Universiteit
Leiden
The Netherlands

Materials and energy : a story of linkages

Kleijn, E.G.M.

Citation
Kleijn, E. G. M. (2012, September 5). *Materials and energy : a story of linkages*. Retrieved from https://hdl.handle.net/1887/19740

Version:	Not Applicable (or Unknown)
License:	Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden
Downloaded from:	https://hdl.handle.net/1887/19740

Note: To cite this publication please use the final published version (if applicable).

Cover Page

Universiteit Leiden

The handle http://hdl.handle.net/1887/19740 holds various files of this Leiden University dissertation.

Author: Kleijn, René
Title: Materials and energy : a story of linkages
Date: 2012-09-05

Chapter 5
Metal scarcity: imminent threat, eternal problem or red herring ?
The current debate in historical context

Abstract
The commodity price explosion of 2008 and its current reverberations have brought the broader issue of resource scarcity back on the research and policy agendas with an intensity not seen since the 1970s. In the last century, periods of increased attention for this issue were interspersed by periods in which resources were abundant and cheap. In this article the question is addressed if, and if so how, the current perception of metal scarcity is different from periods of relative scarcity in the past. We start by reviewing some of the past and current trends in the demand and supply of metals. Next we critically consider how ongoing technology advance and innovation is likely to influence future supply as well as future demand. That is: will the resource pressure of raw economic growth and the dwindling of high-quality resources be compensated by dematerialization, substitution and recycling? On balance we find the evidence suggests that the current episode of metal scarcity is different from those that occurred in the recent past. The world is at the eve of BRICs and other non-OECD climbing the "material ladder" at a speed and scale not seen before. As the world is about to globalize resource demand to levels of consumerist societies, the world of supply is already fully globalized: there are no geographic frontiers anymore which can be moved to expand. Climate constraints enforces a switch to a sustainable energy system, which, within the next few decades will requires orders of magnitude more of some key metals compared to the current energy system. Linkages between resources like materials, water, land and environmental quality further limit the possibilities for continued exponential growth in mining and refining. In summary, while the nature of the questions about scarcity as a major constraint to development are qualitatively identical to what they always were, the quantitative scale at which it plays out is different - namely global- and the time scale is more compressed - decades rather than centuries which decreases the solution space.

Conditionally accepted by the Journal of Industrial Ecology as: Kleijn R., E. van der Voet, G.J. Kramer. Metal scarcity: imminent threat, eternal problem or red herring ? The current debate in historical context.

5.1 Introduction

Concerns about the supply of basic commodities are as old as humanity itself – from the overhunting of big game by hunter-gatherers in prehistoric times (Burney and Flannery 2005), through the salinization of arable land in ancient Sumer (Tainter 1988), concerns about the availability of fertile land for an ever-growing population in the days of Malthus (Malthus 1798) and the availability of (fuel) wood in 17th and 18th century England (Perlin 2005) to the projections of the Club of Rome in the 1970s (Meadows et al. 1972), the prediction of "peak oil" (Campbell 2006) and the metals boom between 2002 and 2008 (Radetzki et al. 2008). Time after time, however, human ingenuity in the form of technological innovation has solved the problem of scarcity, by replacing one natural resource by another or by expanding the resource base. This is perhaps best exemplified by the two greatest revolutions in human history: the agricultural and the industrial revolutions. Some 10,000 years ago, fertile land and agriculture with domesticated livestock were substituted for wild game, enabling a substantial increase in productivity and thus in population.[1] The industrial revolution created an ample supply of mechanical labour and fertilizers that facilitated the use of marginal lands for crop production and substitution of animal labour, freeing up a substantial amount of cropland[2]. These two substitutions of key resources marked major transitions in the development of human society.

The industrial revolution and the two centuries of essentially continuous progress that followed have installed resource optimism as the gold standard for the outlook of what Erasmus Darwin has called 'the active and energetic' who rule the world. The undeniable fact that on average the conditions of human life have improved spectacularly over this period makes for a societal condition in which the pessimist's voice is somewhat muted in the public debate, having little impact on decision makers. Although resource optimists will generally admit that resource use cannot grow indefinitely, many will argue that continued technological advance will save us from worldwide resource scarcity in the future, as it has reliably done in the past (Radetzki 2008; Gordon 2009; Solow 1974). When push comes to shove, governments, companies and individuals count on technology saving the day … somehow.

Radetzki argues that the economic importance of commodities in general is limited and has decreased over time. The share of the primary sector (agriculture, fishery and mining) has steadily declined through the ages and now accounts for less than 5% in most rich market economies (Radetzki 2008). Economists often explain this as being a consequence of the fact that in the modern world added value increasingly comes from knowledge, innovation and related services, rather than from 'stuff'. However,

[1] This is but one interpretation of the agricultural revolution – essentially the Whig interpretation of history. Another reading of how the agricultural revolution succeeded – of how Cain slew Abel – is also possible, though. It states that farmers simply outbred hunter-gatherers, despite their miserable lifestyle. It was thus not improved quality of life that made the agricultural revolution a success, but the sheer force of numbers(Diamond 1987).

[2] Around 1900 one quarter of all arable land in the US was used to feed horses (Ponting 2007).

some economists have pointed out that the apparent increase in relative importance of the service sector might have a very different cause. Kander argues that this relative shift is simply caused by the fact that the prices of manufacturing goods are falling relative to those of services, which in turn is caused by a more rapid productivity growth in manufacturing (Kander 2005). Moreover, the undeniable physical reality remains that the products of mining and agriculture are the ultimate foundation of our welfare. Ecologists have pointed out that classical economics fails to acknowledge this by mislabeling resource extraction as 'production' and generally failing to acknowledge the economic reality of 'natural capital', being the sum of natural resources and ecosystem services. In short: products as well as services cannot exist without a material basis. That material basis is the foundation of the economic pyramid. While the primary production of commodities is but a small fraction of GDP, the global interconnectivity of the economy and the complexity of material service provision mean that disruptions of supply may be more damaging now than at any time in the past (MacNeill et al. 1991).

In this article we review the historical and current debate on resource scarcity, thereby focusing on metals, for which the empirical evidence of the last century is very much in favour of optimistic resource economists. Despite the fact that the production of most metals has grown exponentially, the prices of most have been falling for decades. With the current metals boom, however, the scarcity debate has once more been triggered. The main question addressed in this article is whether the current episode of apparent metals scarcity is any different from the scarcity episodes society has faced in the past century.

The paper is organized as follows. In Section 5.2 we review the trends in demand for metals. In Section 5.3 we consider the meaning of the term 'reserves', both underground and above ground, while in Section 5.4 we analyze trends in the supply of materials. In Section 5.5 we then discuss two options for resolving possible scarcity issues: substitution and dematerialization. In Section 5.6, finally, we discuss our results and draw some conclusions with regard to metal scarcity.

5.2 Trends in demand for metals

The basic equation of environmental impact analysis is IPAT, impact (I) equals population (P) times affluence (A) times technology (T). In the spirit of this equation, the materials demand 'impact' can be tracked over time in three relevant ways: as ton/year (I), as ton/capita/year (I/P) and as ton/GDP (I/PA=T).

5.2.1 Trends in mineral demand

Figures 5-1 to 5-3 show the corresponding global trends in mine production for iron-ore, aluminium and copper from 1905 to 2010. All trends correspond to exponential growth of mine production although periods of rapid growth are interspersed with periods of stabilisation. In the 1905 -2010 period four phases can be distinguished: the

first half of the 20th Century ending in 1945 at the end of the second World War, which in retrospect were the final days of coal-and-steel-based industrial development; the post-war 'long boom' between 1945 and 1975 when the 'modern economies' of the OECD were built up; the last quarter of the 20th Century that saw the consequences of the oil crisis and recession followed by dematerialised growth of the ' new economy' in the OECD; and finally the first decade of the 21st Century up to the present day during which material demand is driven significantly by the build-up of a modern economy in China and other non-OECD countries.

Iron has been and still is by far the most important metal that is produced (>90% of the total metal production). It was of course the metal that facilitated the industrial revolution as it was the metal from which steam-engines, ships, railroads and trains were built. But it still is the leading indicator for urbanisation and infrastructure development. Both copper and aluminium gained importance after the large scale application of electricity that started in the late 19th. Copper because it is used in the production, transmission, distribution and use of electricity and aluminium because electricity is needed to free it from its ore. After WWII mine production experienced a period of rapid growth which can be linked to the build-up of the OECD economies and the start of the consumer society and growing middle class. When the urbanisation and infrastructure build-up in OECD countries stabilised the oil crisis triggered a period of relatively slow growth. Iron mining stabilised but aluminium and copper mining still increased significantly. For copper this can be linked to further electrification and the production of electric and electronic consumer equipment. Aluminium is also linked to electrification but also to the production of cars, planes, packaging materials, buildings and infrastructure, thereby partly replacing iron and steel. The build-up of infrastructure in emerging economies caused a surge in iron and aluminium demand, with China being the major driving force behind the growth since about 2000. For copper, the demand surge began from 1994 on and the surge was more global in origin, driven by the rise of the computer age and internet in combination with the electrification in non-OECD countries, most notably in Asia. For all three metals the 2008 financial crisis can be recognized as small blip in the exponential increase since 2002. For copper, iron and less so for aluminium, there is a trend of relative decoupling between economic growth and mine production after 1960. Both for iron and aluminium this trend was reversed after 2002.

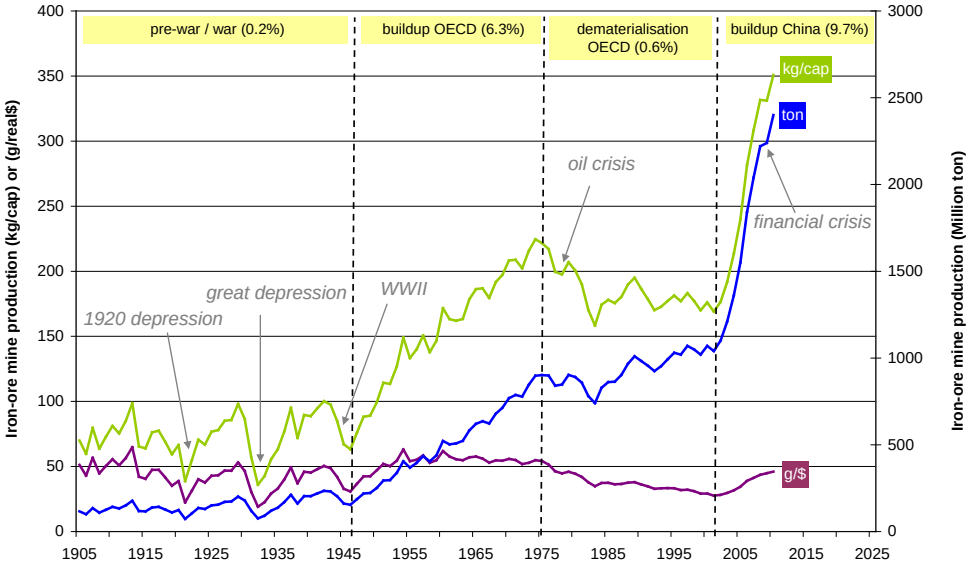

Figure 5-1: Global trends in mine production of iron-ore, 1905-2010. Population and GDP data from Maddison (Maddison 2011) and metal mine production data from USGS (U.S. Geological Survey 2011)

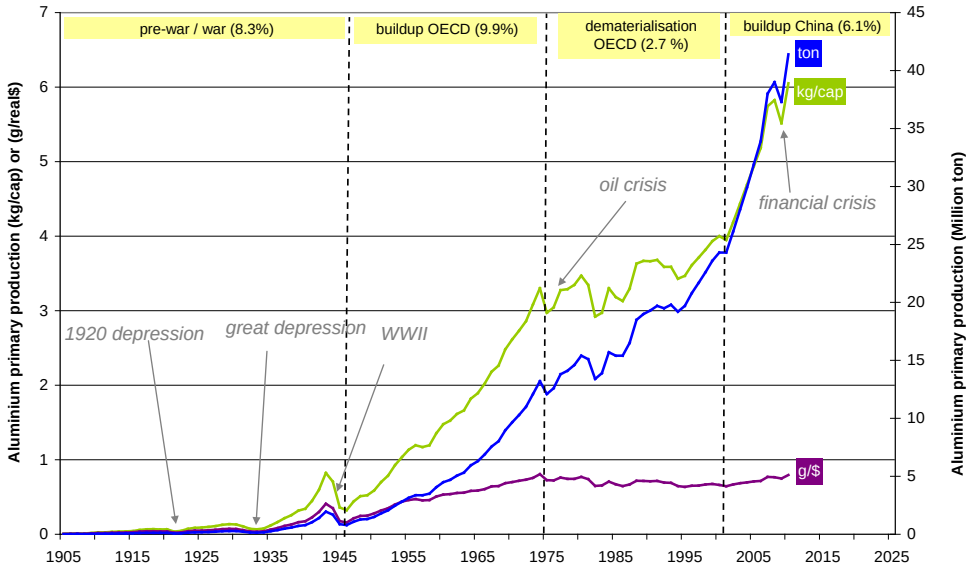

Figure 5-2: Global trends in mine production of aluminium, 1905-2010. Population and GDP data from Maddison (Maddison 2011) and metal mine production data from USGS (U.S. Geological Survey 2011)

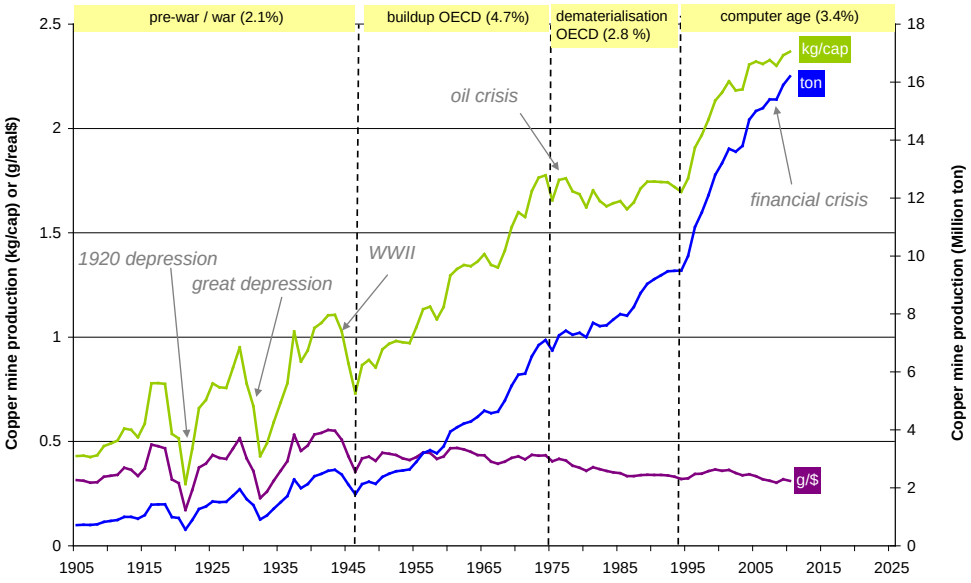

Figure 5-3: Global trends in mine production of copper, 1905-2010. Population and GDP data from Maddison (Maddison 2011) and metal mine production data from USGS (U.S. Geological Survey 2011)

5.2.2 Rapid growth in global material needs for infrastructure

In developed countries, demand for construction materials levelled off after infrastructure had more or less reached completion and metal recycling had become common practice. One key factor underlying the surge in metals demand since the early 2000's has been the very high economic growth of BRIC countries, driving up materials consumptions in particular through urbanisation and the associated booms in house and infrastructure building and industry (Radetzki 2008; Humphreys 2010). This drove the rapid increase of mine production of iron (Figures 5-1 to 5-3) as well as that of its alloying elements like chromium, manganese and molybdenum. In 2009 the world's urban population exceeded the rural population for the first time in human history. If UN projections will turn out to be correct, by 2050 the urban population will almost have doubled from 3.4 billion in 2009 to 6.3 billion in 2050 (UN 2010). This would mean that over the next 40 years we would build the equivalent of all the cities in existence today. In contrast to total world population, the growth in urban population shows little signs of levelling off in that period. Mining companies now expect a period of at least several decades of growth in material demand, with China[3] in the lead, South-East Asia, India and Brazil quickly following and Africa later on (Albanese 2008; Rio Tinto 2011).

[3] A recent study has concluded that the peak in construction for the Beijing area was reached in 2005 and that, without additional policy measures, the need for construction materials would plateau at about 2/3 of the level of 2005 (Hu et al. 2010). Although Beijing, together with Shanghai, indeed seem to have reached levels of saturation for building and construction materials, many other Chinese cities are still in the early stages of development (Rio Tinto 2011).

5.2.3 Trends in the material complexity of products

Electronics are an excellent example of products that have become increasingly complex in terms of material composition and materials that are needed in their production. In the 1970s desktop telephones already contained 42 different elements, including exotic substances like indium, germanium, krypton, lithium and tantalum (Chynoweth 1976). A current desktop computer may contain over 30 elements (Meskers et al. 2009) and a mobile phone over 43 (Hagelüken and Buchert 2008). The number of elements of the periodic table used in the production of a microchip has risen from 12 in 1980s to 16 in the 1990s to over 60 in the 2000s (National Research Council 2008). Furthermore, the number of different electronic products and their widespread use by consumers has grown enormously. With ever greater demands being placed on the functionality of these products, the end of this trend cannot be expected anytime soon.

This trend of increased material complexity of products is not just limited to electronics as such. Although this is due partly to greater use of electronics in products like cars, in this case it also derives from the introduction of airbags, electromotors (for chairs and mirrors, etc), special windscreens and headlights, brake linings and high-alloy engine parts. With the introduction of hybrid cars, plug-in hybrids and full electric vehicles this complexity is set to increase still further, thanks both to the amount of on-board electronics and to the number of special parts like high-performance batteries (Co, Li, La, Ni) and large electromotors (Nd and Dy) (Kleijn and van der Voet 2010).

Even the most commonly used metallic material of all - steel - is becoming an increasingly complex product. Rare earth elements are added to steel to increase its stability at high temperature, while chromium, nickel, molybdenum and manganese are added to improve its resistance to corrosion. That products in general are becoming ever more complex is also illustrated by the fact that humans now dominate the mobilization of 54 of the 90 or so elements that occur naturally on Earth, while accounting for 15-50% of the mobilization of another 12 (Klee and Graedel 2004).

The aggregate effect of how continuous innovation have led to a fuller and richer use of all elements across the whole material economy is shown in Figure 5-4 where we plot the 1970s/2000s ratio of the mine production of elements. In this period population grew by 60% and GDP by 160%. In the past three decades the mine production of some speciality metals has increased at rates even higher than GDP, up to Indium that increased by almost a factor 10 . The reason the mine production of rhenium and indium has grown so fast is that use of these elements is dominated by a single product or technology whose growth exceeds overall GDP growth. Rhenium is used in the nickel-based super-alloys used in turbine blades in aircraft and gas turbine engines, which account for some 70% of rhenium use (U.S. Geological Survey 2010). This allows for an increase in operating temperature, which in turn leads to higher efficiencies. Rhenium is extracted from the flue gases produced during production of molybdenum, which in turn is a by-product of copper production. Around 80% of

indium is used in the production of indium tin oxide (ITO), which is used mainly in flat-panel displays (Harrower 2006). For lithium and cobalt the situation is different: although these metals are used in the rechargeable Li-ion batteries applied widely in mobile electronic devices like laptops, this is still a minor use of both metals. Only 23% of the lithium produced is used in batteries; the main other applications are ceramics and glass and lubricating greases (U.S. Geological Survey 2010). Batteries account for 25% of cobalt use; the main other applications are (super-)alloys, pigments and catalysts (British Geological Survey 2009) The world finds itself at a point where demand for certain rare elements becomes dominated by its application in one or two very specific high-tech applications, where substitution may be difficult and where primary production rates may not be independently set.

Because the material complexity of common products increases, an increasing number of important technologies and products will become vulnerable to supply constraints of small amounts of minor metals, thereby increasing the potential impacts of scarcity. Another problem is that recycling of basic metals becomes more difficult through mixing of metals (in alloys and in products) that are not mixed in the ores from which they are extracted, thereby complicating the closing of material loops. Another complicating factor for closing the material loop is the fact that the use of trace amounts of metals in e.g. electronic equipment will hamper the recycling of these metals.

To the extent that innovation has always been mankind's saviour, making scarcity elusive by always moving it out into the future, to the next generation, it has been observed that ongoing innovation generally leads to increasing complexity in society at large[4]. In the realm of materials we have seen that where in the past a limited number of elements were essential, today virtually all the elements of the periodic table fulfil one essential role or another. If the last 50 years have seen disproportional growth of the use of 'the rest of the periodic table' to keep mankind moving onwards and upwards, the question is: what material innovations will sustain growth over the next century? Will these come from better access to the remaining resources of scarce elements, or will we seek (and find?) replacements through innovative materials made from abundant elements such as carbon?

[4] Increasing complexity is central to the thesis of Tainter as to why complex societies collapse (Tainter 1988).

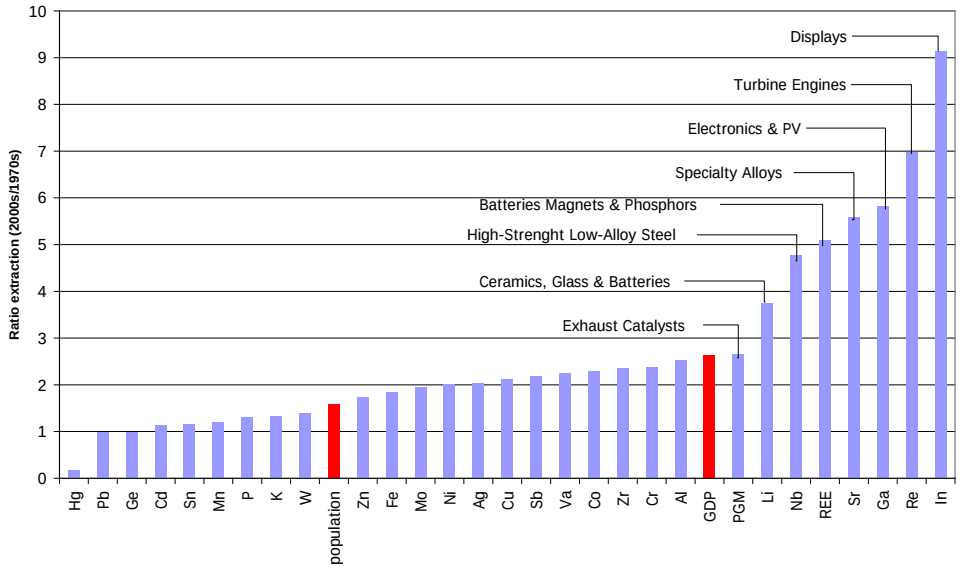

Figure 5-4: Ratio of global mineral mine production (2000-2009 / 1970-1979). GDP and population data from Maddison (Maddison 2011) and metal mine production data from USGS (U.S. Geological Survey 2010). Main applications are given for elements for which the mine production grew faster than GDP. (GDP=Gross Domestic Production; PGM= Platinum Group Metals ; REE= Rare Earth Elements)

5.2.4 The material needs of the energy transition

If the issue of climate change is to be brought under control, global greenhouse gas emissions need to be reduced by 50% to 80% compared to current levels (Metz et al. 2007). This can only be achieved through a high-speed transition to a low-carbon energy system. Most low-carbon energy technologies like CCS, wind turbines and PV solar cells require more materials with a more varied elementary composition than current fossil fuel-based technologies(Kleijn et al. 2011). The sheer size of the energy system implies that the amount of metals needed is also large in absolute terms. In the case of nickel, for example, replacing the current power generation system by non-fossil alternatives would require a fivefold increase in global annual mine production (Kleijn et al. 2011). If a world based solely on non-fossil energy were to be realized by 2050, construction of a worldwide transmission grid by 2050 to make use of the high intensity of solar radiation in desert areas would require 70 times the current annual mine production of virgin copper, equivalent to 90% of the reserve base(Kleijn and van der Voet 2010). In such a scenario increased copper prices would lead to increased substitution. It could be necessary to choose for technically suboptimal solutions like replacing copper by aluminium as a conductor in .

In that same scenario the use of neodymium in direct-drive wind turbines and hybrid and full electric cars would require 400 times current annual output (Kleijn and van der Voet 2010). Similar calculations can be made for the lithium, cobalt and lanthanum used in batteries for hybrid and full electric vehicles (Andersson and Råde 2001; Kleijn and van der Voet 2010; Haakman 2008) and the tellurium, indium,

germanium and gallium used in thin-film PV cells (Wadia et al. 2009; Kleijn and van der Voet 2010).

Furthermore, rare metals like rhenium and rare earth elements (REE) are used to increase the efficiency of fossil fuel-based technologies like jet engines and turbines. For many of these materials this means that levels of mine production and refining will need to be several times what they are today. Since the start-up of large new mines and refineries has a lead time of 5 to 10 years, this may slow down a transition to a low-carbon energy system.

It is important to note that for many of the advanced energy technologies requiring scarce metals there are alternatives available that do not require such materials. For example, wind turbines, including those using direct-drive technologies, can be made without permanent magnets with little loss of functionality but probably at a cost of higher levels of maintenance (Bergen et al. 2011; Jacobson and Delucchi 2011). PV solar cells, including those based on thin-film technology, can be made from abundant materials. However, these technologies still only exist in the lab and the efficiencies are much lower than those of commercial cells and thus also need a relatively large surface area (Wadia et al. 2009); electro motors for electric vehicles can be made without the use of REE-containing magnets, by replacing them by non-REE magnets or by using electromagnets be it a cost increased size and weight (Hitachi 2010; Jacobson and Delucchi 2011); and batteries for these cars can be made without the use of rare earth elements and without cobalt although these technologies are not yet operational (Haakman 2008). Scarcity-induced substitution of rare elements by common elements – if it were to occur – would generally act as a break on market development. After all, innovators have come up with the complex material solutions because they offered advantages. Having to step back from these because of availability issues will in general decrease their competitiveness with incumbent technology.

5.2.5 Implications for future metals demand

In summary, the megatrends that we identified as drivers of materials demand in the decades ahead are (i) the 'globalization of affluence', resulting in global infrastructure and city building, driving up base metal demand. (ii) the ongoing process of innovation, making an ever larger number of elements 'critical' to an ever-more complex and integrated economy, and (iii) the oncoming energy transition which will further increase both base and special metals demand significantly, and subject to a very tough timeline that is set by the imperative of climate change mitigation, Taken together, these trends in demand imply that we are set to enter a period of several decades of continued high demand for bulk metals and even more so for specialty and high-tech metals. This trend might of course be altered by global-scale events like a global economic/financial crisis, war or natural disasters. Otherwise, though, the clear implication is that during the coming decades current mining operations will need to be scaled up to several times current levels in order to fulfil the material requirements of the envisaged transition.

The question is then: is this possible? The answer is not straightforward, depending as it does on several complex and interwoven issues:

- are there sufficient resources on the planet to satisfy rising demand?
- if yes, can we mobilize them in sufficient quantities and at sufficient speed?

An additional question is that, if it appears unfeasible to scale up mining to such an extent and with such speed, would it be possible to slow down the demand for virgin materials in such a way that supply can indeed keep up?

In Section 3 we shall now assess the available stocks of metals on the planet. Section 4 deals with trends in supply, focusing on flows rather than stocks. Section 5 is devoted to options for reducing demand for virgin materials.

5.3 Reserves and resources, underground and above-ground

Above we have argued that demand for metals will in all likelihood continue to grow rapidly over the next few decades. The question therefore arises whether supply will be able to keep pace with demand. In this section we take the first step in answering this question by taking a closer look at available reserves and resources, both underground and above-ground.

5.3.1 Reserves and resources, underground

Of all the planet's metal resources we can only hope to extract a very small portion: those in the upper layer of Earth's crust and those in the atmosphere and ocean water. However, as the economist Nordhaus observed in the wake of the Limits-to-Growth report, even Earth's crust contains millions to billions times the current mine production of most of the minerals used by human society (Nordhaus 1974). Geologists have long assumed that the distribution of ore grades follow a normal distribution. This means that for these ore bodies can be found in many places and, if we assume that the richest ores will be exploited first, ore grades will gradually decrease over time. Skinner, however, argues based on geological theories on the formation of rich deposits, that the geologically scarce elements are distributed in a bimodal fashion, with the bulk of these materials locked up as atomic substitutes in common rock types and only a few rich deposits existing. These rich deposits are formed by the interaction of water and rocks at great depth through which ore forming solutions are formed that penetrate the outer layers of the Earth's crust. It is from these unevenly distributed rich seams that we currently extract most of our non-abundant minerals (Skinner 2001; Skinner 1976; Ayres 2007; Craig et al. 2011).

We can only exploit those ores and deposits that are accessible using existing technologies (reserve base). Of these only those that can be extracted economically is available to humanity (reserves). Therefore, although the amount of any particular element in Earth's crust is fixed, reserves are not. Moreover, only a certain fraction of reserves are known to us. Increased exploration and technological progress in

exploration will expand known reserves, while technological advances in mining and refining will expand the reserve base. After World War I the need for materials rapidly expanded and the mineral exploration became a true profession. Techniques like areal photography and measurements of magnetism, electric fields and gravity were developed to look for deposits beneath a soil cover of tens of meters. The development of rapid inexpensive analytical techniques made it possible to analyse large numbers of rock and soil samples. (Skinner 2001). At the same time decreasing transport costs of both ores and personnel facilitated the globalisation of mineral mining (Skinner 2001; Lundgren 1996). The relation between economic and technical reserves and resources is illustrated in Figure 5-5.

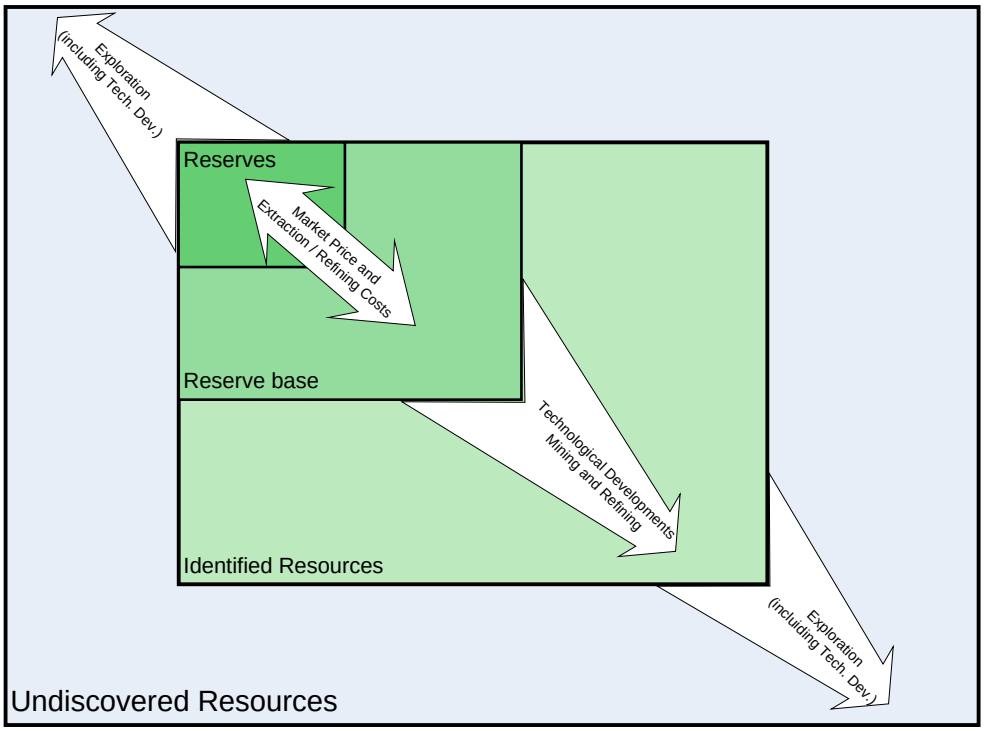

Figure 5-5: The relation between economic and technical reserves and resources. This is a simplification of a more detailed qualification system used by the USGS (U.S. Geological Survey 2010) The term Reserves is used for resources that can be economically extracted today. The term Reserve Base is used for resources that can be extracted with current or proven technologies, now or in the near future. The term Identified Resources is used for resources of which the quantity, grade, quality and location are known or estimated. The term Undiscovered resources is used for resources of which the existence is only postulated.

Tilton & Skinner explain the fluidity of the size of reserves of non-renewable resources by introducing the concept of cumulative supply curves (Tilton 2003; Tilton and Skinner 1987). Yaksic and Tilton demonstrate this curve and the concept of virtually limitless backstop reserves with the case of lithium. For lithium, ocean water is the backstop reserve that can be exploited when the market price reaches a level of

150 to 200 dollar per kg, about five to seven times the market price in 2009 (Yaksic and Tilton 2009).

It is highly likely that a large part of the undiscovered resources lie beneath a cover of younger common rock of 1 to 2 kilometre thickness. These deposits could potentially be mined through underground mines that have already reached depths of over 5 kilometre. However, finding these deposits will require new exploration techniques and a huge effort to prepare large scale three dimensional maps (Skinner 2001). Furthermore, from large scale open pit mines to smaller underground mines would have a substantial negative impact on the overall efficiency and economics of mining.

For many minor metals there is the additional issue that they can only be economically extracted as by-products of bulk metals. This means that the supply of these is set by the use of the bulk metal, making the supply highly inelastic examples are cadmium and indium as by-product of zinc, molybdenum and rhenium by-product of Cu. The linkages within the production of metals is often quite complex, and is thoroughly discussed by Reuter (e.g. Reuter et al. 2005).

5.3.2 Reserves and resources, above-ground

After elements are extracted from underground resources they accumulate in society according to the lifespan of the products (the in-use stock) and eventually end up in waste flows. Some fraction will be dispersed in the environment through use of the products, as in the case of phosphorus from fertilizers, zinc from galvanized infrastructure and copper from overhead railway power lines. The dispersed fraction is difficult or impossible to retrieve. The fraction ending up in stocks in society and in waste flows, however, can easily be seen as a resource for which the term *urban mining* has been coined (Hagelüken and Buchert 2008; Klinglmair and Fellner 2010; Kapur and Graedel 2006). This concept reflects the notion that mining of metals from their ores actually results in a superior reserve: pure metals. Some of this gain is lost when metals are mixed in alloys or in products containing a mix of metals. In general recycling of metals from the in-use stock or waste flows requires much less energy than that required to release the minerals from their ores (Johnson et al. 2008; Ayres 1997; Yellishetty et al. 2011). Recycling of metals from waste flows is already very successful for base and precious metals: for at least 18 metals the recycling rate is now over 50% (Graedel et al. 2011). Building and construction wastes and large consumer products, most notably cars, have been partly recycled ever since they were produced. The stock of metals in products like electronic equipment was already recognized as a potential source for materials during the 1970s (Chynoweth 1976). In printed circuit boards, the concentration of precious metals like gold and palladium is usually much higher (factor 10) than in their ores (Chancerel et al. 2009). Some substitution of metals in infrastructure has developed spontaneously through technological innovation, as in the case of plastics replacing metals in plumbing and glass fibre replacing copper wire in communication. Active efforts to retrieve metals from societal stocks (urban mining) earlier than after their natural life-time are rare. They were made during wartime, notably with limited success (Klinglmair and Fellner

2010). High prices may change this, however, as evidenced by the increasingly common occurrence of thefts of copper from the rail grid and lightning protection systems.

A crucial first step in urban mining efforts is to quantify the stocks and flows in society. The STAF project at Yale's Center for Industrial Ecology has accumulated the most comprehensive database on societal stocks and flows of metals in the world (Graedel 2002; Graedel et al. 2004a; Graedel et al. 2005a; Graedel et al. 2005b; Graedel et al. 2004b; Reck et al. 2006; Reck et al. 2010; Reck et al. 2008; Johnson and Graedel 2008; Johnson et al. 2005; Johnson et al. 2006; Kapur and Graedel 2006; Lanzano et al. 2006; Mao and Graedel 2009; van Beers et al. 2007; Wang et al. 2007; Harper and Graedel 2008; Gerst and Graedel 2008; Du and Graedel 2011). From these publications it is clear that the global societal stocks of metals constitute a considerable resource for all bulk metals. At a local scale, efforts are currently being made to quantify the so-called hibernating stocks, i.e. stocks in discarded pipes and cables still underground. It seems such stocks may be considerable and could be readily mined. However, the potential contribution of secondary production to total demand will be limited in times when the in-use stock is being built up, as in the present development phase of the China and the other BRIC economies, and in cases where the material is used in products with a substantial life span (Grosse 2010).

Now that we have established that mineral stocks as such are not a limiting factor, we turn to the rate of mine production or the mining capacity.

5.4 Trends in mineral supply

After many years of exploration and exploitation, mineral reserves and resources are still substantial. However, in order to asses whether metal scarcity might become a problem in the future it is more important to analyze the flows: can supply keep up with demand ? Until now, commodity booms – i.e. a period of supply/demand stress leading to price hikes – have almost never been caused by falling supply, but almost invariably by surges in demand. During these booms supply struggles to keep with demand primarily because the supply side industry can not keep up with the rapid increase in demand. This is caused mainly by long development lead times in mining and refining operations combined with a lack of investments during times of relatively low demand. However, next to the 'normal supply constraints' connected to every commodity boom, some additional supply constraints are now being recognized. In section 4.1 we describe the additional supply constraints that have recently been described by mining experts while in 4.2 we describe how factors that have increased the efficiency of mining in the past have lost much of their potency. The question arises whether ever rising demand might be checked by the relatively slow pace of developments in the supply sector.

5.4.1 Developments in the mining sector

Since the 1970s globalization, up-scaling of mining operations, liberalization of mining regimes, decreasing energy costs and the introduction of information technology that has decreased labour costs have all led to a decrease in mining costs. This trend has now come to an end for "*a whole raft of reasons including declining ore grades, more complex mineralogy, smaller deposit size, more difficult (e.g. deeper) mining conditions and increasing geographic remoteness*" (Humphreys, 2010). The sustained high energy prices, due in part to the same issues, add to this picture and it will be hard for productivity growth to offset the effects of resource depletion in the decades ahead. Policy-related trends are aggravating this situation further: renewed resource nationalism and minerals taxation, stricter environmental regulations and public resistance to new mining operations are all making it harder for mining companies to expand capacity.

A recent study of mining in Australia concludes that "*it is hard to envisage new discoveries or mining techniques leading to ore grades rising in the future*" and that ore grades will thus continue to decline. The average copper content of Australian ores is expected to decline from 0.95% in 2008 to 0.4% in 2050. The average gold content in ores was 1.94 g/ton in 2005, while the remaining resource has an average content of 1.0 g/ton. According to the author, this decline in ore grades will in turn lead to a higher resource and emission intensity of mining. Between 1989/90 and 2005/06 the energy intensity of mineral production increased by 3.7% per year (Mudd 2010). Others argue that deteriorating ore grades are not caused solely by a lack of high-grade ores but by a technology-driven switch to more abundant low-grade ores (West 2011). Although this argument is certainly valid, it does not contradict the fact that high-grade ores simply do not suffice to fulfil current and future demand. His example of gold, which today is produced more and more as a by-product of copper, actually confirms this.

Another major trend in Australian mining has been to move from underground to open-pit mines. This trend was facilitated by the availability of cheap diesel fuel, progress in engineering which allowed for extremely large mining equipment, and the discovery of major deposits close to the surface (Mudd 2010). According to Mudd, the slow shift back to underground mines for black coal over the last decade may be the start of a trend triggered by the exhaustion of near-surface deposits. He also indicates there is a view that for metals such as gold, copper and uranium future deposits will be located deeper. He adds that it is unclear whether this will lead to a shift back to underground mines or a shift to even larger open-pit mines. The main conclusion that Mudd draws from his analysis of Australian mining is that the availability of metals will not be limited by a physical lack of resources but by the environmental costs of mining. Norgate concludes for the world as a whole that it is almost inevitable that the ore resources will deteriorate over time resulting in an increase in the amount of energy and water that is needed per unit of metal mined (Norgate and Haque 2010; Norgate 2010).

5.4.2 Globalization

One important factor that has reduced commodity prices in the past was the trend of decreasing costs of bulk transport. Prior to 1850 the production and consumption of commodities like food, fibres, fossil fuels and minerals was largely a national or continental affair. The combination of steam ships and railways made long-distance transport of bulk goods considerably cheaper and facilitated globalization that was no longer limited to coastal areas. The introduction of bulk carriers and accompanying infrastructure following the Suez crisis of 1956 made it possible to transport relatively low-price commodities like coal and iron ore over extremely long distances, e.g. from Australia to Europe. These two waves of scaling up long-distance transport reduced bulk transport costs by 90% (in real terms) between the 1870s and the 1990s (Lundgren 1996; Radetzki 2008). The introduction of bulk carriers brought with it a substantial positive feedback: bulk carriers made long-distance transport of crude oil cheaper, which in turn made oil-consuming transport cheaper. It also supplied cheap fuels to the diesel-intensive open-pit mining operations and thereby facilitated the shift from underground to open-pit mines which started in the 1950s (Mudd 2010). Lundgren does not expect a further rapid increase in ship sizes and there seem to be no technological developments in the pipeline that will decrease shipping rates much further than the current levels. In fact, it is more likely that rising fuel prices will increase future freight costs.

5.4.3 Rate of increase of mining

The net result of all these developments in concert is hard to predict. Humphreys does not believe that the developments will lead to ever-increasing prices but rather to a relative rise in commodity prices to a higher plateau (Humphreys 2010). Trends in the global economy and the mining sector do not seem favourable for rapid expansion of mining, even though the geological stocks themselves would allow it. As we have seen in Section 3, it is also unlikely that recycling, even if pushed to its limits, will generate any substantial contribution as long as demand is still growing rapidly. It therefore seems worthwhile to explore some of the options for reducing demand. This is the subject of the following section.

5.5 Possible solutions for metal scarcity

All to often innovation is the presumed panacea for scarcity – especially in non-specialist economics-based literature. It is therefore instructive to see how innovation plays out in the materials domain. As already alluded to earlier, innovation in this context is virtually always substitution. For simplicity's sake, we here omit the issue of material efficiency. As with efficiency in other realms, e.g. energy, this leads to endless debates as to whether or not there is a rebound effect (higher efficiency stimulates demand) and, if so, how large it is. We have seen that, irrespective of one's position on this issue, demand for all materials continues to grow in absolute terms, which is all that matters for the present analysis. Whatever the virtues of efficiency,

total material demand in aggregate has been on the rise for centuries and seems firmly linked to economic growth (Figures 5-1 to 5-3).

Three types of substitution of mineral resources can be distinguished: substitution of one ore for producing a specific element with another, which we shall call *resource substitution* ; substitution of one element by another in a particular product or part, which we shall call *elemental substitution* ; and substitution of the way a certain function is fulfilled by a completely different way to fulfil this function, which we shall call *functional substitution* Resource and elemental substitution are discussed in Section 5.1, functional substitution, including dematerialization, in Section 5.2.

5.5.1 Elemental and resource substitution

Elemental substitution is applied for two very different reasons. Innovation will lead to substitution when the alternative element provides a functional benefit. Scarcity or elevated prices can also lead to substitution but then often at a cost of functionality. Elemental substitution has occurred often in the past: bronze replaced copper because of its superior properties in many applications the same holds for the replacement of bronze by iron, plastic (from fossil fuels) for paper, wood and metals, glass fibre for copper in communication, and so on. As a response to the threat of material scarcity, most of today's scientific and engineering research is aimed at elemental substitution. This sometimes means a shift from one scarce element to another, in which case the reprieve will be short-lived. In the future, though, carbon-based materials might substitute metals in applications like flat screens and PV solar cells. If we can move in the direction of substituting relatively scarce elements by the abundant elements, also known as "the elements of hope" (Diederen 2010), this would solve scarcity and security-of-supply issues.

Resource substitution can be accomplished by increasing exploration efforts or development of new refining technologies that facilitate the use of alternative ores. This is therefore a true *business-as-usual* solution and fits in well with the policies generally adopted by national governments and mining companies.

Solow argued in 1974 that the depletion of natural resources is not a problem if it is very easy to substitute them by *other factors* (Solow 1974). Goeller and Weinberg looked at this issue from a natural-science point of view in which one natural resource replaces another (Goeller and Weinberg 1976). They argue that almost all materials can be extracted from virtually inexhaustible resources as long as there is enough energy and that the amount of additional energy needed for this purpose is very limited: about a factor 2 compared to the levels of that day (1970s). They base this on the fact that aggregate demand for materials is dominated by iron and aluminum, for which mining from virtually inexhaustible resources is at most a factor two more energy-intensive. Resource optimists will argue that if we indeed were to be able to use common rock as a source of metals the life expectancy of this so-called *resource base* would be millions to billions of years for most elements. However, it is clear that we will never use a substantial part of Earth's crust for metal mining. Apart from

environmental and practical considerations the energy and material requirements would be enormous.

Fortunately, we are still far from the age where we would need to use common rock as a source of metals. Based on the current mining (16 million ton in 2008) the resource as for copper as defined by the USGS (3.7 billion tons including deep sea nodules) would last for over 200 years. If the 1950-2008 average growth trend of 3.3% would continue, this would be reduced to less than 70 years. So over such a period humanity should achieve to run society on a stable in-use stock, which requires more or less full recycling and at the same time slow down growth in demand. However, even for currently mined ores Norgate finds an exponential increase in energy requirements for both the grinding and the refining of metal ores with decreasing ore grade for copper and nickel (Norgate 2010).

To illustrate the absurdness of using common rock as a source of metals we will elaborate on the energy and material inefficiency of this route which will also illustrate the mineralogical barrier as introduced by Skinner (Tilton 2003). Three decades after the article by Goeller and Weinberg, Ayres is much less optimistic about the energy that would be needed to extract metals from common rock. He argues that extracting copper present as atomic substitute in common rocks (60 ppm Cu) would require hundreds to thousands of times more energy than extracting it from the average ore with a copper content of 0.9% (Ayres 2007). Steen and Borg support the view of Ayres by empirical work in which they come to the conclusion that the energy costs for grinding alone would be about 400 MJ per ton rock, yielding between 8 and 27 g copper. The energy costs of extracting copper from common rock would then be 15 - 50 MJ/g copper, which is 300 to 1000 times more than the 45 kJ/g copper on average used in current copper production (Steen and Borg 2002). Current production of 15.4 million ton copper requires 0.7 EJ (0.015% of global energy use). If we were to switch to common rock as a resource this would climb to 230-770 EJ (50-160% of present global energy use). It is not only energy that is needed to produce copper from common rock, but, in a life cycle perspective, copper, too. In Table 5-1 the copper return on investment is calculated for the current situation and a possible future based entirely on renewable energy. In the worst case, applying current-technology PV and using the high estimate of grinding energy given by Steen and Borg, the copper ROI is negative: for every four grams of copper invested in this system only one is produced[5]. Although these numbers provide no more than a very rough indication, it is clear that the efficiency of copper production will drop dramatically if we become compelled to use common rock as the main source and, therefore, that copper mining cannot be increased indefinitely.

[5] This might be an underestimate, because the data for copper use per kWh are based on ECOINVENT LCA data (Frischknecht R. 2007), which assume that about 20% of copper production comes from recycled copper. The current global average is in fact less than 10% (Graedel et al. 2011). In a future where demand for copper plateaus, this fraction could be substantially higher lowering the amount of virgin copper needed to produce copper. On the other hand, the figure is an underestimate, because the energy needs calculated by Steen and Borg relate solely to grinding and do not include the extra energy that will be needed for mining and refining, which will be substantial because the copper content in common rock is 150 times lower than in the average ore. If the energy needed for mining an refining would be included this will increase the amount of virgin copper needed to produce copper.

Table 5-1: Copper return on investment in the current situation, i.e. current fuel mix in electricity and copper from average ore (0.9% Cu) compared with a possible future situation where wind or solar PV are the source of energy and copper is extracted from common rock.

	copper use for electricity production		**energy use for copper production**		**copper return on investment**
	g Cu/kWh		**kWh/g Cu**		**g/g**
currents situation	0.0086		0.013		9300
future I	0.040	Wind	4.2	low estimate	6.0
future II	0.30	PV	14	high estimate	0.24
data source	(Kleijn et al. 2011)		(Steen and Borg 2002)		

A similar analysis can be made for many other scarce elements but for some the situation is quite different like in the case of lithium where ocean water can be used as a virtually limitless source for only five to seven times the current market price.

Goeller and Weinberg acknowledge that it will not be easy to reach their 'Age of Substitutability' and they assume there will be a transition phase lasting hundreds of years. Our calculations above show that for copper we will have enough resources available for less than 70 years in a business as usual scenario. Although their thesis of unlimited substitutability might be theoretically possible for most resources, we do not have the luxury of plentiful time. Climate change obliges us to reduce the emissions from our energy system drastically within several decades. In our quest for climate stability, a shortage, even temporarily, of materials crucial for making the transition to a low-carbon energy system might prove to be the show-stopper.

5.5.2 Functional substitution and dematerialization

Examples of functional substitution are the replacement of photographic film and paper by digital photography and the replacement of paper mail and fax by email. Wernick has shown that the relative importance of materials for the US economy has changed substantially over the last century with some materials becoming more important over time and others less (Wernick 1996). In absolute and per capita terms, however, the consumption of almost all materials has increased over time. The amounts of stone, bronze and iron that we now use per capita are many orders of magnitudes higher than in the ages named after these materials. This is analogous to the situation in energy. Oil and natural gas have not in absolute terms replaced coal. They have just been additional to coal.

The term dematerialization is used to describe a process that leads to a decrease in the amount of material required to fulfil a certain function. There are several ways in which this can be achieved. Two concepts that might lead to dematerialization are miniaturization and the service economy. Miniaturization has been a very prominent trend in electronics and computers during the last few decades. Computers and mobile phones are the most prominent examples. The fact that miniaturization can lead to resource conservation was already recognized in the 1970s (Chynoweth 1976). Even then, however, the author already acknowledged that smaller products do not by

definition require less materials to produce. The total material use of a product needs to be calculated from a life-cycle perspective. Despite this early warning, Ayres notes that the advances in microelectronics have been used by economists such as Alan Greenspan and Joseph Stiglitz as an example of radical dematerialization of the economy (Ayres 1998; Stiglitz 1997). In 2002 a study was published that estimated the material requirements of microchip production. The authors came to the conclusion that in order to produce a single 2-gram microchip about 1600 g of fossil fuels and 72 grams of chemicals are needed, in addition to 32,000 g water and 700 g elemental gases (Williams et al. 2002). The authors use thermodynamics to explain the reason behind this extremely high energy input in a very small product: "*Microchips and many other high-tech goods are extremely low-entropy, highly organized forms of matter. Given that they are fabricated using relatively high entropy starting materials, it is natural to expect that a substantial investment of energy and process materials is needed for the transformation into an organized form*".

Another factor that reduces the observed dematerialization effect of miniaturization is that the production of small electronic devices also provides additional functions that lead to an increased volume of electronics per capita. Mobile phones, mp3 players, gaming devices and tablet computers are all good examples of devices that have created an additional demand for electronics. Through this additional demand, miniaturization can also lead to increased dispersion of precious metals simply because the devices are so small that a substantial number will end up in household waste. Furthermore, for certain products there is no trend towards miniaturization, but rather towards bigger products. In principle, flat-screen TVs are more energy-efficient and lighter than their CRT-based predecessors. However, the new LCD technology has also made it possible to make much bigger screens, which are today approaching the power consumption and weight of old CRT TVs (Frauenhofer ISI 2009). The extreme demands that software, especially games and video-editing software, generate for computer hardware has induced a trend which has increased the average power consumption of a desktop computer by a factor 2 between 2001 and 2007 (Frauenhofer ISI 2009). The battle between increased material efficiency and the forces that drive increased consumption will always continue in a free market economy (Wernick 1996).

Like miniaturization, the service economy holds out promise for dematerializing the economy. Car-sharing schemes may indeed lead to fewer privately owned cars. The leasing of all sorts of products, from office carpets to copiers, gives producers an incentive to design their products for durability, easy disassembly and recycling. E-books, mp3 and pay-per-view movies are also examples where e-services substitute for physical products. Although the power consumption of mp3 players and e-book readers are relatively modest, their production, like that of any other electronic device, is relatively material- and energy-intensive (Hagelüken and Meskers 2010). Furthermore, huge server parks are running 24/7 to supply these devices with digital content. The energy demands of server farms, PCs and network equipment together is estimated at 1.3% (84 GW) of global primary energy use in 2008 and is expected to more than triple by 2020 (Pickavet et al. 2008). And this is excluding the energy that is

needed to produce all this equipment. What this means in terms of demand for materials has, to our knowledge, never been reported. One preliminary study on e-newspapers suggests that in Europe the lifecycle energy demands of e-newspapers, including internet use, could be less than 50% than that of printed newspapers (Moberg et al. 2010). Another, relatively old study in terms of IT developments, on different ways to buy music, concludes that downloading music can significantly decrease overall resource consumption compared to CDs bought in shops (Türk et al. 2003). Streaming media directly from the web could further decrease the resource consumption by eliminating the need for a computer and CD player. It should be noted however, that the results of these consumer product oriented studies strongly depend upon the behaviour of the consumer.

When it comes to the replacement of physical services, then, the internet combined with electronic devices has the potential to reduce resource use per unit consumption. Again, though, even if this indeed proves to be the case, the question remains whether this increase in efficiency will be able to outrun the inevitably rising total consumption that will be triggered by these new technologies.

5.6 Conclusions, recommendations, discussion & research agenda

Having surveyed the various aspects of future metals demand and supply we can now return to the central question of this paper namely whether or not the current episode of apparent scarcity of metals any different from what society has faced in the past century and see what conclusions - firm or tentative - may be drawn.

Although Earth is finite, the size of current resources has in the modern era not constrained the mine production of metals or economic development. Although ore grades are deteriorating, reserves of lower-grade ores almost always exceed those of rich ores. Therefore, reserves of almost all minerals have increased rather than decreased over the last century, despite, or perhaps because of, the exponential growth in mining (Tilton 2003; Craig et al. 2011). However, on the basis of the review of the evidence in this paper we believe that the present minerals outlook differs from the outlook in the decades of the past two centuries for three reasons.

Globalization, driven by cheap energy and cheap bulk transport, has opened up virtually every remote corner of the world for exploration and mining. Although certainly not every square kilometre has actually been scanned for mineral resources, globalization generates no more than a one-off gain. Remaining undiscovered deposits exist mainly in regions in which exploitation will be intrinsically difficult, e.g. under a cap of one to two kilometre of common rock. Moreover, the cost of energy and bulk transport may already have reached its lowest possible plateau. The rate at which minerals can be extracted is constraining. Here the analogy with conventional oil is relevant. Like with metals the amount of oil in Earth's crust is not the limiting factor for oil production. Still the global annual production seems to be heading for a plateau

(Kerr 2007). The rate of mining is limited by the amount of equipment required, by the availability of skilled workers, by energy requirements and last but not least by environmental costs. The two metal episodes of high metal prices that have occurred in the recent past (1950s and 1980s) were caused mainly by rapidly increasing demand and insecure supply for OECD countries. Rapid increasing demand is also an important cause of the current metal boom. However the difference is that the insecurity of supply is now a global issue. Furthermore, commodity booms are always associated with supply constraints caused by limited investments in preceding times of low demand combined with long development lead times of mining projects. However, this is now combined with supply side constraints caused by deteriorating ore grades, the lack of discoveries of new large deposits and the linkages with constraints in other resources like water, energy and environmental amenities.

Secondly it seems that for the first time in human history we are truly experiencing the interlinkages between the resources that we use on a global scale. With decreasing ore grades more energy is needed to produce metals from ores while at the same time more metals are needed to build the low-carbon energy system we need tackle the constraints defined by climate change. Water use, land use and the environmental impacts are additional constraints that are interlinked with energy and metal mining. These mutually enhancing constraints will pose new challenges for future generations. We will need to pick our technologies carefully, avoiding obvious material constraints.

Thirdly demand for metals will continue to grow exponentially for decades to come. Demand will increase due to the rapid urbanization which will lead to a rapid built-up of cities and accompanying infrastructure. Furthermore, economic growth in emerging economies will lead to the production of more and more complex products which in turn will lead to increasing metal demand. The transition to a low-carbon energy system will require vast amounts of materials. For some metals this means mining needs to increase by several times the current annual mining. And the most crucial issue is that we need these materials in the next few decades, in order to still be relevant for tackling climate change.

If the long term projections of global economic development and concomitant urbanisation come true the world will build the equivalent of all the cities in existence today inhabited by citizens who earn triple the global average income per capita, easily doubling iron and base metal demand and a multiple for certain rare elements. If in addition the challenge of climate chance is to be addressed by building a low-carbon energy system the demand is increased further still.

Mining and exploration efforts see themselves confronted with environmental and physical constraints and are already struggling to keep up with demand. An ample supply of metals is not only important for producing high-tech electronics; it is also vital for the provision of more sustainable energy and food for the 9 billion people that are projected to be around in 2050.

There are two main directions that could be used to address the issue of metal scarcity: innovation and abandoning the growth paradigm. Although some economists are working on de-growth scenarios the mainstream in economics and politics is still directed at economic growth measured mainly in terms of GDP. Innovation can help through:

- closing metal cycles, although by definition recycling can only be of limited use for reducing virgin input in the growing economy of the next few decades. In a more stable economy it is a key ingredient for a sustainable metal supply;
- dematerialization which also has its limitations, but we clearly need to move in the direction of a more resource-efficient type of growth;
- substitution although substitution of one scarce element for another is clearly not a long-term solution to metal scarcity, developing new high-tech materials based on abundant materials like ceramics and carbon-based nano-materials will provide a reprieve for certain specific scarcity issues.

Besides these in essence technically defined directions for solutions there is clear need for the assessment of the side-effects of the proposed solutions on different scale levels in order to avoid problem-shifting.

All in all, counting on unlimited progress in technology and efficiency to keep resource scarcity at bay seems at the least rather naive. Resource optimists are correct in their statement that resources are abundant. The problem seems to be in the required rate of mining, and here, as we have argued, there is less reason for unbridled optimism. This does not mean that metal scarcity will necessarily lead to future scarcity. There are a range of technical options for addressing the issue, but alongside technological development we will need a change in material policies, product design and business models in order to achieve sustainable global metal metabolism. If economists are right and we can substitute anything that gets scarce, the consequence could be that we run out of everything at the same time. In the run-up to that we would see the clock frequency of innovation go up and up and up, until it stops…

References

Albanese, T. 2008. Rio Tinto. In *Merill Lynch: Global Metals & Mining Conference 2008*: Rio Tinto.

Andersson, B. A. and I. Råde. 2001. Metal resource constraints for electric-vehicle batteries. *Transportation Research Part D: Transport and Environment* 6(5): 297-324.

Ayres, R. U. 1997. Metals recycling: economic and environmental implications. *Resources, Conservation and Recycling* 21(3): 145-173.

Ayres, R. U. 1998. *Industrial Ecology: Depreciation, waste and pollution.* Fountainebleau: INSEAD.

Ayres, R. U. 2007. On the practical limits to substitution. *Ecological Economics* 61(1): 115-128.

Bergen, J., S. Herms, J. Lambers, D. Malone, B. Putman-Cramer, and C. Stubbe. 2011. *Material Scarcity & Renewable Energy Technologies in the EU: Could metal availability affect growth of renewable energy technologies in the EU*. Leiden: Leiden University & Delft University of Technology.

British Geological Survey. 2009. *Cobalt*. Keyworth, Nottingham, UK: BGS NERC.

Burney, D. A. and T. F. Flannery. 2005. Fifty millennia of catastrophic extinctions after human contact. *Trends in Ecology & Evolution* 20(7): 395-401.

Campbell, C. J. 2006. The Rimini Protocol an oil depletion protocol: Heading off economic chaos and political conflict during the second half of the age of oil. *Energy Policy* 34(12): 1319-1325.

Chancerel, P., C. E. M. Meskers, C. Hagelüken, and V. S. Rotter. 2009. Assessment of Precious Metal Flows During Preprocessing of Waste Electrical and Electronic Equipment. *Journal of Industrial Ecology* 13(5): 791-810.

Chynoweth, A. G. 1976. High Technology Materials. *Science* 191(4228): 724-732.

Craig, J. R., D. J. Vaughan, and B. J. Skinner. 2011. *Earth Resources and the Environment*. 4th ed. Upper Saddle River, New Jersey: Pearson Prentice Hall.

Diamond, J. 1987. The Worst Mistake in the History of the Human Race. *Discover Magazine*: 64-66.

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

Frauenhofer ISI. 2009. *Energy Efficiency Trends of IT Appliances in Households(EU 27)* Karlsruhe: Frauenhofer.

Frischknecht R., A. H.-J., Doka, G., Dones, R., Heck T., Hellweg, S., Hischier, R., Jungbluth N., Nemecek, T., Rebitzer, G., Spielmann, M. 2007. *Overview and Methodology. Final report ecoinvent v2.0 No. 1*. Duebendorf, CH.: Swiss Centre for Life Cycle Inventories.

Gerst, M. D. and T. E. Graedel. 2008. In-Use Stocks of Metals: Status and Implications. *Environmental Science & Technology* 42(19): 7038-7045.

Goeller, H. E. and A. M. Weinberg. 1976. The Age of Substitutability. *Science* 191(4228): 683-689.

Gordon, R. L. 2009. Hicks, Hayek, Hotelling, Hubbert, and Hysteria or Energy, Exhaustion, Environmentalism, and Etatism in the 21st Century. *Energy Journal* 30(2): 1-16.

Graedel, T. E. 2002. The contemporary European copper cycle: introduction. *Ecological Economics* 42(1-2): 5-7.

Graedel, T. E., M. Bertram, and B. Reck. 2005a. Exploratory Data Analysis of the Multilevel Anthropogenic Zinc Cycle. *Journal of Industrial Ecology* 9(3): 91-108.

Graedel, T. E., M. Bertram, A. Kapur, B. Reck, and S. Spatari. 2004a. Exploratory Data Analysis of the Multilevel Anthropogenic Copper Cycle. *Environmental Science & Technology* 38(4): 1253-1261.

Graedel, T. E., J. Allwood, J.-P. Birat, M. Buchert, C. Hagelüken, B. K. Reck, S. F. Sibley, and G. Sonnemann. 2011. What Do We Know About Metal Recycling Rates? *Journal of Industrial Ecology*: no-no.

Graedel, T. E., D. van Beers, M. Bertram, K. Fuse, R. B. Gordon, A. Gritsinin, E. M. Harper, A. Kapur, R. J. Klee, R. Lifset, L. Memon, and S. Spatari. 2005b. The Multilevel Cycle of Anthropogenic Zinc. *Journal of Industrial Ecology* 9(3): 67-90.

Graedel, T. E., D. van Beers, M. Bertram, K. Fuse, R. B. Gordon, A. Gritsinin, A. Kapur, R. J. Klee, R. J. Lifset, L. Memon, H. Rechberger, S. Spatari, and D. Vexler. 2004b. Multilevel Cycle of Anthropogenic Copper. *Environmental Science & Technology* 38(4): 1242-1252.

Grosse, F. 2010. Is recycling "part of the solution"? The role of recycling in an expanding society and a world of finite resources *S.A.P.I.EN.S [Online]* 3(1).

Haakman, J. 2008. Material use of lithium-ion batteries for electric cars BSc thesis, Institute of Environmental Sciences, Leiden University, Leiden.

Hagelüken, C. and M. Buchert. 2008. The mine above - opportunities & challenges to recover scarce and valuable metals from EOL electronic devices. In *7th International Electronics Recycling Congress*. Salzburg, Austria.

Hagelüken, C. and C. E. M. Meskers. 2010. Complex Life Cycles of Precious and Special Metals In *Linkages of Sustainability*, edited by T. E. Graedel and E. van der Voet. Cambridge, Massachusetts, USA: MIT Press.

Harper, E. M. and T. E. Graedel. 2008. Illuminating Tungsten's Life Cycle in the United States: 1975−2000. *Environmental Science & Technology* 42(10): 3835-3842.

Harrower, M. 2006. *Indium*. Northants, UK: MCP Ltd.

Hitachi. 2010. *Highly efficient compact permanent magnet motor with amorphous metal cores*. Hitachi.

Hu, M., E. Van Der Voet, and G. Huppes. 2010. Dynamic Material Flow Analysis for Strategic Construction and Demolition Waste Management in Beijing. *Journal of Industrial Ecology* 14(3): 440-456.

Humphreys, D. 2010. The great metals boom: A retrospective. *Resources Policy* 35(1): 1-13.

Jacobson, M. Z. and M. A. Delucchi. 2011. Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials. *Energy Policy* 39(3): 1154-1169.

Johnson, J. and T. E. Graedel. 2008. The "Hidden" Trade of Metals in the United States. *Journal of Industrial Ecology* 12(5-6): 739-753.

Johnson, J., L. Schewel, and T. E. Graedel. 2006. The Contemporary Anthropogenic Chromium Cycle. *Environmental Science & Technology* 40(22): 7060-7069.

Johnson, J., B. K. Reck, T. Wang, and T. E. Graedel. 2008. The energy benefit of stainless steel recycling. *Energy Policy* 36(1): 181-192.

Johnson, J., J. Jirikowic, M. Bertram, D. van Beers, R. B. Gordon, K. Henderson, R. J. Klee, T. Lanzano, R. Lifset, L. Oetjen, and T. E. Graedel. 2005. Contemporary Anthropogenic Silver Cycle: A Multilevel Analysis. *Environmental Science & Technology* 39(12): 4655-4665.

Kander, A. 2005. Baumol's disease and dematerialization of the economy. *Ecological Economics* 55(1): 119-130.

Kapur, A. and T. E. Graedel. 2006. Copper Mines Above and Below the Ground. *Environmental Science & Technology* 40(10): 3135-3141.

Kerr, R. A. 2007. Even Oil Optimists Expect Energy Demand to Outstrip Supply. *Science* 317(5837): 437.

Klee, R. J. and T. E. Graedel. 2004. ELEMENTAL CYCLES: A Status Report on Human or Natural Dominance. *Annual Review of Environment and Resources* 29(1): 69-107.

Kleijn, R. and E. van der Voet. 2010. Resource constraints in a hydrogen economy based on renewable energy sources: An exploration. *Renewable and sustainable energy reviews* 14(9): 2784-2795.

Kleijn, R., E. van der Voet, G. J. Kramer, L. van Oers, and C. van der Giesen. 2011. Metal requirements of low-carbon power generation. *Energy* 36(9): 5640-5648.

Klinglmair, M. and J. Fellner. 2010. Urban Mining in Times of Raw Material Shortage. *Journal of Industrial Ecology* 14(4): 666-679.

Lanzano, T., M. Bertram, M. De Palo, C. Wagner, K. Zyla, and T. E. Graedel. 2006. The contemporary European silver cycle. *Resources, Conservation and Recycling* 46(1): 27-43.

Lundgren, N.-G. 1996. Bulk trade and maritime transport costs : The evolution of global markets. *Resources Policy* 22(1-2): 5-32.

MacNeill, J., P. Winsemius, and T. Yakushiji. 1991. *Beyond Interdependence, the messing of the world's economy and the Earth's ecology*. Oxford, UK: Oxford University Press.

Maddison, A. 2011. Historical Statistics of the World Economy: 1-2008 AD. http://www.ggdc.net/MADDISON/oriindex.htm. Accessed February 15, 2011 2011.

Malthus, T., ed. 1798. *An essay on the principle of population, as it affects the future improvement of population*.

Mao, J. and T. E. Graedel. 2009. Lead In-Use Stock. *Journal of Industrial Ecology* 13(1): 112-126.

Meadows, D. H., D. L. Meadows, J. Randers, and W. W. Behrens. 1972. *The limits to growth: a report for the Club of Rome's project on the predicament of mankind*. New York: Universe Books.

Meskers, C. E. M., C. Hagelüken, S. Salhofer, and M. Spitzbart. 2009. Impact of pre-processing routes on prescious metal recocery from PCs. In *EMC 2010*. Innsbruck: European Metallurgical Conference.

Metz, B., O. R. Davidson, P. R. Bosch, R. Dave, and L. A. Meyer, eds. 2007. *Summary for Policymakers. In: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by IPCC. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Moberg, Å., M. Johansson, G. Finnveden, and A. Jonsson. 2010. Printed and tablet e-paper newspaper from an environmental perspective -- A screening life cycle assessment. *Environmental Impact Assessment Review* 30(3): 177-191.

Mudd, G. M. 2010. The Environmental sustainability of mining in Australia: key mega-trends and looming constraints. *Resources Policy* In Press, Corrected Proof.

National Research Council. 2008. *Minerals, Critical Minerals, and the U.S. Economy* Washington D.C.: The National Academies Press

Nordhaus, W. P. 1974. Resources as a Constraint on Growth. *American Economic Review* 64(2): 22.

Norgate, T. and N. Haque. 2010. Energy and greenhouse gas impacts of mining and mineral processing operations. *Journal of Cleaner Production* 18(3): 266-274.

Norgate, T. E. 2010. Deteriorating ore resources. In *Linkages of Sustainability*, edited by T. E. Graedel and E. v. d. Voet. Cambridge, MA: MIT Press.

Perlin, J. 2005. *A forest journey, the story of wood and civilization*. Woodstock VT: The countryman press.

Pickavet, M., W. Vereecken, S. Demeyer, P. Audenaert, B. Vermeulen, C. Develder, D. Colle, B. Dhoedt, and P. Demeester. 2008. Worldwide Eenergy Needs for ICT: the Rise of Power-Aware Networking. Paper presented at IEEE-ANTS, Bombay (India).

Ponting, C. 2007. *A new green history of the world, the environment and the Collapse of Great Civilisations*. New York: Penguin Group.

Radetzki, M. 2008. *A Handbook of Primary Commodities in the Global Economy*. Cambridge UK: Cambridge University Press.

Radetzki, M., R. G. Eggert, G. Lagos, M. Lima, and J. E. Tilton. 2008. The boom in mineral markets: How long might it last? *Resources Policy* 33(3): 125-128.

Reck, B., M. Bertram, D. B. Müller, and T. E. Graedel. 2006. Multilevel Anthropogenic Cycles of Copper and Zinc: A Comparative Statistical Analysis. *Journal of Industrial Ecology* 10(1-2): 89-110.

Reck, B. K., D. B. Müller, K. Rostkowski, and T. E. Graedel. 2008. Anthropogenic Nickel Cycle: Insights into Use, Trade, and Recycling. *Environmental Science & Technology* 42(9): 3394-3400.

Reck, B. K., M. Chambon, S. Hashimoto, and T. E. Graedel. 2010. Global Stainless Steel Cycle Exemplifies China's Rise to Metal Dominance. *Environmental Science & Technology* 44(10): 3940-3946.

Rio Tinto. 2011. Rio Tinto Presentation to North American Fixed Income Investors: Rio Tinto.

Skinner, B. J. 1976. A second iron age ahead? *American Scientist* 64(3): 11.

Skinner, B. J. 2001. Exploring the resource base. In *The Long-Run Availability of Minerals*. Washington DC: Resources for the Future.

Solow, R. M. 1974. The Economics of Resources or the Resources of Economics. *American Economic Review* 64(2): 1.

Steen, B. and G. Borg. 2002. An estimation of the cost of sustainable production of metal concentrates from the earth's crust. *Ecological Economics* 42(3): 401-413.

Stiglitz, J. E. 1997. Georgescu-Roegen versus Solow/Stiglitz. *Ecological Economics* 22(3): 269-270.

Tainter, J. A. 1988. *The collapse of complex societies*. Cambridge UK: Cambridge University Press.

Tilton, J. E. 2003. *On borrowed time ? Assessing the threat of mineral depletion*. Washington: Resource for the future.

Tilton, J. E. and B. J. Skinner. 1987. The meaning of resources. In *Resources and World Development*, edited by D. J. MacLaren and B. J. Skinner. Chichester, UK: John Wiley & Sons.

Türk, V., M. Kundt, and M. Ritthoff. 2003. *The environmental and social impacts of digital music, a case study with EMI*. Deliverable 12 (D12) of the project DEESD- Digital Europe: e-business and sustainable development. DEESD- Digital Europe: e-business and sustainable development.

U.S. Geological Survey. 2010. *Mineral Commodity Summaries 2010*. U.S. Geological Survey.

U.S. Geological Survey. 2011. *Mineral Commodity Summaries 2011*. U.S. Geological Survey.

UN. 2010. *World Urrbanization Prospects, The 2009 Revision, Highlights*. New York, NY, USA: UN-DESA.

van Beers, D., A. Kapur, and T. E. Graedel. 2007. Copper and zinc recycling in Australia: potential quantities and policy options. *Journal of Cleaner Production* 15(8-9): 862-877.

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

Wang, T., D. B. Müller, and T. E. Graedel. 2007. Forging the Anthropogenic Iron Cycle. *Environmental Science & Technology* 41(14): 5120-5129.

Wernick, I. K. 1996. Consuming materials: The American way. *Technological Forecasting and Social Change* 53(1): 111-122.

West, J. 2011. Decreasing Metal Ore Grades. *Journal of Industrial Ecology* 15(2): 165-168.

Williams, E. D., R. U. Ayres, and M. Heller. 2002. The 1.7 Kilogram Microchip: Energy and Material Use in the Production of Semiconductor Devices. *Environmental Science & Technology* 36(24): 5504-5510.

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

Yellishetty, M., G. M. Mudd, P. G. Ranjith, and A. Tharumarajah. 2011. Environmental life-cycle comparisons of steel production and recycling: sustainability issues, problems and prospects. *Environmental Science & Policy* In Press, Corrected Proof.