Efficiency improvements	Growth in mine production	Share of technology using scarce metals	Growth in metal recycling	Technology uptake
Green Trade Alliance	In 2030, the world is divided and countries are defined economically by whether they belong to the Green Trade Alliance (GTA), formed in 2016 to promote "environmental sustainability without compromising competitiveness." GTA countries, including some industrialised, resource rich and developing countries, have experienced a period of accelerating innovation and lifestyle changes. While there is strong alignment among GTA countries, non-GTA countries operate independently.	Medium Scenario description assumes 2% annual economic growth	High It is assumed that a sufficient number of countries join the GTA for the strong environmental regulation to have a global effect; technology transfer is strongly supported, which would encourage these efficiency improvements	Low to 2020 High 2020 to 2035 Low initially because many producing countries will be outside the GTA; this would stimulate investment in improving environmental performance in non-GTA to release supplies in the long term	Medium Less pressure to substitute metals because of increases in production and efficiency	Medium Investment in infrastructure, but increases in mine production and efficiency improvements reduce pressure to recycle	450 scenario possible Strong focus on environmental regulation and measurement of environmental indicators likely to promote low-carbon technology uptake
Rebased Globalism	In 2030, the world is committed to realising the benefits of global interconnection but has become far more complex and multipolar. Power comes from control of resources as well as possession of capital, with resource-rich countries playing by their own rules. Civil society have gained power, resulting in various local laws that affect global corporations.	High Scenario description assumed 4% annual economic growth	High High prices, high capital investment and strong regulation support efficiency improvements	Low Strong community-level regulation would prevent development of new facilities; economic growth is driven by efficiency and recycling, rather than additional production	Low High investment and high prices drive substitution	High Lack of growth in mine production and high prices drive investment in recycling infrastructure	450 scenario possible Strong regulation likely to promote low-carbon technology uptake.
Resource Security	In 2030, the era of globalisation is a distant memory as nations prioritise narrow self-interest. They hoard domestic resources, enter cartels based on regional and ideological alliances and resource blocs, and engage in neo-colonialism and import substitution strategies.	Low Scenario description assumes 1.5% annual economic growth	Medium Knowledge transfer is more constrained, but countries try to maximise the value of the resources they do have	Low Reductions in cross-border flows limits demand for metals, so there is less incentive to increase production	High Lack of growth in production and reduced access to imported materials drives innovation in substitution	High More pressure to retain materials in the economy as a result of reduced access to imports	450 scenario unlikely to be achieved Poor regulation of environmental impact and high prices likely to suppress uptake of low-carbon technologies

Scenario calculator

We quantified the supply and demand for each of the metals in each scenario with a scenario calculator. This is a custom tool developed as part of this project, using the open-source scenario modelling software IPAT-S, which was designed by SEI to build a variety of sustainability scenarios.[5]

The schematic for the metals model is shown in Figure 5; it is essentially an accounting model that tracks the five metals from their potential production sources metals through to demand. In the model we report values for 2008, 2020, and 2035, three of the years reported in the *World Energy Outlook*. The tool outputs the metal surplus or deficit at each year and calculates the cumulative results over the time period.

Figure 6 is a screenshot of the calculator data entry panel. Once programmed, the IPAT-S scenarios can be displayed in an interface (the scenario navigator) that shows the impact of changing variables on the outputs of the tool (in this case, metal surplus or deficits). This screenshot shows the data entry panel for the "growth in other demand" variable, along with the output surplus and deficit graphs, which are updated automatically as the input variables change. The data behind the graphs can be extracted for analysis. The scenario variables are outlined in Appendix A.

Future scarcity scenario results

Background scenario data

The technology uptake in the IEA *World Energy Outlook* scenarios remains constant throughout the analysis, allowing the comparison of a range of metal demand futures under different supply-side conditions. The total energy demand for each scenario and the resulting cumulative emissions are shown in Figure 7 and Figure 8.

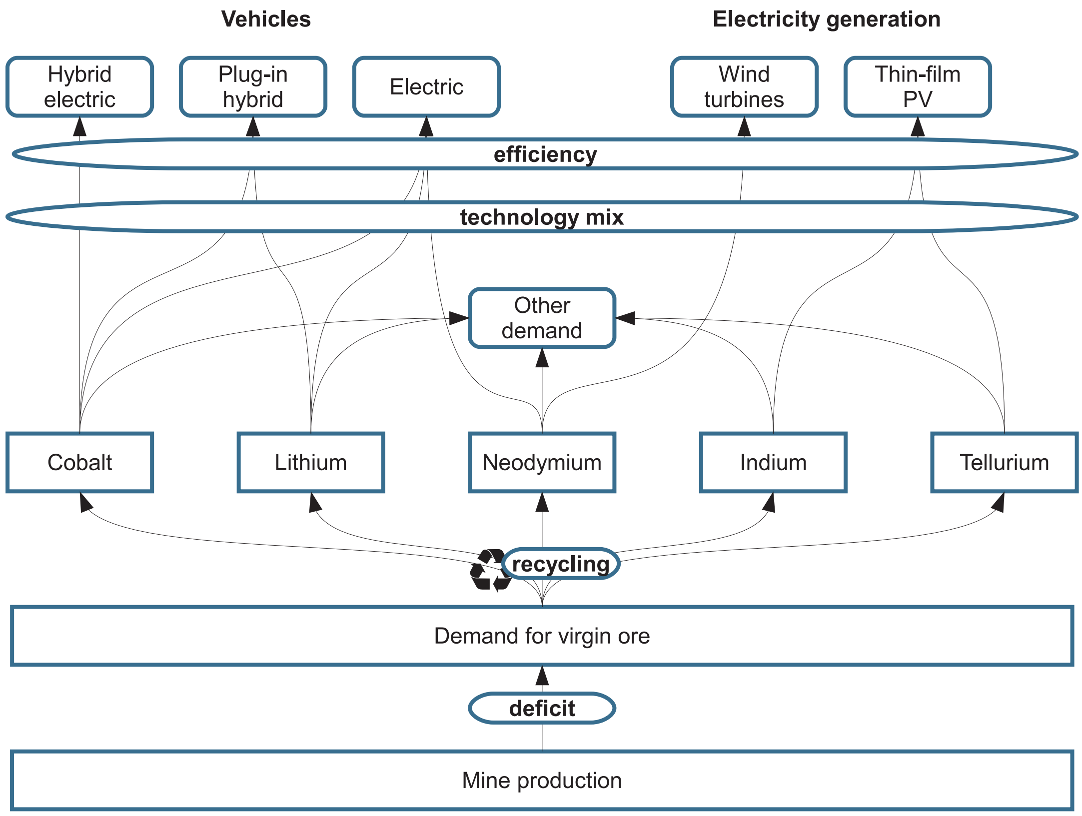


Figure 5: Scenario model schematic

5 IPAT-S is available for download from http://www.ipat-s.org/. The IPAT-S language is a tool: it is a domain language for the domain of scenario development. It was designed with several practical goals in mind, arising from the author's experience building sustainability scenarios.

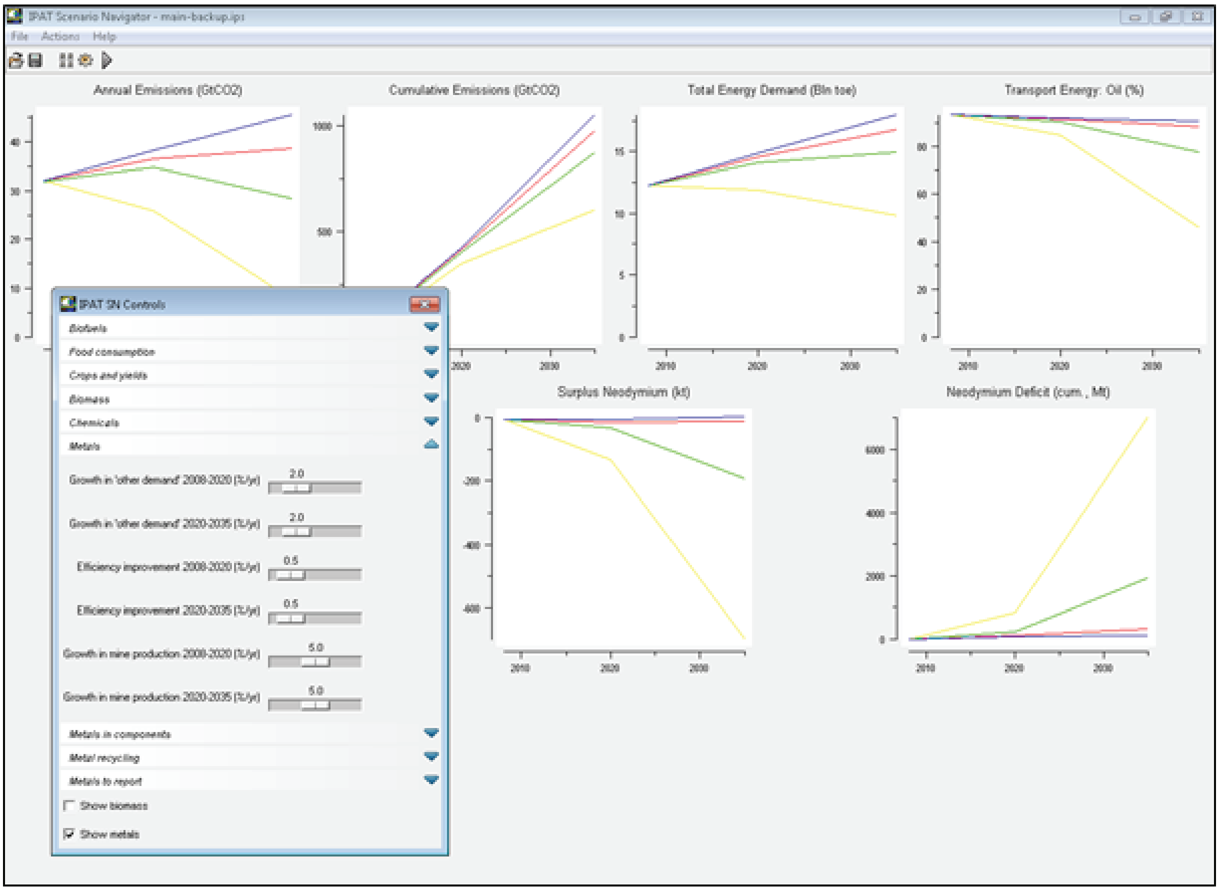


Figure 6: Metals scenario calculator screenshot

The graphs in Figure 7 and Figure 8 indicate that cumulative emissions reflect the overall energy demand in each scenario, but the share of this demand that is met with lower-carbon sources also affects emissions levels. The gigawatts (GW) produced from two key low-carbon technologies and the demand for electric vehicles in each IEA scenario are shown in Figure 9 and Figure 10, respectively.

To calculate the metal requirements for each of the scenarios, baseline assumptions about the metal requirements per technology are required. Figure 11 and Figure 12 show the assumptions made.

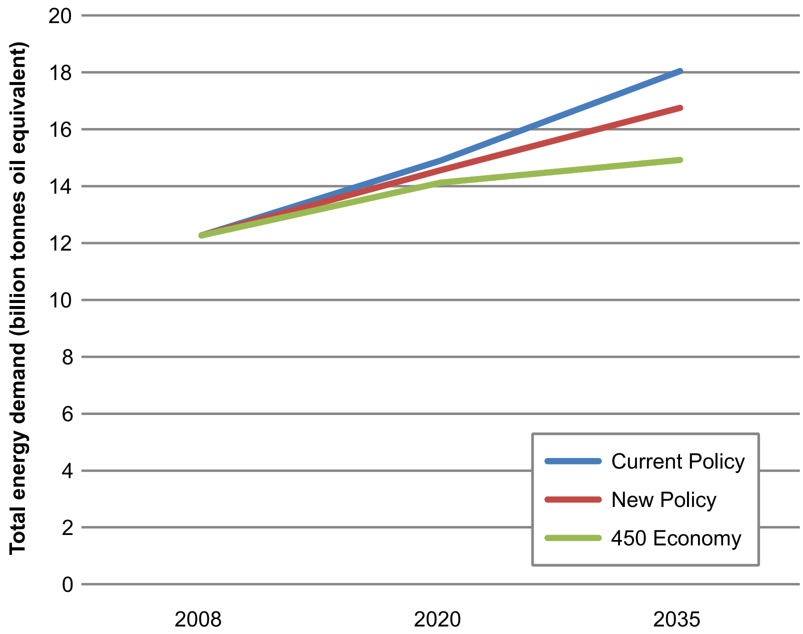


Figure 7: Total energy demand scenarios

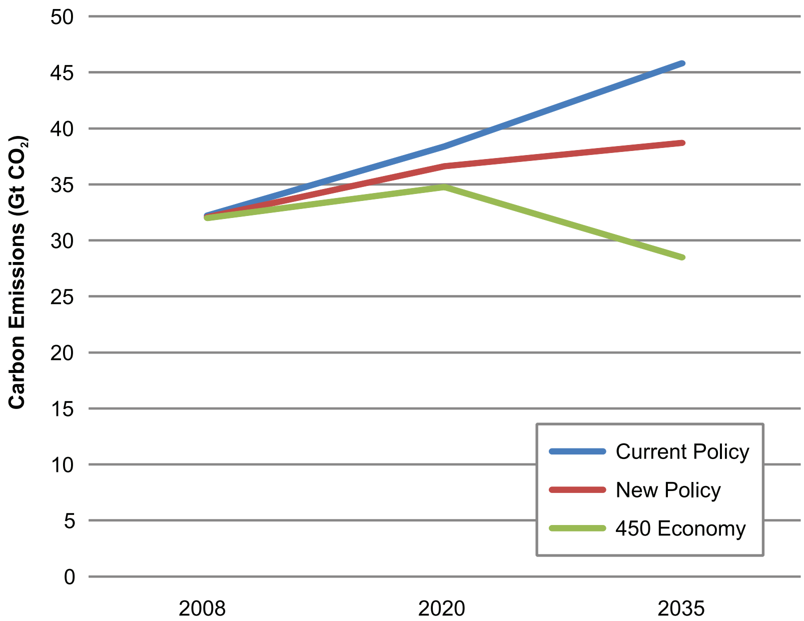


Figure 8: Cumulative carbon emissions scenarios

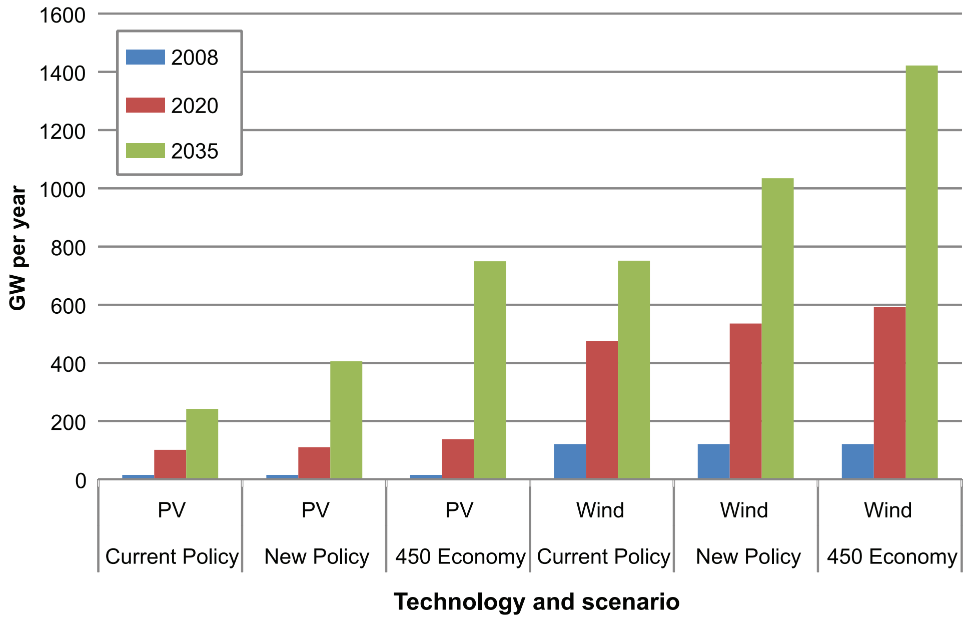


Figure 9: GW (gigawatt) provision from low-carbon technologies (PV: Solar Photovoltaic)
(IEA, 2010)

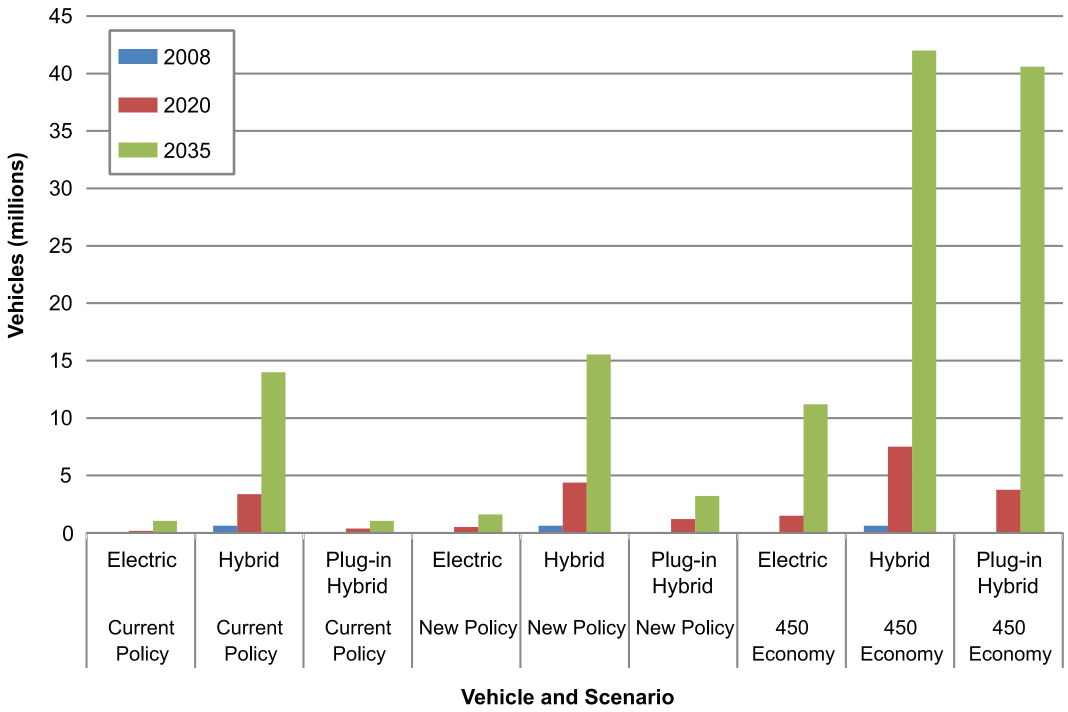


Figure 10: Electric vehicle demand
(IEA 2010)

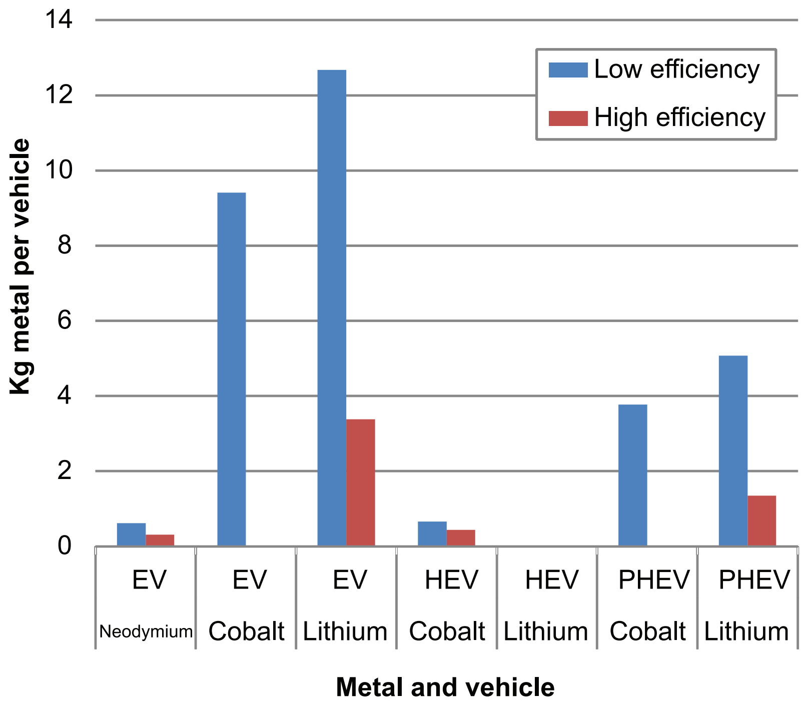


Figure 11: Metal requirements per technology (EV: Electric Vehicle, HEV: Hybrid Electric Vehicle, PHEV: Plug-in Hybrid Electric Vehicle).

Sources: USDOE (2010); Speirs *et al*. (2011), Candelise *et al*. (2011)

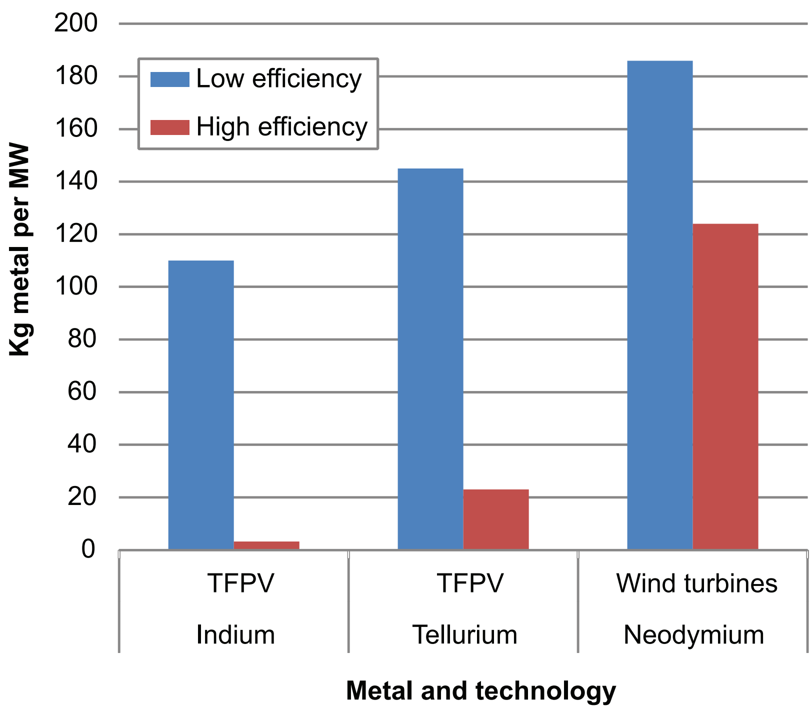


Figure 12: Metal requirements per technology (TFPV: Thin Film Photovoltaic).

Sources: USDOE (2010); Candelise *et al*. (2011); Speirs *et al*. 2011)

Metal surplus and deficits scenario results

The scenarios suggest a deficit in both indium and tellurium under the IEA Current Policies scenario, regardless of the WEF scenario applied, appearing in 2020 and continuing until 2035. Neodymium moves into a supply deficit under the IEA New Policies scenario, and there are deficits of all three metals under the IEA 450 scenario. Cobalt and lithium also show deficits in the IEA 450 scenario under both the WEF Green Trade Alliance and Resource Security scenarios. Only the WEF Rebased Globalism scenario shows a surplus in these two metals under the IEA 450 scenario. The full results for 2035 are displayed in Figure 13.

In order to assess the scale of the deficits, all the results are presented relative to metal supply in that year. This does not change whether the metals are shown to be in surplus or deficit, but means that they can be compared according to the actual metal requirements. For example, a 43,000 tonnes deficit of cobalt may be less of a concern than a 2,500 tonnes deficit in indium, due to the amount of metal used in each of the different technologies. Applying this relative measure highlights the significance of the indium deficit compared to the other metals. Relative to the available supply this deficit is larger than the other metals.

Only lithium and cobalt are in surplus in the majority of scenario combinations considered (except as noted above, in some of the IEA 450 combinations). The surplus under the IEA 450/Rebased Globalism combination is somewhat surprising given the high levels of economic growth (and hence demand from other sources) and low mine production in the Rebased Globalism scenario, but the high efficiency improvements, increasing use of substitute materials, and high growth in metal recycling assumed within that scenario do lead to surpluses for those two metals. The cobalt and lithium deficits under the IEA 450/Green

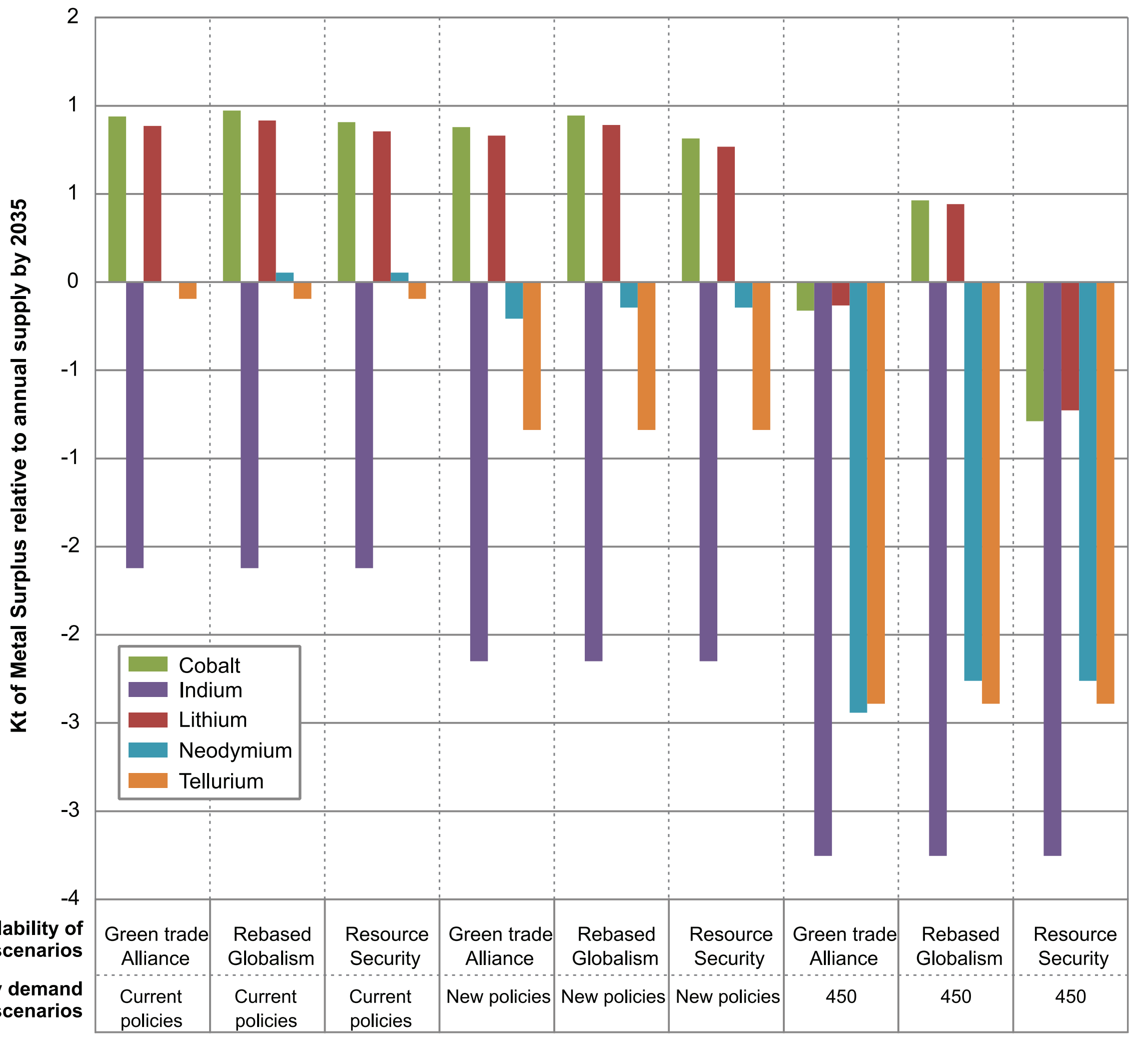


Figure 13: Annual metal surplus/deficit relative to annual supply in 2035

Trade Alliance combination are small; WEF's Resource Security scenario, meanwhile, shows the most significant deficits for all other metals. Neodymium is the only metal for which the Green Trade Alliance scenario shows greater deficits than the Resource Security scenario; for all other metals, Resource Security gives rise to greater deficits. Neodymium may differ from the other metals in this respect because it isused in both electric vehicles and electricity generation, and because the Green Trade Alliance scenario assumes a lower requirement for substitution of metals and lower levels of growth in recycling.

Figure 14 shows how these annual surpluses and deficits add up over time. The cumulative calculation assumes that if metal production exceeds its use, then stockpiles are formed. Any surplus production is in effect credited to a future year, assuming that production could reach this level even if it isn't physically extracted in the surplus year. Any stockpiling is not shown in the results – only cumulative deficits if stockpiles are not enough to cover use.

As expected, the annual deficits also lead to cumulative deficits: most notably for indium, which shows significant cumulative deficits under all scenarios, but also for tellurium and neodymium even though the annual data had not shown a deficit of neodymium under the IEA Current Policies scenario in 2035. The cumulative deficits under that scenario arise from deficits in previous years.

The amount of deficit in both indium and tellurium remain exactly the same within each IEA scenario regardless of the WEF scenario. The changes in the supply-side variables for these metals are not enough to outweigh the demand drivers of the increased low-carbon energy demand.

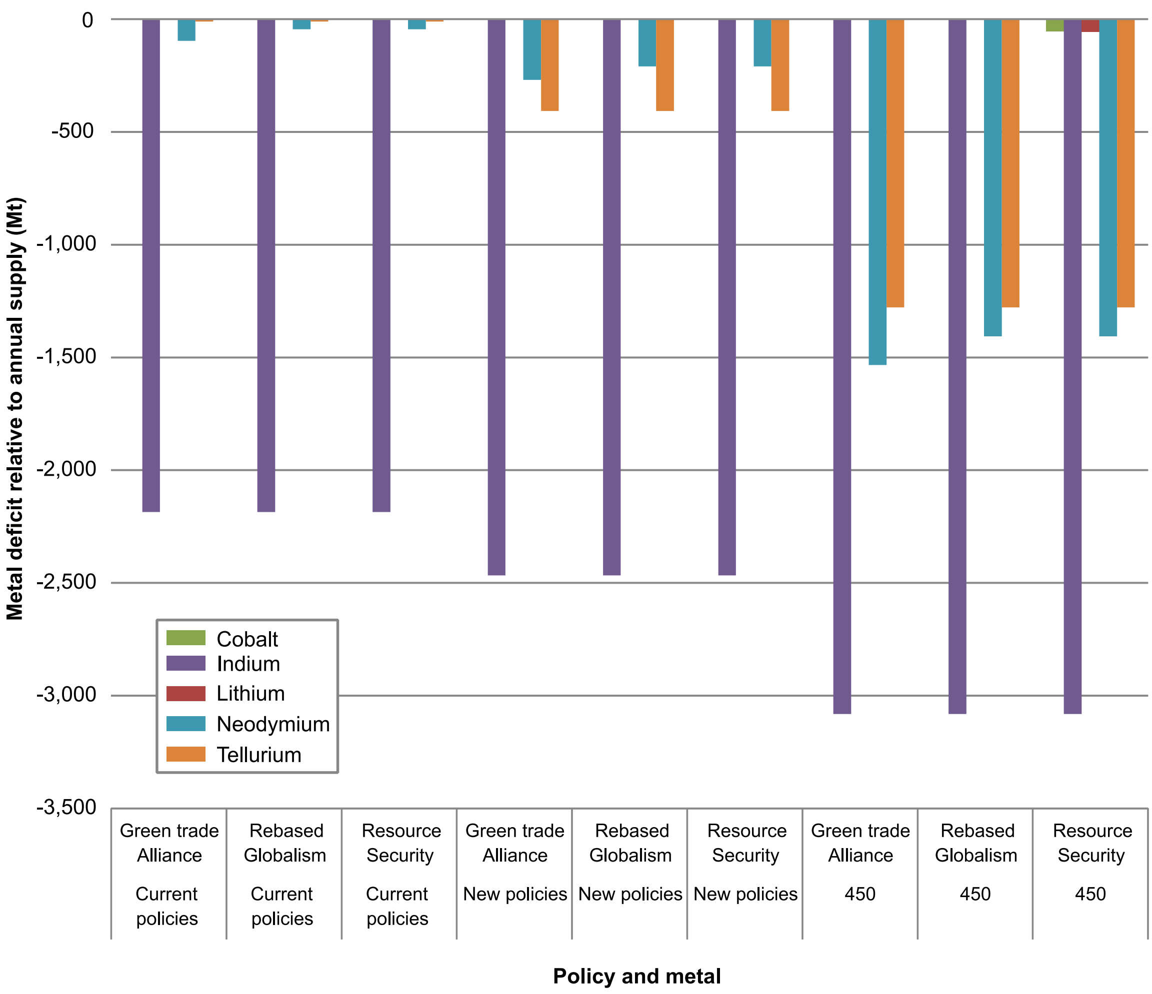


Figure 14: Cumulative metal deficits relative to cumulative supply by 2035

6 CURRENT BUSINESS RESPONSES TO METAL SCARCITY

As detailed above, the reliance of low-carbon technologies on scarce metals poses challenges – but there are a number of options to address this scarcity. Businesses can substitute more abundant and accessible materials, recycle existing stocks, make more efficient use of resources, and seek more efficient production processes. This section examines some issues surrounding these response strategies, and offers practical examples of their implementation to date. It is worth emphasising, however, that public policy can also support and encourage business-led solutions. Some options are discussed below, and relevant policies are also examined in Section 7.

SUBSTITUTION

There are two main approaches to substitution: replace the whole technology with another that achieves the same outcome, or substitute a material within a particular technology.

In considering technology substitution, a first key question to ask is whether there are options available or in the pipeline that could replace the technology in question. There may be alternatives capable of achieving similar emissions reductions that do not rely on scarce materials. Ideally, the substitute would perform at the same level or better, though slightly diminished performance may be acceptable, depending on the application. The ability to effectively "right-size" a technology for its use may enable more efficient use of materials by matching product capabilities with utility required. From a business perspective, this could mean offering a cheaper and less resource-straining, but lower-performance, option which would be sufficient for a given application or market niche.

Of course, technology substitution is only viable if alternatives already exist or will come online before scarcity becomes an issue. Some companies are actively looking for alternatives. Toyota, for example, is exploring options to replace permanent magnets with induction motors in hybrid cars to avoid reliance on neodymium, given supply restrictions by China and associated price increases for rare earth metals.[6]

6 See Ohnsman, A. (2011) 'Toyota Readying Motors That Don't Use Rare Earths'. *Bloomberg News*, 14 January. http://www.bloomberg.com/news/2011-01-14/toyota-readying-electric-motors-that-don-t-use-rare-earths.html.

Another key factor that can influence technology substitution is the existence of incentives. For instance, governments can provide tax incentives or loan guarantees, implement relevant regulations (e.g. renewable portfolio standards, interconnection standards), or offer targeted research and development (R&D) funds that could lead a business to favour one technology over others.

Materials substitution, meanwhile, may often be an option because it is the *function* of the metal that is ultimately desired (e.g. electrical conductivity, catalytic properties, malleability), rather than the metal itself. Scarcity is only one of several reasons why such a substitution could occur, but it is also important to consider the possible impacts of substitution on factors such as toxicity, recyclability, price, and performance. Depending on the particular component, the technology that uses a particular metal may have to be adapted to accommodate the substitute. For instance, the efficiency of the component may be reduced, or the size of the component may increase.

Ideally, a scarce metal will be replaced with one that is less scarce. However, substitutions could also just create a different scarcity problem. Notably, suitable substitutes for low-carbon technology metals often come from the same group of elements, which can have similar scarcity issues (e.g. platinum group metals, rare-earth metals). One example of this displaced scarcity occurred in the 1990s, when replacing some platinum with palladium in automobile catalytic converters led to increased demand and price of the previously less expensive palladium (Hagelüken and Meskers 2010).

Non-metal substitutes may be feasible in some applications as well, again recognising that this could in turn pressure other types of resources. Plastic electronics (also referred to as organic electronics), for instance, are being developed for pertinent low-carbon applications such as organic photovoltaic (PV) cells and light-emitting-diodes (LEDs) (U.K Department for Business Innovation & Skills 2009).

Photovoltaic panels provide an interesting conceptual example for both types of substitution. The technology could be substituted for another option that fulfils the same function of providing low-carbon energy, such as wind turbines. Alternatively, the make-up of the PV components could be switched, replacing materials such as cadmium telluride with organics in thin films.[7]

RECYCLING

Another strategy is to reuse the existing stock of metals. However, as previously discussed, recycling metals poses a number of challenges, and a number of economic, technical, and political factors drive the viability of metals recycling.

Economics can play a large role in whether, for a given metal, it makes sense to source a metal from virgin resources or secondary supply. Even if a metal can be technically recovered, the value of a small amount of metal in a device may not warrant recycling. However, recycling can still occur where a rare metal is not the primary driver. For example, analogous to the extraction of by-product metals when mining for a main (economic) metal, a trace metal may ultimately be recycled if it occurs in the same product as another metal that is cost-effective to recycle; for example, recycling of printed circuit boards is driven by gold, silver, palladium, and copper, but special metals can be recovered in the same process (Hagelüken and Meskers 2010).

Furthermore, even if a metal is highly valued due to its scarcity, if there is not enough of the metal in circulation, development of facilities may not be justified. For instance, one of the business interviewees for this project suggested that there is not enough tellurium in circulation to make the development of a recycling facility viable. Of course, it may be a matter of time: as continued primary extraction depletes reserves of a given metal, prices might rise, and the amount available to recycle would also gradually increase, until the market reaches a tipping point where recycling makes economic sense. In fact, some businesses are beginning to explore recycling of rare earth metals. Hitachi Ltd. is exploring rare earth element recycling, and Kosaska Smelting and Refining is developing a means of recovering rare earths from electronic scrap (Goonan 2011).

In addition to economic constraints, product complexity, metal concentration and distribution, product design and accessibility of metals all play a role in the technical viability of metal recycling. Particular combinations of metals in products can prove challenging for recovery, for instance when a metal is paired with a hazardous material. These combinations may require special techniques for recovery to manage off-gassing and effluents, which in turn require notable investments which could cost more than buying virgin materials (Hagelüken and Meskers 2010). However, pairings with toxic materials may also encourage recovery – for example, collection of cadmium telluride solar PV panels would likely be subject to legislation due to toxicity concerns about cadmium, and could facilitate tellurium recycling (Speirs *et al*. 2011). Pre-processing can also prove challenging for minor metals in complex devices, and consequently limit recoverability through incomplete liberation and poor sorting (Hagelüken and Meskers 2010).

Another important factor is whether products containing the metal of interest are easy to collect. In addition to the difficulties associated with extracting a metal from a product, recovering the product itself is the first challenge. Generally, it is more viable to collect metals if there is a regulation requiring it; notable examples include the European Commission's Batteries Directive and End-of-Life Vehicles Directive. (Policies driving recycling are discussed further in Section 7.) However, even targeted regulations may not encourage recycling of metals used in specific applications. For instance, metals used in dissipative applications, such as current industrial uses of tellurium, hinder recycling (Speirs *et al*. 2011), as the diffuse material cannot be easily collected.

Alternative business models and ownership structures can help in transitioning from open to closed cycles of products. For instance, collecting product deposits refundable upon return, leasing instead of selling products, and selling the service or function provided by a product, such as a heated home, rather than the actual hardware. Should any replacement or repair costs of hardware be necessary to deliver the service, these would include the purchase of the function. These all represent examples of innovative schemes that increase manufacturer control over products, and encourage collection and recycling of key metals in products (Hagelüken and Meskers 2010).

RESOURCE EFFICIENCY

As noted earlier, there is limited potential to increase resource efficiency in production processes. Companies are already incentivised to develop efficient

7 The 3C initiative has funded research exploring the potential growth in biomass use for multiple purposes, including as industrial feedstock, in a low-carbon economy. See Kemp-Benedict *et al*. (2012), *Biomass in a Low-Carbon Economy: Resource Scarcity, Climate Change, and Business in a Finite World. Stockholm Environment Institute, Stockholm, Sweden.*

product processes and minimise waste, particularly when using scarce and expensive materials.

In addition to technological improvements which can lead to decreased required inputs (as in the PV example), improvements can be made in production processes. It is important to determine whether a desired technology can allow more efficient production. For instance, if a material is used in a thin film, it is usually sprayed onto the surface, a practice that is inherently inefficient. Other material deposition techniques, such as roll-to-roll, are under development (Speirs *et al*. 2011), though currently options are limited, and therefore opportunities still exist for innovation in production processes to better utilise scarce materials.

Given the natural desire to seek production efficiency, one may question whether any quick wins remain. If metals are so scarce, it would seem likely that the production process would have been optimised already. However, as the metals become increasingly scarce and their prices rise, this could drive further business innovation. Improving inefficient processes is strategic for businesses, as better use of scarce resources can lower costs of production.

SECONDARY PRODUCTION

There is also room for improvement in production of materials, particularly for those mined as by-products of a primary metal. Indium and tellurium are interesting examples, as they are both mined as by-products (of zinc and copper, respectively) and used in thin-film PV. Refineries focused on processing ores for a primary metal may not have the capability to recover secondary metals, as can be the case with indium and tellurium. Even refineries with this capability do not recover 100 per cent of the by-product, with the remaining metal discarded in tailings or other wastes. Recovery also may not be cost-effective – for example, a number of refineries do not recover tellurium due to the small market size. Though the treatment of wastes containing iridium and tellurium currently poses more technical and economic challenges than exploiting conventional resources, the potential to recover these metals from tailings merits further research (Speirs *et al*. 2011).

There has also been some discussion surrounding the potential of mining metals, including rare earths, from seafloor nodules. However, this is currently largely disregarded due to the technical difficulty and high costs of extraction.[8]

8 See Broad, W. J. (2010) 'Rare-Earth Minerals Hold Promise for Seabed Mining'. *The New York Times*, 8 November. Science in 2011. http://www.nytimes.com/2010/11/09/science/09seafloor.html.

7 BUSINESS PERSPECTIVES AND POLICY RESPONSES

To get an insight into the business strategies that might grow out of the scenario calculator results, the results were shared with a range of stakeholders. Data-gathering in relation to business strategy issues is often challenging, so to get a fuller picture, we contacted a cross-section of individuals with varying perspectives and vested interests, from multi-national energy-sector executives, to mining companies, to economists in academia.[9] In follow-up telephone interviews, they were asked two key questions, adjusted to match their expertise:

- How is your businesses engaged with the issue of rare and critical metal scarcity?
- With reference to the scenario calculator results, how are businesses responding to mitigate the risk that this scarcity implies?

This section summarises the interviews, highlighting areas of consensus, disagreements, internal contradictions, and explicit and implicit connections and interactions. Case studies are used to illustrate the interview process in greater depth. Inherent to the nature of scenario exercises like this one, some interviewees chose to question the premise of the questioning, and in the process provided valuable information on wider issues such as the impact of pricing, geopolitics and global economics, which is also presented.

As the interviews were undertaken under an agreement of anonymity, statements are not personally attributed, and references to businesses are only provided where agreed. It is important to stress that while diverse views were sought, the interview process was in no way meant to be comprehensive, but rather a sampling of perspectives on the findings and their implications for the private sector.

As a reminder, the scenario calculator output suggested that there would be:

- Severe risk of medium and long term CSD (cumulative supply deficits) of indium and tellurium;
- Moderate risk of medium term and severe risk of long term CSD of neodymium; and
- Limited risk of long term CSD of cobalt and lithium.

9 Although cobalt is one of the metals discussed in this report, none of the businesses contacted uses the metal, so it is not covered in this section.

Photovoltaics

Of all the low-carbon technologies affected by the metals covered in this study (neodymium, indium, tellurium, lithium and cobalt), the PV industry appears to have the most complex set of drivers affecting business responses. The scarcity issue is directly relevant to second-generation thin-film photovoltaic (TF PV) technologies: Copper Indium (Gallium) (di) Selenide (CIGS) and Cadmium Telluride (CdTe). Interviewees agreed that indium and tellurium availability is already considered a bottleneck to TF PV expansion, with tellurium being of greatest concern. Indeed, the dominant TF PV producer, First Solar Inc., totalling 70 per cent of market share (EPIA 2010), producing solely CdTe modules, is currently seeking mitigating strategies to alleviate this “potential bottleneck”. When questioned on the time frame of responses, businesses reported that the majority of PV growth is expected to occur between 2020 and 2030, and that is when they are planning for.

Tellurium

In the case of tellurium in CdTe technology, those involved described recycling as the dominant mitigating strategy. This is primarily because CdTe modules are already recycled due to the toxicity of cadmium.

In addition to recycling, there is evidence of vertical integration of businesses. For example, First Solar Inc. is integrating its operations with the mining company 5n Plus, its main telluride supplier. Moving to ensure a dedicated supply chain in this manner has precedence in the oil industry as well as in PVs with regard to first-generation crystalline silicon (c-Si), which experienced a similar integration of silicon supply in the mid-2000s.

Indium

The most likely response, as indicated by interviewees, will be to further develop material substitutions. Although efforts are still at the research and development stage, the idea is to replace indium and gallium with tin and zinc in CIGS technology.

Lithium

Industry concerns about lithium appeared to be centred on power density issues that are currently limiting the utility of EVs in comparison with internal combustion engines, rather than scarcity. That said, the next generation of so called “lithium air” batteries are seen as game-changers for EVs, and clearly still have a lithium demand.

CURRENT POLICIES ON METALS

Policy can help address the challenges outlined above, and provide incentives for appropriate business and consumer responses. On the other hand, some policies, such as those that might be taken under the WEF Resource Security scenario, may exacerbate problems of global scarcity.

The current international scarce metals trade policy environment provides a varied picture. A recent, comprehensive global review of scarce metals policy was undertaken by The Hague Centre for Strategic Studies (Diederen 2009). The review explored four types of polices related to minerals, including scarce minerals. These were: policies based on a national geological survey; local policies; national policies; and policies related to nationalised mining companies. The implementation of these policies is achieved through a varied set of policy instruments (see Box 3).

National governance

The Hague Centre assessment found that national governance approaches relies on four key policy instruments. First, the mineral policies of many countries, including the US, China and Japan, rely heavily on direct state involvement to secure the availability and steady supply of minerals. China and the US use domestic supplier preference as a mineral policy instrument as well, to ensure the continuity of national strategic capacities.

Second, nearly all countries reviewed highlighted the need for a coherent national government policy, seeking to establish a "whole of government approach" with regard to minerals. Germany, for example, pursues active cooperation between the national geological survey, the mining industries, leading producing

Box 3: Key policy instruments regarding scarce metals

Type of policy	Policy instrument
National governance: Intra-governmental collaboration to allocate mineral resources. Control and coordination of mineral policies takes place at the national level.	Domestic supplier preference, direct state involvement, coherent national government policy, national transparency, good governance, public-private partnerships, national enterprise preference, private enterprise preference
Trade Restrictions: Government-imposed restrictions on the free international exchange of goods and services. The instruments listed here are specific to the minerals realm.	Tariffs, export restrictions, import restrictions, direct and export subsidies, layered exchange rates, administrative barriers, anti-dumping policies
Technology advancement: Efforts by governments and collaboration between governments and industry to enhance technological development related to minerals extraction.	Identification of renewable energy and recycling opportunities, examining substitution possibilities for critical minerals, government-led R&D, domestic capacity and knowledge-base improvement
Proactive acquisition: Ensuring the continuity of critical mineral supply through explicit safeguarding methods.	Identification of critical minerals, stockpiling of minerals, international strategic partnerships, foreign direct investment
Development Cooperation: International transfer of public funds; in this context, the aim is to support and promote economic, social and political development in receiving countries in ways that may be beneficial for the minerals industry, such as by building mining infrastructure.	Development aid in the form of loans or grants, through bilateral aid or through non-governmental organisations or multilateral agencies
Global governance: Political interaction among international actors, through which collective interests are articulated globally, rights and obligations are established, and differences are resolved.	Market liberalization, global market regulation

(Source: Adapted from Diederen 2009)

industries, ministries, departments and local and national governmental agencies, in order to create a single comprehensive national policy approach in ensuring mineral availability.

Third, public-private partnerships are used by almost all countries as the policy instrument of choice. These partnerships are used to pool resources, bundle forces (e.g. through the combination of governments' diplomatic contacts and the private sector's subject-matter expertise), in order to gain a better position.

Finally, emerging economies and developing countries – China, India, South Africa and Brazil – emphasise national transparency and good governance measures. These countries are setting up legal frameworks regulating the mineral industry to enhance mineral extraction, usage and trade. The primary purpose is to strengthen governmental oversight and national control over (possible) mineral gains, and to secure a steady supply of minerals.

Trade restrictions

Almost none of the national policies use trade restrictions as the policy instrument of choice. However, the EU is an exception, in that it explicitly provides for import restrictions as policy responses to any trade restrictions put in place by trading partners. Though they may not be as explicit, others also use export restrictions in practice. The report mentioned in particular China, India and Russia, which impose export duties reaching up to 120 per cent on certain minerals, while developing countries use export taxes to raise revenue and encourage domestic processing of raw materials.

Other reports also show that most countries use trade restrictions of various kinds. Japan and China's use of direct subsidies may be explained by the fact that both countries have nationalised most mineral companies. The mineral policies of the US and China both mention the usage of administrative barriers. These non-tariff barriers involve rules and regulations that seek to protect the national mineral extraction industry. As a result, it is much harder for foreign companies, if not impossible, to invest and gain a foothold in the national mineral extraction industry in these countries.

Technology advancement

All national policies examined emphasise the role of technology in coping with minerals availability. Investing in R&D and encouraging technological innovation in the fields of mineral usage, extraction and processing feature prominently among the policy instruments of choice. Almost all countries stimulate knowledge base improvement.

Resource-rich countries, predominantly the US and China, emphasise domestic capacity improvement, mostly in order to decrease dependency on foreign mineral sources or, in the case of developing countries such as South Africa, to optimise output and profits.

The EU has initiated a wide array of policy initiatives in the area of technological development, emphasising technological policy options as well as intra-European resource and knowledge base optimisation with regard to minerals. For example, the EU finances the 7th Framework Programme (FP7); the European Technology Platform on Sustainable Mineral Resources, which focuses on innovative exploration technologies to identify onshore and offshore resources and new extraction technologies.

The EU has many raw material deposits, but their exploration and extraction are hindered by increased competition between different land uses and a highly regulated environment, as well as technological limitations in access to mineral deposits.

Proactive acquisition

A number of national policies explicitly call for proactive acquisition, while other countries do not have any such policies in place. The US and China are active across the entire spectrum of proactive acquisition policies and actively identify mineral reserves, stockpile critical minerals, establish international strategic partnerships, and pursue opportunities for foreign direct investment. This underscores the importance some countries attach to the gathering and safeguarding of critical and (perceived) scarce minerals.

The EU minerals policy covers all dimensions of proactive acquisition, except for stockpiling. In light of the crude oil and petroleum stockpiling directive – which imposes an obligation on Member States to maintain minimum stocks of crude oil and/or petroleum products covering the Member States' energy needs for 90 days – this might change in the future. The policies of individual European countries do not refer to proactive acquisition of minerals. Considering the fact that these countries are largely dependent on import of most minerals, this is striking.

Most countries apply international (bilateral) strategic partnerships, a policy that can help address the challenges outlined above, and provide incentives for desired business and consumer responses. For example, Brazil has established several strategic partnerships with resource-rich African countries, and India has established strategic bilateral partnerships with both Kazakhstan and South Africa. As previously noted, however, these kinds of policies can also exacerbate problems of global scarcity, as shown in the WEF Resource Security scenario.

Development cooperation

The Hague Centre analysis suggests that many western countries use development aid as a policy instrument to advance their respective mineral strategies. Development cooperation is predominantly used to foster good governance, enhance transparency, and create reliable government structures, regulations and policies in resource-rich developing countries. As described by Hague Centre, the US and China's mineral policies do not indicate that development cooperation is used in the context of mineral policies. Other sources, however, show both countries do use development aid as a policy instrument.

Global governance

Many minerals policies discuss global governance and the creation of international regulatory frameworks, in conjunction with organisations such as the WTO, the International Monetary Fund, and free-trade pacts such as the North American Free Trade Agreement. Both industry and resource-importing countries' mineral policies seek to promote a liberalisation of the world market (and as a consequence possibly also a liberalisation of national markets) in order to foster security through market stability and predictability. This guarantees unrestricted market access, and secures the availability and supply of minerals. This policy approach is especially noticeable among European countries.

POLICY TRENDS AND BUSINESS PERSPECTIVES ON POLICY NEEDS

The Hague Centre analysis also outlines several trends in minerals policy. First, policies view **mineral scarcity as primarily a technological issue.** Securing mineral supply is framed in technological terms, and technological innovation is seen as a key strategy. All countries under review have policies that emphasise the importance of technological development, i.e., how to enhance national knowledge and domestic capacity and expand R&D. This is consistent with the views expressed by business leaders who attended the stakeholder review workshop for this project, who said that expertise in rare and scarce metals, and in exploration and mining more generally, is an issue.

Furthermore, business leaders acknowledged the "carrot and stick" role of the state in the energy sector, and they suggested several options with regard to metal scarcity. Particular emphasis was put on coupling long-term government funding of R&D on less metal-intensive technologies with government action to better secure the supply chain through contractual/political agreements with non-EU "resource endowed countries", along with opening up new domestic or EU reserves.

Second, the Hague Centre analysis shows, there is a **limited focus on scarcity in policies.** Most countries, with the exception of China, the US, and Japan, do not focus on this issue in their policies. Instead, they concentrate on technological advancement and environmental sustainability. However, driven by increasing concerns over securing supply of raw materials and growing awareness of the need to manage all finite resources in a prudent and responsible manner, policy-makers and regulators are beginning to appreciate the importance of safeguarding access to mineral resources. Countries that view minerals as a security issue typically focus on the identification and stockpiling of critical minerals. By designating minerals as critical for national security and development, policies are designed to control mineral flow and secure supply of critical minerals. State resources are used to gain access or acquire these critical minerals.

The Hague Centre review identified several policy measures that are particularly relevant to securing the supply of minerals, such as:

Securing mineral supply at the national level: Direct state involvement is used by some countries (the US, China, and Japan) to strengthen the government's grip on mineral supplies. The creation of a system of national overview – who does/needs what and when? – is a typical first step in this endeavour. Strengthening ties with mineral industries, and establishing public-private partnerships, is instrumental in safeguarding mineral supply.

Increasing domestic capacity: Mapping, extracting and refining minerals is an important aspect of securing mineral supply at the national level, especially for countries such as the US, Japan and China and for the EU as a supranational organisation. Mapping domestic dependence on foreign minerals can be a first step toward reducing these dependencies. In this case we see a preference towards domestically extracted minerals and towards preventing national mining endeavours from being uncompetitive and prone to foreign takeovers.

Securing mineral supply at the international level: Some countries such as the Japan, the UK, and Germany implement policies at the international level to secure supply. They do so through international strategic partnerships that cover trade agreements, support in international forums, sharing of technology, and development aid programmes.

In contrast, many companies, especially the larger multinationals appear less interested in state-supported means of securing certain materials, but rather would like to see only a carbon pricing system that does not pick favourites for special investment. Moreover, the geopolitical issues that often stimulate the government responses such as domestic stockpiling do not apply to businesses that operate in multiple countries; it is these businesses who favour only a liberal market system response. Therefore, it can be inferred that in a resource-scarce world, large multinationals would move away from rare-material-intensive low-carbon technologies on a cost basis. In fact, interviews for this study revealed that such moves have already occurred, such as BP's and Shell's surrendering of PV operations, though these were claimed to be due to issues of environmental health and overall competencies. Moreover Shell's dominant low-carbon technology is currently natural gas, which is of course neither low-carbon nor subject to rare metal scarcity.

A final major insight from the Hague Centre analysis is that **international partnerships are used strategically to secure mineral supply.** A number of countries aim to create open markets and an international level playing field, both to secure a steady flow of mineral resources, and to promote openness in pricing and trading. International rules and regulations – and the institutions that implement them – can also play a critical role.

Promoting recycling and materials reuse

Different types of policies are being developed to better address resource scarcity, with notable efforts related to encouraging recovery and reuse of materials.

Extended producer responsibility (EPR) is a policy approach that makes producers responsible for disposing of a product at the end of its life. EPR, which is intended to influence product design, encourages increased material reuse and recycling, while reducing waste and associated waste management costs. The policy instruments implemented under EPR can take a number of forms, such as advance recycling fees, product take-back mandates, and taxes on virgin materials. Waste electronics and electrical equipment (WEEE) take-back programmes in the Netherlands and South Korea have encouraged recycling of a number of appliances and electronic products. Studies on EPR and its effectiveness in impacting materials recycling and product design are ongoing, as the concept continues to be applied in different settings (OECD 2006).

Legislation can help raise awareness and establish a supportive framework, though there is still room for improvement, particularly with respect to scarce metals. For instance, collection targets that are based on mass do not sufficiently address metal scarcity used in trace quantities. Allowing the market to determine recycling of these trace metals would require waiting for metals to become scarcer and for prices to rise to a point that makes recycling cost-effective. However, this delay exacerbates losses of this secondary metal supply. Therefore, considering legislative support, rather than solely deferring to the market to regulate, could save scarce metals that would otherwise be lost (Hagelüken and Meskers 2010). Metal recycling is gaining more attention in policy circles. For example, the European Commission has recently called for industry to play a much greater role in recycling metal scarcity (European Commission 2011), indicating that this issue is rapidly moving up the political agenda.

Regulations that encourage smart product design by businesses can facilitate recycling and address the concerns of metal scarcity. Encouraging standardisation in product design can make end-of-life recovery less technically complicated. Furthermore, promoting long-lived products dampens the need for frequent production and recycling in the first place, limiting wasted materials.

8 CONCLUSIONS

In the last two decades, there has been rapid growth in the development and installation of low-carbon technologies to reduce greenhouse gas emissions and secure energy supplies. However, interest in these technologies has been matched by concern that potential bottlenecks in the supply chains for various metals, critical for low-carbon technologies, could hinder the deployment of these technologies on a substantial scale (Moss *et al*. 2011).

This research, applied a custom-made metal scarcity calculator in combination with a range of supply and demand scenarios, found that indeed there is a risk, suggesting that there would be:

- Severe risk of medium and long term CSD (cumulative supply deficits) of **indium** and **tellurium**;
- Moderate risk of medium term and severe risk of long term CSD of **neodymium**; and
- Limited risk of long term CSD of **cobalt** and **lithium.**

Such projected shortages are, of course, a concern to businesses, as indicated by interviews and stakeholder workshops conducted for this project. A survey of 69 leading companies by PricewaterhouseCoopers also found such concerns (Schoolderman and Mathlener 2011).

Of all the low-carbon technologies affected by the metals examined in this study, the photovoltaic industry appears to have the most complex set of factors driving the business response. The scarcity issue is directly relevant to second-generation thin-film photovoltaic (TF PV) technologies, Copper Indium (Gallium) (di) Selenide (CIGS) and Cadmium Telluride (CdTe). In relation to these technologies, indium and tellurium availability is already considered a bottleneck to TF PV expansion, with tellurium being of greatest concern. Recycling was the dominant mitigating strategy cited in interviews; this is primarily because CdTe modules are already recycled due to the toxicity of cadmium.

Policy initiatives can help address the challenges identified in our analysis and provide incentives for appropriate business and consumer responses. The wrong policies, however, such as those described in the WEF Resource Security scenario, may exacerbate problems of global scarcity.

Our review of current policies and policy trends, based on one major report (HCSS, 2009), suggests that governments view scarcity primarily as a technological issue and see technological innovation as the key response. Consequently, many minerals policies do not focus on the issue of scarcity and security of supply, but rather concentrate on technological advancement and environmental sustainability. While such efforts are important, they are insufficient, given that our analysis indicates that economic and political risks are likely to significantly contribute to medium- to long-term management difficulties.

That said, there are increasing concerns over securing supply of raw materials, and growing awareness of the need to manage all finite resources in a prudent and responsible manner. Policies most frequently tackle resource availability concerns by either securing mineral supply at the national level, or by increasing domestic capacity. Securing mineral supply at the international level through international strategic partnerships (trade agreements, support in international forums, sharing of technology and development aid programmes) needs to be a vigorous long-term sustainability strategy.

As we noted, however, many companies, especially the larger multinationals, are less interested in state-supported efforts to secure certain materials, often because they have access to resources in multiple countries. Such businesses favour a liberalisation of international markets, with minimal government intervention, except to set a carbon pricing system to foster low-carbon technology industries. While this may be the most beneficial approach for such companies, however, it is important to also remember the valuable roles played by government and international institutions in protecting the environment and the public interest and ensuring a fair and equitable distribution of limited resources.

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ANNEX

Calculator variable	Metal	Technology	High (upper limit)	Low (lower limit)	Information Source	Comments/ additional information
Growth in other demand	Cobalt	N/A	Economic growth	Economic growth	Assumption	
	Indium		Economic growth	Economic growth	Assumption	
	Gallium		Economic growth	Economic growth	Assumption	
	Lithium		8% growth per year 2007-2020	2.8% growth per year	Tru Group Inc. (2011)	
	Neodym-ium		3.67 %	2.67 %	Kara *et al*. (2010)	
	Tellurium		Economic growth	Economic growth		
Efficiency improve-ments (per year)	Cobalt	Hybrid electric vehicles (HEV)	-1.61%	0.00%	US Department of Energy (2010)	
		Plug-in hybrid electric vehicles (PHEV)	-100.00%	0.00%	US Department of Energy (2010)	
		Electric vehicles (EV)	-100.00%	0.00%	US Department of Energy (2010)	
		All above end uses	-5.15%	0.00%	All above for cobalt	Weighted average by technology
	Indium	Thin-film photo-voltaic (TFPV)	-13.19%	-3.41%	Speirs *et al*. (2011)	
	Lithium	HEV	0.00%	0.00%	US Department of Energy (2010)	
		PHEV	-5.16%	0.00%	US Department of Energy (2010)	
		EV	-5.15%	0.00%	US Department of Energy (2010)	
		All above end uses	-5.15%	0.00%	All above for lithium	Weighted average by technology
	Neodym-ium	Wind turbines	-1.61%	0.00%	US Department of Energy (2010)	
		EV	-2.73%	0.00%	US Department of Energy (2010)	
		All above end uses	-1.68%	0.00%	All above for neo-dymium	Weighted average by technology
	Tellurium	Thin-film photo-voltaic (TFPV)	-7.10%	-4.58%	Speirs *et al*. (2011)	

Growth in mine production	Cobalt	N/A	7.5%	0%	Andersson & Rade (2001)	
	Indium		5.6%	2.0%	Fthenakis (2009)	
	Lithium		12 %	6 %	Tru Group Inc. (2011)	
	Neodymium		7.5%	4.2%	Kara *et al.* (2010)	Combined growth weighted by size of current production
	Tellurium		20%	5%	USGS (2008)	
Proportion of technology using metal of interest	Cobalt	EV	100%	30%	Kara *et al.* (2010)	
	Indium	TFPV	20%	15%	Speirs *et al.* (2011)	
	Lithium	EV	100%	30%	Kara *et al.* (2010)	
	Neodymium	Wind turbines	20%	10%	Kara *et al.* (2010)	
		EV	100%	100%	Kara *et al.* (2010)	
	Tellurium	TFPV	20%	15%	Speirs *et al.* (2011)	
Growth in metal recycling	Cobalt	N/A	25%	18%	UNEP (2011)	
	Indium		10%	5%	UNEP (2011)	92% of TF PV based on laboratory recovery (Li *et al.* 2009)
	Lithium		10%	1%	UNEP (2011)	
	Neodymium		10%	5%	UNEP (2011)	
	Tellurium		10%	5%	UNEP (2011)	95% of TF PV based on laboratory recovery (Candelise *et al.* 2011)

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