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Material Security

Ensuring resource availability for the UK economy

Environment Agency

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Considerable expertise resides within the science, technology and engineering base within the UK and elsewhere, knowledge which if fully exploited would significantly improve resource usage to the commercial benefit of business and to society as a whole.

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Material Security

Ensuring resource availability for the UK economy

Strategic report produced by the Resource Efficiency Knowledge Transfer Network

March 2008

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Foreword

The climate of waste management is changing into one of resource recovery. The public awareness of 'green issues' means that many companies are including real environmental targets within their corporate social responsibility statements, an approach supported by BERR.

End of life and indeed 'second life' issues of products such as cars and electronics are now becoming eco-design development criteria. The larger waste handling companies are becoming recycling organisations as opposed to logistic specialists and increasing their portfolio of innovation technologies in everything from thermal recovery unit to advanced material separation plants.

It has been demonstrated many times that good design can aid recovery of materials for them to be used again. Good design complemented by effective collection, reuse and recycling of the materials we already have will help ensure their long-term availability.

The conclusion of this report not only points out the size of challenge facing us but also the opportunity for UK companies to take a world wide lead to avert a material supply crisis.

April Vesey

April Vesey

Deputy Director, Sustainable Development Policy

BERR | Department for Business Enterprise & Regulatory Reform

1 Executive Summary

Material security concerns the access to raw materials to ensure military and economic sufficiency. Recently, its importance has increased due to limited short term availability of some raw materials, widespread large increases in raw material prices, oligopolistic industry structures and dependence on a limited number of sometimes politically unstable countries as sources of key materials. Materials are most insecure when lack of substitutability in critical applications is combined with the above factors.

In the short term, material prices will respond to supply and demand in the market, but interventions from financial speculators and other intermediaries add complexity. In the longer term, prices may not be a reliable indicator if technology reduces the costs of production. Recycling will be promoted by higher prices, but dispersed applications of even precious metals can make recovery uneconomic.

Reserve and reserve base figures do not reliably predict material shortages, often underestimating true resource levels. However, with certain geologically rarer metals such as copper, the adoption worldwide of the current intensity of use seen in developed countries appears impossible.

The environmental impact of mining, extraction and primary production is uncertain but likely to be large: perhaps responsible for around 5% of global carbon dioxide emissions. The resulting external costs to society are not fully accounted for, presenting challenges to governments and regulators, especially in less developed countries where mining companies increasingly operate. Environmental concerns will probably restrict mining and extraction activities sooner, and to a greater extent, than raw material availability. The paradox that several of the more insecure materials are used in applications to improve environmental performance further complicates the situation.

We analyse 69 insecure materials - mainly metals – using eight basic criteria and show that gold, rhodium, platinum, strontium, silver, antimony and tin deserve attention.

Resource efficiency measures can help reduce demand for primary materials. Substitutes based on more secure metals are being developed, increasingly facilitated by nanotechnology. Minimisation of material use is a common theme, usually for cost efficiency reasons. Closing substance loops through product re-use or material recycling is an area of both technical and policy development and is well exemplified by the secondary lead industry. Future examples could include rare earth magnets and high temperature aerospace alloys. Lastly, avoidance of dispersion of critical materials to the environment currently requires policy intervention to assist collection, such as in the WEEE Directive.

2 Introduction

The issue of material security – the access of industries, companies and countries to raw materials to ensure social, economic and military sufficiency – has grown in importance over the past few years. It has been fuelled by a period of continuous world economic growth, in particular rapid growth in the economies of China, India and other Asian countries, which has increased demand substantially for natural resources such as metals, timber and oil. This has been combined with demand for more exotic and specialised materials and metals from growing industries such as aerospace and electronics. Concerns of developed economies have been raised by:

- High prices of key materials affecting industrial profitability and/or inflation if these increases are passed on to consumers
- Shortages of supply inhibiting volume growth
- Measures such as export tariffs by countries who control raw material supply in order to encourage allocation of resources to their domestic economies
- Increasing control of these resources by fewer organisations

Rapidly industrialising countries such as China, which are large raw material importers as well as exporters, have similar concerns over basic raw materials such as iron ore[a].

An additional factor of concern is the environmental impact of the resource extraction industries themselves, either because of their impact on local ecosystems or because the extractive industries are large consumers of energy and hence likely contributors to global warming.

2.1 Definition

Material security has no single agreed definition. The concept can be expressed as narrowly as 'material scarcity' or more broadly as 'resource efficiency'. Also necessary is pin-pointing where in the supply chain the availability of specialist production rather than materials causes bottlenecks. In high technology engineering, for example, the level of investment and expertise required by specialist processes, and their limited capacity to expand quickly, usually present high barriers to entry. However, they fall outside the present discussion of material security.

Our working definition, based on the concerns above, is that material security means that "there is no significant disadvantage to the national economy or national defence caused by restricted access to specific materials". It is expressed as a negative, a lack of scarcity meeting a minimum standard, rather than a positive need for abundance.

This study focuses on non-renewable raw materials, especially metals, and excludes energy sources such as oil.

Conclusion: We need to separate material security from limitations in downstream production, although grey areas will always exist.

2.2 Historical context

Material security has a long history, with a miscellany of diverse examples:

- A shortage of tin - caused by interruption of traditional trading routes in c. 1,000 BC - arguably stimulated the Greeks to develop iron as a substitute for bronze and hence initiate the beginning of the Iron Age[b]
- The Banda Islands are a remote archipelago in Indonesia, but in the sixteenth and seventeenth centuries were a source of fierce competition between Dutch, English and Portuguese traders as the world's primary source of the spice nutmeg[c]
- The world wars of the twentieth century resulted in the recycling of metals from non-critical applications (e.g. cooking pans, iron fences) to reduce import dependency
- In the Cold War of the mid-late twentieth century, concerns over access to materials critical to national defence led to the creation of large strategic stockpiles of metals such as tungsten, used at that time in inter-continental ballistic missiles

These exemplify different responses to the issue: materials substitution, competition for privileged access, recycling and creation of reserves.

Economists, and those responsible for measuring and forecasting natural resources, have explored the significance of material security over many decades. In the case of economics, discussion of the issue dates from the foundation of economics and the work of Adam Smith, Thomas Robert Malthus, David Ricardo and John Stuart Mill. This is not surprising since economics is often defined as the study of the management of scarce resources. Mill can perhaps lay claim to being an early environmental economist: noting that expansion of a mine may not be preferred due to its impact on the beauty of the surroundings.

Material security should be distinguished from simply a tight market in materials caused by high levels of economic growth and peaks in an economic cycle. Current economic activity, particularly in Asia, is generally seen as a long term structural change in the nature of the world economy, not just a cyclical high point: these economies are “catching up” rather than simply subject to the international business cycle.

The raised demand for primary materials will persist[d]. Resource extraction is also increasingly shifting to less developed countries[e] with consequent geo-political and governance issues.

2.3 Is this an issue?

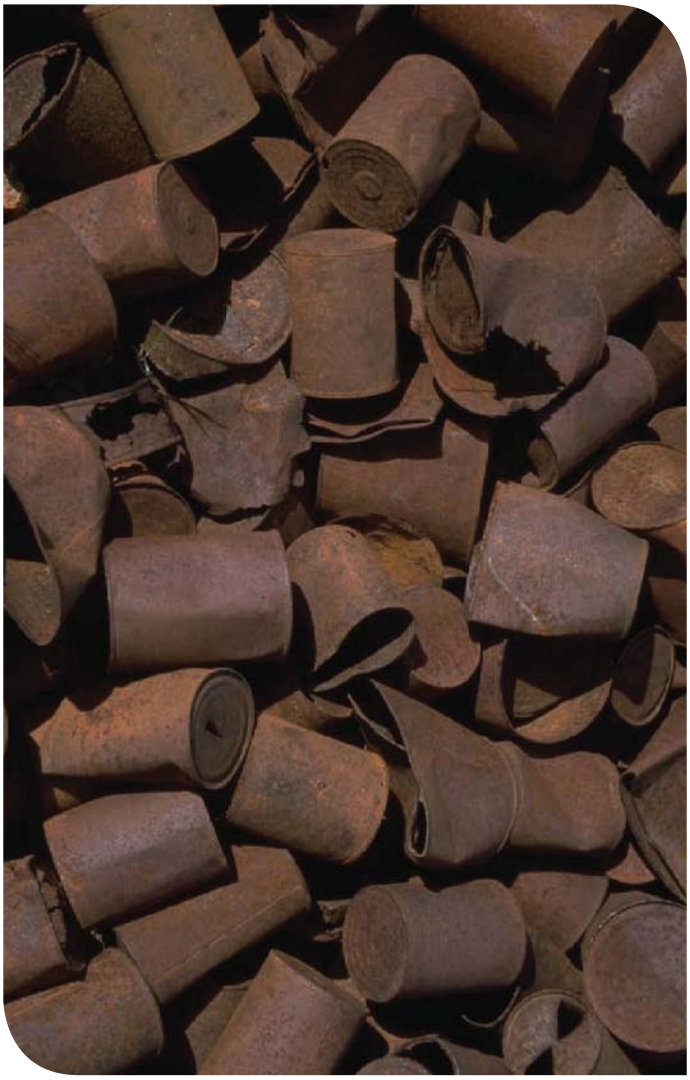
The historical examples given in Section 2.2 largely arise from groups or countries in conflict. In the current age of greater peace between major powers and of greater global economic inter-connectedness, an economic analysis of the material security idea is needed.

Such an analysis will largely determine whether material security requires a more strategic view from countries now, or whether the concerns raised will be addressed by the “invisible hand” of the market that will solve the problem through increased prices of the materials. This in turn will encourage:

- Consumers to reduce demand by using the material more efficiently
- Consumers and competitors to locate substitute materials that cost less but perform equally well
- Producers to increase production by:
  - ramping up existing production
  - locating new raw material sources
  - technological innovation to increase yields from existing or previously uneconomic sources
  - a combination of all three

The greatest problems arise in industries where the key materials are sufficiently expensive that companies believe they have exhausted most reasonable measures to improve efficient production and use; and also where the opportunity for substitution with more readily available materials is low. This often occurs with materials that have themselves been developed as substitutes with improved performance e.g. carbon fibre in airframes instead of aluminium alloys, or rare platinum group metals such as ruthenium used to improve data storage density in IT equipment (see case study 1).

Solutions to these problems depend upon technological innovation whose timescale to development and adoption is usually much longer than usual material supply contracts and the dynamics of the metals markets.



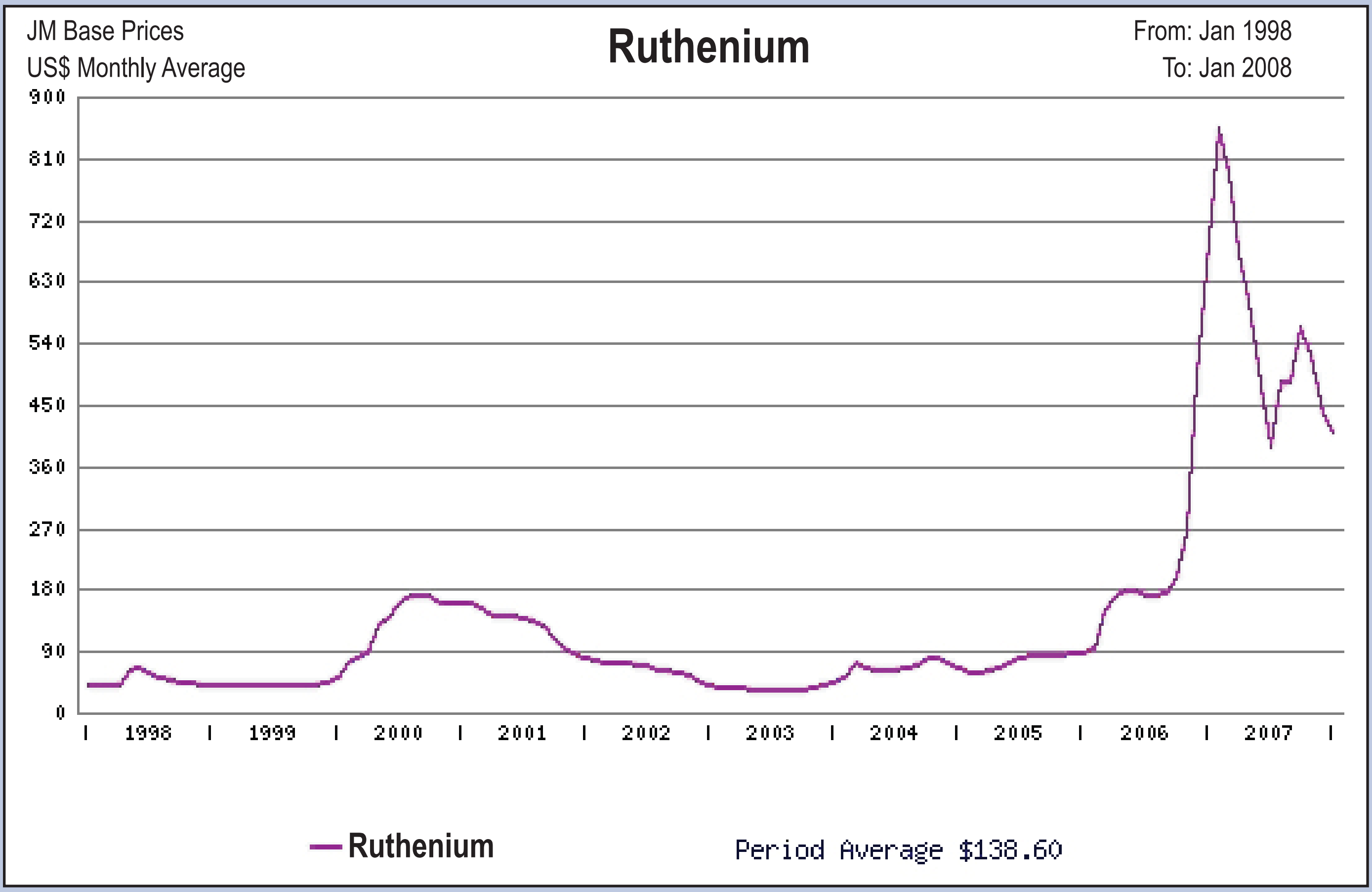
Case Study 1: RUTHENIUM

Once viewed mainly as a contaminant, ruthenium (Ru) is today highly-prized by the high-tech industries. A by-product of the platinum mining industry, ruthenium is one of several ‘platinum group metals’ (PGMs). Other PGMs include palladium, rhodium and iridium.

The 74th most abundant metal on earth, ruthenium is exceedingly rare: less than ca. 30 tonnes per annum is mined in South Africa (SA), Russia and the Americas. Traditionally, the metal has been used to harden and resist corrosion in platinum, palladium, titanium, stainless steel and gold alloys in electrical contacts, jewellery, fountain pen nibs, drills and jet engines.

About a decade ago, prompted by the relatively modest price of ruthenium compared with other PGMs, SA-based mining companies financed research into new uses for the metal. The investment paid off (Figure CS1.1) with new applications in hard disk drives, flat-screen plasma displays and chip resistors driving up the price.

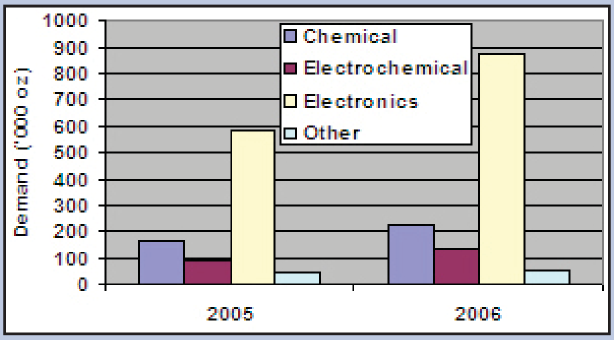
Figure CS1.1 Monthly average ruthenium prices (1998-2008)



Courtesy of Johnson Matthey

Demand for ruthenium soared by 45% in 2006 (Figure CS1.2) with the emergence of a new technology called 'perpendicular magnetic recording' permitting a ten-fold increase in digital information storage densities in hard disks. The major disk manufacturers switched much of their production over to this new technology in the same year and the price for ruthenium rocketed from \$87/oz to \$610/oz. Plasma screen manufacturers have so far been able to avoid the full costs of surging prices by recycling or substituting the metal, but hard disk makers are taking the full force.

Figure CS1.2 Ruthenium demand by application
Source: Johnson Matthey



Although a large proportion of the ruthenium used in hard disk manufacture is from recycled metal, the supply is unlikely to improve in the near future as novel applications for ruthenium continue to appear.

For example, the metal's versatility as a catalyst and ability to resist high temperatures was recently exploited by University of Illinois scientists who have coated micro-reactors used in hydrogen fuel cells with ruthenium. The coating allows the silicon carbide micro-reactors to withstand temperatures of more than 800°C. Ruthenium is also now used to remove hydrogen sulphide from oil refineries, in solar cells, in microscopy and even in anti-cancer drugs. A growing use is in high temperature superalloys for advanced aero engines.

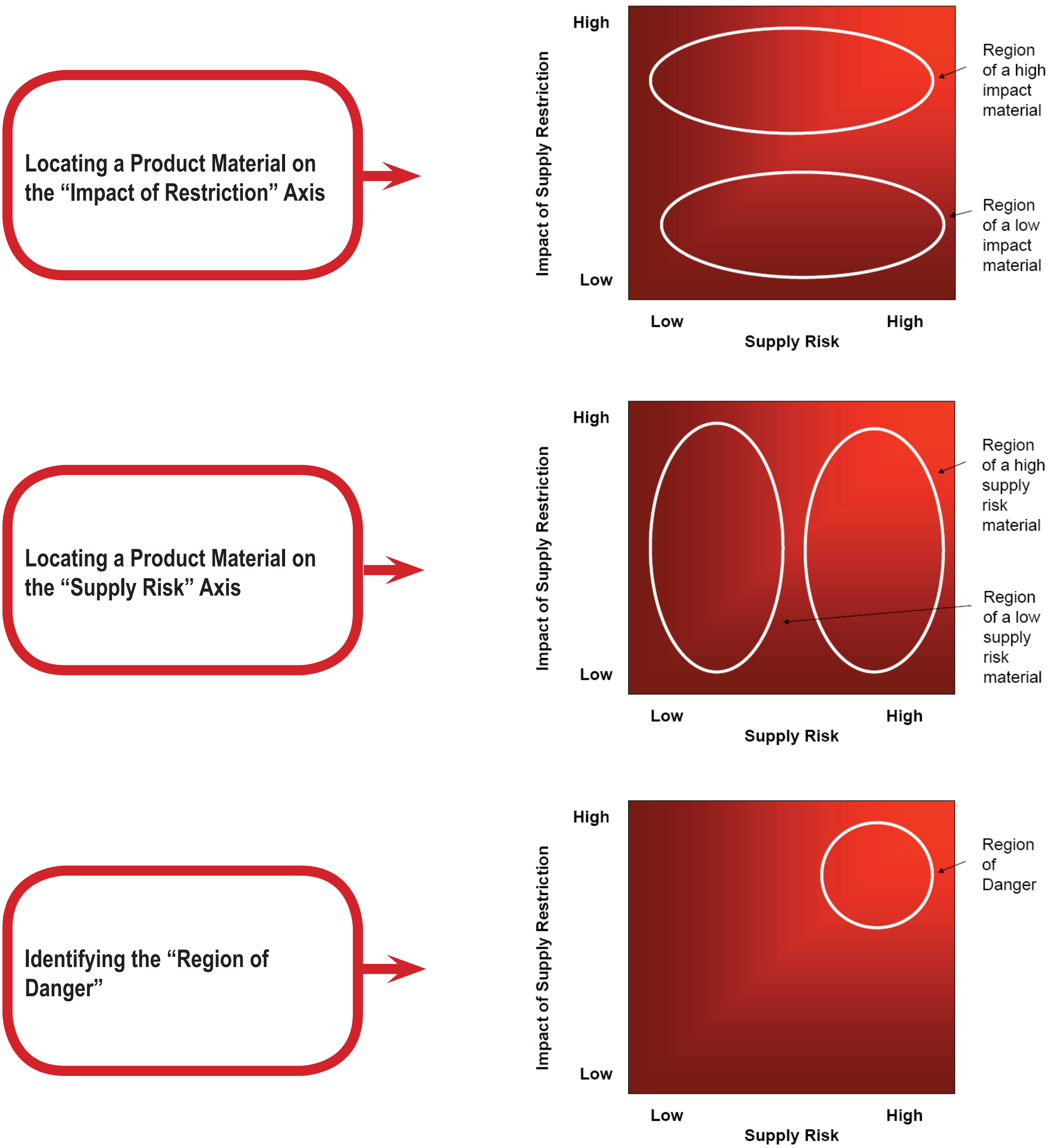
Conclusion: Ruthenium will be difficult to recover in the many applications where it is used in only small quantities in many products. In larger products (e.g. engines), tracking and end of life management will be required to effectively recover the metal.

Material security problems are compounded when the supply of the raw material is controlled by a small number of producers, or emanates from just one or two countries. In this case, the risk of interruption of supply due to catastrophic events, geopolitical concerns or monopolistic practices is consequently greater.

Figure 1 represents this combination of "material risk" (lack of substitutability in key applications) and "supply risk".

Where increased production is a potential response to increased demand, the economics of non-renewable resources - and the reliability of price as a signal - should be scrutinised to encourage expansion of production.

Figure 1: Risks associated with supply of materials of different substitution rates. Reproduced with permission from T.E. Graedel and B.R. Allenby, Indusrial Ecology, 3rd edition, Upper Saddle River, NJ: Prentice Hall, 2008.

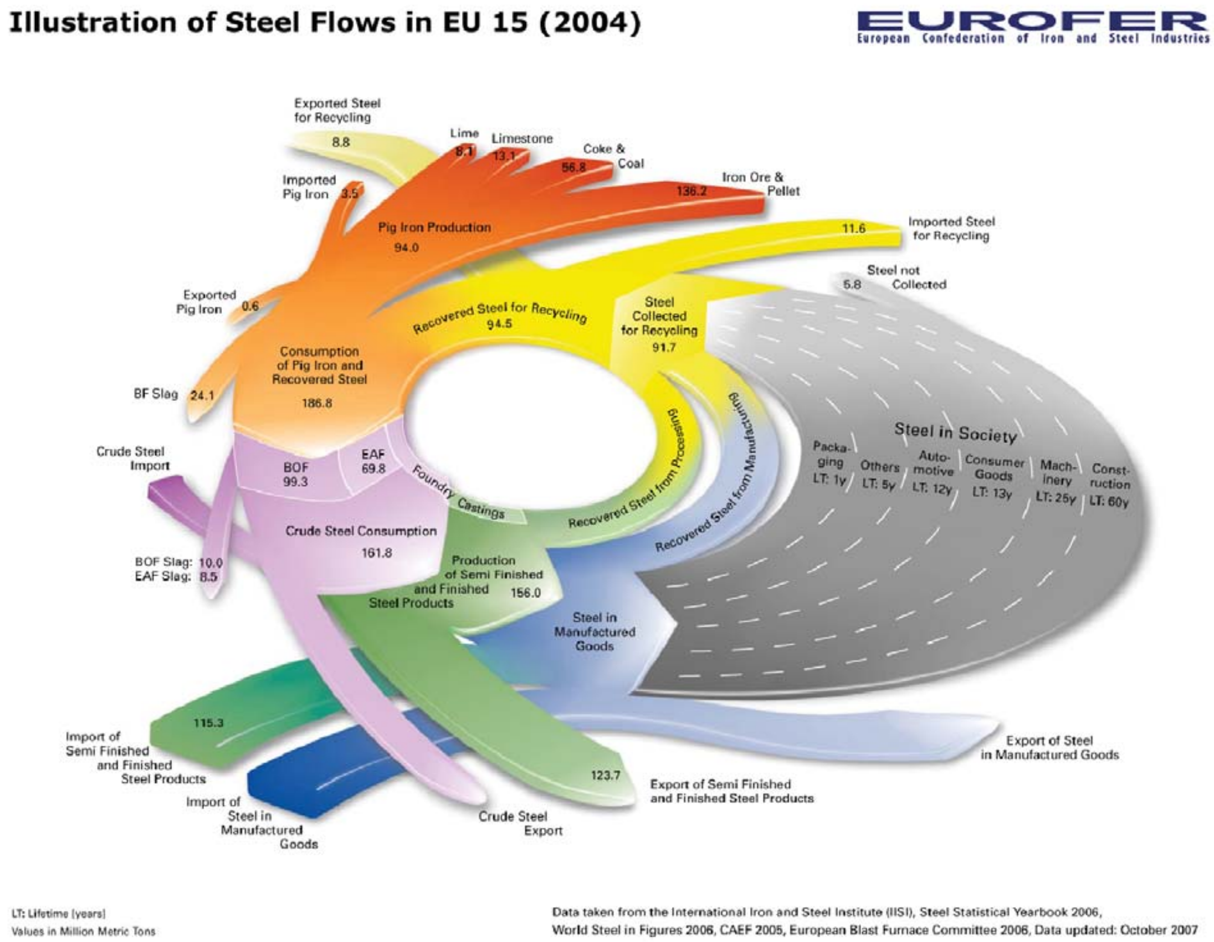


2.4 The economics of resource depletion

Most natural resources which are not chemically transformed (such as oil) are ultimately non-depletable. However, most elements are located and mined at places where they occur in substantial excess of their average concentration in the earth's crust. Notwithstanding some recycling, these resources become depleted as they are dispersed into the biosphere during extraction, production, use and disposal.

While natural processes still dictate cycles for soluble materials such as the alkali metals, alkaline earths and halogens, man's activities now perturb or even dominate the cycles for stable and insoluble resources[f]. The circulation of iron and steel in the economy is a good example of this (Figure 2).

Figure 2: Steel flows in the European Union, 2004.
Reproduced with permission from EUROFER European Confederation of Iron and Steel Industries

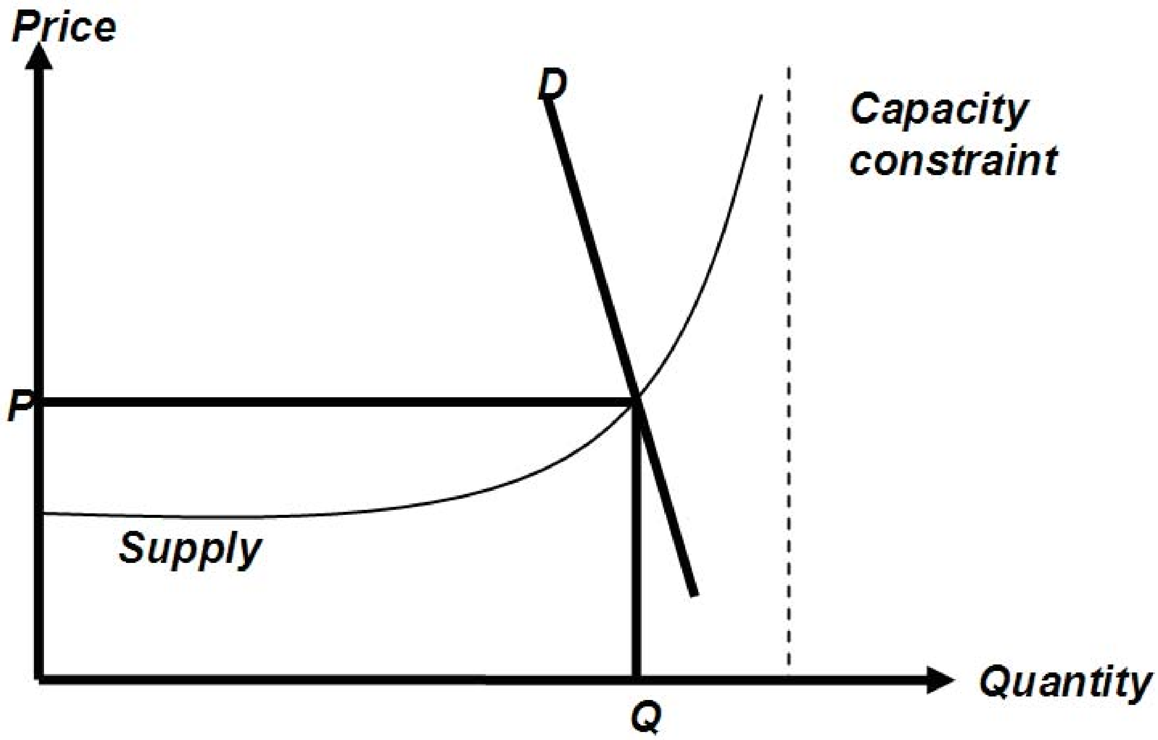


Expansion of demand should result in higher prices that encourage expansion of supply to meet it. Whether this is a complete explanation depends on considering both the short and long term dynamics of the market, as exemplified in the work of Tilton[g] and Simpson, Toman and Ayres[h] from whom this analysis is drawn.

2.5 Short-term considerations

In the short-term (perhaps three to five years while new investment such as a mine or production facility cannot be brought on-stream and production is constrained), the traditional economics of supply and demand dominate, notwithstanding the additional impact of "supply risk". Typical supply and demand curves are as shown in Figure 3.

Figure 3: Price and output at the middle of the business cycle



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These sensitivities to demand and supply, particularly the steepness of the demand curve for many metals, mean that prices can fluctuate substantially with small changes in either factor. Most of the current concerns about lack of production capacity and lead times on engineered components or raw materials are of this short term nature. New capacity will eventually be introduced to meet this need, albeit slowed down by:

- Qualification of new suppliers by customers
- Lead times on equipment, permissions, capital raising, necessary skills

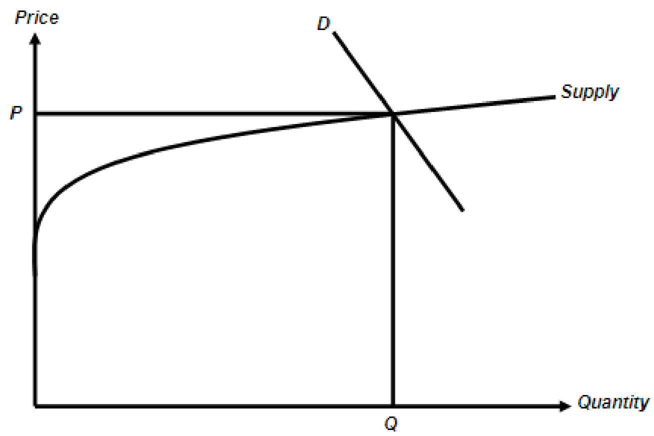
Conclusion: we need to separate strategic concerns from short term demand signals.

2.6 Long-term considerations

Perhaps surprisingly, debate over the longer term considerations of resource depletion has exercised economists for decades. The view that society will eventually run out of extractable minerals in the earth due to our growing demand for a fixed stock of minerals is not generally held. Instead, the depletion of existing stocks (tending to increase prices) and new technology and exploitation of new stocks (tending to depress prices) will compete to determine prices. So the price of a rapidly depleting resource can actually fall - rather than rise - if technology is also reducing the cost of production by a greater degree. Such observations were supported by theoretical work started by Hotelling[i] and developed further by other economists starting in the 1960s.

Generally the supply curve flattens as quantities increase (Figure 4), as marginal deposits of lower purity are more widespread, therefore the cost of extraction rises at a slower rate.

Figure 4: Price and output with fast growing demand



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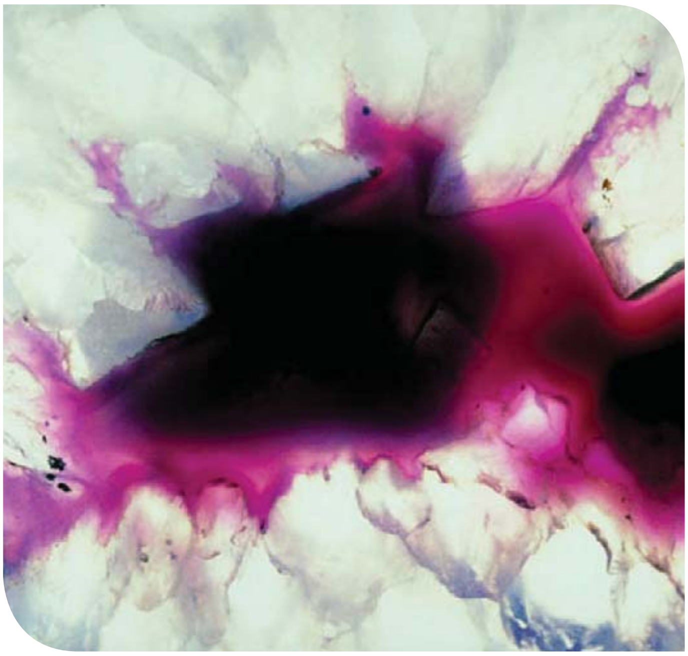


Hence shifts in demand have little impact on long term prices, which is supported by the reduction in the real prices of minerals over past decades. This optimistic analysis derives from resource economists such at Tilton [j], from whom the above diagrams are sourced, and generally relies upon the following assumptions:

Assumption 1: Recycling of metals will depress the rate at which virgin resources are required.

Metals are infinitely recyclable, and most can be recycled with a potential efficiency of around 60-90%. For example, in the EU-15[k] recycled non-ferrous metals make 40-60% of metals output[l]. Incorporation of recyclate reduces production from primary resources.

Allowance has to be made for the metal stock being held in manufactured products in-between production and recycling. This is a well-known problem with one or two special cases. The best known of these is copper, which is geologically scarce, yet is held in the physical assets of the electricity generation and consumption infrastructure for decades, sometimes generations. Gordon et al[m], for example, calculated that the copper stock in use in the USA was 170kg per person in 1999, roughly comparable to figures calculated for Switzerland, Australia and Sweden.

Increased prices for virgin materials make recycling more attractive, so recent rises in metal costs are expected to stimulate recycling of less attractive materials containing scrap metals. Anecdotal evidence on lead-acid battery recycling apparently supports this prediction[n]. But some applications of metals inevitably lead to dispersion into the environment. This is particularly true for materials used in coatings or additives, such as zinc galvanising, cobalt paint dryers, and pottery glazes. The corrosion process also returns metals to the environment. Moreover, in the case of dispersed metal sources, the additional energy needed to recover and recycle the metal can exceed that required during virgin extraction.

Conclusion: Metal recycling will increase with increased metal prices but is likely to remain economically difficult from dispersed applications.

Case Study 2: LEAD

Lead's electrochemical properties lend themselves to use in batteries. Indeed, Deutsche Bank estimates that seventy-five percent of the world's lead is used in this application. Lead is also used in glass; sheeting and piping; construction; cable sheaths; in solder, pewter; in fusible alloys; and as a gasoline additive. Its toxicity means the use of lead in gasoline, paints, solders, and water systems has been reduced or eliminated.

Despite this, the last six years have seen a five-fold rise in lead prices – a surge exceeded only by copper and iron ore among the base metals. Underlying the trend is a trebling in demand in China since 2002. China now dominates the worldwide market for the metal; accounting for a third of global usage. The International Lead and Zinc Study Group (ILZSG) expects China's consumption to exceed 2.5 million tonnes this year. Increases in vehicle production and electric bicycles, combined with rising need for back-up power and growing battery exports explain Chinese demand.

As China's need for lead has risen so its imports have outstripped exports, but increased outputs are stabilising the world lead metal balance. Around 8 million tonnes of lead is produced a year, mainly in Australia, China and the US.
The depressed lead price during the early 2000s and emphasis on exploiting zinc-rich rather than lead-rich deposits dampened exploration activity for lead and investment in new lead mine capacity, so constraining growth in primary supply. Now that the price differential with zinc has reversed, the mining industry can be expected to accelerate lead mine development.
The ILZSG now predicts global lead mine production to increase by 10.4% in 2008. Refined lead production is forecast to rise by 5.4% in 2008, driven by China, India and Canada amongst others.

Some have predicted resource scarcity by 2050 based on current reserve levels, but it is more likely that reserve levels will increase. Nevertheless, the economics of lead supply also depend on access to secondary lead. Lead-acid batteries can, and are, readily recycled. The ILZSG calculated that in 2005 almost 2 million tonnes of lead was available for recycling from a range of end-of-life products in the EU-15, with half reportedly exploited in secondary lead production. Compared with other metals this recycling rate is high.

Lead recycling efficiencies can be further enhanced if end-of-life products are returned to original manufacturers who possess information on materials. For example, Kohmei Halada from Japan's National Institute for Materials Science estimates that more than 90% of the lead in a car battery is recycled when returned to the maker.

Constraints on maintaining and increasing lead recycle rates exist:

- Scrap batteries are classed as hazardous waste, so exports to non-OECD countries (including China) are banned. This situation favours the use of virgin rather than recovered lead in manufacturing new batteries.

- Any pressure to increase battery recycling rates must address concerns over about unregulated activities, sometimes involving child labour (Figure CS2.1).

Figure CS2.1: Lead recycling on the streets of New Delhi. A child disassembles a spent truck battery to sell lead to unregistered recycling units

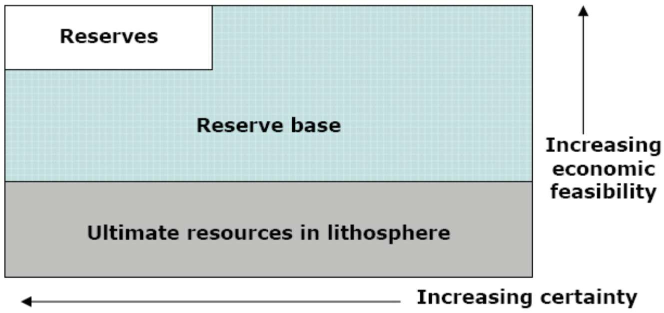
Image reproduced with permission from Occupational Knowledge Occupational Knowledge. International (USA) is launching the Better Environmental Sustainability Targets environmental certification programme to encourage the adoption of sustainable environmental practices at lead battery manufacturing facilities.

Conclusion: High levels of lead recycling have depressed demand for virgin lead until recently, eliminating much of the requirement for new mines. Lead availability will depend on the efficiency of scrap collection and processing, and the production mix between lead and zinc in existing mines and those under development.

Assumption 2: Reserve bases of metals are very large

Metal 'reserves' are defined by the extractive industry as those identified as currently cost-effective to mine. The 'reserve base' refers to metal in the earth's crust meeting minimum specification relating to current mining and extraction practice. Thus the reserve base includes certain elements not currently economic to mine (Figure 6). 'Ultimate resources' refer to the total amount of metal or mineral contained within the lithosphere.

Figure 6: A Common Typology of Mineral Resources



Neither the estimates of the reserves nor the reserve base are robust indicators of the true availability of natural resources, which has long been underestimated. For example, the Club of Rome's Limits to Growth report published in 1972[o] was criticised for extrapolating against known reserves. Even when current reserves were increased five-fold this was inadequate in predicting how both technology and exploration would lead to greater mineral resource availability.

The reserve base is an unreliable indicator of long term mineral availability because it relies on current thinking on technology and economics and does not allow for more radical innovation or discovery of new deposits. For example, according to Gordon et al. 2006, estimates of the reserve base for non-ferrous metals have often increased at a similar rate as the rate of extraction[p]. However, the same authors note that only one sixth of the increase in the reserve base for copper - relatively rare in the lithosphere - has come from discovering new sources. In addition, the developing world cannot accumulate the same stock of copper as the developed nations, since this exceeds the total amount of copper present in the lithosphere (as opposed to merely in the reserve base). Hence substitution and greater efficiency will eventually be required in the use of copper.

Similar results were obtained by Gordon et al. for zinc (where uses frequently result in dissipation of zinc products to the environment) and concerns were raised for platinum if widespread adoption of the current fuel cell technology for vehicles takes place. However, there was much less concern for metals such as silver, nickel and tin.

Conclusion: We should be cautious in predicting long term metal shortages based on lack of reserves. However, substitution of geologically rare metals by commoner ones, and new technologies for more efficient use are required as world population grows and countries develop.

Case Study 3: COPPER

Copper is a geologically rare resource with principal uses in construction, electrical and communication infrastructure, domestic and industrial equipment and transport.

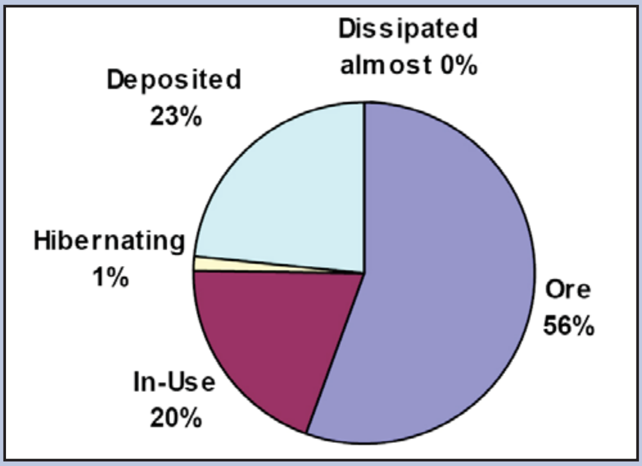
As with most metals, copper exploitation has occurred only recently; indeed, only 2.5% of the 400 million metric tonnes of the material produced by human society was extracted before 1900. A large stock of the metal now resides in cabling, motors (Figure CS3.1), electrical generators and appliances.

Figure CS3.1 A newly cast copper motor rotor

Reproduced with permission from National Renewable Energy Laboratory/Copper Development Association, Inc.

While electrical transmission lines and transformers containing copper are used for decades, small but significant quantities of copper exist as 'hibernating stock': a resource previously consumed for technological purposes but no longer used. Examples include copper residing in obsolete cell phones, televisions, VCRs and computers. A 2004 study in Connecticut found the ratio of in-use copper to hibernating copper was 13:1. On average, each household had 1.1kg of hibernating copper.

Figure CS3.2 Estimated global copper stocks in 2000



Source: Kapur & Graedel (2006) Copper Mines Above and Below the Ground

Of the copper deposited worldwide, almost 99% is potentially reusable with very little dissipating beyond recovery. However, reclaiming copper from items which have been discarded is not easy as they are often deposited without regard for reuse. Nevertheless, around 40% of the world's discarded copper is recycled.

As Figure CS3.2 shows, good copper ore reserves remain but as the quality of life in the developing world improves the ratio of lithospheric to anthropospheric stock will decline rapidly leading to concerns over scarcity.

If every human predicted to be alive in 2100 were provided with 170kg of copper (North America's per-capita average), 1.7 billion tonnes of the metal would be needed, well exceeding the current estimate for world reserves of 1.6 billion tonnes. Historically low, copper prices are already starting to rise. Between 2000 and 2008 the price quadrupled to $8,000 a tonne. If prices grow further, efficiency of usage and ease of recoverability will be incentivised. Substitution with iron, aluminium and magnesium is also starting to become economic as during the last copper price surge in the 1960s.

Conclusion: For rare metals such as copper, economic development of the developing world to Western standards creates an ultimate level of resource consumption that cannot physically be achieved and would result in exhaustion of the ultimate resources in the lithosphere.

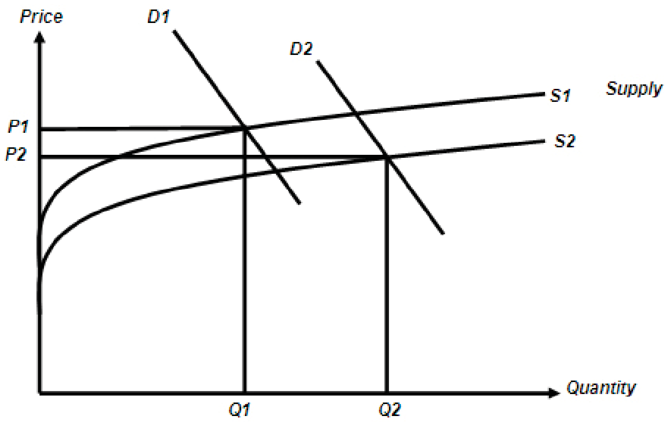
Assumption 3: Rising prices will depress demand as metals get scarcer

Whilst the market mechanism allocates scarce resources efficiently, this works best in the short term, when prices rise as capacity decreases. Prices are not such good indicators of resource scarcity over the long run:

- We have already noted that prices may fall whilst resources become scarcer, if technology improvements reduce the price of extraction and production. This is shown diagrammatically in Figure 7. However, the rising prices for energy, and the energy-intensive nature of most extraction and production will set challenging targets for technology in this regard

- Prices in the market are, arguably, limited by the planning horizons of organisations and the individuals within them. Long term, inter-generational factors are less easy to incorporate into pricing decisions, a factor recognised by Stern in his discussion on the economics of climate change [q]

Figure 7. Commodity prices fall in long run reflecting falling costs of extraction



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It is worth noting that real commodity prices (including minerals) have declined at an average of about 1.3% per year over the past 140 years[r], with some arguing that this trend will continue[s]. This could be due to greater mineral availability, or technological improvement, or both.

Eventually, both of these factors will be overcome by ultimate resource shortages. However problems may arise with industries that are "locked in" to particular metals. If the rate at which substitution may take place is slow compared to the timescale given by the price indicator this may cause economic disruption.

Conclusion: Low metal prices do not necessarily indicate a lack of long term supply problems

Case Study 4: TELLURIUM

In the same chemical family as oxygen and selenium, tellurium (Te) is 37 times rarer than platinum in the earth's crust. The world's annual production is only around 128 tonnes in 2006 according to the US Geological Survey. The element mainly accumulates as a by-product during the copper refining process – but not all copper mines contain tellurium.

Chile produces a third of the world's copper but little tellurium. Tellurium was traditionally used to strengthen metal alloys, but in more recent times its semi-conductor properties have been exploited in CDs, DVDs, 'phase change' memory chips and cadmium telluride (CdTe) solar panels (Figure CS4.1).

Figure CS4.1: Centrifuged cadmium telluride nanocrystals used in solar cells

Reproduced with permission from National Renewable Energy Laboratory/Jim Yost

The rise in applications has resulted in a severe shortage and escalating prices. In 2006, the price per pound jumped from $4 to $100. As with other rare minerals, investors and speculators have tended to aggravate the situation by increasing price volatility. Because of the question mark over future tellurium supplies, some analysts have warned against investing in companies whose business relies on availability of the element for solar panel manufacture.

Conclusion: Examples exist of material security issues influencing share prices of user companies.

Assumption 4: Environmental and social constraints will not limit supply

Resource extraction has significant environmental and social impacts:

- Direct pollution impacts of mining, extraction and production, often in highly sensitive and biodiverse local environments

- Direct social impacts on isolated mining communities, or on country populations reliant upon extractive industries

- Climate change impacts due to the direct impacts of CO2 from production and indirect impacts from the energy used in all phases

All of these impacts will rise with increasing production of metals (offset by metal recycling when incorporated in the material flows).

The overall environmental impacts of extractive industries are extremely large. According to a 2004 report by Earthworks and Oxfam America[t] the metals mining industry is responsible for 7-10% of global energy consumption. In the long-term, carbon intensities will grow, as more energy is required to process lower grades of ore, unless technological change can offset the impact.

Table 1 shows estimated carbon impacts from the initial extraction of different materials from the earth. Due to lack of data, the emissions may not always refer to precisely the same processes so should be treated with caution. However, the data nevertheless indicate that carbon emissions vary widely from material to material. For example, mining rhodium apparently results in many times more carbon dioxide equivalent emissions than extracting the same weight of iron. However, far more iron is extracted every year than rhodium.

To gain an impression of the global carbon impact of mining particular materials, the data in Table 1 is multiplied by the annual production of the material in question. Figure 8 presents the results which indicate that world production of magnesium and copper apparently generates more carbon than that of any other materials listed in Table 1.

These figures do not take into account what happens to the materials once they have been extracted from the ground. For example, according to one report, the global iron and steel industry produces 1.7 billion tonnes of greenhouse gas emissions each year, mostly during the smelting stage in the blast furnace[u], while aluminium smelting alone releases almost three tonnes of CO2 equivalents for each tonne of metal produced[v]. Other pollutants, particularly the acidic gases such as sulphur dioxide, are also emitted.

External environmental and social costs are rarely incorporated into the internal costs of production, either by compulsory or voluntary schemes[w,x].

Such omissions arguably inflate profits by corporations and public bodies at society's expense. Due to the increasing extraction of many minerals from less developed countries[x] with less stringent environmental governance, this situation is unlikely to improve through national regulatory mechanisms[y]. The mismatch between the increasing control of many resources by a handful of corporations versus the regulatory regimes of countries where they operate, combined with the potential environmental damage, is leading to calls for new institutional frameworks governing resource management. Set alongside a desire to preserve the world's natural capital and the services it provides, as well as the specific actions required on climate change, environmental constraints may limit the growth in supply.

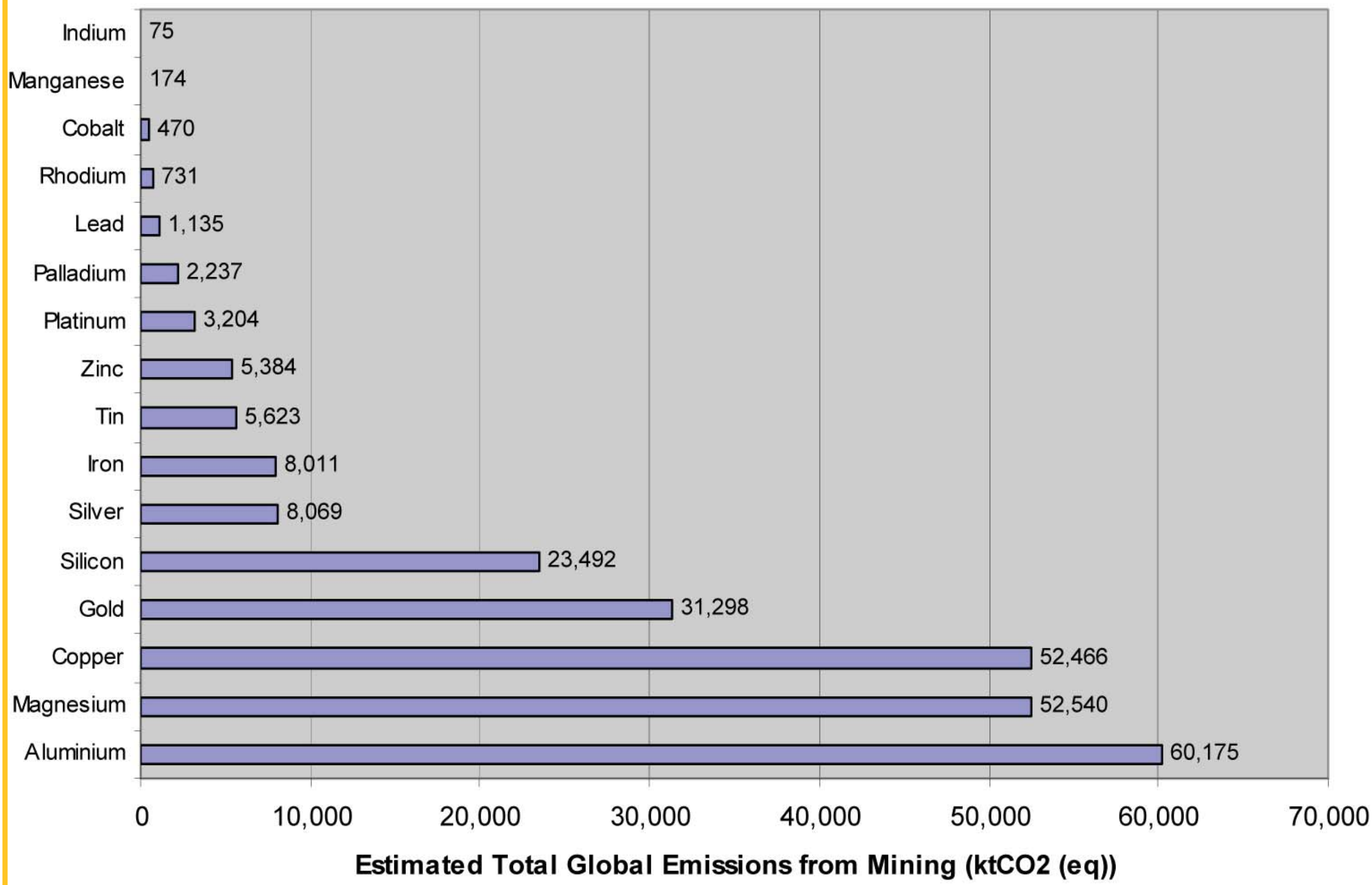
Table 1. Carbon impacts of mining a sample of minerals

Material	Carbon emissions incurred in mining 1kg of material (kgCO_2-eq)
Rhodium	32,208
Platinum	14,704
Gold	12,806
Palladium	9,912
Silver	440
Gallium	186
Indium	156
Magnesium	72
Tin	17
Cobalt	9
Tellurium	8
Silicon	5
Copper	3
Aluminium	1
Zinc	0.5
Lead	0.3
Manganese	0.02
Iron	0.005

Source: ecoinvent database.
Note: Excludes processing and refining

Conclusion: Actions to preserve the environment and restrict climate change are likely to have an impact before actual material shortages do.

Figure 8: Total carbon impacts from world's production of a sample of materials



Global production data sources: Int. Magnesium Assoc., Int. Copper Study Gp., GFMS consultancy, Metal Bulletin Monthly, The Silver Inst., Int. Lead & Zinc Study Gp., Int. Lead & Zinc Study Gp, Johnson Matthey, Int. Aluminium Inst., Cobalt Development Inst. Note: 2006 data used where possible, exceptions include: silver (based on 2004 data), tin (2005), manganese (2005).

2.7 Market failures

Hence, to answer our original criticism that the market is left to take care of material security issues:

- We should exclude strategic materials for military purposes from this analysis. Military need and geopolitical analysis fall outside of the scope of this report
- In the short run, the market will encourage new capacity if prices are high, but this may be delayed through lags in establishing production and obtaining product approvals from customers
- The market will be slow to address long running issues, bringing possible economic disruption in materials lacking substitutes
- The market fails to address environmental and climate change concerns adequately. Actions by society in this regard are likely to far outweigh any impact caused by eventual shortage of material
- Environmental impacts, already very large, are likely to increase as production shifts to countries with laxer governance, and to lower grade of ores requiring greater energy for metals extraction

3 Methodology

Using the framework developed by Graedel[a2] and our analysis of the importance of the various long run influences, the following factors are used to determine the most "insecure" materials (Figure 9):

Figure 9. Determination of material security

	Material Risk	Supply Risk
Primary Importance	Lack of substitutability *Application critical to enabling security or economic growth* Associated Environmental Impact (e.g. Global Warming Potential or Total Material Requirement) Global Consumption Levels Global Warming Potential from Extraction and Production Process Total Material Requirement for Extraction and Production Process	Monopoly supply Political Instability in Major Supplying Region/Country Vulnerability of Major Supplying Region/Country to the Effects of Climate Change *Geopolitical - privileged supply to own or other countries* Dependence on virgin resources (lack of recycling) *Potential to displace virgin material by resource efficiency strategies (potential to increase recycling, re-use, durability, minimisation)*
Secondary Importance	Price	Scarcity, Reserves or reserve base

Hence, material security is not primarily concerned with the market prices of metals. More important is the extent to which national economy or security:

- Is being disadvantaged relative to other economies or organisations
- Depends on virgin materials whose extraction and production generates high environmental impact
- Depends on imported materials

If substantial resource efficiency measures are already in place, such as the high recycling rates seen with lead (see Case Study 2), material security is improved since dependence on primary sources is reduced.

For materials with low recycling rates, the potential for improving resource efficiency should be assessed. The least secure materials are those where with a high dependence on virgin resources and a low technical, economic or logistical potential to improve the situation.

3.1 Materials and industrial impacts

A wide range of materials are assessed according to the following eight criteria:

- 'Material risk' criteria:
  - global consumption levels (A)
  - lack of substitutability (B)
  - global warming potential (C)
  - total material requirement (D)
- 'Supply risk' criteria:
  - scarcity (E)
  - monopoly supply (F)
  - political instability in key supplying regions (G)
  - vulnerability to the effects of climate change in key supplying regions (H)

The major problems in trying to analyse materials according to these criteria are lack of data, multiple applications for single materials, making an overall assessment difficult, and the need to make qualitative judgements with some of these criteria. Nevertheless, a crude ranking of 69 elements and minerals according to these criteria gives an preliminary idea of critical materials and helps indicate which of resource efficiency measures are most relevant.

The ranking system used in the current study is based on scoring each criterion between 1 and 3 for every material. A score of 1 indicates that severity of the criterion in question was deemed "Low", while a score of 3 meant the criterion severity was considered "high". Where data were unavailable, a mid score of 2 was given. The detailed methodology behind the 1, 2, 3 scoring system is given in Appendix 1

Figure 10 maps the position of 69 materials with respect to one supply risk criterion (G, Political Instability in Key Supplying Region) and one material risk criterion (B, Lack of Substitutability). Magnesium, ruthenium, strontium and tin are revealed to be positioned in Graedel's 'region of danger' in the top right-hand corner of the matrix, where both criteria are scored as 3.

Figure 10. Material Security Matrix: Political Instability vs Lack of Substitutality

		Material		
Supply Risk: Political Instability in Key Supplying Region (G)	3	Manganese	Ammonia, Antimony, Arsenic, Asbestos, Baryte, Bismuth, Borate, Boron, Cobalt, Diamonds, Europium, Fluorspar, Gadolinium, Gold, Graphite, Holmium, Mercury, Nickel, Osmium, Palladium, Silver, Talc, Terbium, Tungsten, Zinc	Magnesium, Ruthenium, Strontium, Tin
	2	Iridium	Andalusite, Barium, Bentonite, Beryllium, Bromine, Cadmium, Diatomite, Feldspar, Gallium, Kaolin, Kyanite, Lead, Lutetium, Mica, Niobium, Perlite, Phosphate, Platinum, Selenium, Silicon, Soda Ash, Tellurium, Vanadium, Vermiculite	Rhodium, Molybdenum, Germanium, Chromium, Iron
	1	Aluminium, Copper	Indium, Iodine, Lithium, Potash, Rhenium, Titanium	Zirconium
		1	2	3
		Material Risk: Lack of Substitutability (B)		

Figure 11 maps the same materials with respect to different supply and material risk criteria (C, Global Warming Potential; and F, Monopoly Supply, respectively). In this case, mercury, platinum and rhodium appear in the 'region of danger'.

Figure 11. Material Security Matrix: Monopoly Supply vs. Global Warming Potential

		Material		
Supply Risk: Monopoly Supply (F)	3		Andalusite, Antimony, Beryllium, Boron, Kyanite	Mercury, Platinum, Rhodium
	2	Aluminium, Bentonite, Cadmium, Fluorspar, Graphite, Iron, Lead, Perlite, Vermiculite	Arsenic, Asbestos, Barium, Baryte, Bismuth, Bromine, Chromium, Cobalt, Diatomite, Europium, Gadolinium, Germanium, Holmium, Iodine, Iridium, Lithium, Lutetium, Magnesium, Mica, Molybdenum, Nickel Niobium, Osmium, Potash, Rhenium, Ruthenium, Selenium, Strontium, Talc, Tellurium, Terbium, Titanium, Tungsten, Vanadium Zirconium	Gallium, Gold, Indium, Palladium
	1	Kaolin, Manganese, Phosphate, Zinc	Ammonia, Borate, Copper, Diamonds, Feldspar, Silicon, Soda Ash, Tin	Silver
		1	2	3
		Material Risk: Global Warming Potential (C)		

A crude Material Insecurity Index (MII) can be derived by simply summing the scores for all eight criteria. Table 2 ranks the top eight[b2] most insecure materials in terms of MII. A full listing for the 69 different materials (mostly metallic elements) analysed appears in Appendix 1.

Unsurprisingly, some of the earth's most valuable metals such as gold and platinum appear near the top of the list (Note: our analysis excludes stockpiling, for example as bullion reserves). Several of these metals are already subject to attempts to create substitutes. Usually this is due to their high price, but sometimes (in the case of mercury and to an extent with antimony, because of their toxicity). In almost all cases the key supplying regions are subject to both high political instability (G) and high vulnerability to the effects of climate change (H).

As Table 2 shows, while supply risks are substantial for most materials, the significance of material risks varies. For example, antimony does not appear as vulnerable to material risks as rhodium whose extraction has a relatively high global warming potential (C) and total material requirement (D). A basic typology can be produced of "material risk materials" vs "supply risk materials" by summing the scores for the material risk criteria and for the supply risk criteria and subtracting one from the other. A material risk material can be defined as one where the total material risk value exceeds the total supply risk, and vice versa.

Table 2. The Top Eight Most Insecure Materials?

	Material	Overal Material Insecurity	Material Risks				Supply Risks			
			A	B	C	D	E	F	G	H
1	Gold	21	2	2	3	3	3	2	3	3
2	Rhodium	20	1	3	3	3	2	3	2	3
3	Mercury	20	2	2	3	2	2	3	3	3
4	Platinum	20	1	2	3	3	3	3	2	3
5	Strontium	19	2	3	2	2	2	2	3	3
6	Silver	19	2	2	3	2	3	1	3	3
7	Antimony	19	2	2	2	1	3	3	3	3
8	Tin	19	2	3	2	2	3	1	3	3

Table 3 summarises 39 materials where supply risks are likely to be important on the basis of this methodology, while Table 4 summarises 11 materials where material risks are probably more significant.

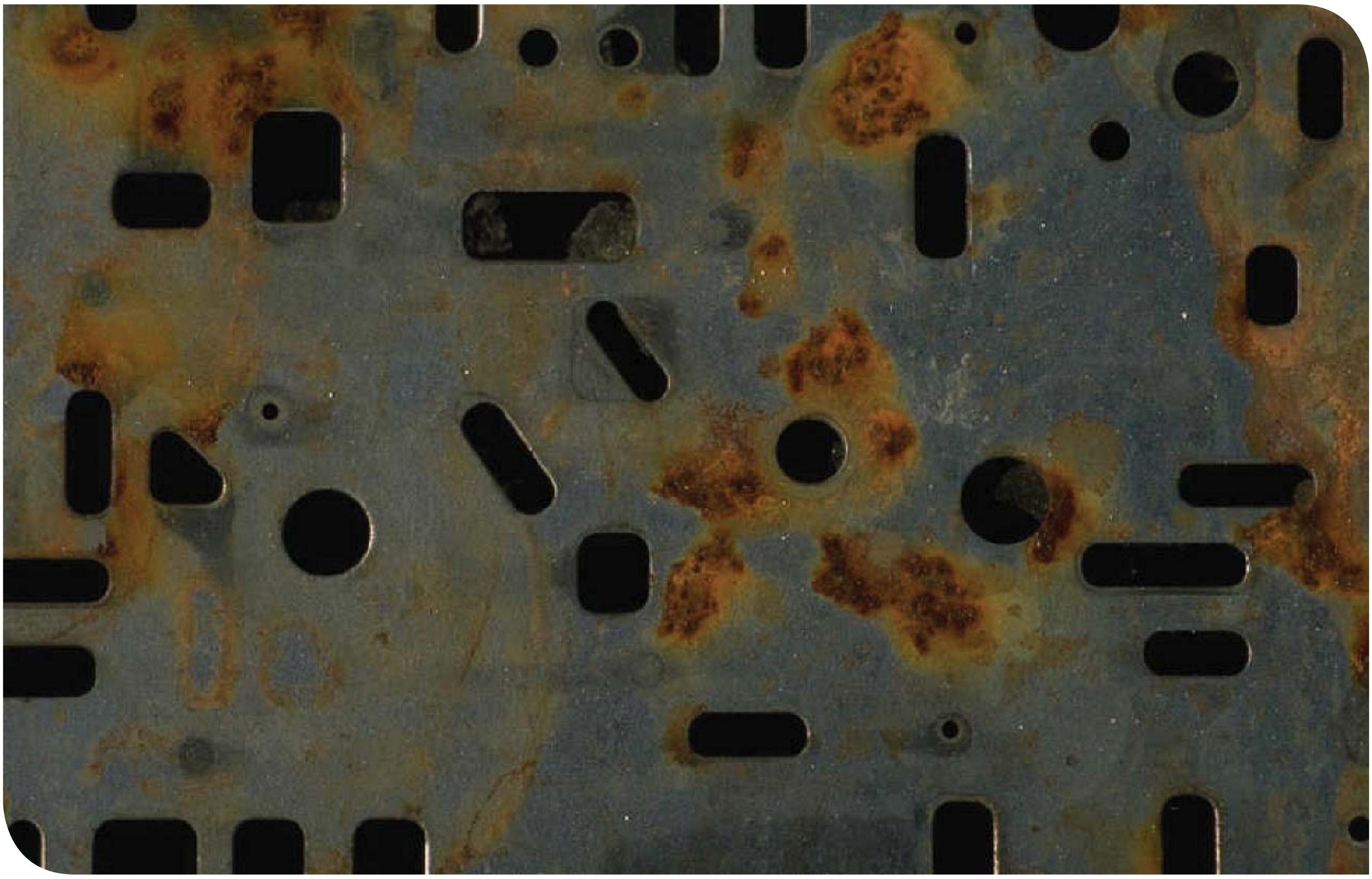
Table 3. "Supply Risk" Materials

	Material	Total Material Risk	Total Supply Risk	Total Supply Risk - Total Material Risk		Material	Total Material Risk	Total Supply Risk	Total Supply Risk - Total Material Risk
1	Antimony	7	12	-5	**21**	Lead	7	9	-2
2	Zinc	7	10	-3	**22**	Cadmium	6	8	-2
3	Holmium	7	10	-3	**23**	Gold	10	11	-1
4	Terbium	7	10	-3	**24**	Strontium	9	10	-1
5	Fluorspar	7	10	-3	**25**	Silver	9	10	-1
6	Arsenic	7	10	-3	**26**	Tin	9	10	-1
7	Graphite	7	10	-3	**27**	Ammonia	8	9	-1
8	Europium	7	10	-3	**28**	Cobalt	8	9	-1
9	Gadolinium	7	10	-3	**29**	Osmium	8	9	-1
10	Manganese	6	9	-3	**30**	Niobium	8	9	-1
11	Mercury	9	11	-2	**31**	Kyanite	8	9	-1
12	Platinum	9	11	-2	**32**	Beryllium	8	9	-1
13	Magnesium	8	10	-2	**33**	Selenium	7	8	-1
14	Tungsten	8	10	-2	**34**	Lutetium	7	8	-1
15	Baryte	8	10	-2	**35**	Bromine	7	8	-1
16	Talc	8	10	-2	**36**	Bentonite	7	8	-1
17	Bismuth	8	10	-2	**37**	Perlite	7	8	-1
18	Boron	8	10	-2	**38**	Rhenium	7	8	-1
19	Andalusite	8	10	-2	**39**	Iridium	7	8	-1
20	Vermiculite	7	9	-2					

Table 4. "Material Risk" Materials

	Material	Total Material Risk	Total Supply Risk	Total Supply Risk - Total Material Risk
1	Zirconium	9	6	**-3**
2	Indium	9	7	**-2**
3	Lithium	8	6	**-2**
4	Potash	8	6	**-2**
5	Molybdenum	9	8	**-1**
6	Borate	9	8	**-1**
7	Iron	8	7	**-1**
8	Feldspar	8	7	**-1**
9	Soda Ash	8	7	**-1**
10	Silicon	8	7	**-1**
11	Titanium	7	6	**-1**

These ratings are based in many cases on incomplete data, so they form an initial scoping study which will require more comprehensive research in order to completely validate. However, they form an initial guide for policy makers, innovation support bodies and businesses.



4 Resource Efficiency Strategies Addressing Material Security

A number of countries have implemented national strategies with a view to making more efficient use of materials within their economies:

- The Japanese "3R" (Reduce, Re-use, Recycle) strategy
- The Chinese "Circular Econonomy"

The recent launch of the International Panel for Sustainable Resource Management by the UN Environment Programme is another indication of the increasing international visibility of this issue. Such strategies have often focused in the past on material flows at the expense of energy/carbon impacts, an emphasis that is changing with higher energy prices and increased emphasis on climate change impacts.

Some countries, notably China and the USA, are pursuing strategies to address supply risk which are beyond the scope of this report. These include forging political alliances to secure supply and devising competition policy to discourage monopoly or excessive oligopoly (made difficult by the international nature of the industry). During the Cold War, researchers recommended the USA forms cartels to protect the supplies of strategic materials such as manganese, cobalt, chromium and platinum group metals. These materials are critical for US military and economic security and are mainly found in countries such as the Soviet Union and apartheid South Africa which were considered 'unfriendly' at the time [c2].

A set of generic strategies on resource efficiency can be proposed that mirror those suggested for managing material flows by Berkhout[d2] and Bringezu[e2].

4.1 Substitutes

The use of substitutes is likely to be a longer-term solution to material security as finding replacements can sometimes take years. However, an increasing number of cases do exist – particularly when prices of the substituted material increase rapidly. Palladium, for example, is increasingly being used by automotive manufacturers as a substitute for platinum in catalytic converters, but technological limitations constrain light duty diesel cars and trucks (a growing market in Europe) to using platinum-only or platinum-rich catalytic converters. No more a third of the platinum in an individual catalyst can be displaced by palladium in diesel vehicles[f2]. In any case, substitution with palladium might not be the best solution in the long run since palladium is itself among the world's most insecure materials according to Table 2.

A more sustainable strategy is to substitute an insecure material with a significantly more available one. As far back as the 1980s, the US military was able to replace cobalt with a nickel-aluminium-molybdenum alloy in the engines of its F-15/16 jet fighters [g2].

Coming up to the present day, nanotechnology may now play an important role in facilitating substitution of rare materials with less insecure ones. One example is the development of alternatives to indium tin oxide, the transparent electrode commonly used in LCD televisions. Indium has similar properties to aluminium, but is far rarer, and prices have increased eight-fold in the last five years following the boom in popularity of flat-screen televisions. Some geologists have predicted that indium supplies could be exhausted in just four years. Researchers at the Tokyo Institute of Technology have modified aluminium oxide – far more common than indium – at the nano-level to allow it to conduct electricity. When sliced into thin membranes, the modified alumina cement becomes transparent and so can substitute for indium.

4.2 Minimisation of material use

With a view to minimising the use of insecure materials, UK-based Oxford Catalysts is currently developing new catalysts for industrial applications such as Fischer-Tropsch (Figure 12). Until now, the cobalt-carbide catalysts used in these processes required platinum, ruthenium or rhenium promoters to function effectively. The adapted catalysts work without these promoters.

Figure 12. A new hydrodesulfurisation catalyst functioning without platinum group metal promoters

Source: Photo courtesy of Oxford Catalysts

Partially supported by the Carbon Trust, Oxford Catalysts is also working on a new cobalt-based catalyst for small scale reforming applications such as hydrogen extraction from natural gas (Figure 13). Again, one aim is to remove the need for a platinum promoter. The hydrogen produced might power fuel cells for domestic use.

Figure 13. Spider high throughput screening reactors used to speed up catalyst development

Source: Photo courtesy of Amtec GMbh and Oxford Catalysts

Car manufacturers are becoming more thrifty in their use of platinum in catalytic converters, although, as mentioned above a lower limit exists on minimisation of material usage, especially in diesel vehicles.

4.3 Closing substance loops

Initiatives to close substance loops for rare materials are numerous. Catalytic converters in automobiles again provide a good example since a long history now exists of successful extraction of platinum and PGMs from these. Chromium has also long been recovered from steel-making, industrial and chemical waste. As mentioned in Case Study 5, some companies are working on recycling the cobalt from used lithium-ion batteries, while others are looking to extract neodymium from scrap magnets. Neodymium is a rare earth metal and is used in powerful permanent magnets so is increasingly found in energy-saving applications such as in the Toyota Prius. With the world's supplies of rare earth metals largely controlled by a single country (China), incentives are growing to recycle these magnets. One approach taken by Japanese scientists is to use molten metals to extract neodymium, however, somewhat paradoxically, silver (the sixth most insecure element according to Table 2) is one that has been championed for this purpose[h2].

The use of ruthenium as an alloying element in the latest generation of high temperature superalloys for aeroengines means that the scrap value of such engines at end of life will be increased, so long as the alloy can be identified. Such long term identification may be required in order to close substance loops and produce more of the superalloy, assuming that the composition remains similar in the new engines being produced when the current generation is reaching the end of their lives.

4.4 Minimisation of dispersal of residuals into the environment

The copper case study has already illustrated that the prevention of the rarer metals dispersing back into the environment is important in reducing environmental impact and ultimately conserving resources.

Legislation such as the WEEE Directive will assist in collecting electronic items which contain formerly uneconomic amounts of metal and ensure that these are recycled. Once collection is assured, other technological developments may also become economic to recover small proportions of other relatively high value materials such as liquid crystals[i2].

Where dispersal of residuals has taken place, their re-concentration through waste management activities may result in commercial opportunities. For example, the concentration of PGMs in roadsweepings from city centres has been monitored to see if the concentrations arising from autocatalysts will become sufficiently high to allow commercial refining[j2].

The "mining" of landfill sites has sometimes been predicted as a future activity. Although this cannot be ruled out and no detailed economic analysis has been carried out, this seems unlikely in mixed landfill unless the prices of common metals increase substantially still further. However, where more concentrated industrial wastes exist, this process is well established, for example with metal slags and dusts.

Strategies for minimisation of dispersal need to take a whole life-cycle approach and factor in the environmental impacts of the collection and reprocessing steps. This may lead to the approaches that possess higher levels of resource efficiency, such as re-use and remanufacture.

4.5 The environmental paradox

The imperative to achieve more sustainable consumption of resources is having unexpected repercussions in the area of material security. A surprisingly large number of new 'environmentally-friendly' technologies now rely on materials for which demand was previously low.

Frequently, the materials in demand are rare in the earth's crust or concentrated in regions subject to political instability. The most obvious example is the large increase in demand for platinum group metals (PGMs) in catalytic converters in response to tightening worldwide vehicle emissions standards. PGM catalysts are also used to produce fuel cells and low-sulphur petroleum. Demand for such catalysts is only likely to heighten as oil deposits become increasingly sulphur-rich, and legislation demands ever 'cleaner' fuel.

Other examples of 'green technologies' relying on insecure materials include:

- Solar cells which use tellurium and indium
- Rechargeable lithium ion car batteries, as used in hybrid cars such as the Toyota Prius, which depend on cobalt (see Case Study 5)
- The energy-efficient car magnets, again in the Prius among others, made from neodymium

Hence a paradox exists that greater environmental performance or efficiency is often achieved through the use of materials with greater environmental impacts and with less material security. The paradox may be substantially avoided by developing new material processing techniques that give more secure or common materials exceptional performance characteristics. Such strategies are evident in many nanotechnological solutions currently being developed. The paradox may also be successfully managed by the application of life-cycle assessment tools, provided that the system boundaries are chosen wisely.

Whichever approach is taken, a key strategy agreed by commentators on material security is that the cost of sourcing metals and minerals should more closely reflect impacts on the global environment and climate change.

Case Study 5: COBALT

Oxides and silicates of cobalt, originally found in silver mines, have been used to colour ceramics for almost 3,000 years. The metal itself was only isolated in the 18th century. A major application of the metal is in superalloys used in aircraft and electrical generation turbines as well as 'Alnico' (Aluminium-Nickel-Cobalt) magnets.

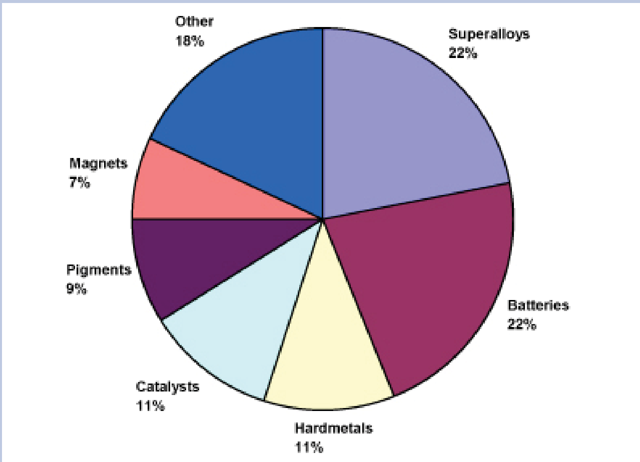
Figure CS5.1 A broken cathode containing cobalt

Source: Cobalt Development Institute

Cobalt is also increasingly employed in catalysts and powerful lithium-ion (LiMH) batteries used in electric or hybrid cars. The Toyota Prius hybrid car requires about 2.5kg of cobalt. Currently around 9,000 tonnes of cobalt are used each year to make some 1.4 billion cells. According to the Cobalt Development Institute (CDI), such specialist chemical applications accounted for over half the world's consumption of the metal in 2006. An 80% increase in Asian (especially Chinese) demand for cobalt has been seen since 2002, while European and USA demand has remained constant over the same period.

In 2006, cobalt demand stood at 55,000 tonnes, and is expected to continue rising at around 3% leading to some pressure on supplies and rising prices. In September 2007, cobalt rose to an 11 year high of \$70/kg. Scope exists to recover cobalt from used batteries. For example, Umicore, a leading recycler of precious metals recently developed a process by which cobalt is converted into lithium cobaltite used in new lithium-ion batteries. Umicore expects more stringent legislation will lead to increased recovery of cobalt.

Figure CS5.2 Current uses for cobalt



Source: Cobalt Development Institute

Cobalt is primarily a secondary product and heavily dependent on new production of copper and nickel units. Historically, cobalt has mainly been sourced in central Africa, particularly the Democratic Republic of Congo (DRC) and Zambia. However, chronic political unrest in the region has limited supplies in the past. For example, the 1976 civil war in Angola halted the production of cobalt from Zaire (the former name for the DRC) which at the time was responsible for 63% of the world's supply. Umicore anticipates that a stabler DRC together with more professional production will dramatically increase supplies; significant reserves of cobalt remain exploited in DRC, for example, at the Tenke Fungurume deposit. Increased production of cobalt as a by-product of nickel extraction is also predicted with more of the metal expected to come from Australia, Canada, Cuba and East Asia.

The CDI estimates world cobalt resources at about 15 million tonnes. The vast majority of these resources are in nickel-bearing laterite deposits, with most of the rest occurring in nickel-copper sulfide deposits hosted in mafic and ultramafic rocks in Canada, and Russia, and in the sedimentary copper deposits of the DRC and Zambia. In addition, millions of tonnes of hypothetical and speculative cobalt resources exist in manganese nodules and crusts on the ocean floor. CDI believes sufficient land and sea sources of cobalt exist for another 300 years albeit with some short-term market volatility as the new nickel-ore based supplies come on-stream.

Figure CS5.3 Cobalt-containing alloys used in hardening a saw

Source: Umicore

5 Conclusions

Material security is more than material scarcity, although it involves the latter. Military security is a given concern, but key economic sectors as well have legitimate concerns over long-term material availability.

Although reductions in demand are possible due to economic downturn, it does seem likely that new, substantial and sustainably higher levels of demand for metals are being experienced primarily due to economic growth in Asia.

The market mechanism cannot necessarily be relied upon to deliver solutions within the timescale required and is certainly failing to incorporate environmental and climate change concerns.

Using a typology developed by Graedel, and using public information we have rated elements and minerals according to a number of "material risk" or "supply risk" characteristics. Allowing for incomplete data, key "insecure" metals include gold, rhodium, platinum, strontium, silver, antimony and tin. Mercury has been discounted due to its declining importance resulting from continuous efforts at material substitution over many years due to its toxicity.

5.1 Recommendations for policy makers

- Incorporation of the social costs of environmental impact into the costs of mining and metal production companies
- Assistance with environmental and social regulation of industries in developing countries
- Adopt policies that encourage aggregation rather than dispersal to the environment of insecure materials, whilst taking into account whole system environmental impacts
- Maximising recycling and recovery rates with metals that show greatest environmental benefit

5.2 Recommendations for business

- Promotion of products mined and produced using green strategies
- Voluntary codes and agreements to incorporate environmental externalities
- Products should be designed to discourage dispersal to the environment and easier recovery
- Adopt Life-Cycle Management policies

5.3 Recommendations for innovation funders

- Encourage projects that develop substitutes for the least secure metals
- Take account of displacement effects when funding "green" technologies that use insecure materials
- Technologies such as nanotechnology that are potentially able to transform common materials as substitutes for insecure materials may be especially worthy of note for this reason
- Technologies to enable "mining" of waste streams for insecure metals are especially worthy of consideration
- Stimulate sustainable design approaches that consider the overall life-cycle issues rather than one specific component (energy consumption during use)

Appendix 1
Material security spreadsheet

Introduction and methodology

An Excel spreadsheet was used as a basic tool to rank 69 materials in terms of the likely risk to their security. The ranking system was based on eight different criteria scored between 1 and 3.

- Material risk' criteria:
  - global consumption levels (A)
  - lack of substitutability (B)
  - global warming potential (C)
  - total material requirement (D)
  - 'supply risk' criteria:
  - scarcity (E)
  - monopoly supply (F)
  - political instability in key supplying regions (G)
  - vulnerability to the effects of climate change in key supplying regions (H)

A score of 1 indicates that severity of the criterion in question was deemed "Low", while a score of 3 meant the criterion severity was considered "High". Scores of 1, 2 and 3 were colour-coded yellow, orange and red, respectively. The scores for each criterion are then totalled to give an overall material insecurity index (MII): the larger the MII, the more insecure are supplies of that particular material.

The rationale behind each criterion is now detailed in turn:

A Global Consumption Levels

Figure A2 provides data on total yearly consumption for some materials. These indicate how dependent national or global economies are on the future availability of the material.

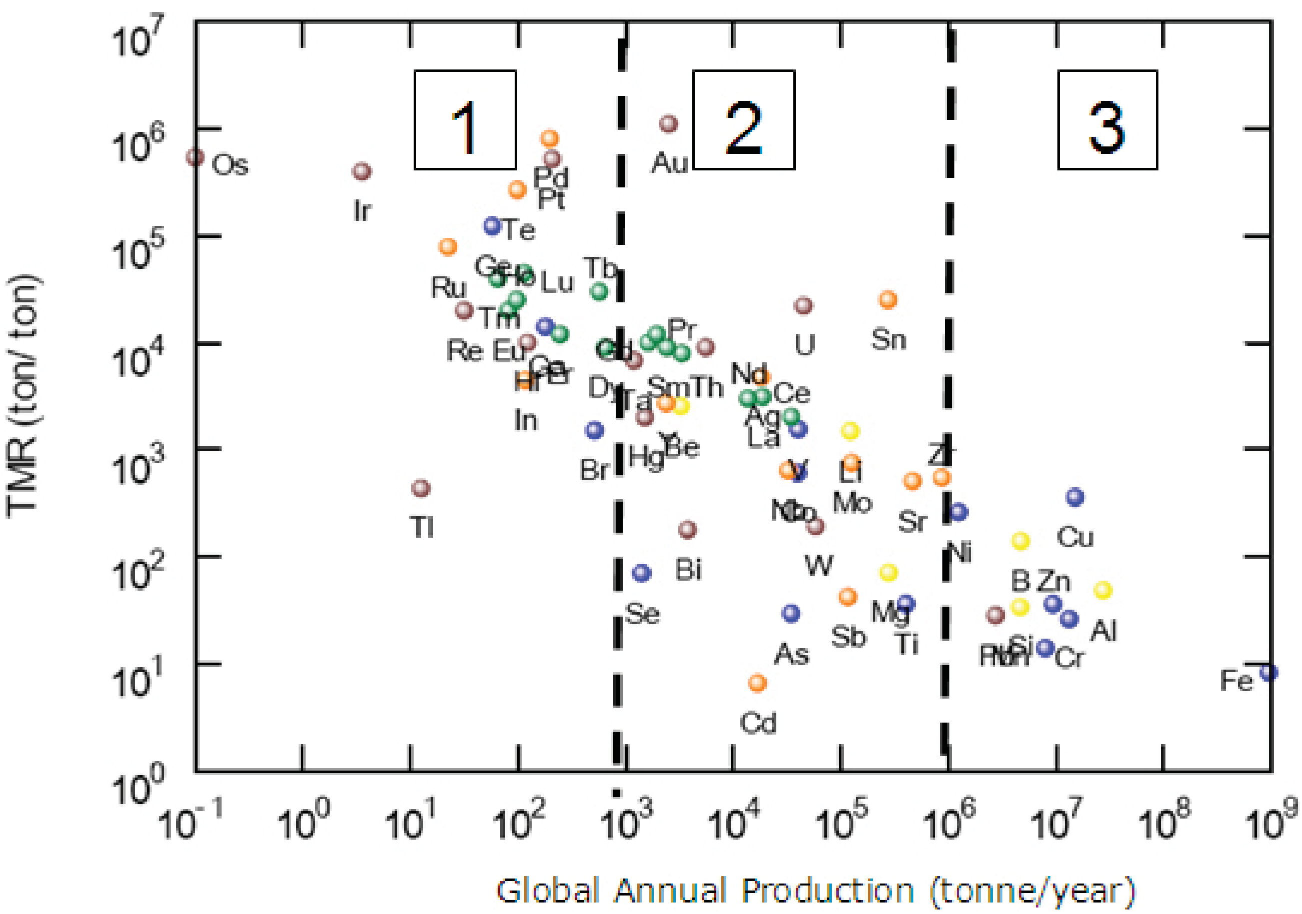
These consumption data are used in the Material Security Spreadsheet as follows:

Global Annual Consumption Scoring:

1 (Low)	= less than 1,000 tonnes/yr
2 (Medium)	= between 1,000 and 1,000,000 tonnes/yr
3 (High)	= more than 1,000,000 tonnes/yr

If data are not available for a particular material a score of 2 was given.

Figure A2: The total material requirements for extracting a range of minerals, with scoring system



Source: Halada (2007) Resources, energy security and climate change and climate change. Powerpoint Presentation

B Lack of Substitutability

The less readily a material can be substituted by another, the more vulnerable economies are due to future lack of supply. Copper, a relatively rare metal, can and has been substituted by aluminium, a more common element, in certain applications. On the other hand, replacements for magnesium used to harden steel are less readily available.

In the Material Security Spreadsheet a score is given for substitutability for each material, with 1 indicating high substitutability, and 3 low substitutability. The scoring is based on various sources. Where data are not available for a particular material a score of 2 was given.

Environmental factors impact on the future security of materials. International and national laws curbing greenhouse gas emissions may come to restrict the more carbon-intensive extraction processes required for a range of minerals.

Two proxies for environmental impacts are used in the spreadsheet:

- Global Warming Potential (GWP)
- Total Material Requirement (TMR)

C Global Warming Potential (GWP)

GWP over a 100 year scenario in terms of kgCO2 equivalents generated per kilogramme of material extracted is obtained from the ecoinvent database. The GWP varies enormously among minerals. For example, according to a detailed life-cycle inventory analysis (LCIA) published on 'ecoinvent', the mining and beneficiation steps for extracting a kilogramme of platinum releases almost 15 tonnes of CO2 equivalents, while extracting the same weight of aluminium from a bauxite mine generates just 8 grammes.

The GWP100a is translated into scores in the Material Security Spreadsheet as follows:

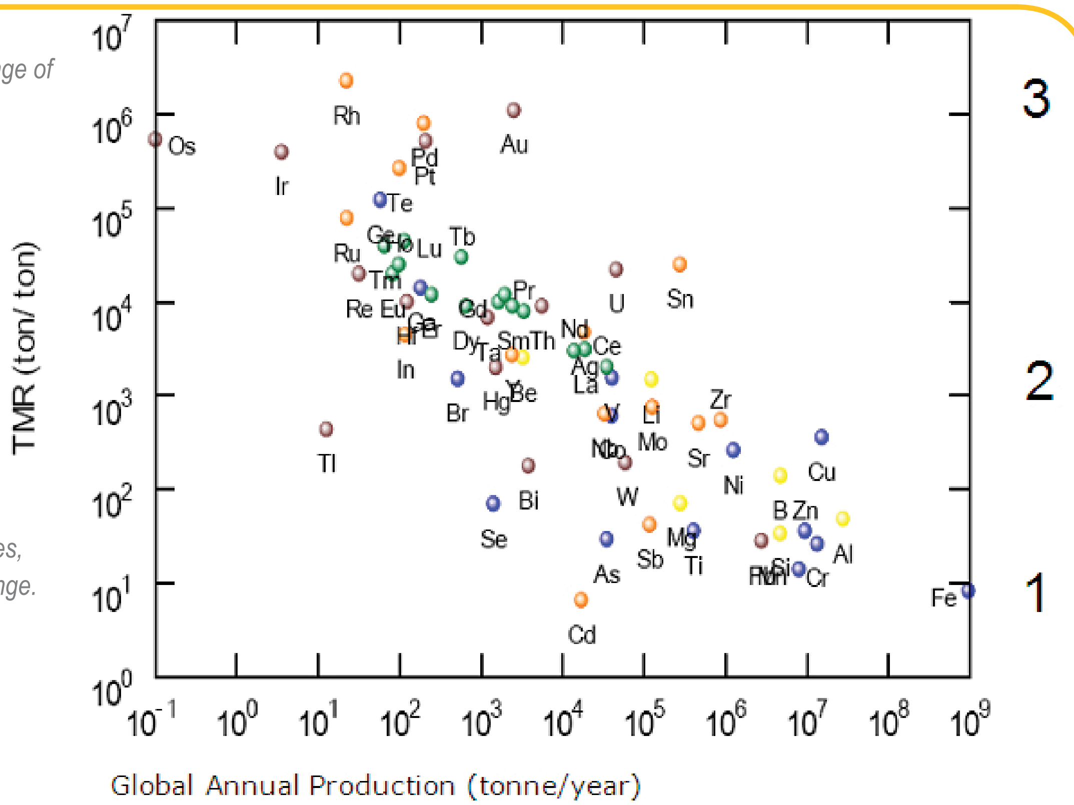
1 (Low)	= less than 1 kgCO2 (e) per kg material extracted
2 (Medium)	= between 1 and 100 kgCO2 (e) per kg material extracted
3 High)	= more than 100 kgCO2 (e) per kg material extracted

If data were not available for a particular material a score of 2 was given.

D Total Material Requirement (TMR)

The total weight of rocks and other substrate which need to be mined in order to obtain a given weight of metal or other mineral also gives a crude indication of environmental impact. Figure A5 indicates the total material requirement (TMR) for a range of minerals.

Figure A5: The total material requirements for extracting a range of minerals, with scoring system



Source: Halada (2007) Resources, energy security and climate change. Powerpoint Presentation

The TMR is translated into scores in the Material Security Spreadsheet as follows:

1 (Low) = less than 100 tonnes/tonne mineral
2 (Medium) = between 100 and 10,000 tonnes/tonne mineral
3 (High) = more than 10,000 tonnes/tonne mineral

If data were not available for a particular material a score of 2 was given.

E Scarcity

The physical scarcity of a material will also clearly impact on its overall security, but determining scarcity is notoriously difficult.

Kohmei Halada of Japan's National Institute for Material Science has recently presented predictions for which metals will exceed their reserves and, in some cases, their reserve bases by 2050 (Figure A1). For example, aluminium consumption is not expected to impact on reserves by 2050. Conversely, Halada predicts that silver will overrun its reserve base by a considerable amount in the same time span. We have previously concluded that such projections are likely to be overly pessimistic, and therefore data on material scarcity is judged to be of only secondary importance.

Halada's scarcity predictions are scored as follows in the Material Security Spreadsheet:

1 (Low) = not predicted to reach reserves by 2050
2 (Medium) = predicted to overrun reserves by 2050
3 (High) = predicted to overrun reserve base by 2050

If data was not available for a particular material a score of 2 was given.

F Monopoly Supply

When the world's production of a particular material is concentrated in just one or two countries this can result in vulnerability of future supply. For example around 80% of the world's platinum is currently sourced in South Africa. Kogel et al.'s Industrial Minerals & Rocks presents data on minerals where more than 20% of the world's supply is concentrated in a single country. Data on supply concentration are also sometimes available from Wikipedia. These two sources were used to allocate to each material:

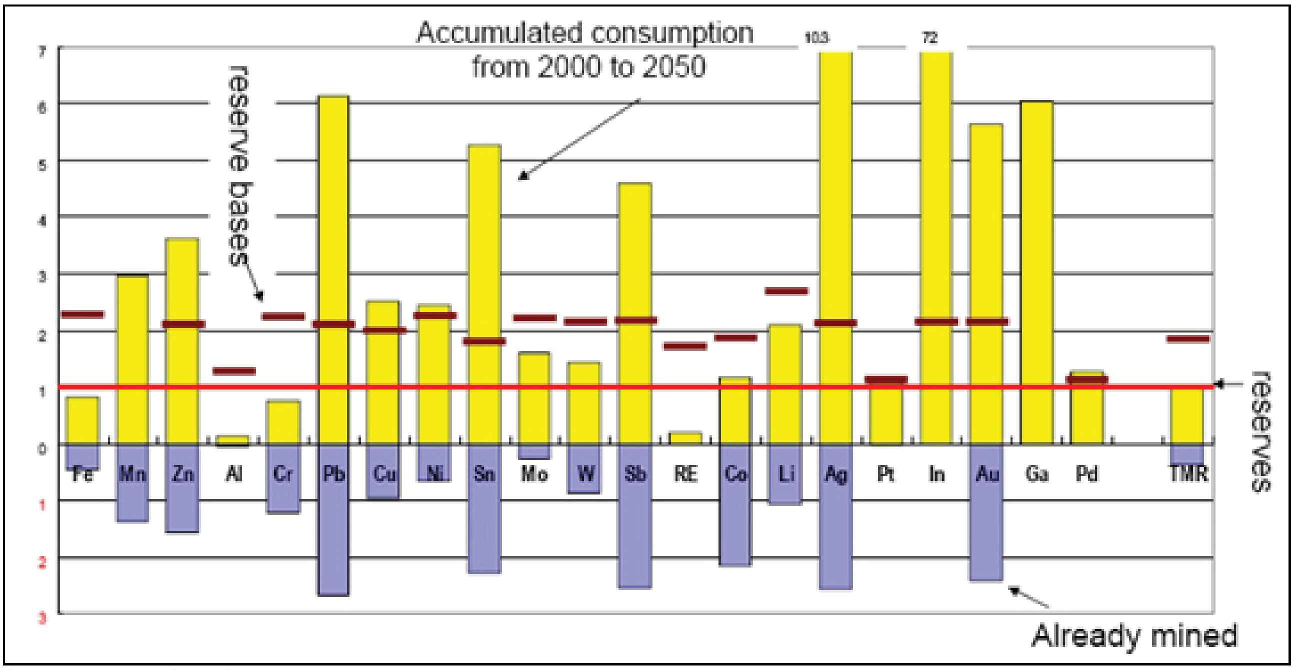
- The major supplying country
- The percentage of world supply for which that country is responsible

These percentage concentration data were scored for each material as follows in the Material Security Spreadsheet:

1 (Low) = Concentration less than 33.3% in any one country
2 (Medium) = Concentration between 33.3% - 66.6% in any one country
3 (High) = Concentration greater than 66.6% in any one country

If country data were not available for a particular material a score of 2 was given.

Figure A1: Predicted consumption patterns for 21 metal elements for 2050, with scoring system



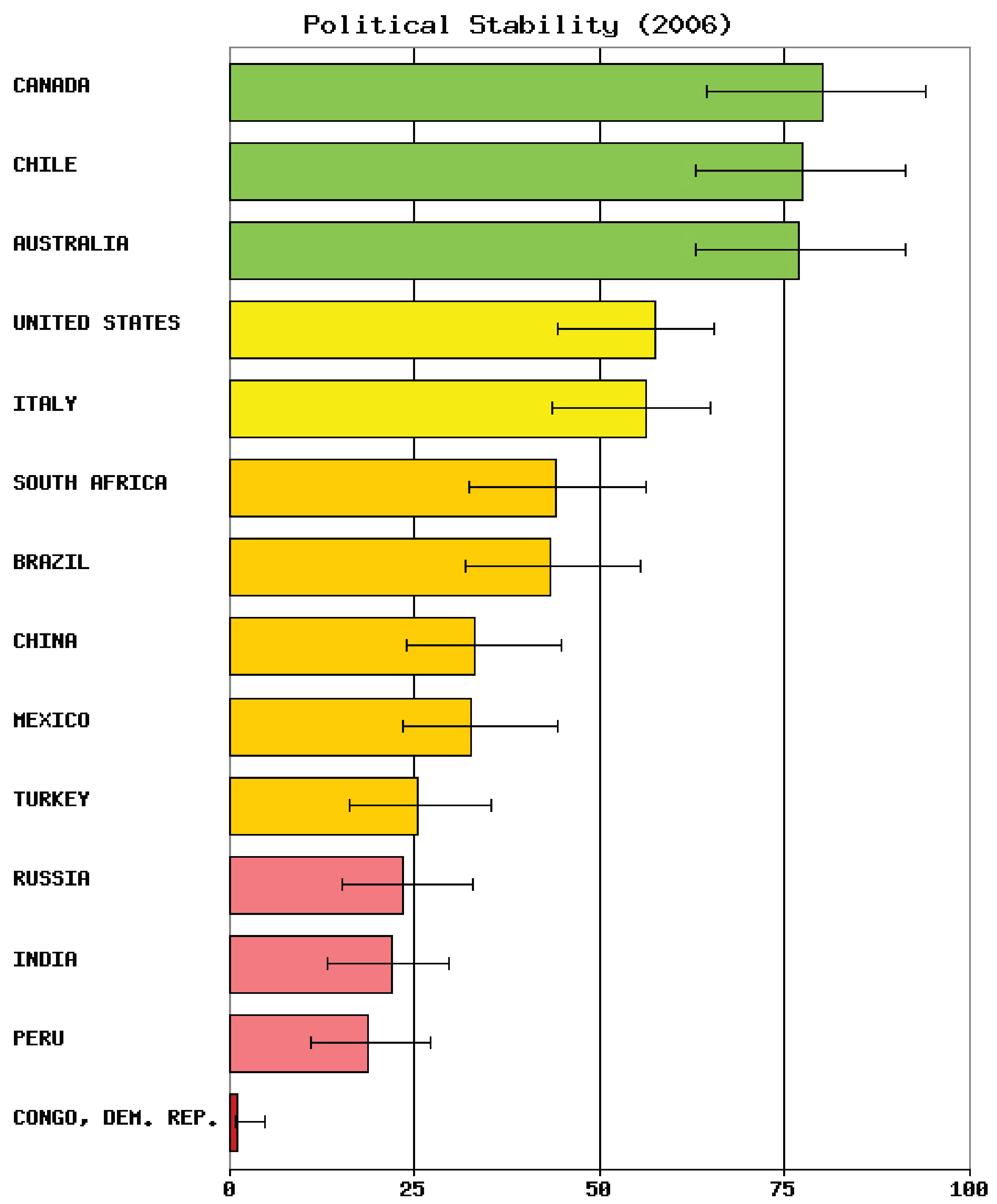
Source: Halada (2007) Resources, energy security and climate change. Powerpoint Presentation

G Political Instability

The governance of a country, particularly its political stability, where materials are sourced, arguably, impact on material security. Supplies can be interrupted by wars, famines, and other unrest. Allocating a (crude) political stability score to each material is possible, using the major country of production data collected from Kogel et al. and Wikipedia.

Political stability information was obtained from the World Bank's Governance Indicator's website[k2]. The website provides percentile rank data for 212 different countries and territories on various criteria including "Political Stability and absence of Violence/Terrorism". Other criteria available but not used in the current study include "Voice and Accountability", "Government Effectiveness", "Regulatory Quality", "Rule of Law" and "Control of Corruption". Figure A3 presents Political Stability data for fourteen countries where supplies of particular materials are concentrated.

Fig. A3: Political stability of countries where material production is concentrated, with scoring system



Source: http://info.worldbank.org/governance/wgi2007/sc_country.asp

In the Material Security Spreadsheet, these political stability data were scored for each material as follows:

1 (Low)	= Political Stability Percentile greater than 66.6%
2 (Medium)	= Political Stability Percentile between 33.3% - 66.6%
3 (High)	= Political Stability Percentile less than 33.3%

If country data were not available for a particular material a score of 2 was given.

So, for example, the Democratic Republic of Congo (currently supplying 40% of the world's cobalt) – has a percentile rank of just 1.0 and is scored 3, while Canada with a percentile rank of 80.3 scores 1.

H Climate Change Vulnerability

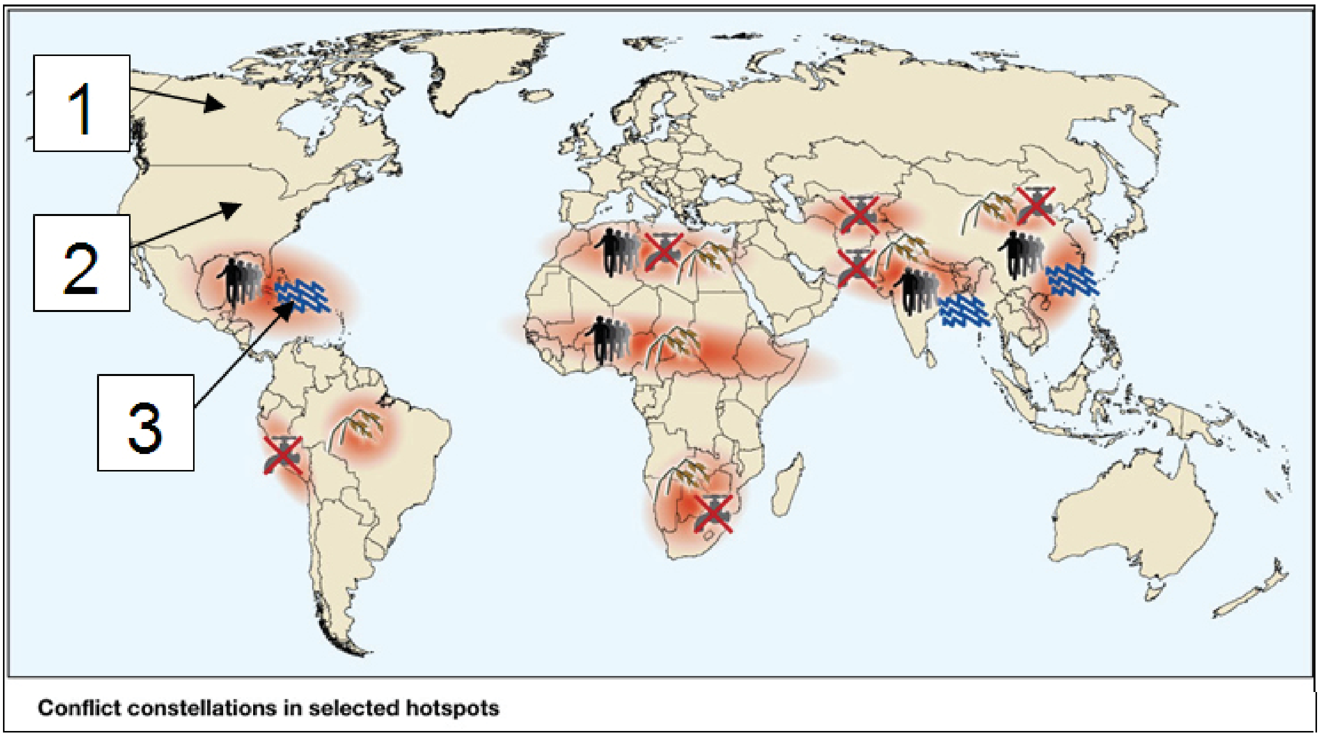
Some regions are predicted to be more vulnerable to the effects of climate change than others. This vulnerability can also be used as a measure of future material insecurity. WBGU, the German Advisory Council on Climate Change, recently published a map predicting parts of the world likely to suffer disproportionate consequences of climate change (Figure A4).

In the Material Security Spreadsheet, these hotspots were very crudely translated into Climate Change Vulnerability scores dependent on the promixity to the hot spots as shown in Fig 5. If country data were not available for a particular material a score of 2 was given.

A note on weighting and interdependence

In practice, the eight criteria discussed above are not independent of each other. For example, the significance of a country's political stability (Criterion F) or its vulnerability to climate change (Criterion G) is more important when monopoly supply of materials (Criterion E) is high for that country. An argument exists therefore for taking this into account and weighting criteria accordingly. However, the crude nature of the current approach, based on limited data does not warrant this level of detail. Future, more in-depth, work should address the issue of interdependence.

Figure A4: Security risks associated with climate change: Selected hotspots



Used with permission. German Advisory Council on Global Change WBGU (2007): Climate Change as a Security Risk

Results and conclusion

Table 5 ranks 69 materials in order of decreasing Material Insecurity Index (MII) based on an analysis of nine criteria affecting material security. Since the analysis is necessarily crude and based on limited data, drawing too many firm conclusions from the spreadsheet is inadvisable.

Table 5 – Material Security Criteria and Index for 69 materials

Material	Symbol	Overal Material Insecurity	Material Risk				Supply Risk			
			A - Global Consumption	B - Substitutability	C - GWP	D - TMR	E - Scarcity	F - Monopoly Supply	G - Political Stability	H - CC Vulnerability
Gold	Au	21	2	2	3	3	3	2	3	3
Rhodium	Rh	20	1	3	3	3	2	3	2	3
Mercury	Hg	20	2	2	3	2	2	3	3	3
Platinum	Pt	20	1	2	3	3	3	3	2	3
Strontium	Sr	19	2	3	2	2	2	2	3	3
Silver	Ag	19	2	2	3	2	3	1	3	3
Antimony	Sb	19	2	2	2	1	3	3	3	3
Tin	Sn	19	2	3	2	2	3	1	3	3
Magnesium	Mg	18	2	3	2	1	2	2	3	3
Tungsten	W	18	2	2	2	2	2	2	3	3
Baryte	$BaSO_4$	18	2	2	2	2	2	2	3	3
Talc	$H_2Mg_3(SiO_3)_4$	18	2	2	2	2	2	2	3	3
Bismuth	Bi	18	2	2	2	2	2	2	3	3
Palladium	Pd	18	1	2	3	3	3	2	3	1
Nickel	Ni	18	3	2	2	2	3	2	3	1
Boron	B	18	3	2	2	1	2	3	3	2
Andalusite	Al_2SiO_5	18	2	2	2	2	2	3	2	3
Molybdenum	Mo	17	2	3	2	2	2	2	2	2
Zinc	Zn	17	3	2	1	1	3	1	3	3
Holmium	Ho	17	1	2	2	2	2	2	3	3
Terbium	Tb	17	1	2	2	2	2	2	3	3
Fluorspar	CaF_2	17	2	2	1	2	2	2	3	3
Arsenic	As	17	2	2	2	1	2	2	3	3
Graphite	C	17	2	2	1	2	2	2	3	3
Ammonia	NH3	17	2	2	2	2	2	1	3	3
Cobalt	Co	17	2	2	2	2	2	2	3	2
Europium	Eu	17	1	2	2	2	2	2	3	3
Gadolinium	Gd	17	1	2	2	2	2	2	3	3
Osmium	Os	17	1	2	2	3	2	2	3	2
Borate	$B(OR)_3$	17	3	2	2	2	2	1	3	2
Niobium	Nb	17	2	2	2	2	2	2	2	3
Kyanite	Var	17	2	2	2	2	2	3	2	2
Beryllium	Be	17	2	2	2	2	2	3	2	2
Ruthenium	Ru	16	1	3	2	2	2	2	3	1
Germanium	Ge	16	1	3	2	2	2	2	2	2
Chromium	Cr	16	2	3	2	1	1	2	2	3
Diamonds	C	16	2	2	2	2	2	1	3	2
Asbestos	Var.	16	2	2	2	2	2	2	3	1
Vanadium	V	16	2	2	2	2	2	2	2	2
Barium	Ba	16	2	2	2	2	2	2	2	2
Vermiculite	Var	16	2	2	1	2	2	2	2	3
Tellurium	Te	16	1	2	2	3	2	2	2	2
Diatomite	Var	16	2	2	2	2	2	2	2	2
Mica	Var	16	2	2	2	2	2	2	2	2
Lead	Pb	16	2	2	1	2	3	2	2	2
Gallium	Ga	16	1	2	3	2	2	2	2	2
Indium	In	16	2	2	3	2	3	2	1	1
Iodine	I	16	2	2	2	2	2	2	1	3
Copper	Cu	16	3	1	2	2	3	1	1	3
Iron	Fe	15	3	3	1	1	1	2	2	2
Zirconium	Zr	15	2	3	2	2	2	2	1	1
Feldspar	Var	15	2	2	2	2	2	1	2	2
Selenium	Se	15	2	2	2	1	2	2	2	2
Lutetium	Lu	15	1	2	2	2	2	2	2	2
Bromine	Br	15	1	2	2	2	2	2	2	2
Bentonite	Var	15	2	2	1	2	2	2	2	2
Perlite	Var	15	2	2	1	2	2	2	2	2
Soda Ash	Na_2CO_3	15	2	2	2	2	2	1	2	2
Silicon	Si	15	3	2	2	1	2	1	2	2
Rhenium	Re	15	1	2	2	2	2	2	1	3

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