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Materials and energy : a story of linkages

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Materials and energy: a story of linkages

René Kleijn



Materials and energy: a story of linkages

Colophon

Materials and energy: a story of linkages

Material requirements of new energy technologies, resource scarcity, and
interconnected material flows

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Materials and energy: a story of linkages

Material requirements of new energy technologies,
resource scarcity, and interconnected material flows

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Chapter 1

General introduction

This Chapter introduces the material basis of society, with a focus on metals related to low-carbon energy technologies. It also introduces the research questions that will be answered in this dissertation.

1.1 The importance of the material basis of society

In a time where the service economy is booming and the experience economy and/or dream society are seen as the next stage of economic development (Jensen 1999; Pine and Gilmore 1999), it is easy to lose track of the physical basis of our prosperity: materials. The value of the raw materials we use is, in monetary terms, very small compared with global GDP¹. However, raw materials provide over 97% of our energy in the form of fossil fuels, uranium and combustible renewables (International Energy Agency 2010). In order to produce the remaining 3% with hydropower, wind and sunlight we need concrete, steel and many other elements to produce the devices needed to capture significant amounts of energy from these diffuse sources. The bulk of our food is produced with the aid of a mix of mainly fossil fuels, phosphate rock, atmospheric nitrogen, steel and concrete. Even the internet can only exist within servers made with the aid of at least two-thirds of the elements in the periodic table and which need to be continuously fed by energy that is currently derived mainly from fossil fuels. The supply of materials and energy are inextricably linked: the copious supply of cheap energy in the form of easily recoverable oil and coal has facilitated the production of cheap materials while at the same time the copious supply of cheap materials has facilitated the production of cheap energy. This linkage is the core theme of this dissertation.

Throughout history the scarcity of raw materials has been an important issue, with access to resources a key pre-requisite for the development of complex societies. In ancient times, materials were pivotal for the production of tools that could be used to increase the efficacy of hunting and gathering and the efficiency of agriculture. Precious metals were an essential ingredient facilitating the transition from a gift and barter economy to a monetary economy, which in turn facilitated the development of early civilizations. Alongside the development of tactics and strategy, materials were (and still are) of crucial importance in warfare. An advantage in either weaponry or armour will quickly pay off on the battlefield. In the modern era, too, sufficient supplies to the military has always been a key concern. In periods of relative material scarcity it is often the military that is the first to develop an interest in the security of

¹ In 2009 the total value of traded fuels, mining products and agricultural products was about \$ 3.4 trillion, while the value of traded manufactured products was about \$ 8.3 trillion (WTO 2010). In that same year global GDP was around \$ 60 trillion.

supply of materials that are important for their gear and equipment (The President's materials policy commission 1952; Haglund 1986) .

Although a secure and sufficient supply of materials has been a consistent concern over the ages, the availability and thus the production of materials has increased exponentially since the start of the industrial revolution. Economic and technological development have simultaneously increased both demand for and supply of materials. Today we live in an era in which we use more materials than ever before, while at the same time the availability of these materials is greater than ever before. There has also been a significant increase in both the number of elements to be found in everyday products and the number of complex products we use on an everyday basis. Moreover, these products can only be manufactured through complex production processes with the aid of virtually every element in the periodic table. Since the industrial revolution there have been times in which material supply could barely keep up with demand, resulting in high commodity prices. Time after time, such periods were followed by periods in which supply exceeded demand and prices were low.

The supply, demand and price of materials is by definition a topic that is studied within the discipline of economics. In the early 20th century, Gray and Hotelling and others laid the foundations of so-called Resource Economics. From the 1960s to the 1980s a fierce debate took place between such economists as Solow and Simon and environmentalists and ecological economists like Ehrlich and Georgescu-Roegen. The former, the resource optimists, argued that resources were more plentiful at that time than ever before and that technological progress would ensure that this trend would continue into the foreseeable future. The latter, the resource pessimists, argued that the use of finite resources and, more so, exponential growth of resource extraction is by definition unsustainable and that we therefore needed to decrease the rate of extraction so as not to diminish or limit the opportunities of future generations.

One could argue that the resource optimists have been proved right, at least up to the previous century. In earlier eras there had been shortages of key metals. There are solid indications that the development of the production of 'good iron' was triggered by a major disruption in the supply of tin around 1200 BC (Raymond 1984). Once it became clear that iron and steel were superior in many applications, the technology to produce these materials spread swiftly from Asia Minor to Europe, India and China, thereby replacing bronze as the main metal in use (Gilmour 2009). Metal scarcity was also one of the factors that darkened the dark ages that lasted from the fall of the Roman Empire to the end of the first millennium. After Roman technology, infrastructure and organization were lost, metal mining in Europe almost ceased to exist except for local and readily accessible sources of iron for weapons and tools. The mines in the Rio Tinto area of Spain and the copper mines of Cyprus were forgotten. This led to a shortage of precious metals as a basis for currency and external trade, severely hampering economic and societal development in the dark ages (Raymond 1984).

The period of high commodity prices in the late 1970s was followed by a period of low prices and ample availability that lasted until 2002. However, the 2002-2008 metals boom, a period of steeply rising metal prices, combined with the birth of virtual monopolies for the production of certain scarce metals like the rare earths, indium and others put materials scarcity firmly back on the political agenda. Over the past decade, numerous reports have been published or initiated by governmental organizations on the criticality of resources and the possible effects of future scarcity for national and global economic development, including (American Physical Society & Materials Research Society 2011), (National Research Council 2008), (U.S. Department of Energy 2010), (Ad-hoc Working Group on defining critical raw materials 2010), (Angerer et al. 2009), (Oakdene Hollins 2008), (National Institute for Materials Science 2008), (Statistics Netherlands 2010).

These reports often start out by defining a framework for determining the criticality of specific raw materials. Key factors are then their economic importance, their substitutability, the diversity of supply, the size of known resources and reserves and the potential for recycling. Although these analyses are useful for identifying supply risks, they focus mainly on the short term and seldom take future demand for new technologies into account. A noteworthy exception is the German study by Angerer (Angerer et al. 2009), which focuses specifically on this issue. Furthermore, in these reports there is scarcely any analysis of past episodes of material scarcity or of current trends in supply and demand that will determine the long-term future availability of materials. This dissertation is concerned precisely with such an analysis of long-term trends in the supply and demand of metals, with a specific focus on the metal requirements of the transition to a low-carbon energy system.

1.2 The debate on scarcity in recent history

The 2nd World War led to massive worldwide destruction of infrastructure and other capital goods, while the development of new weapon systems and defence technologies at the same time led to rapid technological progress. After the war this led to an increased demand for mineral resources for rebuilding the lost infrastructure and for manufacturing all manner of newly developed consumer goods. In addition, though, the supply of mineral resources was hampered by the dwindling reserves in developed countries, the weakening or severing of colonial ties and the disruption of normal trade patterns engendered by the start of the Cold War (The President's materials policy commission 1952; Geiser 2001). In the US *The President's Materials Policy Commission* (known as the Paley Commission, after its chairman) was established in 1951, during the Korean War. The commission was charged "*to make an objective inquiry into all major aspects of the problem of assuring an adequate supply of production materials for our long-range needs and to make recommendations which will assist me in formulating a comprehensive policy on such materials*" (Truman 1951). The commission's report discussed the basic principles of the depletion debate, including the formulation of possible policies and research agendas. It was this report that laid the foundation of US policy on scarcity and resource depletion. Strategic stockpiles of a large number of materials

that were deemed critical to the US economy and military were established. The non-profit corporation Resources for the Future (RFF) was established in 1952 with Paley as its Chairman. In 1963 one of the most important works in this field, *Scarcity and Growth* by Barnett and Morse, was published under the flag of RFF.

In the 1970s the oil crisis and the peak in commodity prices combined with growing environmental awareness led a whole series of publications on the implications of resource scarcity. In 1972 the Club of Rome published their famous "Limits to Growth" report (Meadows et al. 1972) and in 1976 an entire issue of *Science* was dedicated to the scarcity of biotic and abiotic resources. Since then, a fierce debate has raged between resource optimists (mainly resource economists) and resource pessimists (mainly ecological economists, scientists and environmentalists). It is important to note that some of the arguments used by both sides are clearly valid. Resource optimists point out that the amount of virtually all elements in Earth's crust and oceans is more than future generations can conceivably consume. However, as resource pessimists point out, exponential growth in resource use, as we are experiencing today, is by definition unsustainable. Resource optimists will gladly explain that technological progress will increase the efficiency of mining, refining and recycling and that this has led to more copious supplies than ever before. Then again, however, resource pessimists will point out that ore grades are diminishing in quality and that new deposits are often smaller and harder to access.

1.3 Metal requirements of the energy transition

Materials and especially metals are not only crucial for the production of electronic gadgets; they are also indispensable for many future energy technologies. Hydrogen fuel cells and electrolysis depend on platinum as a catalyst, Carbon Capture and Sequestration (CCS) requires stainless and other special steels for pipelines and capture installations, thin-film photovoltaic (PV) solar cells require exotic materials like indium and gallium, electric vehicles use lithium or lanthanum in their batteries, new-generation direct-drive wind turbines use neodymium- and dysprosium-containing permanent magnets, and this list goes on.

Climate science tells us that we require a transition from our current fossil fuel-based energy system to a low-carbon energy system within the next few decades. This raises the question whether the supply of metals can keep up with demand if these low-carbon technologies are scaled up to substantial levels. This is one of the key questions addressed in this dissertation. Pioneering work in this field has been done at Chalmers University in Göteborg, Sweden (Andersson and Råde 2001; Råde 2001; Abelson and Hammond 1976; Andersson 2001). Andersson and Råde have made detailed analyses of the material requirements of two specific technologies: PV solar cells and batteries for electric vehicles. Their analysis was based on forecasts of the introduction of these technologies and they concluded that the supply of certain metals might be an important constraint for specific technologies if no additional measures were taken to secure future supply.

1.4 Relation of metal scarcity to other issues

The topic of mineral scarcity cannot be interpreted as an isolated issue. In this dissertation some of the linkages between metal scarcity and other scarcities and environmental issues are described. Although the study of the linkages among these various scarcities is still in its infancy, Graedel and van der Voet have dedicated a whole volume to probing this topic (Graedel and van der Voet 2010). In the first place, energy is required for the extraction of minerals and we will need more energy per kg material in the future than we did in the past. Energy is needed mainly in form of diesel in mining and in the form of coke (partly as reducing agent) and electricity to free the metals from their ores. With respect to copper and nickel, Norgate reports an exponential increase in the energy demand of both mining and refining with decreasing ore grade (Norgate 2010). At the same time, we will also need huge amounts of minerals to tackle the problem of climate change. As will be shown in Chapter 3 and 4, most low-carbon energy technologies are more metal-intensive than their current fossil fuel-based counterparts. Furthermore, the mix of materials within these low-carbon energy technologies is often more complex, too. This follows naturally from the fact that it is a move from highly concentrated energy sources (fossil fuels) to diffuse energy sources (wind, sunlight, etc.). Another crucial resource that is needed in mining operations is water. It is used in the mining itself but above all in the refining processes (Humphreys 2010; Mudd 2010). Mudd identifies increasing water use and competition for water as a key issue for the future of mining in Australia.

The extraction and refining of ores also contributes significantly to other environmental problems. Landscape destruction and the disposal of mining overburden, including leakages of toxics and accidents with waste water reservoirs and tailing ponds, are perhaps the most obvious impacts². The energy used in mining and processing contributes significantly to the emission of greenhouse gases. In Australia mining accounts for 10% of total direct GHG emissions (Australian Government 2010). These environmental impacts will increase as ore grades decline. As discussed earlier, it is even argued that environmental costs will be the main constraint on material supply in the future (Mudd 2010). And last, but certainly not least, there are the social and geopolitical issues associated with the extraction of resources. Workers' safety and health are important issues in the mining and refining of metals, especially in developing countries. Furthermore, there are significant ethical issues related to the massive flow of resources from the developing world to the developed countries and emerging economies.

² The most recent example was the tailings dam failure at Kolontar, Hungary in October 2010, involving 700,000 cubic metres of red mud from a bauxite mine. A list of major tailings dam failures can be found at <http://www.wise-uranium.org/mdaf.html>.

1.5 Methods and tools for analysing the complex interactions between material flows

The use of materials lies at the heart of almost all the environmental problems with which we are confronted today. Climate change, pollution and depletion are all directly linked to the way we use natural resources. Early work on Industrial Metabolism (Ayres 1989) has paved the way for a more systemic analysis of the material flows in society. In the 1980s and 1990s consistent frameworks for analysis (tools) were developed to analyze material flows within the emerging field of Industrial Ecology. Economy-wide material and substance flow analysis (MFA and SFA) are now used systematically in many countries to analyze the flows of all or selected materials. Life Cycle Assessment (LCA) is a widely accepted tool for analysing the material flows and related environmental impacts associated with a unit product or service. Environmentally extended Input Output Analysis (E-IOA) is now being developed for economy-wide analysis of production and consumption, including environmental impacts. Although the field of Industrial Ecology is still young as a scientific discipline, these tools are now widely used as policy-supporting instruments within private companies, NGOs and national and international governmental institutions.

LCA can be used as a tool to analyse the metal requirements of different energy technologies. It has the major advantage of being a comprehensive approach in which the entire life cycle is taken into account. This means that not only the materials in the wind turbines or CO₂ capture facilities are taken into account, but also all those used in the production of components, extraction of raw materials, maintenance and processing of waste. The LCA approach therefore yields a more complete picture of the full range of materials required for producing electricity. However, LCA also has several important limitations. First of all, the level of detail in LCA databases is limited. This is a problem when there is a need to quantify the volumes of scarce elements which are used in relatively small amounts. Thus, LCA databases are not very suitable for answering questions relating to the amount of rare earth elements used in computers, for example. Even if one specified the amounts of rare earth elements used in the production of hard disks themselves, the LCA would add very little information on the use of these scarce elements in the background processes (e.g. the production of the materials and electricity needed to produce the hard disk), simply because the level of detail on the background processes in the LCA database is too low. The LCA approach would therefore have little added value when endeavouring to answer such a question. LCA is therefore not particularly suitable for calculating the total amount of minor metals used to produce a product or service.

Another important limitation is the fact that the use of a static database for background data implies that it can only be employed to analyse the impacts of minor changes, i.e. those that do not change the current production system in any significant way. A case in point would be the analysis of the effects of an overall change in our energy system. LCA is perfectly suitable for comparing 1 kWh produced with a coal-

fired power plant with 1 kWh produced with a PV solar cell. However, if the question is to quantify the implications of a national-scale transition from coal-fired power plants to PV solar cells, traditional LCA cannot provide an answer. In a traditional LCA only the foreground processes are specified by the user, in this case typically the production and use of the PV solar cell. All the other production processes are taken from a static LCA database that contains processes like the production of steel and concrete, transport *and* electricity production – which in the database is based on the energy mix currently used. The aluminium used in the PV module is therefore produced using the electricity deriving from the current mix. In order to identify the implications of a national energy transition, then, the background database needs to be modified. However, the energy mix will not be the only thing to change if a national energy transition takes place. The entire grid would change, buffer capacity would need to be installed, the industry would change its focus, land use might change from agriculture to PV solar farms, which in turn would lead to larger food imports, and so on.

Integrated Assessment (IA) tools and Material and Substance Flow Analysis (MFA/SFA) are much more suitable tools for the analysis of system-wide transitions. However, both have limitations of their own. Material Flow Accounting is often focused on generating single indicators in which material use is aggregated based solely on mass and proceeds from a very high level of aggregation (one nation, or just a few sectors), while Substance Flow Analysis focuses on a single (group of) substance(s). Integrated Assessment tools also proceed from a very high level of aggregation of processes and sectors and lack the life cycle perspective. Although several attempts have been made to include these dynamics in the framework of traditional LCA, it is clear that an alternative analysis framework is required that permits analysis of system-wide transitions and includes a life-cycle perspective. To fill this gap, Life Cycle Sustainability Analysis (LCSA) has recently been introduced (Guinée and Heijungs 2011).

1.6 Aim, scope and contents

The aim of this dissertation is to analyze the problem of metal scarcity, specifically in the context of the introduction of new energy technologies, and to assess the potential for using analytical tools from the realm of Industrial Ecology and Integrated Assessment to include the complexity of material flows through society in sustainability analyses.

This leads to the following research questions:

1. How did the use of metals co-evolve with human progress and what was the role of metals scarcity in that process?
2. What was the nature of scarcity in previous eras and what was its nature perceived to be at the time? And how does the current scarcity situation and scarcity debate differ from those in the past?
3. What are the metal requirements of the transition to a low-carbon energy system and will these requirements constrain the scale-up of individual technologies or constrain the pace of the energy transition as a whole?
4. Will these metal requirements, combined with other types of demand, lead to significant scarcity in the short- and medium-term future?
5. What are the possibilities and limitations of Industrial Ecology and other analytical tools when it comes to including the real complexity of material flows in societies in sustainability analyses?

In Chapter 3 of this dissertation the analysis of the material requirements of low-carbon energy technologies is taken a step further in two ways. First of all a back-casting approach is used to analyze the metal requirements for the scenario of a future hydrogen economy (2050) based entirely on renewable energy sources. Secondly, the whole energy system is taken into account, from energy capture by wind turbines and PV solar cells and hydrogen production through transmission via power lines and hydrogen pipelines to end-use in fuel cells and electric motors. The main rationale behind this part of the study is that we need a massive and rapid transition to a low-carbon energy system in order to avoid catastrophic climate change. It is therefore useful to take a complete transition to a renewables-based energy system as a starting point for identifying possible material constraints that might hinder such a transition.

Chapter 4 focuses on the metal requirements of electrical power generation, and here the analysis is taken one step further by including the life-cycle perspective. Life Cycle Assessment is used to calculate the metal requirements over the entire life cycle of power generation, including the mining and transport of fossil fuels and the materials required to produce wind turbines, solar cells and the infrastructure for capturing and sequestering carbon dioxide. The metal requirements of three electricity mixes, based on three future scenarios for electricity production, are compared. The first is a mix based on a scenario in which Carbon Capture and Sequestration (CCS) is applied to all fossil fuel-based energy systems. The second is based on a complete transition to non-fossil energy sources (PV-solar, wind, biomass, hydro and nuclear). The final electricity mix is taken from the IEA Blue map scenario and consists of a mix of fossil fuels with and without CCS and non-fossil energy sources. The metal requirements of all mixes were then compared with current mining output in order to identify possible supply bottlenecks on a global scale.

In Chapter 5 current and future trends in the supply and demand of metals are analysed, in an attempt to answer the question whether or not materials scarcity might constrain the development of society. Metals are of special interest, first of all because

approximately three-quarters of all naturally occurring elements are in fact metals. Secondly, their specific properties makes them suitable for making complicated, strong and yet ductile structures through a process of melting and moulding.

In Chapter 6 the limited scope of both Industrial ecology and Integrated Assessment tools, and thus the need for a new analysis framework, is illustrated with the example of a hypothetical ban on PVC. It is shown that the complex interactions within a small subsector of the economy, the chlorine industry, can have unexpected macro-scale implications.

In Chapter 7 the overarching conclusions of this dissertation are presented, followed by a general discussion and a proposal for a research agenda.

References

- Abelson, P. H. and A. L. Hammond. 1976. The New World of Materials. *Science* 191(4228): 633-636.
- Ad-hoc Working Group on defining critical raw materials. 2010. *Critical raw materials for the EU*. Brussels European Commission.
- American Physical Society & Materials Research Society. 2011. *Energy Critical Elements: Securing Materials for Emerging Technologies*. APS & MRS.
- Andersson, B. A. 2001. Material Constraints on Technology Evolution: The Case of Scarce Metals and Emerging Energy Technologies thesis, Department of Physical Resource Theory, Chalmers University of Technology and Göteborg University, Göteborg.
- 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.
- Angerer, G., L. Erdmann, F. Marscheider-Weidemann, M. Scharp, A. Lüllmann, V. Handke, and M. Marwede. 2009. *Rohstoffe für Zukunftstechnologien*. Stuttgart: Fraunhofer-Institut für System- und Innovationsforschung ISI.
- Australian Government. 2010. *Australian national greenhouse accounts, National Inventory by Economic Sector 2008*. Department of Climate Change and Energy Efficiency.
- Ayres, R. U. 1989. Industrial metabolism and global change. *International Social Science Journal* 121: 363-373.
- Geiser, K. 2001. *Materials matter: towards a sustainable materials policy*. Edited by R. Gottlieb, *Urban and industrial Environment*. Cambridge, Massachusetts: The MIT Press.
- Gilmour, B. 2009. Specialisation in iron- and steel-making in the early Middle East and Central Asia: myths, assumptions and reassessment of early manuscript evidence. In *Metallurgy and civilisation, Eurasia and Beyond*, edited by J. Mei and T. Rehren. London: Archetype Publications Ltd.
- Graedel, T. E. and E. van der Voet. 2010. *Linkages of Sustainability*. Edited by J. Lupp, *Strüngmann Forum Reports*. Cambridge: MIT-press.
- Guinée, J. B. and R. Heijungs. 2011. Life Cycle Sustainability Analysis. *Journal of Industrial Ecology* 15(5): 656-658.
- Haglund, D. G. 1986. The new geopolitics of minerals: An inquiry into the changing international significance of strategic minerals. *Political Geography Quarterly* 5(3): 221-240.
- Humphreys, D. 2010. The great metals boom: A retrospective. *Resources Policy* 35(1): 1-13.
- International Energy Agency. 2010. *Key World Energy Statistics*. Paris: IEA.

Chapter 1

- Jensen, R. 1999. *The Dream Society*: McGraw-Hill.
- 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.
- Mudd, G. M. 2010. The Environmental sustainability of mining in Australia: key mega-trends and looming constraints. *Resources Policy* In Press, Corrected Proof.
- National Institute for Materials Science. 2008. *Study on global flow of metals - An example of material recycling* -. Tsukuba: National Institute for Materials Science.
- National Research Council. 2008. *Minerals, Critical Minerals, and the U.S. Economy* Washington D.C.: The National Academies Press
- 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.
- Oakdene Hollins. 2008. *Material Security, Ensuring resource availability for the UK economy*. Chester, Cheshire, UK: Oakdene Hollins.
- Pine, B. J. and J. H. Gilmore. 1999. *The Experience Economy: Work Is Theater & Every Business a Stage* Cambridge: Harvard Business Press.
- Råde, I. 2001. Requirement and Availability of Scarce Metals for Fuel-Cell and Battery Electric Vehiclesthe thesis, Department of Physical Resource Theory, Chalmers University and Göteborg University, Göteborg.
- Raymond, R. 1984. *Out of the Fiery Furnace: The Impact of Metals on the History of Mankind*. South Melbourne: MacMillan Company.
- Statistics Netherlands. 2010. *Critical materials in the Dutch economy, preliminary results*. The Hague: Statistics Netherlands.
- The President's materials policy commission. 1952. *Resources for Freedom, Summary of Volume I*. Washington: The President's materials policy commission.
- Truman, H. S. 1951. Letter to William S. Paley on the Creation of the President's Materials Policy Commission. <http://www.presidency.ucsb.edu/ws/index.php?pid=13876>. Accessed February 18 2011.
- U.S. Department of Energy. 2010. *Critical Materials Strategy*. Washington: U.S. Department of Energy.
- WTO. 2010. *World Commodity Profiles 2009*. Washington DC: WTO.

Chapter 2

A short history of the importance of metals for humanity and the debate on their scarcity

Metals that occur in their metallic form in nature have probably been used for as long as humans roam the world. It was probably some time in the 6th millennium BC that humans managed to develop the technology required to release metals from their ores. Since then, metals have had a profound impact on human society, most prominently through improvements in agriculture, the development of new technologies and in warfare. Today metals are an integral part of society and in many applications it is hard to imagine non-metallic substitutes.

For as long as metals have been used, scarcity has been an important issue. Precious metals are precious because they are scarce. In our time, gold, silver and the platinum-group metals are considered *precious* simply because ore deposits of these metals are relatively scarce. Their scarcity, together with their relative inertness, makes these metals eminently suitable for making jewelry. This, in turn, makes it a useful object for investment. In the time of the Egyptian pharaohs, however, iron was much scarcer simply because the technology to free iron from its ore was not yet available, despite iron-ore resources being very common. The same is true of aluminium, which was not freed from its ore until the late 19th century.

Shortages of metals have led to several periods of scarcity. The causes of these shortages have varied throughout history. Security of supply routes is one of the key issues that has caused shortages ever since metals were first introduced, right up until current times, with export quota for rare-earth elements currently a topic of discussion within the WTO. Today, the combination of the scale of the use of metals, the interdependency throughout global supply chains and the concentration of mining and refining in a limited number of countries mean the supply of metals is quite vulnerable. Another aspect of supply insecurity relates to the linkages between various different resources. In particular, the availability of energy and a suitable reducing agent have acted as limiting factors in the past. Until 1740 metal smelting was entirely dependent on wood as a source of energy and charcoal, which led to massive deforestation. In our era we face a deterioration of ore grades, which is increasing the demand for energy, water and land per kilogram of metal produced. At the same time, these resources are themselves under pressure from other types of use and through the environmental impacts associated with their use.

Finally, shortages of supply may be caused by the fact that supply simply cannot keep up with growing demand. Demand shocks have been the major cause of the supply shortages encountered over the last century. Until now these shortages were solved through additional investments and innovations in mining and exploration but, looking into the future, declining ore grades together with the linkages with other resources will make this considerably harder.

This chapter provides a brief summary of the historical development of the importance of metals for humanity and the scarcity associated with that use¹.

2.1 The importance and scarcity of metals pre-1740

For every living being the availability of sufficient resources is important to sustain its existence and that of its offspring. In nature this relates mainly to the availability of resources that fulfil basic needs, i.e. air, water, food and shelter.

Before the introduction of agriculture, around 8000 B.C., humans were dependent on the availability of game that could be hunted and food that could be gathered from nearby ecosystems. Key materials included animal products like bones and skins, and wood and other plant materials that could be used for providing shelter and fabricating simple tools. The main mineral resources used during what is now called the Stone Age were silicon-based: mud, clay, stones (e.g. flint) and rocks. The only metals that were used were those that could be found in their metallic or alloyed form: gold, silver, copper and meteoric iron/nickel alloys (Craig et al. 2011; Raymond 1984). Because of the scarcity of these metallic metals, their use was generally limited to ornaments. Use of these metals to be found in nature in their metallic form was widespread and occurred everywhere people and metals co-existed.

Climatic changes, population growth and the mass extinction of megafauna at the end of last ice age triggered a transition to an agricultural society, which in turn paved the way for the development of more complex societies (Ruddiman 2005; Tainter 1988)². During the period between 10,000 and 5,000 years ago, early agricultural societies were still Stone Age communities lacking the technology for metal smelting. From a mineral resource perspective, little had changed compared with the hunting and gathering era. Clay, stone and rock were still the main mineral resources in use. Around 9000 B.C. the techniques for making pottery from clay were developed, providing superior means of storing and transporting food and water. They also led to improvements in building methods, because of the development of bricks and glass. The techniques for freeing copper and other metals from their ores were probably discovered accidentally in fireplaces and pottery ovens made partially from ore-containing rocks. The heat together with charcoal as a reducing agent provided the right conditions to free the metal from its ore. Metal had three big advantages over stone: it was not as brittle, it could be readily formed into the desired shape and it

¹ A more comprehensive overview of the impact of metals on humankind can be found in a volume by Raymond (Raymond 1984). A more complete overview of the literature on resource scarcity is provided in an essay by Krautkraemer (Krautkraemer 2003), the works of Barnett and Morse, the revisit of the 1963 Barnett & Morse analysis by Simpson, Toman and Ayres (Simpson et al. 2005) and the works of Robinson, Geiser, Tilton and Radetzki (Robinson 1989; Geiser 2001; Tilton 2003; Radetzki 2008).

² Whether this transition from hunting and gathering to agriculture was by choice or a necessity caused by a growing population, and whether or not this was a good thing for humanity is debatable, as Jared Diamond does in his essay "The worst mistake in the history of the human race" (Diamond 1987).

could be recycled after a tool, ornament or weapon was broken (Raymond 1984; Craig et al. 2011). Early metallurgy was developed more or less independently at different times in different locations. The earliest metal smelting probably dates back to the 6th millennium BC in Mesopotamia. As in biological evolution, there is a growing body of evidence that the development of metallurgy not only proceeded through incremental improvements but also through a series of periods of rapid change and innovation. One example is given by what Chernykh calls an explosive development in the northern Balkans and the Carpathian basin during the Copper Age of the 5th millennium BC. He also describes how pastoral nomads formed an important link for the spread of metallurgical processes between what are now called Europe and the Middle East and China. However, he also notes that although some of the early technologies were imported from the West, the development of metallurgy in China proceeded in a fairly independent manner, spawning metallurgy that in many ways was much more advanced than in the West (Chernykh 2009).

In South America, both Peru and Colombia were rich in placer deposits³ of pure metals, mainly copper and gold. Beaten gold objects have been found that date back to around 2000 BC. Around the year 0 the technologies to smelt and cast metals were developed in Peru. In Colombia a material called 'tumbaga', an alloy of about 30% gold and 70% copper was very common. This alloy had the advantage that its melting point was lower (800 °C) than that of the individual metals (1064 °C and 1084 °C respectively) which made casting much easier. The Colombians were probably the first to use platinum, mixed with gold, which also occurred as small grains in placer deposits. In Australia there is no evidence of the use of pure metals until the arrival of the Europeans (Raymond 1984).

By 3000 BC other metals like silver, tin, lead and zinc were regularly extracted from their ores and bronze and bronze-like alloys were being produced in Eurasia. Metals became important mineral resources for society (Craig et al. 2011; Raymond 1984). Lead only became important when the Greeks and Romans started using it for piping and storing water. By combining copper with tin to form bronze a far less ductile metal was produced that gave societies the opportunity to produce more sophisticated craftwork, tools, weapons and armour. The start of the Bronze Age coincided with the development of the first major cities in Mesopotamia. Because of the dispersion of sources of copper and tin, the Bronze Age also marked the first time in human history that civilizations were dependent on foreign resources and long-range transport of minerals (Craig et al. 2011).

After bronze, some time around 1300-1000 B.C., iron (in the form of wrought iron) became the material of choice for tools, weapons and armour because it is much stronger and tougher than bronze (Craig et al. 2011; Raymond 1984). Although iron is far more abundant than copper, it is harder to extract from its ores. The fires that were used to melt bronze and copper were not hot enough to melt iron (1537 °C), but the soft iron that was produced was pounded and forged into the desired shape. There

³ Deposits of metals that are released from rocks through erosion and have accumulated in river beds.

is evidence that this technique was already known from the start of the Bronze Age, but that iron was avoided because of the inferior quality of the iron that was produced in the rudimentary production processes of the time. It was only after (local) shortages of copper and tin occurred that iron was used as an inferior substitute and that technologies to produce the superior-quality iron were gradually developed (Raymond 1984). This may have been the first time in human history that societies were confronted with the scarcity of metal resources that were truly important to their functioning. In this case the problem was solved by substitution of one metal by another, which led to a technological breakthrough and to the development of superior materials (wrought iron).

The Eurasian practice of iron extraction from ores probably had a common origin in Asia Minor in the early 2nd millennium BC. In pre-modern times, iron production from ores was confined to Eurasia; on other continents only meteoric iron was used, as a rarity. The basic invention of iron smelting was further developed along three different lines in Europe, the Middle East and central southern Asia and China (Gilmour 2009). In the 8th century BC the scale of the industry can be illustrated by a find of 163 tons of the metal in the form of mainly fish shaped bars in the palace of a neo-Assyrian ruler. Iron was probably introduced in China in the 9th to 8th century BC, probably through cultural interaction with western Asia. In China, which had a very rich tradition of bronze casting, the production of cast iron followed soon after the introduction of the metal. Cast iron objects have been found at a site in the province of Shangxi that date back to the 8th century BC (Han and Duan 2009; Guo 2009). In China, blast furnace technology was in use in the 1st century BC, almost 1500 years before it was introduced in Europe around 1340 (Wagner 1999). In a blast furnace, ore and charcoal are introduced at the top together with the *flux*, a mineral material that serves as a reducing agent and impurity absorbent, while air is blown in from the bottom. The main advantages of a blast furnace are that the temperature easily reaches the melting point of iron and that it can be used in a continuous process: ore, charcoal and flux can be added at the top while molten iron can be poured into casts from the bottom. This innovation made it possible to substantially increase the production of (cast) iron objects .

Steel, an alloy of iron and carbon (0.2-2%), which is much stronger and tougher than wrought iron and cast iron, was known long before its large-scale introduction in Europe in the 18th century. There are still many gaps in our knowledge about the development and dissemination of the technologies for producing steel. Steel swords dating back to the late 2nd millennium BC have been found in western Iran (Gilmour 2009). In India high-carbon steel artifacts have been found that were made between 800 and 400 BC (Srinivasan et al. 2009).

The first steel was probably made during *bloomery* iron production⁴. In this process part of the end-product, *the bloom*, with a high carbon content (1.2-1.7%), is separated

⁴ A bloomery is a simple chimney-like oven with an air inlet at the bottom (blown or draught) in which a mix of charcoal and iron ore is ignited. In its simplest form the bloomery creates conditions such that the

and subjected to a process of controlled decarburization consisting of repeated heating, forging and folding. This process is stopped when the carbon content has been reduced to 0.7-0.8%. There is some evidence that this process, which today is still used to make traditional Japanese Samurai swords, was used by the Romans to produce steel. Later, steel was produced by heating a mixture of pure or wrought iron together with a (biotic) source of carbon in a crucible (carburization) (Gilmour 2009). This process allowed for a more homogeneous distribution of the carbon, resulting in higher-quality steel. The crucible process was first developed in India around 600 BC and it was used to produce 'wootz', a type of steel that was highly valued throughout the world from 600 BC until the middle ages. In the Middle East, Indian wootz was used to make so-called 'Damascus steel' swords and daggers, which were far superior to other steels produced at that time owing to elemental impurities in the ores (including rare earths) and the accidental formation of carbon nanotubes in the production process (Tripathi and Upadhyay 2009; Raymond 1984; Reibold et al. 2006).

In Europe the large-scale application of cast iron started with the introduction of the blast furnace around AD 1340. This led to the ample availability of cheap iron objects, an important factor in the later industrial revolution. The main disadvantage of cast iron is that it has a high carbon content (2-4%), making it brittle. The development of the technology for larger-scale crucible steel production in the mid-18th century and the Bessemer process in 1858, both in England, marked two major breakthroughs for the truly widespread use of metals in society. Steel is now one of the most commonly used and most versatile materials. Iron mining now accounts for over 90% of all primary metal production (U.S. Geological Survey 2010). By changing its composition and by adding different kinds of alloys, the properties of steel can be tailor-made for many applications.

Although the large-scale use of metals was of key importance for military successes and for manufacturing tools and craftwork, until the industrial revolution the material basis of societies was still very much bio-based. Building and construction were based on a combination of wood and silicon-based materials like rocks and clay. Wood was the main source of energy and biomass was the main source of fibres. Even the economies of the ancient civilizations like the Greeks and Romans in Europe, the Shang and Zhou dynasties in China and the Maya civilization in the Americas were dominated by agricultural production (Tainter 1988). However, metals did play an important role in both in the military and agricultural realm, providing tools that allowed a significant increase in yields (Han and Duan 2009). Military success was important in economic terms only as long as the marginal returns of territorial expansion were favourable. When opponents were encountered that were of equivalent strength or of very low wealth, war became a bad investment (Tainter 1988; Han and Duan 2009).

iron oxide is reduced to iron, but with the temperature not high enough to actually melt the iron. The product is a mix of iron and slag, from which pure, carbon-free iron is then produced through a process of repeated hammering (Raymond 1984).

2.2 Metals and wood: interlinked until 1740

The fact that wood/charcoal was the only fuel that could be used for the smelting of metals created a strong link between abiotic and biotic resources. Perlin describes how Cyprus, which at the time had huge copper ore reserves, was deforested twice because of the need for fuel for copper smelting: during the Late Bronze Age between 1500-1200 BC and during the Roman annexation, starting in 50 BC. He also argues that Roman wealth was to a major extent financed through silver production in Spain, which led to the deforestation of over 18,000 km² of woodlands. He blames part of the economic problems of the Roman empire after 200 A.D. on declining silver production as result of fuelwood scarcity in Spain, even though ample quantities of ore still remained (Perlin 2005).

Perlin describes how the close link between iron smelting and wood remained intact until 1750, leading to massive deforestation in England from the 16th to 18th century. The scarcity of wood became a serious constraint on economic growth, even after coal had become an important energy source. Halfway through the 16th century the navy started complaining about the shortage of timber for shipbuilding. In the late 16th century coal starts to replace wood for heating, despite the 'foul fumes' it produced. Perlin quotes Josiah Tucker, an economist of the time, who attributes this scarcity to "*the superior numbers of people and to the rapid progress which the inhabitants of the island have lately made in all arts and sciences, trades and manufacturers.*" The impurities in coal made it impossible to make iron of sufficient quality from unprocessed coal. Only after the process to derive coke from coal was optimized in the 1740s could coal substitute for charcoal. This allowed for the tripling of iron production in England in the period from 1750 to the end of the 18th century (Perlin 2005). Again, the substitution of one resource by another was forced by scarcity, but again it led to a significant technological breakthrough that allowed for increased growth. Wood remained an important resource during the industrial revolution, though, since it was extensively used in coal mining, where timber props were used to hold up the mine shafts (Perlin 2005).

2.3 The industrial revolution, conservatism and resource economics (1740-1930)

Just prior to the industrial revolution, the scarcity of wood paved the way for the use of (inferior) coal as a household fuel. In coal mining, pumps were needed to pump off water, which led to the development of the steam engine: perhaps the key ingredient of the industrial revolution. This revolution triggered a period of rapid economic expansion in the Western world that was literally fuelled by the availability of a relatively cheap and apparently inexhaustible source of (fossil) energy. This economic growth coincided with a huge increase in the consumption of base metals such as iron, copper, zinc, tin and lead. These metals were needed for building new infrastructure, railways, bridges and modern cities as well as steam engines, trains, ships and cars. At

the same time, these new inventions and infrastructure provided a means of bulk transport and the heavy equipment and industry required for large-scale mining and refining (Burke 1978; Lundgren 1996).

Until the 18th century only nine metals were known to man: antimony, tin, lead, mercury, silver, copper, gold, iron and arsenic. From the time of the discovery of iron smelting, some 3000 years ago, it took until the late 19th century to find a way to free the only metal which is more abundant in Earth's crust: aluminum. The main reason for this late development was that aluminum oxide cannot be reduced to form aluminum metal by using carbon (charcoal or coke) as a reducing agent (the common process used to free other metals like iron and copper from their ores), simply because the chemical bond between aluminum and oxygen is stronger than that between carbon and oxygen. The industrial revolution and the introduction of cheap electricity paved the way for the electrolysis process that was used in the first commercial aluminum smelters, which became operational in the final decade of the 19th century (Raymond 1984).

About a century after the start of the industrial revolution the issue of fast-depleting (national/continental) resources, biotic, mineral as well as environmental, was recognized by governments and scientists. This resulted in a strong movement of conservationists, led amongst others by Theodore Roosevelt. In the US this resulted in the regulation of the use of natural resources and the creation of national parks. In 1908 Roosevelt called a special Governor's Conference on Conservation at the White House which focused on the depletion of natural resources within the US (Geiser 2001).

During the same period economists like Gray (1914) and Hotelling (1931) developed the first theoretical economic frameworks of so-called exhaustion theory (Gordon and Tilton 2008; Robinson 1989). One of the results of their efforts was the idea that a mine owner will always maximize the returns of the deposit by distributing the extraction over time (Hotelling 1931). The cake should thus be eaten at just the right rate to maximize the returns. For example, if the price of a resource is expected to rise in the future, the mine owner will halt extraction and wait for these higher prices. The reduced rate of extraction would drive up prices to a level equal to the anticipated future price. If this simplest version of Hotelling's exhaustion theory indeed holds, current resource prices would be a good indicator for future scarcity. However, Hotelling assumed completely rational actors with access to perfect information about the future and in practice, therefore, his theory does not hold.

A good example is the discovery of a giant gas field in the north of the Netherlands in 1959. This discovery was made at a time that the mainstream opinion was that science in general and nuclear power in particular would make energy virtually free. The Dutch government therefore decided that the natural gas in the Groningen field should be capitalized as soon as possible, i.e. before it became worthless. It started a huge infrastructural project to introduce natural gas as a fuel for domestic heating and cooking, for industrial and horticultural use and for power production. A dense distribution network of pipelines was constructed and long-distance pipelines were built to export the gas to other European countries. Of course, energy never became a free resource and current natural gas prices are much higher than those in of the 1960s, when this strategy of quick capitalization was implemented.

Since the publication of Hotelling's theory it has been refined frequently within the field of mineral economics which emerged as a separate academic discipline after World War II (Gordon and Tilton 2008).

2.4 World War II and the take-off of consumerism (1930-1970)

World War II led to huge worldwide destruction and rapid technological development. After the war this led to an increased demand for mineral resources for rebuilding the lost infrastructure and producing all the newly developed consumer goods. In addition, the supply of minerals was hampered by the dwindling resources in developed countries, the weakening or severing of colonial ties and the disruption of normal trade patterns caused by the start of the Cold War (The President's materials policy commission 1952; Geiser 2001). In the US *The President's Materials Policy Commission* (known as the Paley Commission after its chairman⁵) was established in 1951, during the Korean War. The commission was charged "*to make an objective inquiry into all major aspects of the problem of assuring an adequate supply of production materials for our long-range needs and to make recommendations which will assist me in formulating a comprehensive policy on such materials*" (Truman 1951). The commission's report laid down the basic principles of the material scarcity debate, including the formulation of possible policies and research agendas. It framed the depletion problem as a problem of resources that are harder to retrieve: "*The threat of the Materials Problem is not that we will suddenly wake up to find the last barrel of oil exhausted or the last ton of lead gone, and that economic activity has suddenly collapsed. The real problem and deeply serious threat is that we shall have to devote constantly increasing efforts to acquire each pound of materials from natural resources which are dwindling both in quality and quantity; thus finding ourselves running faster and faster in order to stay standing still. In short, the essence of the Material Problem is costs. The real costs of materials are not measured primarily in money; they lie in the hours of human work and the amounts of capital required to bring a pound of industrial material or unit of energy into useful form*".

⁵ William S. Paley was best known for his turning CBS into one of the largest broadcasting corporations in the US after he bought the company in 1927.

In many areas the commission's conclusions can easily be translated to current times. For example, it was stated that:

- technologies should be developed in the areas of exploration of new deposits, recycling, bio-based materials and substitution of scarce materials by more abundant ones;
- resources should be used less wastefully and that waste should be treated as a source of materials;
- there should be a shift of focus in the research community (both in academia and in private firms) from the generation of basic knowledge to the application of this knowledge;
- there is a trend towards more complex alloys and electronics that will require more exotic materials;
- there is a gap between developed Western nations that have depleted the best of their own resources and the developing world that is poor but still resource-rich. The commission argued that free trade and the income generated by exporting raw materials will help these developing countries to increase their standard of living, which in turn will lead to more exports of US high-tech products to these countries. It also emphasized the need to invest in resource-rich countries to improve their industrial capacity and infrastructure;
- despite many decades of resource depletion and wasteful resource use, resources had never before been in more ample supply and that therefore this might well be true for coming generations;
- the resource base of societies shifts over time and it is therefore hard to predict which resources should be saved for coming generations;
- industries are only interested in materials research when confronted with a crisis;
- the problems of resolving the scarcity of materials do not lie in the realm of high scientific difficulty but in costs;
- the problem of material scarcity cannot be solved only by physical science; social science, economics and political science are just as important and a combined effort by industry, academia and government is needed to resolve this issue;
- oil is a great energy source for now, but sooner or later a return to coal (possibly via underground gasification) and/or shale oil will have to be made. Energy efficiency is key to a sustainable energy supply and cars should be made far more efficient.

The commission took a strong stand against self-sufficiency as a leading principle for securing supply. In contrast, it propagated the Least Cost Principle as leading: the main aim of any resource policy should be to supply the nation's industry with the cheapest resources. It therefore also focused on international free trade and investing in resource-rich countries as something that should be promoted by policy makers. It also stated that tariffs and other restrictions on trade would have a detrimental effect

on the resource availability. However, at the same time it proposed the expansion of national stockpiling of materials and bilateral agreements with resource-exporting countries, both of which disrupt free markets and trade. The stockpiling strategy that followed until the end of the 1950s was in fact used to keep resource prices high in support of domestic mining in an attempt to retain self-sufficiency, and thus against the advice of the commission. It was driven by fears that the Cold War might turn into a hot war and that domestic supply of materials would be essential for victory. This policy resulted first in artificially high world market prices and, after the policy was abandoned, in huge stocks with a much depreciated value. In turn, these high prices gave foreign producers a chance to build their own mines and refineries, which after this period of stockpiling outcompeted US mines, with a disastrous effect on US mining (Huddle 1976).

All in all, the report of the Paley commission was a landmark in the debate on resource scarcity. Many of the arguments and analyses can readily be translated to the current debate. However, after the Korean War commodity prices relaxed and a period of relatively little concern about materials scarcity followed until the oil crisis of the 1970s (Radetzki 2008).

2.5 Environmentalism, the oil crisis and the framing of sustainability (1960-1980)

In 1952, mainly as a result of the Paley report, *Resources for the Future Inc.* (RfF) was established as *a non-profit corporation for research and education in the development, conservation and use of natural resources*. It was financed by the Ford Foundation and Paley himself took the job as Chairman of the board of directors. In 1963, RfF published a book by Barnett and Morse in which an empirical analysis was made of resource scarcity for the US in the period 1870-1958 (Barnett and Morse 1963). Their main conclusion was that no empirical evidence could be found for increased scarcity, but that in fact the availability of all resources had increased during that period, with the sole exception of forests.

However, the 1960s also marked the start of awareness of the environmental consequences of exponential growth in industrial activities and connected material flows. With her book “Silent Spring” Rachel Carson brought the environmental problems caused by the widespread use of persistent pesticides to public attention (Carson 1962). In 1968 Paul Ehrlich sketched a Malthusian doom scenario for the decades ahead (Ehrlich 1968). In his analysis, global food production would be unable to keep up with exponential population growth, and starvation would be the fate for millions.

In 1968 the Club of Rome was founded as a global think-tank on a variety of issues and in 1972 its report “The Limits to Growth” was published (Meadows et al. 1972). The report demonstrated the interdependence of the world’s economies and the

vulnerability of resource-importing countries to supply disruptions. As with the Paley report, the Club of Rome triggered a debate about materials scarcity and again much of the discussion of the 1970s can easily be translated to the debate underway today. Security of supply, strategic stockpiling, self-sufficiency, recycling and dematerialization were back on top of the political agenda.

The "Limits to Growth" report, which was published as a book, was unique because the first computers made it possible to create system dynamic models that could be used to calculate the effects of different scenarios on resource depletion and emissions. About a year later, in October 1973, the first oil crisis was a fact and the resource dependency that had been described by the Club of Rome moved from being an academic exercise to an event that disrupted everyday life in many parts of the world. If there was ever a time that resource scarcity received wide public attention, it was then. The report's main conclusion was that if the exponential growth of population, industrial activities and resource use remained unchecked, the result would be resource depletion and collapse of environmental quality by the middle of the 21st century. Although the report received a lot of criticism and certain assumptions were over-pessimistic, recent updates and analysis have shown that in many respects the global economy is still following the path of the scenarios described in "Limits to Growth" (Turner 2008).

The scientific community regained interest in the topic, which in February 1976 culminated in an entire issue of Science (Volume 191, Number 4228) containing 25 articles devoted to materials but with a focus on scarcity. Again, as with the Paley report, many of the articles can easily be translated to the current debate. The range of topics addressed in these articles show that the discussions of the problem, including possible strategies for solutions, are very similar to those at the time of the Paley Commission and the ongoing discussion today.

Cook discusses the limits to the exploitation of non-renewable materials (Cook 1976). His first observation is that in the previous two centuries the cost of resources has decreased and reserves have increased. However, he also finds that over the same period the energy intensity of resource recovery has increased as ore grades have declined. He argues that this can be explained by decreasing real costs of energy. He does not believe this trend will continue much further in the future, because of decreasing efficiency of the production and conversion of energy resources. He argues that the efficiency of energy conversion is approaching the thermodynamic limits, while the energy required for recovering certain resources is increasing exponentially. Similar arguments concerning thermodynamic limits of mining and refining efficiency can also be found in more recent work (Ayres 2007)

Blum discusses the possibility of tapping the resources present in municipal waste (Blum 1976). He recognizes that recycling is a means and not an end in itself. While terming municipal solid waste an "*urban ore*", he considers that although we have the technology to recover most of the components it contains it is not always

economically prudent to do so. Urban mining is now a common phrase that is used by waste processors and industrial ecologists when they discuss recycling and urban materials stocks (Kapur and Graedel 2006; Krook et al. 2011).

Chynoweth describes the importance of electronic equipment with respect to both the demand for more exotic materials and its potential to reduce demand for materials and energy (Chynoweth 1976). He starts by pointing out the enormous potential of miniaturization. As an example he takes the pocket calculator that replaced the electromechanical desk-top calculator, which was far bulkier and more materials-intensive. At the same time, however, he recognizes that electronics are more complex in terms of materials composition. In a telephone he counted 42 chemical elements, present as 35 metals and alloys, 14 types of plastic, 12 varieties of adhesives and 20 different semi-conductor devices. A similar study of current mobile phones has also found over 40 elements in these devices (Meskers and Hagelüken 2009). Chynoweth also discusses the vulnerability of the electronics industry to the export policies of raw material-producing countries. He concludes, though, that these risks for the sector are probably low, because the value of the materials is relatively low compared with the price of the products. The electronics industry would thus be better able than other industries to absorb raw materials price increases. When it comes to the potential for of raw materials substitution he is fairly negative, because the materials have already been chosen in such a way that the overall performance of components is optimized. More generally, he argues that *"the more a society depends on complex and sophisticated equipment, the more vulnerable it is to scarcities of certain key materials, even if these are used in very modest amounts"*. He also includes a Life Cycle thought in his analysis when he discusses, in quite similar fashion to Williams and Ayres a quarter of a century later (Williams et al. 2002), that although the amounts of materials in semi-conductor devices are themselves very small, a far great quantity of materials is required for their production: *"It could well turn out that the principle material constraint on the availability of electronic devices will not be in the electronic material itself, but the availability of the necessary processing chemicals. Also, it should be kept in mind that the small quantities of electronic materials often represent not insignificant expenditures of energy in obtaining them"*. He also examines the potential of electronics for reducing demand for materials through functional innovations. He mentions innovations that are common practice today, e.g. the potential for telecommunications to reduce personal travel, including telecommuting (*"communicating to work rather than commuting to work"*) and the internet (*"wired community"*). He goes on to give other examples that can now be found all around us: sensors that increase the efficiency of vehicle fuel combustion or monitor room occupancy to control lighting and heating.

Claassen describes the material needs of advanced energy technologies (Claassen 1976). Although climate change was not yet on the political agenda, he focuses on the materials required to increase the efficiency of existing energy technologies and the technologies to decrease dependency on exhaustible fossil fuels. Since many elements of energy infrastructure require thermal conversion processes, he argues that there is a need for materials that can resist higher temperatures. In general, higher temperatures

would allow for more efficient thermal energy conversion. Although in general he is not worried about shortages of supply of the materials needed to increase the efficiency of the energy system, he points out a number of examples where these problems might occur: 1) chromium, used in the alloys required in many parts of the system, mainly because it comes from a limited number of countries with unknown future political stability; 2) gallium arsenide, needed for thin-film PV cells, for which it is easy to calculate that reserves would not allow for substantial scale-up, and 3) platinum for fuel cells, for which the same holds true. He expected that solar cells would be based on abundant materials like silicon, copper and sulphur and that molten carbonate fuel cells with nickel-based electrodes would be a good alternative for fuel cells with platinum electrodes. Interestingly, all these issues are still being discussed today (Wadia et al. 2009; Råde and Andersson 2001; Kanan and Nocera 2008). He also sees a problem in the supply of equipment made from abundant bulk materials. To illustrate this, he points to shortages of steel pipes, generators and turbines, as well as draglines and mine trucks and other items with a long delivery lead time. Today, the extractive industry is still haunted by a triple pork cycle between material demand, mining investments and supplies of draglines, mining truck tyres and other mining equipment.

Carpenter describes the tension between materials and environmental quality (Carpenter 1976). He starts by framing the problem as a problem of rapidly increasing demand for raw materials, combined with a lack effective management of material flows which results in both depletion and pollution. He also discusses the fact that ore grades are deteriorating and that this will cause increasing energy requirements and environmental impacts of mining and refining. Again, these are issues that are still being debated today (Mudd 2010, 2007; Norgate and Haque 2010; Norgate 2010). He is not very positive about the bio-based economy and notes that agriculture is in itself an important source of diffuse pollutants like fertilizers and pesticides. He believes that economic instruments and the internalization of environmental costs in raw material prices are the best way to manage the environmental effects due to the production of these materials. This discussion is well reflected in today's debate on biofuels and bioenergy (Doornbosch and Steenblik 2007).

Fried discusses the international trade in raw materials (Fried 1976). He describes how the enormous fluctuations in raw material prices are due mainly to rapid changes in demand. He eases fears that resource-exporting countries might use their exports as a political weapon, as the OPEC did during the 1973 oil crisis, arguing that oil is unique in both in its importance and its unequal distribution over the globe and in the fact that there is an international organization governing exports (OPEC). He favours the free market without trade barriers as the best way to achieve an adequate supply of materials and does not believe in resource diplomacy. We have now seen that this depends very much on the type of mineral resource concerned and on the organization of the production chain. Although deposits of rare-earth elements can be found in many places on every continent, the fact that 95% of production is now in

the hands of a single country makes it a possible to use it as political weapon. Chinese export quota have led to official complaints within the framework of the WTO.

In 1980 a famous wager was entered by Julian Simon (with a background in business administration and business economics) and Paul Ehrlich (with a background in population studies and biology). In the late 1960s and 1970s Ehrlich had written a number of books and papers on the disastrous consequences of an exponentially growing population, predicting Malthusian collapse. Simon, a true cornucopian, believed that population growth should be regarded as growth of human capital, which he calls *the ultimate resource*, and thereby a source of innovation (Simon 1981). Simon asked Ehrlich to pick any raw material and any date in the future, further than a year away, and he would bet that the material's price on that date would be lower than at the time of the wager. Ehrlich and some of his colleagues chose copper, chromium, nickel, tin and tungsten and a period of 10 years starting in 1980. The outcome of the wager is illustrated in Figure 1-1.

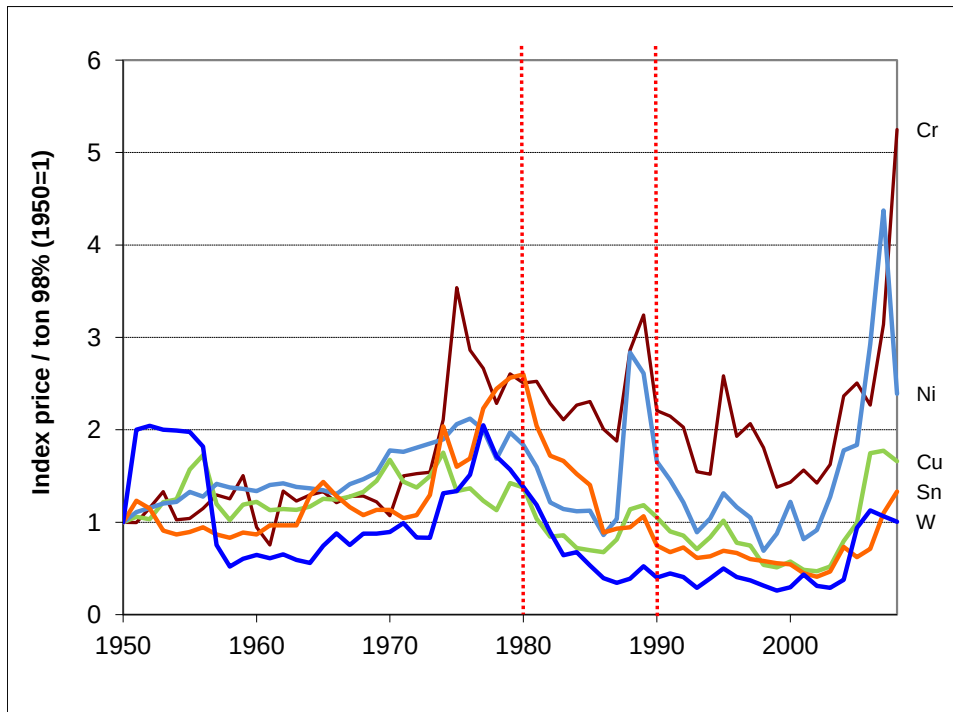


Figure 1-1: Index of price/ton 1998\$, 1950=1 for the metals included in the Simon - Ehrlich wager. Data source: USGS.

Figure 1-1 shows that Ehrlich and his colleagues lost the wager and that their timing was not very good. If the wager had been accepted two years earlier or five years later, Ehrlich would have won. Ehrlich explained the loss of the wager as a combination of the drop in oil prices in that period and the economic recession in the 1980s (Ehrlich

and Ehrlich 1998). However, in the period of the wager only the price of tin actually correlates well with the oil price. Furthermore, metal prices kept on decreasing through the 1990s, a period of global economic growth. Looking at the development of mining of different bulk metals (see Chapter 5) it seems more reasonable to assume that the reason that Ehrlich lost the wager was that metal demand per capita in the OECD stabilized in the period from 1975 to 2002.

2.6 Dematerialization in the OECD and the metals boom (1980-2011)

Again, this period of high commodity prices was followed by a period of relative abundance of cheap commodities. Bulk carriers were still getting larger and combined with low fuel prices this led to a period of extremely low transport costs (Lundgren 1996). The scale-up of mining also provided economic advantages, which pushed down metal prices despite annual growth rates in mine production of 3-6%. Metal prices remained low until what is referred to as the 'great metals boom' (Humphreys 2010), which in fact was a big boom of all commodities, as can be seen in Figure 1-2. The rapid exponential growth in emerging economies in the 1990s and 2000s increased demand in those countries from negligible to substantial around the year 2000. This boom in demand was mainly a result of the rapid build-up of the so-called BRIC countries, most notably China. During that period the prices of non-fuel commodities almost doubled in real terms.

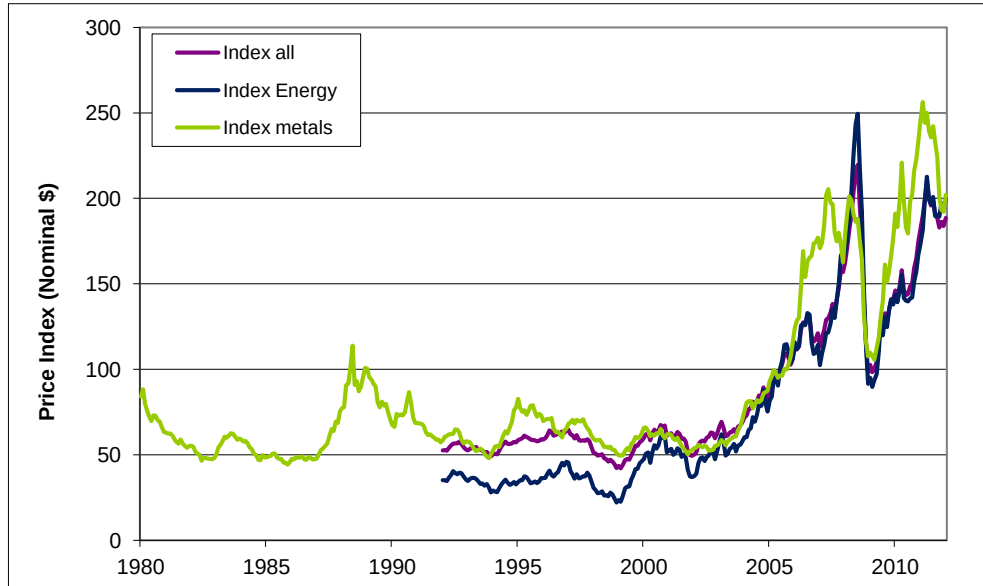


Figure 1-2: Price index of commodities, nominal \$. Data source: IMF.

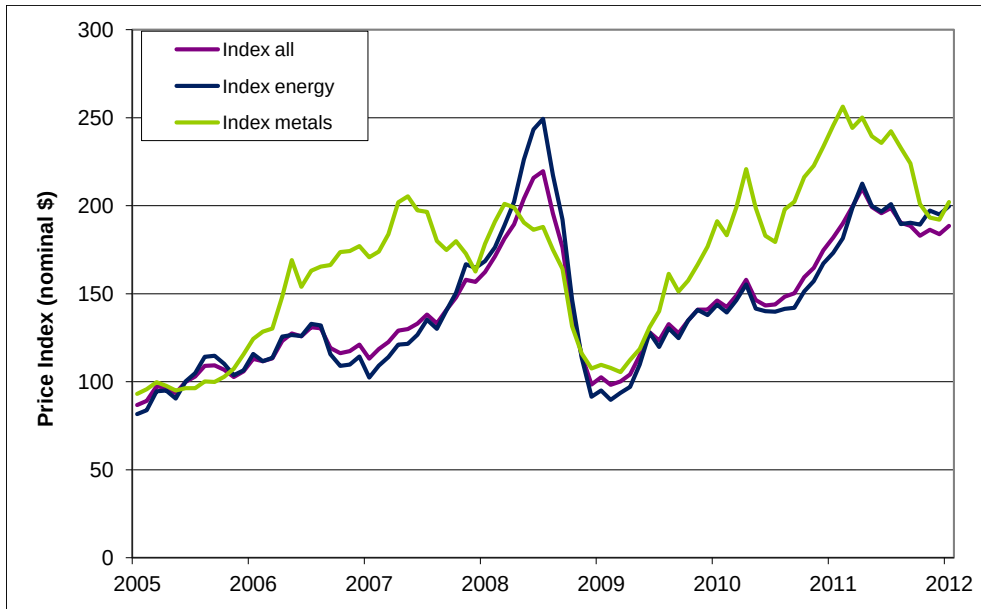


Figure 1-3: Price index of commodities, nominal \$, Data source: IMF.

Although the global financial crisis that started at the end of the summer 2008 caused a significant price decrease, prices only very briefly reached pre-2002 levels (Figure 1-2). Although the crisis lasted until mid-2009, non-fuel commodity prices started rising again as early as March 2009 (Figure 1-3). Prices peaked again in February-March 2011 at a level almost 20% higher than that of the 2008 peak. After that the European sovereign debt crisis again caused concern about the global economy, leading to a fall in commodity prices. In November 2011 non-fuel commodity prices were back at the level of the 2008 peak (Figure 1-3).

In the period between 2002 and 2011 a number of publications by authors well familiar with the mining industry showed concerns about the supply of metals (Humphreys 2010; Mudd 2007; Norgate 2010). Degrading ore grades, the decreased deposit size of newly found deposits, constraints in the supply of water and energy, and increased local and global environmental concerns were all cited as causing cracks in the supply lines.

As a result of the 2002-2008 metals boom and recent supply constraints on certain rare (earth) metals, many governmental organizations, NGOs and research organizations have issued reports in which critical materials for the local and global economy have been defined⁶. All the world's major economies are now assessing the

⁶ (RWI et al. 2006; National Research Council 2007; Morley and Eatherley 2008; National Institute for Materials Science 2008; Angerer et al. 2009; Ad-hoc Working Group on defining critical raw materials 2010; Statistics Netherlands 2010; U.S. Department of Energy 2010; American Physical Society &

possible impact of metals scarcity and policy measures, including the mechanisms of the WTO, to ensure free commodity trade, national stockpiles for strategic materials and bilateral agreements with supplier countries. The establishment of the UN Resource Panel is a clear sign that the international community deems resource-related issues to be a major concern for the coming decades.

The question is whether the current episode of apparent metals scarcity is any different from the scarcity episodes society has faced in the past. In the past, scarcity has always been a temporary issue and was followed by periods of abundance, either through technological progress increasing mining efficiency and allowing access to formerly unsuitable deposits, or through the scope for accessing new materials to replace the old ones. Will this happen in the present period of scarcity? There are some indications that solutions from the past now no longer work. This question will be addressed further in Chapter 5.

References

- Ad-hoc Working Group on defining critical raw materials. 2010. *Critical raw materials for the EU*. Brussels European Commission.
- American Physical Society & Materials Research Society. 2011. *Energy Critical Elements: Securing Materials for Emerging Technologies*. APS & MRS.
- Angerer, G., L. Erdmann, F. Marscheider-Weidemann, M. Scharp, A. Lüllmann, V. Handke, and M. Marwede. 2009. *Rawstoffe für Zukunftstechnologien*. Stuttgart: Fraunhofer-Institut für System- und Innovationsforschung ISI.
- Ayres, R. U. 2007. On the practical limits to substitution. *Ecological Economics* 61(1): 115-128.
- Barnett, H. J. and C. Morse. 1963. *Scarcity and Growth*. Washington: Resources for the Future.
- Blum, S. L. 1976. Tapping Resources in Municipal Solid Waste. *Science* 191(4228): 669-675.
- Burke, J. 1978. *Connections*. London: Macmillan.
- Carpenter, R. A. 1976. Tensions Between Materials and Environmental Quality. *Science* 191(4228): 665-668.
- Carson, R. 1962. *Silent Spring*. Boston: Houghton Mifflin Company.
- Chernykh, E. 2009. Ancient metallurgy in the Eurasian steppes and China: problems of interactions. In *Metallurgy and civilisation*, edited by J. Mei and T. Rehren. London: Archetype Publications Ltd.
- Chynoweth, A. G. 1976. High Technology Materials. *Science* 191(4228): 724-732.
- Claassen, R. S. 1976. Materials for Advanced Energy Technologies. *Science* 191(4228): 739-745.
- Cook, E. 1976. Perspectives on Needs and Supplies of Resources. *Science* 191(4228): 676-682.
- 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.
- Doornbosch, R. and R. Steenblik. 2007. *Biofuels: is the cure worse than the disease?* . SG/SD/RT(2007)3. Paris: OECD.
- Ehrlich, P. and A. Ehrlich. 1998. *Betrayal of Science and Reason: How Anti-Environmental Rhetoric Threatens Our Future*. Island Press.

Chapter 2

- Ehrlich, P. R. 1968. *The population bomb, A Sierra Club-Ballantine book*. New York: Ballentine Books.
- Fried, E. R. 1976. International Trade in Raw Materials: Myths and Realities. *Science* 191(4228): 641-646.
- Geiser, K. 2001. *Materials matter: towards a sustainable materials policy*. Edited by R. Gottlieb, *Urban and industrial Environment*. Cambridge, Massachusetts: The MIT Press.
- Gilmour, B. 2009. Specialisation in iron- and steel-making in the early Middle East and Central Asia: myths, assumptions and reassessment of early manuscript evidence. In *Metallurgy and civilisation, Eurasia and Beyond*, edited by J. Mei and T. Rehren. London: Archetype Publications Ltd.
- Gordon, R. L. and J. E. Tilton. 2008. Mineral economics: Overview of a discipline. *Resources Policy* 33(1): 4-11.
- Guo, W. 2009. From western Asia to the Tianshan Mountains: on the early iron artefacts found in Xinjiang. In *Metallurgy and civilisation*, edited by J. Mei and T. Rehren. London: Archetype Publications Ltd.
- Han, R. and H. Duan. 2009. An early iron-using centre in the ancient Jin state region (8th-3rd century BC). In *Metallurgy and civilisation*, edited by J. Mei and T. Rehren. London: Archetype Publications Ltd.
- Hotelling, H. 1931. The Economics of Exhaustible Resources. *The Journal of Political Economy* 39(2): 137-175.
- Huddle, F. P. 1976. The Evolving National Policy for Materials. *Science* 191(4228): 654-659.
- Humphreys, D. 2010. The great metals boom: A retrospective. *Resources Policy* 35(1): 1-13.
- Kanan, M. W. and D. G. Nocera. 2008. In Situ Formation of an Oxygen-Evolving Catalyst in Neutral Water Containing Phosphate and Co²⁺. *Science* 321(5892): 1072-1075.
- Kapur, A. and T. E. Graedel. 2006. Copper Mines Above and Below the Ground. *Environmental Science & Technology* 40(10): 3135-3141.
- Krautkraemer, J. A. 2003. Economics of scarcity: State of the debate: UC Davis.
- Krook, J., A. Carlsson, M. Eklund, P. Frändegård, and N. Svensson. 2011. Urban mining: hibernating copper stocks in local power grids. *Journal of Cleaner Production* 19(9-10): 1052-1056.
- Lundgren, N.-G. 1996. Bulk trade and maritime transport costs : The evolution of global markets. *Resources Policy* 22(1-2): 5-32.
- Meskers, C. E. M. and C. Hagelüken. 2009. Closed loop WEEE recycling? Challenges and opportunities for a global recycling society. Paper presented at TMS 2009 Annual Meeting & Exhibition, February 15-19, 2009, San Francisco, California, USA.
- Morley, N. and D. Eatherley. 2008. *Material Security, Ensuring resource availability for the UK economy*. Chester, Cheshire, UK: Oakdene Hollins.
- Moss, R. L., E. Tzimas, H. Kara, P. Willis, and J. Kooroshy. 2011. *Critical Metals in Strategic Energy Technologies Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies* EUR 24884 EN. Petten, The Netherlands: European Commission, Joint Research Centre, Institute for Energy and Transport
- Mudd, G. M. 2007. An analysis of historic production trends in Australian base metal mining. *Ore Geology Reviews* 32(1-2): 227-261.
- Mudd, G. M. 2010. The Environmental sustainability of mining in Australia: key mega-trends and looming constraints. *Resources Policy* 35(2): 98-115.
- National Institute for Materials Science. 2008. *Study on global flow of metals - An example of material recycling* -. Tsukuba: National Institute for Materials Science.
- National Research Council. 2007. *Minerals, Critical Minerals, and the U.S. Economy* Washington D.C.: The National Academies Press

- 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.
- Råde, I. and B. A. Andersson. 2001. *Platinum group metal resource constraints for fuel-cell vehicles*. PRT Report 2001:01. Göteborg, Sweden: Chalmers University of Technology and Göteborg University.
- Radetzki, M. 2008. *A Handbook of Primary Commodities in the Global Economy*. Cambridge UK: Cambridge University Press.
- Raymond, R. 1984. *Out of the Fiery Furnace: The Impact of Metals on the History of Mankind*. South Melbourne: MacMillan Company.
- Reibold, M., P. Paufler, A. A. Levin, W. Kochmann, N. Patzke, and D. C. Meyer. 2006. Materials: Carbon nanotubes in an ancient Damascus sabre. *Nature* 444(7117): 286-286.
- Robinson, T. J. C. 1989. *Economic theories of exhaustible resources*. London: Routledge.
- Ruddiman, W. F. 2005. *Plows Plagues & Petroleum, How humans took control of climate*. Princeton & Oxford: Princeton University Press.
- RWI, Fraunhofer ISI, and BGR-BA für Geowissenschaften Rohstoffe. 2006. *Trends der Angebots- und Nachfragesituation bei mineralischen Rohstoffen*. . Essen, Germany: RWI.
- Simon, J. L. 1981. *The ultimate resource*. Martin Robertson.
- Simpson, R. D., M. A. Toman, and R. U. Ayres, eds. 2005. *Scarcity and growth revisited: natural resources and the environment in the new millennium*. Washington: Resources for the Future.
- Srinivasan, S., C. M. Sinopoli, K. D. Morrison, R. Gopal, and S. Ranganathan. 2009. South Indian Iron Age and high carbon steel: with reference to Kadebakele and comparative insights from Mel-siruvalur. In *Metallurgy and civilisation*, edited by J. Mei and T. Rehren. London: Archetype Publications Ltd.
- Statistics Netherlands. 2010. *Critical materials in the Dutch economy, preliminary results*. The Hague: Statistics Netherlands.
- Tainter, J. A. 1988. *The collapse of complex societies*. Cambridge UK: Cambridge University Press.
- The President's materials policy commission. 1952. *Resources for Freedom, Summary of Volume I*. Washington: The President's materials policy commission.
- Tilton, J. E. 2003. *On borrowed time ? Assessing the threat of mineral depletion*. Washington: Resource for the future.
- Tripathi, V. and P. Upadhyay. 2009. Survival of traditional Indian ironworking In *Metallurgy and civilisation*, edited by J. Mei and T. Rehren. London: Archetype Publications Ltd.
- Truman, H. S. 1951. Letter to William S. Paley on the Creation of the President's Materials Policy Commission. <http://www.presidency.ucsb.edu/ws/index.php?pid=13876>. Accessed February 18 2011.
- Turner, G. M. 2008. A comparison of The Limits to Growth with 30 years of reality. *Global Environmental Change* 18(3): 397-411.
- U.S. Department of Energy. 2010. *Critical Materials Strategy*. Washington: U.S. Department of Energy.
- U.S. Department of Energy. 2011. *Critical Materials Strategy*. DOE/PI-0009. Washington: U.S. Department of Energy.
- U.S. Geological Survey. 2010. *Mineral Commodity Summaries 2010*. U.S. Geological Survey.
- US Under Secretary of Defense for Acquisition, T. a. L. 2011. *Assessment and Plan for Critical Rare Earth Materials in Defense Applications, Interim Report* Washington DC: US Departments of Defense.

Chapter 2

- 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.
- Wagner, D. B. 1999. The earliest use of iron in China. In *Metals in antiquity*, edited by S. M. M. Young, et al. Oxford: Archaeopress.
- 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.

Chapter 3

Resource constraints in a hydrogen economy based on renewable energy sources: an exploration.

Abstract

In order to tackle climate change, a transition to a renewable based energy system is crucial. A renewable based hydrogen economy is one of the possible implementations of such a system. The world receives ample energy from the sun that can be harvested by PV solar cells and, indirectly, by wind turbines. In order to use the most optimal locations for collecting and concentrating energy from these diffuse sources a long distance transmission network is needed. Mature and semi-mature technologies are available for all parts of the system: from collection to transmission to end-use. In an early stage the development, when new technologies have to win market share from the existing energy system, their development is driven almost exclusively by the reduction of costs per J delivered. However, if a technology should be able to deliver tens to hundreds of EJ, resource constraints can become show-stoppers. Many of the newest, most cost-efficient, energy technologies make use scarce resources and, although they may play an important role in the transition process, they cannot be scaled up the level we need for a complete transition. In most cases however other technologies are available that use more abundant materials, be it often at a cost of efficiency. The issue is not only with scarce resources. The sheer size of the energy transition will also challenge the industrial capacity for the mining and production of bulk materials like steel and copper.

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3.1 Introduction

The world is preparing for a transition from a fossil fuels based energy system to a system of renewable energy. One important option being discussed is the so-called hydrogen economy (European Commission 2003; The White House 2004; U.S. Department of Energy 2004; Okano 2003): an energy system relying on hydrogen as its main energy carrier, instead of fossil fuels. This envisaged transition is partly driven by concerns about the environmental impact, especially global warming, connected to the current energy system, and partly by arguments related to security of energy supply.

Large-scale transitions cause many changes in society. It is a good idea, therefore, to assess beforehand what the consequences might be of such a transition. These consequences can be various. A first question is: does it actually solve the problem it is supposed to solve? Although a hydrogen economy is generally propagated as a "clean"

alternative for the current fossil fuel based economy, it is the question how "clean" this hydrogen economy truly may be. Even if renewable energy sources would be used to produce hydrogen, a number of environmental issues would remain whilst additional new problems might occur. In a hydrogen economy, hydrogen and water are emitted. The emission of molecular hydrogen has been the topic of a debate on the possible effects of these emissions, specifically on stratospheric ozone and on climate change (Tromp et al. 2003; Schultz et al. 2003; Prather 2003).

A second question relates to the feasibility of such a new system. Can it actually be built and implemented? When starting to envisage what a hydrogen economy would look like, a first step is to conceive a technological description of such a system. The production, transport and use of hydrogen as a fuel requires a whole series of new processes, materials, products and infrastructure which all will require resources and will have an environmental impact of their own. The same is true for the actual generation of energy, which in a renewable energy system will be done by other means than combusting fossil fuels, for example by using solar cells, wind power, biomass etc. There is a high risk of running into resource constraints of one sort or another, simply because of the stunningly large scale of such a transition.

In this article, we will address this last issue, as a very important one. The central question in this paper is the following: Will a transition to a hydrogen economy based on renewable energy sources run into resource constraints? In order to answer this question we try to create a picture of a world with hydrogen and electricity as the main energy carriers and renewables as the only energy source. We will, as well as possible, quantify the main parts of such a system, and we will assess whether or not resource constraints can be expected. Although it is clear to us that a world without fossil fuels is an extreme case (Odell 2004). and there will be many hurdles on the way towards such a world, the dynamics of the transition process itself will not be addressed in this exploratory work. Also, we will not address economic and social consequences or the difficulties of actually realizing the transition politically or legally. It will be a technical description, targeted at the issue of potential "show stoppers" in a technical sense.

3.2 Core assumptions in the case study

For the technical specification of a renewables based hydrogen economy, we have defined the following starting points:

- the case describes a hypothetical energy system, roughly in the year 2050; the path towards this situation is not a part of the study;
- basic data like population, GDP and energy demand in 2050 are taken from the UNEP Markets First Scenario, see Table 3-1 (UNEP 2002);
- although in the Markets First Scenario the bulk of the primary energy still comes from fossil fuels, we describe a purely hypothetical situation in which all energy comes from renewable sources;
- we assume that the role of biomass based energy will be limited;

- we assume that the renewables mix for primary energy will be 80% PV solar, 15% wind and 5% other (renewable) sources;
- electricity and hydrogen are considered the only two energy carriers.

These starting points are elaborated below.

Table 3-1: Key variables of the IPCC SRES Markets First Scenario

	1990	2050	unit	multiplier
population	5302	9386	million	1.8
GDP	25293	191767	billion US \$ (1995)	7.6
primary energy use	356	1278	EJ	3.6

Source: (UNEP 2002).

3.2.1 Base year & scenario

The choice for the year 2050 is rather arbitrary as a year which is sufficiently far in the future to envisage a novel energy system while not too distant to still have reasonable estimates of basic data like world population and GDP. Furthermore, if we seriously want to address climate change the energy system needs to change dramatically within this time frame. The Markets First Scenario was chosen because (1) it is most in line with current world economic and demographic developments and (2) it results in a relatively high future energy demand which makes it a worst case. The Markets First scenario envisages a world in which market-driven developments converge on the values and expectations that prevail in industrialized countries (UNEP 2002). World integration, globalization, free trade and reliance on market-based approaches are the main directions for development. GDP/capita and energy consumption/capita both grow rapidly in this scenario between now and 2050.

3.2.2 Renewables only

In the Markets First Scenario, the total primary energy production in 2050 will be about 1300 EJ, more than 2.5 times the primary energy use in 2005 (about 514 EJ) (see Table 3-1). In almost all current projections of future energy use fossil fuels will still be the dominant source of energy in the coming decades (IEA 2007; Shell 2008). However, in our extreme case study we assume that all energy is generated from renewable sources. In the Markets First scenario, where globalization and free trade rule, the primary energy mix will be dependent on local availability and world market prices. If one looks at the potential availability of the different renewable sources (Table 3-2) it is clear that the bulk of the primary energy in the Markets First scenario will have to come from wind and solar power.

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Table 3-2: Availability of renewable energy (excluding biomass and extraterrestrial collection)

	W	J/a	multiplier for 1990 energy use ($3.56 \cdot 10^{20}$ J)	multiplier for 2050 energy use in MF scenario ($1.28 \cdot 10^{21}$ J)	source
Solar					
solar energy reaching Earth surface	$2.6 \cdot 10^{16}$	$8.2 \cdot 10^{23}$	2303	642	(Sørensen 2000)
collectable in Sahara desert with current PV efficiency (10%)	$2.1 \cdot 10^{14}$	$6.5 \cdot 10^{21}$	18	5	Calculated
Wind					
total kinetic energy in Earth atmosphere	$3.5 \cdot 10^{15}$	$1.1 \cdot 10^{23}$	310	86	(Leijendeckers et al. 2008)
total in bottom 100 meter	$1.3 \cdot 10^{15}$	$4.0 \cdot 10^{22}$	113	31	(Leijendeckers et al. 2008)
maximum practically realizable	$5.7 \cdot 10^{12}$	$1.8 \cdot 10^{20}$	0.51	0.14	(Williams 2001)
technical potential	$1.5 \cdot 10^{13}$	$4.8 \cdot 10^{20}$	1.3	0.37	(Hoogwijk 2004)
Hydro					
on basis of precipitation on land	$1.0 \cdot 10^{13}$	$3.0 \cdot 10^{20}$	0.8	0.2	(Sørensen 2000)
principally available	$1.2 \cdot 10^{12}$	$3.8 \cdot 10^{19}$	0.11	0.030	(Sørensen 2000)
realistic reserve hydro	$6.3 \cdot 10^{11}$	$2.0 \cdot 10^{19}$	0.055	0.015	(Sørensen 2000)
Tidal					
total tidal energy	$3.0 \cdot 10^{12}$	$9.5 \cdot 10^{19}$	0.27	0.074	(Sørensen 2000)
tidal world potential at best sites	$1.2 \cdot 10^{11}$	$3.8 \cdot 10^{18}$	0.011	0.0030	(Sørensen 2000)
Wave					
total wave energy	$1.1 \cdot 10^{11}$	$3.6 \cdot 10^{18}$	0.010	0.0028	(Sørensen 2000)
Geothermal					
total stored on Earth		$4.0 \cdot 10^{30}$	$1.1 \cdot 10^{10}$	$3.1 \cdot 10^9$	(Sørensen 2000)
total heat outflow	$3.0 \cdot 10^{13}$	$9.5 \cdot 10^{20}$	2.7	0.7	(Sørensen 2000)

3.2.3 Large scale biomass is not included

Next to wind and solar sources, biomass is the only source that could in theory provide a substantial contribution to the world's energy supply in 2050. The estimates of the potential contribution of biomass to the total world energy supply vary from 0 to over 1000 EJ/a of which over 90% would have to come from high quality agricultural land (Hoogwijk et al. 2003). In a detailed and regionalized study Hoogwijk

concludes that the contribution of biomass to the fuel production in 2050 could reach a level equal to the present oil demand (180 EJ/a) (Hoogwijk 2004). The largest part of the biomass would have to come from the former USSR, East Asia, Africa and South America, assuming a large increase in agricultural productivity in these areas. Others (Doornbosch and Steenblik 2007) dispute this and state that the required increase in biomass production of an order of magnitude is impossible in view of land and water constraints. By-and-by it is becoming clear that biomass can provide only a limited amount of the world's energy. We consider competition with nature and food production for the limited land area that can be used for the production of biomass¹ such a problem that we exclude biomass as a significant source of renewable energy. This in contrast to solar energy which can be collected in areas where biodiversity is minimal and agriculture is not possible, and to wind turbines which can either be used off shore or combined with agriculture. Moreover, biomass production dedicated for energy purposes is less efficient from an energy perspective than PV solar cells². The use of waste biomass and residues as a source of energy is less problematic. However, the contribution to the total primary energy production will probably be relatively small: 30 -108 EJ/a (Hoogwijk 2004).

3.2.4 Wind and solar provide 95% of energy

Wind may provide about 180 EJ /a (Williams 2001) or about 15% of the 2050 total energy demand, hydropower up to 3% (Sørensen 2000). All other renewable energy sources will be used in addition in places where they are readily available but will probably not provide more than 1% of the world's total primary energy use³. In order to simplify the analysis at hand we will focus on the 95% that can be provided via wind power (15%) and solar radiation (80%) leaving out all other sources.

3.2.5 Hydrogen and electricity as carriers

We will focus on two main carriers for the future energy system: electricity and hydrogen. Current renewable energy sources (except biomass) directly produce electricity. Since any energy conversion is associated with a loss of exergy, conversions are limited as much as possible in an optimal energy system. Electricity is an excellent

¹ The production algae and kelp does not require arable land but is related to problems of its own. For example in order to have substantial production levels of kelp nutrient rich water would have to be pumped towards the kelp fields which would require energy and lower the overall efficiency dramatically (Bungay 2004).

² The energy need for the production of Rape Methyl Ester is for example 16 GJ ha⁻¹ a⁻¹ while it delivers an equivalent of 43 GJ of fossil energy (Kaltschmitt and Reinhardt 1997). With poplar clones a net energy collection of 260 GJ ha⁻¹ a⁻¹ has been reported (European Commission 2005). This is equivalent to an efficiency of respectively 0.08 % and 0.8 % (biomass out (HHV)/ solar in) while current PV systems have an efficiency between 6-15 % (Green et al. 2006).

³ At the moment the way in which society uses energy is quite wasteful. High exergy energy sources like fossil fuels are often used in applications that actually only require low-exergy energy. An example is heating of buildings. Although some heating is done by using waste heat from industry, low temperature geothermal sources and passive solar energy, the contribution of these sources is still very limited, mainly because the use of high-exergy energy is relatively cheap and requires little investments because existing infrastructure can be used. Based on the current trends and the Markets First scenario, we explore the scenario in which low-exergy energy sources will remain of marginal importance.

energy carrier for stationary applications but it is difficult to store in large quantities. This is problematic in a renewable based energy system because the availability of renewable sources is highly variable through weather conditions, seasonal changes and day and night rhythms. It also implies that electricity is not very useful in mobile applications that require more than a few Watt, like transportation. Only recently battery technology has improved in such a way that the first full electric vehicles are being brought to consumer market. It is not clear which technology, hydrogen fuel cells or full electric cars will be dominant. Hydrogen is still seen by many as the preferable energy carrier for the use in mobile applications. In our scenario for 2050 we assume hydrogen will be used as the energy carrier in high power mobile applications (mainly in transport).

3.3 System specification

The key figures from the Markets First scenario are combined with data from literature on the availability of renewable energy sources and data on relevant energy technologies. We have used this information to generate a rough but more or less complete and quantitative overview of what a world based on renewable energy sources and hydrogen as an energy carrier could look like in 2050. The entire energy "life-cycle" will be taken into account: from the energy collection, via the transmission and distribution of this energy, to the utilization of this energy by the end-users. The infrastructure of the renewable based hydrogen economy is described and the material flows connected to this infrastructure are quantified over the next sections. On the basis of this quantified system description, the bottlenecks with regard to resource availability will be identified.

A general overview of our hydrogen energy system based on renewable energy sources is given in Figures 3-1 and 3-2. Renewable energy is collected and concentrated, preferably in locations where conditions are optimal for a given source, transmitted to the centres of economic activity and distributed to the end users. Both electricity (Figure 1) and hydrogen (Figure 2) can be used as a carrier for long range transmission.

Resource constraints H₂-economy

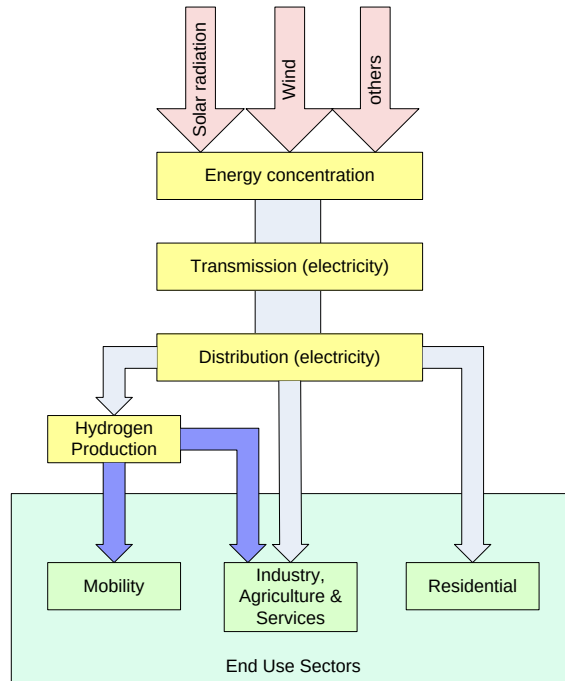


Figure 3-1: Main structure of a renewable based hydrogen energy system with electricity as the carrier in transmission.

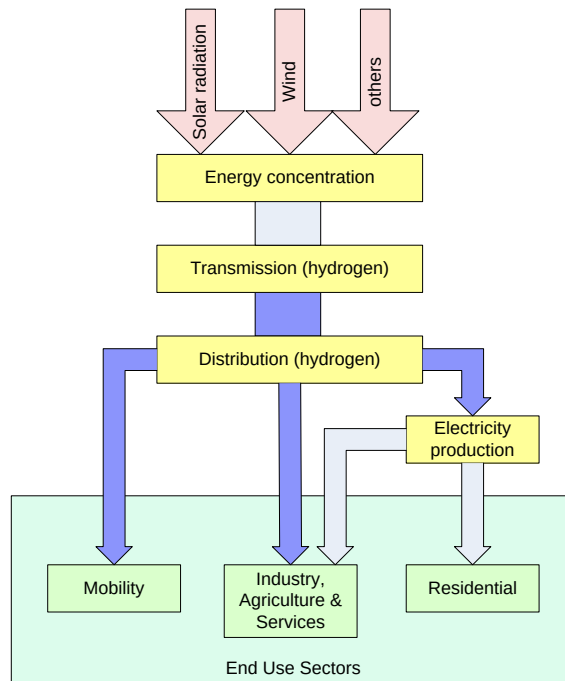


Figure 3-2: Main structure of a renewable based hydrogen energy system with hydrogen as the carrier in transmission.

3.3.1 Collection and concentration

In order to collect substantial amounts of useful energy from wind and solar radiation, large surface areas are needed, preferably in places with optimal conditions for collection. These optimal locations are often not the same as the locations where the energy is used. For example, the best places to collect solar energy, deserts, are often located far from the economic and industrial centers of the world (Knies and Bennouna 2002; Czisch 2004). Therefore, an extensive long distance transmission and distribution infrastructure is needed to get the energy to the end-users. Next to that, solar and wind energy are intermittent by nature which increases the importance of a long distance transmission network in order to buffer the system for temporal local shortages (Seboldt 2004).

3.3.2 Hydrogen production

Hydrogen can be produced via two routes:

1. via electricity in a two step process: solar and wind energy are used to produce electricity, which in a next step is used for the electrolysis of water to form hydrogen.
2. directly from water and solar energy via photolysis.

The second route has two main advantages: an energy transformation step would be eliminated, thereby increasing the efficiency of energy system as a whole, and two expensive and complex pieces of equipment, PV cells and electrolysis cells, would be replaced by one piece of equipment, the photolysis cell. However, the technology still suffers from severe practical problems and needs to be developed further⁴.

Next to this photochemical photolysis, a biological route exists. Algae or bacteria or their enzymes (hydrogenases) are used in light-driven bioreactors to split water (Melis and Happe 2001). However, this route is also still in the phase of early laboratory scale experiments. Because both the direct photolytic route and the biological route are still in the early stages of development, it is hard to say anything about their practical potential or link them to an estimate of resource requirements. We will therefore focus on PV coupled to electrolysis for hydrogen production.

Electrolysis of water can be done with different processes:

- Alkaline electrolyzers (commercial large scale units)
- Polymer Electrolyte Membrane (PEM) electrolyzers (prototypes and commercial units)
- Solid Oxide electrolyzers (lab-stage and commercial units)

All three of these options will be analysed although the main focus will be on alkaline electrolyzers.

⁴ This technique was first demonstrated by (Fujishima and Honda 1972). Problems like the lack of efficient light absorption and the corrosion of the semiconductor have been identified by (Khaselev and Turner 1998). In order to avoid these problems, tandem cells are now being developed in which a photo-electrolysis cell is put in series with a solar cell which allows the use of semiconductors that are more stable in water like tungsten oxide. However, the published efficiencies of these tandem cells are at the moment as low as 4.5% (Grätzel 2001).

3.3.3 Transmission

Both hydrogen and electricity can be used for long range transmission of energy, and both options will be explored in this study. The technology to transport electricity over long distance via high voltage AC power grid is already operational today. Transmission losses depend on the transport distances. In the 1990s the UK the average losses, excluding transformation and distribution, were 1.5 to 2% (Oxera 2003). In Table 3-3 an overview is given of the losses in different types of transmission: overhead AC, HVDC and hydrogen pipelines. High Voltage DC (HVDC) lines are today used to transport about 2% of all electricity in around 90 projects all over the world (International Energy Agency 2008). Trans-ocean HVDC cables that have been used to transport electricity from Scandinavia to other parts of Europe have losses of under 0.4% per 100 km. However, a 1-2% loss should be added for the AC/DC/AC conversion (International Energy Agency 2008; Sørensen 2007) so, from an energy efficiency perspective, this technique is only preferred for distances over 300 km. From a viewpoint of investment costs, DC transmission becomes favourable over AC lines over 50 km⁵. In our case study we therefore assume HVDC for long distance transmission. HVDC cables are either bipolar or monopolar. A bipolar cable has a better performance (Basslink 2002) and will therefore be assumed in our case study. Conductors in HVDC lines are traditionally made from copper although aluminium conductors are nowadays sometimes used in light weight, low capacity cables that are applied for shorter distances.

Table 3-3: A comparison of transmission losses between AC, HVDC and H₂ pipelines

	overhead AC	HVDC	H ₂ pipeline
energy losses / 100 km(%)	1	0.4	0.8
AC/DC conversion losses	0	1-2%	NA
% losses for 1500 km	15	8	12
% losses for 3000 km	30	14	24
Source	(Sørensen 2000)	(International Energy Agency 2008)	(Weindorf et al. 2003)

Hydrogen can be transported as a gas via pipelines or as a liquid in cryogenic dewar vessels on ships, trucks or trains. Since hydrogen is widely used in oil refining and chemical industry, a commercial system of hydrogen distribution is already in place for the use of hydrogen in oil refining and in the chemical industry (e.g. (Zittel and Altmann 1996)). When hydrogen is transported via pipelines specifically designed for hydrogen transport, losses can be very low. Overall losses from the pipelines in Germany are about 0.1% per year (Zittel and Altmann 1996). The pumping of a gas

⁵ Other advantages of DC lines are (Wright et al. 2002): (1) it is possible to link two asynchronous power grids (i.e. the frequency at either end can differ); (2) DC lines, unlike AC lines, do not have the drawback of so-called reactive current which can substantially reduce the power throughput. This problem does not occur in overhead lines; (3) the direction and the magnitude of the power flow can be controlled; and (4) a given cable can carry more power in DC than in AC.

through a pipeline requires energy. In natural gas pipelines about 0.2% of the transported amount of gas is used for compressors every 100 km at a rate of 10 m/s (Bossel et al. 2003). Because hydrogen contains roughly a factor three less energy per unit of volume than natural gas, more energy is needed for compression when transporting hydrogen through pipelines: about 0.8 % every 100 km (Bossel et al. 2003; International Energy Agency 2008). In Table 3-3 transmission via electricity is compared with hydrogen pipelines. For a transmission distance of 1500 km losses from H₂ pipelines are 1.5 times as high as those from HVDC cables. If the distances increase the relative difference increases as well. However, by optimizing the hydrogen pipelines (larger diameter, improved gas turbines for compression etc.) losses could be reduced to less than 10% for 3000 km (Weindorf et al. 2003; Ball et al. 2009).

Because hydrogen molecules are very small hydrogen can easily diffuse through most materials and seals and it can cause severe degradation of steels. Therefore, pipelines used for transporting hydrogen must be made of high quality non-porous materials such as stainless steel (Ball et al. 2009). Hydrogen can be added to steel natural gas pipelines in mixtures up to 30 vol % (10% in energy terms) (Ball et al. 2009; Blazek et al. 1992). A problem for transport through steel pipes is the so-called hydrogen embrittlement. This phenomenon is not completely understood, but it refers to cracks and blisters in the metal due to hydrogen permeation in the steel, which result in leakages. To avoid embrittlement pipes can be coated, small quantities of CO, SO₂ or O₂ can be added or embrittlement-resistant steels can be used. Transport of hydrogen through plastic pipes is also problematic because hydrogen permeates through plastic four to six times as fast as natural gas (Ball et al. 2009; Ogden 1999) .

Liquefaction of hydrogen can be applied by cooling hydrogen to extremely low temperatures (below -253 °C). The energy content of one litre of liquefied hydrogen is much higher than the energy content of a litre of compressed gaseous hydrogen. The main disadvantages are that the energy costs are high and that the losses during handling and transport are relatively high too. One of the reasons for these losses is that boil-off, evaporation of hydrogen due to temperature changes, is inevitable. However, the hydrogen that escapes in this way can, in some cases, be captured again and used for the propulsion of the vehicle in which the transport takes place. Although the transport of liquid hydrogen is technically feasible, the costs, both in terms of energy as in terms of money, will be so high that it will probably only be used under very specific circumstances and it will not compete with pipeline transport. Pipelines are the preferred transport option for large quantities and long distances while liquid hydrogen is preferred for smaller volumes over long distances (Ball et al. 2009). Therefore, in our case we assume pipelines for long distance bulk transport of hydrogen.

3.3.4 End Use

Although electricity and hydrogen are interchangeable as energy carriers in distribution, this is not the case in end-use. As transport fuel, hydrogen can either be combusted like gasoline and kerosene, or used in fuel cells. Fuel cells convert

hydrogen into electricity which is used to power the electric motors that are used to make the wheels turn and propel the vehicles. Even fuel cell cars that are filled up with hydrogen will thus ultimately be powered by electricity. In cars, the dominant hydrogen based technology is fuel cell cars. Prototypes of internal combustion engine (ICE) based hydrogen cars exist (e.g. BMW), but this should be seen purely as an intermediate technology that will help the transition to a hydrogen fuel cell vehicles (Wietschel et al. 2009). In aviation, the dominating propulsion technology is jet engines. Since these make direct use of the exhaust gases to propel the plane, combustion of hydrogen would be the preferred option here (Faaß 2001). Consumer electronics that need a lot of power, like refrigerators, washing machines, TV's and stereos, will remain grid connected and powered by electricity. Smaller electronics like laptops and mobile phones will either be battery powered or powered by small fuel cells, that in turn produce the electricity that powers these devices.

3.4 Identification of possible resource constraints

To identify possible resource constraints of the hydrogen economy, a quantification will be attempted with regard to the most important elements of the system described above:

- energy collection via PV cells and wind turbines
- hydrogen production via electrolysis
- long range electricity and hydrogen transmission
- end-use: fuel cells & electric motors

3.4.1 Resource constraints related to energy collection

PV Solar Cells

If 80% of the primary energy in 2050 comes from solar, this means that around 1000 EJ will be produced via solar energy. Part of this could come from built-up area. The IEA (IEA 2002) concludes that in selected developed countries between 30 and 120 % of the electricity use in that year could come from rooftops. Here we assume a theoretical maximum of about 15% of primary energy in 2050 (around 200 EJ) that could come from built-up area⁶. Even with this maximized amount of PV from built-up area this would mean that 65% of the primary energy would have to come from other surfaces. This implies that land will be used that is currently used for agriculture, or that is currently not used by humans. In (sub)tropical desert areas on average about 7.2 GJ/m² reaches Earth surface every year (Leijendeckers et al. 2008). Assuming a 10% efficiency, an area of 1.0 million km² would be needed to produce 845 EJ/a (65% of 1300 EJ/a, see earlier). This area is equivalent to about 10% of the Sahara desert area, divided over the different continents. At a latitude of 50° (Vancouver , Paris) the average annual incoming solar energy on ground level is around 3.6 GJ/m²

⁶ This assumption is based on data on built-up area in different countries (WRI online database land use), the assumption that 20% of this area would be suited for PV collection, an average incoming solar radiation of about 110 W/m² and a PV efficiency of 10%.

(Leijendeckers et al. 2008). Based on this irradiation an area of 2.0 million km² would be needed to supply the remaining 65% of the total energy use, equivalent to about four times area of France. If, for example, OECD Europe would want to be self-sufficient in energy terms, it should be able to collect 100 EJ/a in 2050 (IMAGE team 2001). In order to achieve this, 4% of the total land area (or 10% of the agricultural area) would have to be re-allocated to collect solar energy, in addition to a 15% use of wind energy and a 15% use of solar cells on built-up land, and the assumed 5% other renewable sources.

At the moment, different solar cells are available. There are different types of silicon cells: monocrystalline, polycrystalline and amorphous. All three forms of silicon are produced from sand of which supply is abundant. The only other materials in the cells themselves are dopants, mostly phosphorus and boron. For both materials the application in electronics is only a very small fraction of the total production so no constraints are in sight (USGS 2009b). Amorphous Si cells are cheap but have low efficiency, while crystalline Si cells have high efficiencies but they are also expensive and energy intensive to produce (Wadia et al. 2009). Therefore new thin-film PV cells have been developed that can be produced at lower costs (Wadia et al. 2009; Fthenakis 2009). At the moment the main thin-film technologies are cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS) (Fthenakis 2009). Typical efficiencies of different cells are given in Table 3-4. Since these thin film cells use a combination of less common materials, the supply of these materials can be an issue of concern once production reaches a substantial level.

Table 3-4: Efficiency of PV cells

	record cell efficiency (%)	record module efficiency (%)
Si (crystalline)	24.7	22.7
Si (multicrystalline)	20.3	15.3
Si (thin film)	16.6	8.2
Si (amorphous)	9.5	N/A
CIGS (cell)	18.4	13.4
CdTe	16.5	10.7
concentrator Si (parabolic disc)	26.8	N/A
concentrator GaInP/GaAs/Ge (2-terminal)	34.7	N/A

Source: (Green et al. 2006)

During the last decade several studies have addressed the issue of material constraints of thin-film PV (Wadia et al. 2009; Fthenakis 2009; Andersson et al. 1998; Andersson 2001; Andersson and Jacobsson 2000). The material needs of the four main non-silicon solar cells have been calculated by (Andersson and Jacobsson 2000). On the basis of these numbers and our scenario we calculated resources constraints for these technologies which are presented in Table 3-5. It is apparent that current reserves would not allow a substantial contribution of these cells to the solar energy collection we need in our scenario for 2050. All four technologies will be limited to a maximum

of less than 1% (10 EJ/a) of the total required energy collection. In more recent and more detailed work the limits for current thin film technologies (CdTe and CIGS) are estimated at around 10-100 EJ/a. However there are large differences in the material constraints for different technologies. Some, more unconventional, thin film PV technologies (especially FeS₂) look very promising from the perspectives of material constraints and can be scaled up to the level of over thousand EJ/a (Wadia et al. 2009; Fthenakis 2009). Considering these material constraints⁷ it seems that the use of current thin film cells based on rare materials will be limited. In a world based largely based on solar energy, the bulk of the solar cells would thus have to be based on new thin film materials or amorphous silicon. Next to the PV cells themselves the production of PV modules requires additional materials, these are not quantified in this study.

Table 3-5: Material constraints of different elements for four thin film solar cell technologies

cell type	element	require- ment g/m ²	reserve 1998 (Gg)	reserve 2012 (Gg)	production 1997 (Gg/a)	produc- tion 2010 (Gg/a)	needed for 1.7 10 ⁶ km ² (Gg)
CdTe							
	Cd	6.3	600	640	20	21	10000
	Te	6.5	20	24	0.29	NA	11000
CIGS							
	Se	4.8	70	93	2.2	2.1	7900
	Ga	0.53	110	NA	0.054	0.18	880
	In	2.9	2.6	NA	0.2	0.61	4800
aSiGe							
	Ge	0.44	2	NA	0.063	0.12	730
dye-sensitised							
	Ru	0.1	6	NA	0.011	NA	170

Sources: (Andersson et al. 1998; Andersson 2001; Andersson and Jacobsson 2000). The 1.7 10⁶ km² is based on 15% of the total energy demand from roofs on higher latitudes (50°) (0.7 10⁶ km²) and 65% PV cells in desert areas (1.0 10⁶ km²).

Wind

As stated before wind may provide about 180 EJ or about 15% of the 2050 total energy demand. This would mean that about 195 EJ/a will be produced via wind

⁷ Another issue with technologies using rare materials is, that the energy pay-back time as well as environmental impacts are relatively high because of the energy-intensive mining and refining processes. It was calculated, based on current technologies, that the full life cycle energy payback time is 6.3 years for an indium gallium phosphide (InGaP) module and only 3.5 years for a mono-crystalline Si module (Meijer et al. 2003). They also estimated that the environmental impact of the InGaP module was 80% higher than the impact of a mono-crystalline Si module. This reinforces the conclusion that these types of solar cells cannot contribute more than a small fraction to worldwide energy generation.

turbines. In January 2008, 94 GWe of wind power was installed, delivering about 1.4% of global electricity demand (International Energy Agency 2008). Thus in order to produce 190 EJ in 2050 the installed capacity has to increase by a factor of 250⁸, resulting in a capacity of 24 TWe. Present turbines have a capacity of around 1-2 MWe on land and up to 3-5 MWe for offshore sites. However, the size of wind turbines has been growing rapidly: from 0.5 MW in 1992 to 4.5 MW in 2002 (Kuik 2001). If we assume an average capacity of 2 MWe, 12 million of these large turbines would have to be installed.

An indication of the material use in wind turbines is given in Table 3-6. The amount of copper needed for these turbines is between 2 tons/MWe (onshore) and 3 tons/MWe (offshore) per turbine. This means that for the total 24 TWe, more than 50 million ton copper is needed. This is equivalent to about 7% of current reserve base⁹ and more than 4 times the worldwide mine production in 2008. The use of iron and steel is around 140 ton/MWe and thus more than 3 billion ton for the total 24 TWe. This is equivalent to around 2% of the base reserve of iron ore and, in terms of iron content of the ore, about 3 times the current iron ore production.

Table 3-6: Material use wind turbines

	2MW offshore	800 kW onshore	2MW offshore	800 kW onshore	% reserve base 24 TWe with 2 MW offshore	% reserve base 24 TWe with 800kW onshore	multiplier of world annual mine production 2008	
	ton/MWe	ton/MWe	Mton / 24 TWe	Mton / 24 TWe			2MW offshore	800kW onshore
steel	148	135	3551	3244	2.2	2.0	3.0	2.7
aluminium	0.42	0.26	10	6				
copper	2.75	1.83	66	44	6.6	4.4	4.2	2.8
lead	3.79	0	91	0				
plastics	2.09	1.92	50	46				
concrete	1050	306	25100	7340			1.3	0.38
gravel	150	0	3600	0				
neodymium	0.15		3.6				180	

Source: (Frischknecht R. 2007); Neodymium (Polinder et al. 2006; USGS 2009a), reserves & production USGS Reserve Base is defined by the USGS as "That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth. The reserve base is the in place demonstrated (measured plus indicated) resource from which reserves are estimated." (USGS 2009a)

Next to the base metals which are used in wind turbines more exotic materials are sometimes used as well. Neodymium is a rare earth metal which is used in permanent

⁸ This may seem like a very high number but at an annual growth rate of 14% would be enough to achieve this in 2050. The last ten years, 1999 to 2008, the annual growth rate in installed wind capacity has been around 25% (International Energy Agency 2008).

⁹ As defined by the USGS: base reserve: "That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth."

magnets. Neodymium magnets are preferred above other permanent magnets because they can provide the same magnetic strength with smaller and lighter magnets. Using permanent Nd magnets in wind turbines can slightly increase their efficiency, reduce maintenance costs and reduce the weight of the generator, all because in a they can make gearboxes redundant. In state of the art wind turbines with direct-drive permanent-magnet generators about 550 kg permanent magnets or 150 kg of neodymium is used per MWe (Polinder et al. 2006; Hatch 2008). This would mean that around 3.6 million ton Nd would be needed for the total 24 TWe in our scenario. This is about 180 times the current annual mine production. At the moment very few wind turbines actually use direct-drive with permanent magnets and most use electromagnets in geared generators which are made of copper and iron. Neodymium constraints will therefore not be a show stopper for large scale application of wind turbines in general but it will limit the market share of certain new types of wind turbines. Even more so because the turbine producers would have to compete with car manufacturers (see under 4.4) and with other renewable energy sources in which permanent magnets are used (Hatch 2008).

The amount of concrete needed to build a wind turbine is between 300 ton/MWe (onshore) and 1000 ton/MWe (offshore) which means that for 24 TWe between 7 and 25 billion ton of concrete needs to be produced. If the average cement content of concrete is set at 15% the amount of cement needed to produce this concrete is between 40% and 130% of the annual world cement production in 2008 (USGS 2009a). For cement, the base reserve is not very relevant: although there can be regional shortages of the raw materials, like limestone and sand, are geologically abundant and widespread. However, there may be environmental constraints: cement production is an important source of CO₂ (Kleijn et al. 2008).

The conclusion that can be drawn is that if wind energy is to contribute 15% to the global primary energy use in 2050, this would mean that a substantial amount of the base reserve of copper and iron ore needs to be invested in this sector. The worldwide production of copper, iron ore and cement would have to increase dramatically. If wind turbines are to be scaled up to the level of TWhs it does not seem likely that neodymium containing direct-drive permanent-magnet generators will play a significant role because of resource constraints related to Neodymium.

3.4.2 Resource constraints related to hydrogen production

Electrolysers based on the alkaline process have been in commercial use for decades. PEM electrolysis cells and solid oxide based electrolysers have recently been commercially introduced. In this analysis we will therefore focus on alkaline electrolysis. The electrolyte is an alkaline solution, usually potassium or sodium hydroxide, and the electrodes are made of different coated metals. The anode is often made of nickel and copper and coated with oxides of metals and the cathode is made of platinum coated nickel. A theoretical maximum efficiency of 83% is given by

(Sørensen 2000). In practice the efficiency based on LHV¹⁰ is between 50 and 75 % (Ogden 1999; IEA 2005; Koroneos et al. 2004). Here we assume a future efficiency for the production of hydrogen from water of 75%. This means that if hydrogen is used as the energy carrier in transmission, the energy collection and the connected material flows and land use will have to be 25% higher than calculated above.

In electrolysis, hydrogen is produced from fresh water. This is problematic in many places that would be ideal for PV solar power plants. In desert-like areas that are close to oceans, like the Western part of the Sahara, one could overcome this problem by combining PV plants with desalination installations. Although desalination has become much more efficient over recent years it still requires a significant energy input which would decrease the overall efficiency of hydrogen production.

Current electrolyzers are made from stainless steel, plastics and the materials needed for membranes and electrodes and the electrolyte. There is little quantitative information on the material use in the membranes and electrodes in the public domain. The electrolyte is normally potassium hydroxide or sodium hydroxide. Both of them are bulk chemicals and the use in this application would still be small compared the total annual use. The membranes are made of organic polymers, such as nafion and polybenzimidazole, and are not related to material constraints either. The electrodes are made of metals: the anode is usually a combination of nickel and copper coated with a layer of metal oxides. The anode is made of nickel coated with a layer of platinum (Koroneos et al. 2004). Although we do not have much specific data on the quantity of the metals in electrolyzers we assume here that they will be in the same range as that of fuel cells. This would imply potential resource constraints with regard to Platinum (see further in this text, under “Resource constraints related to hydrogen use: Fuel Cells”). Technological innovations have a potential to solve these material issues. Recently a study was published on a promising new technique that uses a solution of much more abundant cobalt and phosphate as the main active components¹¹ (Kanan and Nocera 2008).

It can be concluded that material constraints of hydrogen production via electrolysis using alkalines can be expected related to platinum. PEM electrolyzers also use platinum as a catalysts and these would run into similar constraints (see 4.4). For solid oxide this is presently unclear, as they are not developed fully yet, but resource constraints are not necessarily absent.

¹⁰ The LHV assumes that the latent heat of vaporization of the water that is produced during the electrolysis is not recovered. For hydrogen the Higher Heating Value is about 18% higher than the lower heating value.

¹¹ The authors use a solution with cobalt and phosphate ions in aqueous solution at neutral pH. In the experiments a newly formed catalyst is deposited on the electrode consisting of both cobalt and phosphate. This catalyst is highly active and will regenerate spontaneously. In the experiment an indium tin oxide (ITO) catalyst was used which by including indium has its own resource scarcity issues. However, this material was itself did not seem to be taking part the electrolysis mechanism.

3.4.3 Resource constraints related to transmission

In May 2008 the longest HVDC cable became operational and connects the electricity grids of Norway and the Netherlands. Specifications of this cable are given in Table 3-7. The capacity of the cable about 600 MW and it has a copper conductor of 760 mm². Total transmission losses are estimated at 4% with full load (Tennet 2007; Statnett 2002). In a scenario where solar energy is collected in remote desert areas power cables would be needed that are about a factor 10 longer than the longest operational cables today. The main materials used in these cables are copper, steel, lead and polyethylene. In Table 3-8 the material needs for transmission of 65% of the primary energy in 2050 through HVDV cables is calculated. The copper use in the 600 MW NorNed cable is about 7.5 kg/m. With increased conductor size the maximum power through this types of cables today can be several 1000 MW (ABB 2009). If it is assumed that the conductor size would have to double when doubling the power throughput. In a 1200 MW cable the copper use would also be doubled to 14 kg/m, in a bipolar cable this would again be doubled to 28 kg/m. If 65 % of the primary energy use in 2050 would be transmitted over an average distance of 1500 km, 22 thousand 1200 MW (bipolar) cables would be needed. In order to produce these cables 900 million ton copper would be needed. This is equivalent to about 90 % of current reserve base and twice the cumulative production between 1900 and 2001 (Porter and Edelstein 2003), 24% of the total copper resource and almost 60 times the current annual world production. The long term availability of copper has been discussed in literature (Gordon et al. 2006; Tilton and Lagos 2007). Although copper is not a rare element, still resource constraints are in sight if electricity transmission has to take place in these amounts over these large distances.

Table 3-7: Details of the HVDC power cable between Norway and the Netherlands

conductor size	2 x 760 mm ² (bipolar)
conductor material	Copper
weight	85 kg/m (bipolar)
outer diameter	120 mm
rated power	600 MW
rated voltage	450 kV
length	580 km
maximum water depth	410 m

Source: (Tennet 2007; Statnett 2002)

If 65% of the primary energy use in 2050 would be delivered by hydrogen through stainless steel pipelines (current technology) this would require substantial amounts of nickel and chromium. The exact specifications of pipelines may vary substantially. An estimate is given in Table 3-9. The starting point of the calculations was that 600 MW_{H₂} stainless steel (API 303/304/316) pipelines would be used. The number of pipelines would then be identical to the number of HVDC cables in the case of electricity transmission. Based on typical wall thickness and diameter from (Ball et al. 2009) and typical chromium and nickel content in stainless steel this result a demand for Ni of about 45 times the current annual mine production and for Cr of about 5500 times the current annual mine production. The amount of nickel needed would be

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about halve the current reserve base. The USGS does not give global reserves for chromium but the amount is about a third of the base reserve of countries that are included in their data.

Table 3-8: Calculation copper use in transmission if 65% of the world primary energy supply in 2050 (845 EJ) would come from PV solar plants in the deserts, assuming transmission with HVDC power cables..

Data on HVDC cables			
	unit	amount	source
power through existing cable	W	$6.00 \cdot 10^8$	(Tennet 2007; Statnett 2002)
conductor cross section for 600 MW	mm ²	760	(Statnett 2002)
maximum power per cable	W	$1.20 \cdot 10^9$	(ABB 2009)
conductor cross section for 1200 MW	mm ²	1520	assumption: double power, double conductor cross section
volume copper per m cable	cm ³	3200	calculated
density conductor (copper)	g/cm ³	8.9	(CRC 2009)
mass copper	g/m cable	13500	calculated
Calculation cables needed			
total energy use 2050	J/a	$1.3 \cdot 10^{21}$	assumption in this study
total energy use 2050	W	$4.1 \cdot 10^{13}$	calculated
65% from deserts	W	$2.6 \cdot 10^{13}$	calculated
number of cables needed	-	21951	calculated
average distance to end-users	km	1500	assumption in this study
km cable needed	km	$3.3 \cdot 10^7$	calculated
Calculation total copper use for transmission			
total copper use monopolar	kg	$4.5 \cdot 10^{11}$	calculated
total copper use if bipolar	kg	$8.9 \cdot 10^{11}$	calculated
Comparison to copper production & base reserve			
base reserve (Cu)	Kg	$1 \cdot 10^{12}$	(USGS 2009a)
resources (land and ocean)	Kg	$3.7 \cdot 10^{12}$	(USGS 2009a)
mine production	Kg/a	$1.6 \cdot 10^{10}$	(USGS 2009a)
cumulative world production 1900-2001	Kg	$4.2 \cdot 10^{11}$	(Porter and Edelstein 2003)
multiplier copper use transmission vs base reserve	-	0.89	calculated
multiplier copper use transmission vs resources	-	0.24	calculated
multiplier copper use transmission vs mine production	-	57	calculated
multiplier copper use transmission vs cumulative mine production (1900-2001)	-	2.1	calculated

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Table 3-9: Calculation nickel, chromium and iron use in transmission if 65% of the world primary energy supply in 2050 (845 EJ) would come from PV solar plants in the deserts, assuming transmission with hydrogen pipelines.

Data on hydrogen pipelines			
	unit	amount	source
power through pipeline (600 MW_H ₂)	W	6.0 10 ⁸	(Ball et al. 2009)
pipe diameter	cm	25	(Ball et al. 2009)
wall thickness	cm	1.0	average API 10 pipe
volume steel per m pipe	cm ³	2500	calculated (The Physics Factbook 2009)
density stainless steel	g/cm ³	8	
mass steel	kg/m pipe	20	calculated
fraction Ni in stainless steel	-	0.11	average 304,306,316
fraction Cr in stainless steel	-	0.18	average 304,306,316
fraction Fe in stainless steel	-	0.71	remaining fraction
mass Ni	kg/km pipe	2200	calculated
mass Cr	kg/km pipe	3600	calculated
mass Fe	kg/km pipe	14200	calculated
Calculation pipelines needed			
total energy use 2050	J/a	1.3 10 ²¹	assumption in this study
total energy use 2050	W	4.1 10 ¹³	calculated
65% in centralised scenario from deserts	W	2.6 10 ¹³	calculated
number of pipelines needed	-	22000	calculated
average distance to end-users	km	1500	assumption in this study
km pipeline needed	km	3.3 10 ⁷	calculated
Calculation total Ni and Cr use for transmission			
total Ni use	kg	7.2 10 ¹⁰	calculated
total Cr use	kg	1.2 10 ¹¹	calculated
total Fe use	kg	4.7 10 ¹¹	calculated
Comparison to production & base reserves			
base reserve (Ni)	kg	1.50 10 ¹¹	(USGS 2009a)
mine production (Ni)	kg/a	1.61 10 ⁹	(USGS 2009a)
			(USGS 2009a) total based on main producers
base reserve (Cr)	kg	3.74 10 ¹¹	
mine production (Cr)	kg/a	2.15 10 ⁷	(USGS 2009a)
base reserve (Fe)	kg	1.6 10 ¹⁴	(USGS 2009a)
mine production (Fe)	kg/a	1.2 10 ¹²	(USGS 2009a)
multiplier Ni use pipelines / base reserve	-	0.48	calculated
multiplier Ni use pipelines / mine production	-	45	calculated
multiplier Cr use pipelines / base reserve	-	0.32	calculated
multiplier Cr use pipelines / mine production	-	5500	calculated
multiplier Fe use pipelines / base reserve	-	0.0029	calculated
multiplier Fe use pipelines / mine production	-	0.39	calculated

From the analysis above it is clear that, using current technologies, the use of copper in HVDC lines would be prohibit the use of HVDC transmission in our extreme scenario. The use of the much more abundant aluminium conductors might solve this issue but it would also decrease the overall efficiency of the transmission. Also the use of current technology stainless steel for the transport of hydrogen cannot be scaled up to the level that we would need in our scenario due to material constraints of chromium and nickel. Other steels or coated steels might be the best alternative here or possibly steel could be avoided completely by the use of new composite materials.

3.4.4 Resource constraints related to end use: fuel cells & electric motors

Fuel cells in cars

In 2001 there were 555 million cars in the world (Worldwatch Institute 2002). In the Markets First scenario, GDP per capita will grow by a factor of 3.7 from 2001 to 2050. It is assumed that the number of cars will grow with the same factor. This would mean that there will be roughly 2 billion cars on the road by 2050. We assume that all these cars will have a PEM fuel cell on board. Rade & Andersson (Råde and Andersson 2001) use in their baseline scenario, based on current technologies, that in PEM fuel cells on average 0.39 g of Pt is needed per kW. With 2 billion cars on the road in 2050 this would mean that 39,000 ton of Pt would be needed. Since the platinum catalyst is an expensive part of the fuel cell, R&D will be aimed at reducing the amount of platinum needed in fuel cell vehicles. The UK Department for Transport reports an ultimate goal of about 3 g per car which would mean a demand for Platinum of about 6,000 ton in 2050 (UK Department for Transport 2003). Currently platinum group metals (PGM) are used as catalysts. The USGS estimates the reserve base at 80,000 ton and world resources at over 100,000 ton (USGS 2009a). World production in 2008 was 200 ton Platinum and 206 ton Palladium (USGS 2009a). The cumulative production of PGM from 1900 to 2000 is 9120 ton (Kelly and Hilliard 2003). In Table 3-10 the amount of platinum in fuel cells is calculated. If the goals for the reduction of Pt in fuels cells are met less than 10% of the base reserve is needed. However, using current technologies the amount of Pt in cars in 2050 would exceed the world resources. In any case the production rates would have to grow dramatically to fulfil the demand.

The problem of Pt use might be solved in future by using alternative catalysts which do not contain rare metals. The two main alternatives are the use of base metals and the use of enzymes. However, for hydrogen fuelled fuel cells there are no known (combinations of) base metals that can be practical substitutes for PGM metals yet. The enzyme route is more promising although a practical enzyme based biofuel cell is (Armstrong et al. 2009) also still in the early stages of fundamental research. Currently technologies are being developed to adsorb enzymes like hydrogenase on electrodes which brings the biofuel cell a bit closer to practical application (Lamle et al. 2003).

Table 3-10: Calculation of Pt and Nd use in fuel cell cars in 2050.

		unit	source
number of cars on the road in 2050	2.0 10 ⁹	-	Assumption based on GDP growth
Pt per car (high)	60	g/car	(UK Department for Transport 2003)
Pt per car (low)	20	g/car	(Råde and Andersson 2001)
Pt per car (minimum)	3	g/car	(UK Department for Transport 2003)
Pt for all cars in 2050 (high)	120000	ton	calculated
Pt for all cars in 2050 (low)	47000	ton	calculated
Pt for all cars 2050 (minimum)	6000	ton	calculated
world production Pt 2007	220	ton	(USGS 2009b)
multiplier (high)	530	-	calculated
multiplier (low)	220	-	calculated
multiplier (minimum)	28	-	calculated
Nd per car (low)	1	kg/car	(Gorman 2009) uncertain !
Nd per car (high)	2	kg/car	(Gorman 2009) uncertain !
Nd for all cars in 2050 (low)	2000	kton	calculated
Nd for all cars in 2050 (high)	4000	kton	calculated
world production Nd 2008	20	kton	(Gorman 2009)
multiplier (high)	100	-	calculated
multiplier (low)	200	-	calculated

Stationary fuel cells for power generation

If hydrogen is used for the transmission of energy a substantial part of this should be transformed again to electricity. This can be done by combustion of hydrogen which in power plants that are comparable to current natural gas fired power plants. This option would thus not be confronted with additional material constraints. However, it would be more efficient to use fuel cells instead. This would mean that stationary fuel cells would be used to convert hydrogen into electricity. Large stationary fuel cells are small compared to current power plants. This means that power generation will be distributed in which case the power grid would only be used for local distribution. There are different types of stationary fuel cells: Phosphoric-acid fuel cells (PAFC), Molten-carbonate fuel cells (MCFC) and solid oxide fuel cell (SOFC). Although we did not quantify this it seems likely that both PAFCs and SOFCs would be confronted with resource constraints: in PAFCs platinum is used and in SOFCs lanthanum is

used. In MCFCs less scarce materials like Ni, Cr and Al can be used as electrode materials. The material constraints with in stationary fuel cells will be less severe than for the use of fuel cells in cars.

Electric motors in cars

Fuel cells in cars are used to produce electricity which is used to power the electromotors that make the wheels turn. The use of neodymium in electromotors make these motors smaller, lighter and more efficient. Reliable sources on the amount of Nd in cars have not been found. However, figures of 1 to 2 kg of neodymium for a Toyota Prius can be found in the media (e.g. (Gorman 2009)). For the 2 billion cars on the road in 2050, 2 to 4 million ton of neodymium would be needed, about 200 times the current annual production. For full electric cars using permanent magnet motors these number would be higher. However, like in wind turbines alternatives are possible. The Tesla roadster for example, uses an induction motor without permanent magnets.

Resource constraints will prohibit the scale up of the use of fuel cells in cars due to constraints in the availability of platinum. An extreme reduction of the amount of platinum per fuel cell might solve this issue. The use of other, less scarce, electrode materials might also be a way out. Stationary fuel cells needed to produce electricity in a scenario where hydrogen will be used for the transmission will run into similar, though less severe because the installed capacity can be much lower because they are used almost 24/7. Neodymium magnets are an issue in electric vehicles if permanent magnet motors will be used. However, alternatives like the induction motor that do not contain permanent motors are available.

3.5 Conclusions and Discussion

The limiting factor for a renewable based hydrogen energy system does not lie in the amount of renewable energy that is available. There is plenty of wind and especially solar energy to provide for an exponentially growing world economy. However, since wind and solar energy are diffusive energy sources the infrastructure needed to harvest substantial amounts is huge. In order to limit the amount of infrastructure needed for harvesting it is important to choose locations where the circumstances for harvesting are optimal. Especially for solar energy these locations are quite often far from the locations where this energy is used. Therefore an extensive transmission network is needed in addition, to get the energy in the right place.

In this study we have shown that the choice of technology has a strong influence on the material resources that are needed in such a system. In three crucial parts of the system we describe the use of relatively scarce materials as *show stoppers* for specific technologies: rare elements in current thin film solar cells, neodymium in direct-drive permanent magnet wind turbines and electro motors, and platinum in electrolysis and fuel cells. Resource constraints prevent these technologies from upscaling to a level

that would be needed for a substantial transition to a renewable based hydrogen economy. For a worldwide conversion to renewable energy, therefore, different technologies must be chosen and/or developed that do not rely on these scarce materials. Many of these technologies are available but it sometimes at the cost of efficiency and/or economics.

Furthermore, the amount of steel that would be needed for both wind turbines and hydrogen pipelines is very high. For wind turbines, this would be 6 times the current annual production of iron for hydrogen pipelines 40%. However, if current technology stainless steel is used for the pipelines about 45 times the annual production of nickel would be needed and 5500 times the annual production of chromium. If electricity is chosen as a carrier, the amount of copper that would be needed in the system is equivalent to 70 times the current annual world production. For the wind turbines an additional 4 times the current annual world copper production would be needed. Although resource constraints for iron ore are not in sight, it would imply a major increase in worldwide energy and, in the current system, fossil fuel use. The same is true for copper. While scarcity is not an immediate issue, the energy required to mine increasingly lower ore grades could become very large, thus creating a negative spiral.

This paper is a first step in the analysis of changes in material needs as a result of energy transitions. There are some important issues that we have not addressed yet. This study focuses on the direct material needs only. The life cycle perspective is not applied. If it would be, the material needs would probably be much higher. Moreover, the energy system that we use as a starting point is an extreme case that is not predicted in any of the major energy scenarios. However, it was not our intention to sketch a realistic energy scenario for 2050 but to explore the material needs of a complete transition. A partial transition would of course decrease the material needs, as would a limitation of primary energy needs. However, we also made some major simplifications that underestimate material needs. For example the intermittent nature of solar and wind as energy sources will make some sort of buffering an essential part of the energy system. In the large scale energy system perspective that we have used here, this could be done for example by high capacity east-west power lines that would compensate for the day-night rhythm of PV. These cables would have to be much longer than the ones we have assumed here, which would decrease the efficiency of the system as a whole. If hydrogen would be the energy carrier of choice for transmission, intermittency might be buffered by allowing changes in pressures in the pipelines.

Further in-depth analysis is needed to assess the material needs of a transition to a renewable based energy systems. Including the life cycle perspective could be a means to detect mechanisms that have a potential to make the system spiralling out of control. The increasing use of energy to produce the materials required to generate energy could be such a mechanism. Another large research area is introducing the

dynamics of actual transformations. This will lead to more detailed and realistic estimations of material needs through time in different scenarios.

Another issue is the environmental aspects of these energy systems. The systems are designed to reduce greenhouse gas emissions. A first relevant question would be, if this is indeed the case. If material requirements explode, so might the use of fossil fuels in build-up phase of the system. But even if a substantial reduction of greenhouse gas emissions would be reached, still there may be side-effects in other areas of environmental impacts, such as land and water use, emissions of toxic substances etc.. These side-effects need to be investigated as well, in order to be able to have a balanced assessment of alternative energy systems.

Finally, A sustainability approach is not limited to scarcity and environmental impacts, but also includes economic and social aspects. These have not been addressed in this paper, but should be addressed in a more comprehensive sustainability assessment.

References

- ABB. 2009. HVDC delivering success. Accessed November 12 2009 2009.
- Andersson, B. A. 2001. Material Constraints on Technology Evolution: The Case of Scarce Metals and Emerging Energy Technologies thesis, Department of Physical Resource Theory, Chalmers University of Technology and Göteborg University, Göteborg.
- Andersson, B. A. and S. Jacobsson. 2000. Monitoring and assessing technology choice: the case of solar cells. *Energy Policy* 28(14): 1037-1049.
- Andersson, B. A., C. Azar, J. Holmberg, and S. Karlsson. 1998. Material constraints for thin-film solar cells. *Energy* 23(5): 407-411.
- Armstrong, F. A., N. A. Belsey, J. A. Cracknell, G. Goldet, A. Parkin, E. Reisner, K. A. Vincent, and A. F. Wait. 2009. Dynamic electrochemical investigations of hydrogen oxidation and production by enzymes and implications for future technology. *Chemical Society Reviews* 38(1).
- Ball, M., W. Weindorf, and U. Bünger. 2009. Hydrogen Distribution In *The Hydrogen Economy, Opportunities and Challenges* edited by M. Ball and M. Wietschel. New York: Cambridge University Press.
- Basslink. 2002. *Response by Basslink Pty Ltd to Draft Report of the Basslink Joint Advisory Panel. Submission 2 of 3, Proposed Metallic Return*. Melbourne: Basslink.
- Blazek, C. F., R. T. Biederman, F. S. E, and W. Jasionowski. 1992. Underground Storage and Transmission of Hydrogen. In *Third Annual US Hydrogen Meeting*. Washington, DC.
- Bossel, U., B. Eliasson, and G. Taylor. 2003. The future of the hydrogen economy Bright or Bleak. Energy and the Hydrogen Economy. In *2003 Fuel Cell Seminar*. European Fuel Cell Forum.
- Bungay, H. R. 2004. Confessions of a bioenergy advocate. *Trends in Biotechnology* 22(2): 67-71.
- CRC. 2009. *Handbook of Physics and Chemistry*: Taylor and Francis Group, LLC.
- Czisch, G. 2004. *Least-Cost European/Transeuropean Electricity Supply Entirely with Renewable Energies*. Kassel, Germany: ISET, Universität Kassel.
- Doornbosch, R. and R. Steenblik. 2007. *Biofuels: is the cure worse than the disease?* . SG/SD/RT(2007)3. Paris: OECD.
- European Commission. 2003. Hydrogen Energy and Fuel Cells; A vision of our future. Brussels: European Commission.

- European Commission. 2005. *Biomass, green energy for Europe*. EUR 21350. Directorate-General for Research, Directorate J – Energy, Unit 3 – New and Renewable Energy Sources.
- Faaß, R. 2001. *Flugzeuge mit wasserstoffantrieb (Aircraft with hydrogen propulsion)*. Hamburg: Airbus Deutschland.
- Frischknecht R., A. H.-J., Doka, G., Dones, R., Heck T., Hellweg, S., Hirschier, R., Jungbluth N., Nemecek, T., Rebitzer, G., Spielmann, M. 2007. *Overview and Methodology. Final reportecoinvent v2.0 No. 1*. Duebendorf, CH.: Swiss Centre for Life Cycle Inventories.
- Fthenakis, V. 2009. Sustainability of photovoltaics: The case for thin-film solar cells. *Renewable and sustainable energy reviews* 13(9): 2746-2750.
- Fujishima, A. and K. Honda. 1972. Electrochemical Photolysis of Water at a Semiconductor Electrode. *Nature* 238(5358): 37-38.
- Gordon, R. B., M. Bertram, and T. E. Graedel. 2006. Metal stocks and sustainability. *Proceedings of the National Academy of Sciences of the United States of America* 103(5): 1209-1214.
- Gorman, S. 2009. As hybrid cars gobble rare metals, shortage looms. *Reuters* [Los Angeles], August 31, 2009.
- Grätzel, M. 2001. Photoelectrochemical cells. *Nature* 414(6861): 338-344.
- Green, M. A., K. Emery, D. L. King, Y. Hishikawa, and W. Warta. 2006. Solar cell efficiency tables (version 28). *Progress in Photovoltaics: Research and Applications* 14(5): 455-461.
- Hatch, G. P. 2008. Going Green: The Growing Role of Permanent Magnets in Renewable Energy Production and Environmental Protection. In *Magnetics 2008* Denver (CO), USA.
- Hoogwijk, M., A. Faaij, R. van den Broek, G. Berndes, D. Gielen, and W. Turkenburg. 2003. Exploration of the ranges of the global potential of biomass for energy. *Biomass and Bioenergy* 25(2): 119-133.
- Hoogwijk, M. M. 2004. On the global and regional potential of renewable energy sources. thesis, Universiteit Utrecht, Utrecht, The Netherlands.
- IEA. 2002. *Potential for Building Integrated Photovoltaics* Paris: IEA.
- IEA. 2005. *Prospects for hydrogen and fuel cells*. Paris, France: OECD/IEA.
- IEA. 2007. *World Energy Outlook 2007. China and India Insights*. Paris, France.: OECD/IEA
- IMAGE team. 2001. *The IMAGE 2.2 implementation of the SRES scenarios: A comprehensive analysis of emissions, climate impacts in the 21st century*. RIVM CD-ROM publication 481508018. Bilthoven, The Netherlands: National Institute for Public Health and the Environment.
- International Energy Agency. 2008. *Energy Technology Perspectives*. Paris: EIA.
- Kaltschmitt, M. and G. A. Reinhardt. 1997. *Nachwachsende Energieträger. Grundlagen, Verfahren, ökologische Bilanzierung*. : Vieweg Verlagsgesellschaft.
- Kanan, M. W. and D. G. Nocera. 2008. In Situ Formation of an Oxygen-Evolving Catalyst in Neutral Water Containing Phosphate and Co²⁺. *Science* 321(5892): 1072-1075.
- Kelly, T. D. and H. E. Hilliard. 2003. *Platinum-Group Metals Statistics*. USGS.
- Khaselev, O. and J. A. Turner. 1998. A Monolithic Photovoltaic-Photoelectrochemical Device for Hydrogen Production via Water Splitting. *Science* 280(5362): 425-427.
- Kleijn, R., E. van der Voet, and H. A. Udo de Haes. 2008. The need for combining IEA and IE tools: The potential effects of a global ban on PVC on climate change. *Ecological Economics* 65(2): 266-281.
- Knies, G. and A. Bennouna. 2002. Potential of Moroccan renewable energies for the defence against climate change. . In *FIER 2002*. Tetuoan, Morocco.
- Koroneos, C., A. Dompros, G. Roumbas, and N. Moussiopoulos. 2004. Life cycle assessment of hydrogen fuel production processes. *International Journal of Hydrogen Energy* 29(14): 1443-1450.

- Kuik, G. A. M. v. 2001. Are wind turbines growing too fast? In *European Wind Energy Conference*. Copenhagen.
- Lamle, S. E., K. A. Vincent, L. M. Halliwell, S. P. J. Albracht, and F. A. Armstrong. 2003. Hydrogenase on an electrode: a remarkable heterogeneous catalyst. *Dalton Transactions*(21).
- Leijendeckers, P. H. H., J. L. A. Jansen, and D. C. E. M. Keukeleere. 2008. *Energie zakboek (Energy Handbook)*. Doetinchem, The Netherlands: Reed Business.
- Meijer, A., M. A. J. Huijbregts, J. J. Schermer, and L. Reijnders. 2003. Life-cycle assessment of photovoltaic modules: Comparison of mc-Si, InGaP and InGaP/mc-Si solar modules. *Progress in Photovoltaics: Research and Applications* 11(4): 275-287.
- Melis, A. and T. Happe. 2001. Hydrogen Production. Green Algae as a Source of Energy. *Plant Physiology* 127(3): 740-748.
- Odell, P. R. 2004. *Why carbon fuels will dominate the 21st century's global energy economy*. Brentwood Essex, UK: Multi-Science Publishing Co. Ltd.
- Ogden, J. M. 1999. Prospects for building a hydrogen energy infrastructure. *Annual Review of Energy and the Environment* 24(1): 227-279.
- Okano, K. 2003. Hydrogen and fuel cell activities in Japan. In *PATH hydrogen workshop*. Mexico.
- Oxera. 2003. *The impact of average zonal transmission losses applied throughout Great Britain*. Oxford: Department of Trade and Industry.
- Polinder, H., F. A. van der Pijl, G.-J. de Vilder, and P. J. Tavner. 2006. Comparison of Direct-Drive and Geared Generator Concepts for Wind Turbines. *IEEE Transactions on energy conversion* 21(3): 8.
- Porter, K. E. and D. I. L. Edelman. 2003. *Copper Statistics*. USGS.
- Prather, M. J. 2003. An Environmental Experiment with H₂? *Science* 302(5645): 581-582.
- Råde, I. and B. A. Andersson. 2001. *Platinum group metal resource constraints for fuel-cell vehicles*. PRT Report 2001:01. Göteborg, Sweden: Chalmers University of Technology and Göteborg University.
- Schultz, M. G., T. Diehl, G. P. Brasseur, and W. Zittel. 2003. Air Pollution and Climate-Forcing Impacts of a Global Hydrogen Economy. *Science* 302(5645): 624-627.
- Seboldt, W. 2004. Space- and Earth-based solar power for the growing energy needs of future generations. *Acta Astronautica* 55(3-9): 389-399.
- Shell. 2008. *Shell energy scenarios to 2050*. Shell International BV. .
- Sørensen, B. 2000. *Renewable Energy, Its physics, engineering, use, environmental impacts, economy and planning aspects*. . London: Academic Press.
- Sørensen, B. 2007. *Renewable Energy, conversion, transmission and storage*. . London: Academic Press.
- Statnett. 2002. *NorNed cable, HVDC project*. Oslo, Norway: Statnett.
- Tennet. 2007. *NorNed, Europe's link to the future*. Arnhem, The Netherlands: Tennet.
- The Physics Factbook. 2009. The Physics Factbook. <http://hypertextbook.com/facts/>. Accessed.
- The White House. 2004. A new generation of American innovation, edited by T. W. House: The White House.
- Tilton, J. E. and G. Lagos. 2007. Assessing the long-run availability of copper. *Resources Policy* 32(1-2): 19-23.
- Tromp, T. K., R.-L. Shia, M. Allen, J. M. Eiler, and Y. L. Yung. 2003. Potential Environmental Impact of a Hydrogen Economy on the Stratosphere. *Science* 300(5626): 1740-1742.
- U.S. Department of Energy. 2004. *Hydrogen posture plan. An integrated research, development and demonstration plan*. U.S. Department of Energy,.
- UK Department for Transport. 2003. *Platinum and hydrogen for fuel cell vehicles*. UK Department for Transport.
- UNEP. 2002. *Global Environment Outlook 3*. London: Earthscan Publications Ltd.

- USGS. 2009a. *Mineral Commodity Summaries 2009*. USGS.
- USGS. 2009b. *Minerals Yearbook 2007*. USGS.
- 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.
- Weindorf, W., U. Bünger, and J. Schindler. 2003. *Comments on the paper by Baldur Eliasson and Ulf Bossel "The Future of the Hydrogen Economy: Bright or Bleak"*. Ottobrun, Germany L-B-Systemtechnik GmbH.
- Wietschel, M., M. Ball, and P. Seydel. 2009. Hydrogen Today. In *The Hydrogen Economy, Opportunities and Challenges*, edited by M. Ball and M. Wietschel. New York: Cambridge University Press.
- Williams, R. H. 2001. Nuclear and Alternative Energy Supply Options for an Environmentally Constrained World; A Long-Term Perspective. In *Nuclear Control Institutes 20th Anniversary Conference Nuclear Power and the Spread of Nuclear Weapons: Can We Have One Without the Other?*. Center for Energy and Environmental Studies, Princeton University
- Worldwatch Institute. 2002. *Vital Signs 2002, Database CD-ROM*: Worldwatch Institute.
- Wright, S. D., A. L. Rogers, J. F. Manwell, and A. Ellis. 2002. *Transmission options for offshore wind farms in the United States*. Amherst, USA: University of Massachusetts.
- Zittel, W. and M. Altmann. 1996. Molecular hydrogen and water vapour emissions in a global hydrogen energy economy. Paper presented at 11th World Hydrogen Energy Conference, June 1996, Stuttgart, Germany.

Chapter 4

Metal requirements of low-carbon power generation

Abstract

Today, almost 70% of the electricity is produced from fossil fuels and power generation accounts for over 40% of global CO₂ emissions. If the targets to reduce climate change are to be met, substantial reductions in emissions are necessary. Compared to other sectors emission reductions in the power sector are relatively easy to achieve because of it consists mainly of point-sources. Carbon capture and storage (CCS) and the use of low-carbon alternative energy sources are the two categories of options to reduce CO₂ emissions. However, for both options additional infrastructure and equipment is needed. This article compares CO₂ emissions and metal requirements of different low-carbon power generation technologies on the basis of Life Cycle Assessment. We analyze the most critical output (CO₂) and the most critical input (metals) in the same methodological framework. CO₂ emissions and metal requirements are compared with annual global emissions and annual production for different metals. It was found that all technologies are very effective in reducing CO₂ emissions. However, CCS and especially non-fossil technologies are substantially more metal intensive than existing power generation. A transition to a low-carbon based power generation would require a substantial upscaling of current mining of several metals.

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4.1 Introduction

The demand for electricity has been rising steadily ever since its introduction in the late 19th century (Fouquet 2008). Since 1980 the average annual growth in demand has been over 3% and this growth is projected to continue in the future (International Energy Agency 2009a). The expected introduction of new technologies such as electric vehicles and heat pumps may even accelerate this demand growth in the future. In 2007 the installed capacity for power generation was over 4,000 GW and the world electricity production in that year was almost 20,000 TWh (International Energy Agency 2009a). Almost 70% of this electricity is produced from fossil fuels (International Energy Agency 2009b) mainly coal (41%) and natural gas (21%). Power generation accounts for over 40% of global CO₂ emissions with an annual emission of 29 Gt in 2007 (International Energy Agency 2009c). Hence, power generation is one of the major contributors to climate change.

If the targets to reduce climate change are to be met, the share of electricity in the energy sector should increase while the emissions from this sector should be substantially reduced. According to the IPCC, emissions need to be reduced by 50 to

85% below 2000 levels by 2050, in order to stabilize atmospheric CO₂ concentrations at 450-490 ppm (Metz et al. 2007). This is estimated to correspond with a temperature increase of 2 °C to 2.4 °C. More than half of this decrease can be achieved by efficiency improvements, the remainder would have to come from Carbon Capture and Storage (CCS) and non-fossil alternatives (International Energy Agency 2009a).

4.1.1 Material requirements of power generation

In this paper we explore how and to what extent material requirements may constrain the scale-up of low-carbon power generation technologies. In an earlier study we found that for some specific technologies the use of minor metals may prevent them from growing to a significant global scale (Kleijn and van der Voet 2010a). The requirements of minor metals will not be discussed here. Next to these minor metals it is also clear that in general the material intensity of new energy technologies is higher than for existing technologies. For CCS this is a logical consequence of the additional infrastructure that is needed for the capture, transport and storage of CO₂ in combination with the loss of efficiency in power plants. For non-fossil technologies this is related to the relatively high material intensity that is needed for harvesting energy from diffuse sources, such as wind and sunlight.

4.1.2 Goal of the study

In this article we will present an analysis of the effectiveness of CO₂ emission reduction and the requirements of selected metals in low-carbon electricity technologies: iron, aluminum, nickel, copper, zinc, tin, molybdenum, silver and uranium. These metals are chosen as a mix of major metals that are important for the general infrastructure: iron, aluminum, copper and zinc; metals that are important for special alloys: nickel, tin and molybdenum; and metals that are important for specific technologies: silver and uranium.

The main research questions addressed here are:

1. to what extent can CCS and current non-fossil technologies contribute to CO₂ emission reduction targets of 50-85% ?
2. what are the metal requirements of these CCS and non-fossil technologies?
3. how does this metal demand compare to current mine production ?

We will start by comparing CO₂ emissions and metal requirements of different electricity producing technologies on a life cycle basis. After that CO₂ emissions and metal requirements of four cases will be compared:

- the current electricity mix (International Energy Agency 2009b)
- the current electricity mix but with the assumption that all fossil fuel based electricity would be fitted with CCS
- an electricity mix consisting of only existing non-fossil technologies
- the 2050 electricity mix as described in the IEA Blue Map Scenario (International Energy Agency 2008).

The emissions and metal requirements are then compared with annual global CO₂ emissions and annual mine production for different metals. Possible bottlenecks are identified and possible solutions are discussed.

4.1.3 Other constraints for low-carbon power generation

Material availability is only one of several factors that might constrain the scale up of the low-carbon electricity technologies. Although these are not the subject of this paper, the most important constraints are briefly discussed in this section: economic constraints, constraints of industrial capacity and spatial and infrastructure planning.

Under the existing economic regime, low-carbon electricity technologies are often more expensive than the dominant fossil fuel based technologies. Only large scale hydropower, nuclear power and wind turbines can compete with fossil fuel based electricity under specific circumstances, while the production price solar electricity is much higher per kWh produced (Raugei and Frankl 2009; Kammen and Pacca 2004) . Furthermore, massive investments are needed for additional infrastructure, either in power transmission for non-fossil energy sources or in CO₂ pipelines for the CCS (Hammond et al. 2011). Subsidies, feed-in-tariffs and other economic instruments are used to overcome this price-gap but this requires considerable shifts in tax regimes and legislation.

However, even if new technologies are competitive with the existing ones, it takes time to build the human and industrial capacity to scale them up to substantial levels i.e.. more than 10% of current production (Kramer and Haigh 2009). In 2007 world installed power generation capacity was around 4500 GW and this is projected to increase to around 7800 GW by 2030 (International Energy Agency 2009a). Around 37.5 GW newly installed wind capacity was added in 2009 (Global Wind Eenergy Council 2009). With a capacity factor of around 0.25-0.4 (Global Wind Energy Council 2010) this is equivalent to about 15 GW installed coal or nuclear capacity (assuming capacity factors of between 0.7 and 0.9) (U.S. Energy Information Administration 2010). PV solar is still far from this level with a newly installed capacity of 5,4 GW in 2008 (REN21 2009). With a capacity factor of around 0.14 (Schiermeier et al. 2008) this is equivalent to 1.5 GW installed coal or nuclear power. In order to contribute significantly to the global power generation capacity in 2030 the production of both wind and PV solar need to be scaled up dramatically.

Next to the economic issues the and industrial capacity, discussions on spatial and infrastructure planning are common when new nuclear power plants, wind turbines and CCS projects are planned and this can slow down the implementation of these technologies considerably (Kintisch 2010b, 2010a).

4.2. Analysis of CO₂ emissions and metal requirements of different technologies

Life Cycle Assessment (LCA) is used here to analyze the CO₂ emissions and metal requirements of different technologies for power generation. In a LCA all emissions and extractions over the whole life cycle of products and services are considered. In this article we limit the scope to CO₂ emissions and the metal requirements. Furthermore, we limit the study to the production of the electricity. This means that the transmission, distribution and use of the electricity is not included. This simplification might lead to a relative overestimation of material needs for distributed power generation options like rooftop PV and distributed wind power. Both of these options would reduce the amount of transmission capacity that is needed. However, in practice, large scale centralized wind and PV farms are needed in order to achieve a substantial contribution to the global electricity production (Kleijn and van der Voet 2010a; MacKay 2009). Centralized wind and PV farms will actually increase the transmission network that is needed. Next to that, a substantial buffering infrastructure would be needed in order to facilitate a substantial share of the renewables in the electricity mix.

The production of the infrastructure, equipment and materials, the transport and mining of fossil fuels and raw materials that are needed for the electricity production are all taken into account. The functional unit of this LCA, which is the basis for comparison of the different technologies, is 1 kWh of electricity delivered to the grid.

4.3 Implications for mass deployment – three cases

In order to assess the effectiveness with regard to CO₂ emission reduction and the metal requirements, three cases for world electricity supply will be compared with a reference case (Table 4-1). The reference case is based on the 2007 energy mix for power generation as given by the IEA (International Energy Agency 2009b). We defined two alternative cases based on different technologies to reduce global CO₂ emissions: CCS and non-fossil energy sources. The cases are not meant to represent a realistic future electricity mix but they are used here as two extremes of the spectrum of low-carbon power generation. Future power generation will most likely consist of a mix of CCS and non-fossil electricity. Therefore, next to these extreme cases, a fourth case was introduced which was based on the electricity mix from IEA BLUE Map scenario as described in (International Energy Agency 2008). This mix was combined with the global electricity supply in 2007. For the electricity production part, the IEA BLUE Map case is based on a combination of low-carbon technologies and CCS.

The CCS case is identical to the reference case but all incineration based electricity (coal, natural gas, oil and biomass) is assumed to be connected to a CCS infrastructure. The non-fossil case assumes a power mix with an equal distribution

over the different non-fossil technologies: 20% nuclear, 20% hydro, 20% wind, 20% PV and 20% biomass. Although this choice seems arbitrary, it is actually a reasonable reflection of the potential (and limitations) of each of these technologies. Intermittency of wind and solar will mean that buffering is needed and that it is sensible to mix them with other sources. Allocating 20% of the electricity mix to both seems therefore reasonable. Although recent growth in hydropower has been substantial and some large projects are still in the pipeline a limited increase from the current 15.6% to 20% of the mix seems reasonable to assume. The best locations for hydropower have been developed already and the environmental and social implications of large projects will limit its growth potential. Nuclear power is back on the political agenda in developed countries and many developing countries are just beginning to explore its potential (International Atomic Energy Agency 2009; Guang and Wenjie 2010). However, the lack of industrial capacity, risks of proliferation, limited capacity for the storage of nuclear waste and difficulties to scale up uranium supply are likely to limit the extent of the growth (Lior 2008). An expansion from the current 14% to 20% seems just doable. In the IEA BLUE Map case the contribution of fossil fuels is limited to 32% which is almost completely combined with CCS. Nuclear is scaled up to 24% and hydro scaled down (relatively) to 13%. Solar and wind combined deliver 25%, and 6% is derived from biomass¹.

Table 4-1: Electricity mix in different cases based on the 2007 global power generation of 19855 TWh (International Energy Agency 2009b)

	current mix		CCS		low carbon		IEA BLUE map	
	%	TWh	%	TWh	%	TWh	%	TWh
coal	41.4%	8220					0%	
coal + CCS			41.8%	8302			14%	2694
natural gas	20.8%	4130					4%	863
natural gas + CCS			21.0%	4171			14%	2689
oil	5.6%	1112					0%	66
oil + CCS			5.7%	1123			0%	0
nuclear	13.7%	2720	13.8%	2747	20%	3971	24%	4856
hydro	15.6%	3097	15.8%	3128	10%	1986	13%	2591
biomass rape seed oil					15%	2978	3%	604
biomass waste wood								
chips in CHP	0.96%	191	0.97%	193	15%	2978	3%	604
wind	0.87%	173	0.88%	174	20%	3971	13%	2549
PV solar	0.02%	4	0.02%	4	20%	3971	12%	2342
others	1.1%	218						
total	100%	19865	100%	19843	100%	19855	100%	19855

In the CCS and low carbon scenario the 1.1 % others is proportionally distributed over the other categories. In the IEA BLUE map scenario the category 'others' accounted for 5%. This 5% was also proportionally distributed over the other categories.

¹ It should be kept in mind that the IEA BLUE Map mix is based on the electricity production in 2030 which is assumed to be about double that of 2007.

4.4 Methods & data sources

LCA is used to calculate CO₂ emissions and metal requirements per kWh electricity produced with different technologies. The LCA was performed using version 5.0 of CMLCA (Heijungs 2010). EcoInvent 2.0 (Frischknecht et al., 2007) was used as the LCA database for all electricity technologies and all background data and it was supplemented with additional data for Carbon Capture and Storage (van der Giesen 2008). Abbreviations, descriptions and data sources of the different technologies are given in Table 4-2. The basic data that was used for the natural gas and coal fired power plants with CCS is given in Table 4-3. For biomass two technologies have been analyzed which more or less represent a worst and best case. The 'best case' is Combined Heat and Power with waste woodchips as a source of biomass. The 'worst case' is rape seed oil which is fed into an oil fired power plant. The metal intensities and CO₂ emissions of the different technologies are then multiplied by the total electricity demand and mix as given in Table 4-1. This results in the total annual CO₂ emissions and metal requirements for the current mix, the CCS mix and the non-fossil mix.

This bottom-up approach to calculate global CO₂ emissions and metal requirements on the basis of individual technologies should be seen as rough estimations of actual emissions and metal requirements. In reality the mix of energy technologies is much more diverse than the one used here. Secondly, when the total energy production is used as the basis for calculations the substantial extra installed capacity which is needed for peak-demand is not taken into account. Finally, in the non-fossil scenario buffering will be needed because 40% of the sources (solar and wind) are intermittent by nature. This buffering can either be done by installing back-up capacity of non-intermittent technologies like nuclear and biomass, or by adding storing options like compressed gas, pumped hydro, batteries etc. Both options will add to the metal requirements and increase CO₂ emissions of the system as a whole. In this very simplified analysis we did not take these factors into account.

In a final step the reduction in CO₂ emission is compared with the emission reduction of 50% to 85% below 2000 levels which is needed for stabilization of atmospheric CO₂ concentrations. The metal requirements are compared with the annual global production of these metals. Data on annual global production are taken from the US Geological Survey (U.S. Geological Survey 2010).

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Table 4-2: Description of power generation pathways, other data from Eco-invent 2.0

abbreviation	description	additional data
<i>current mix electricity</i>		
coal	production of electricity via burning of coal UCTE (European weighted average)	-
natural gas	production of electricity via burning of natural gas UCTE (European weighted average)	-
oil	production of electricity via burning of crude oil UCTE (European weighted average)	-
nuclear	production of electricity in nuclear power plant UCTE (European weighted average)	-
wind	production of electricity with 2 MW offshore wind turbine OCE	-
solar biomass	production of electricity with 3 kWp flat roof PV installations based on mc-Si rape seed oil in oil fired power plant	- a combination of two ecoinvent processes: rape seed oil production and an oil fired power plant
biomass	CHP waste wood chips	-
hydro	Alpine region hydropower	-
<i>electricity with CCS</i>		
coal + CCS	as coal but with Carbon Capture and Storage (CCS)	CCS (van der Giesen 2008)
natural Gas + CCS	as gas but with Carbon Capture and Storage (CCS)	CCS (van der Giesen 2008)
oil + CCS	as coal but with Carbon Capture and Storage (CCS)	CCS (van der Giesen 2008)
biomass+CCS	as biomass but with Carbon Capture and Storage as in natural gas CCS	CCS (van der Giesen 2008)

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Table 4-3: Basic data natural gas and coal power plants with CCS (based on (van der Giesen 2008))

	natural gas	coal	source
power plant			
type	Combined Cycle	pulverized coal	(Frischknecht R. 2007)
size	400MWe	400MWe	(Frischknecht R. 2007)
efficiency	57.7%	35.9%	(Frischknecht R. 2007)
lifetime	180000 hours	150000 hours	(Frischknecht R. 2007)
operation	8000 hours/a	8000 hours/a	(Frischknecht R. 2007)
CO ₂ emission	350 g/kWh (plant only)	930 g/kWh (plant only)	(Frischknecht R. 2007)
CO ₂ concentration flue gas	3.9 mol%	12.8 mol%	(Ramezan and Skone 2007; Fluor and Statoil 2005)
steel in construction	10600 ton	35000 ton	(Frischknecht R. 2007)
efficiency loss due to capture and compression	25%	15%	(Odeh and Cockerill 2008; Spath and Mann 2004)
capture installation			
type	post combustion	post combustion	
solvent	35% MEA	35% MEA	(Fluor and Statoil 2005)
capture efficiency	90%	90%	(Fluor and Statoil 2005)
carbon steel	3700 ton	5560 ton	(van der Giesen 2008)
stainless steel	950 ton	1470 ton	(van der Giesen 2008)
life time	30 year	30 year	(van der Giesen 2008)
compression			
pressure at injectionpoint	100 bar	100 bar	(van der Giesen 2008)
pressure after compression	140 bar	140 bar	(van der Giesen 2008)
weight compressor and pump	210 ton	550 ton	(van der Giesen 2008)
electricity needs	86.5 kWh/ton CO ₂	86.5 kWh/ton CO ₂	(van der Giesen 2008)
life time	15 years	15 years	(van der Giesen 2008)
Pipeline			
length	200 km	200 km	(van der Giesen 2008)
size	NPS 10	NPS 16	(van der Giesen 2008)
wall thickness	6.4 mm	8.9 mm	(van der Giesen 2008)
weight	42 kg/m	93 kg/m	(van der Giesen 2008)
total weight	8400 ton	18600 ton	(van der Giesen 2008)
Injection			
depth of well	1000 m	1000 m	(van der Giesen 2008)
number of wells	1	2.7	(van der Giesen 2008)
stainless steel	210	570	(van der Giesen 2008)

4.5 Results

4.5.1 Analysis of the CO₂ emissions and metal requirements of individual technologies

The results of the calculations of CO₂ emissions and metal requirements of the different electricity producing technologies are given in Figure 4-1 to 4-3. Figure 4-1 shows the CO₂ emissions of different technologies. The application of CCS, will reduce CO₂ emissions from fossil fuel based power plants with a factor 10. For biomass the emissions related to the use of rape seed oil are about half of those of natural gas fired power, without CCS. For the CHP with waste wood the emissions are a factor 30 lower. For nuclear, hydro and wind, CO₂ emissions are very low but not zero. This is caused by the necessary production of equipment, capital goods and infrastructure. In a static attributional LCA, as we have used here, this uses the inputs of the current fossil fuel dominated energy system. For the same reason and because construction and production is relatively more material and energy intensive the emissions related to solar electricity are comparable with those of fossil fuels with CCS.

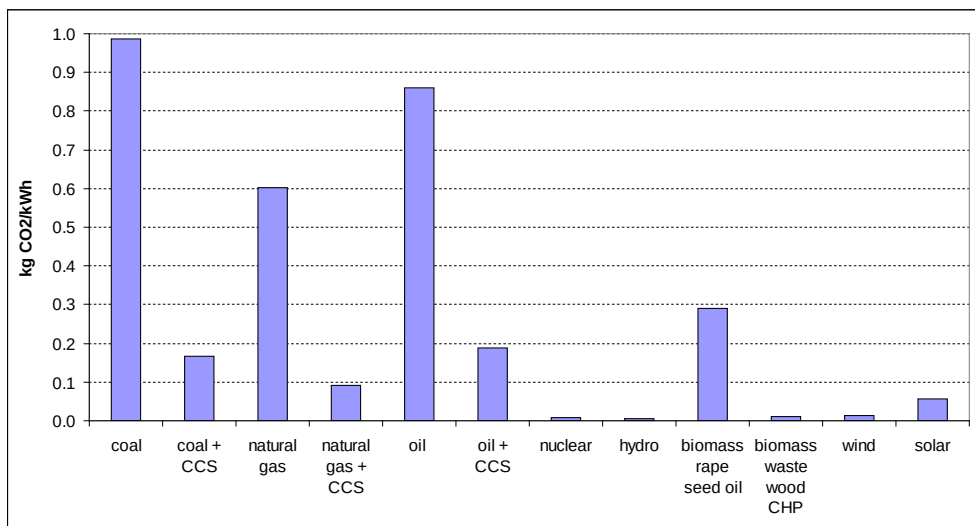


Figure 4-1: CO₂ emissions of different power generation technologies

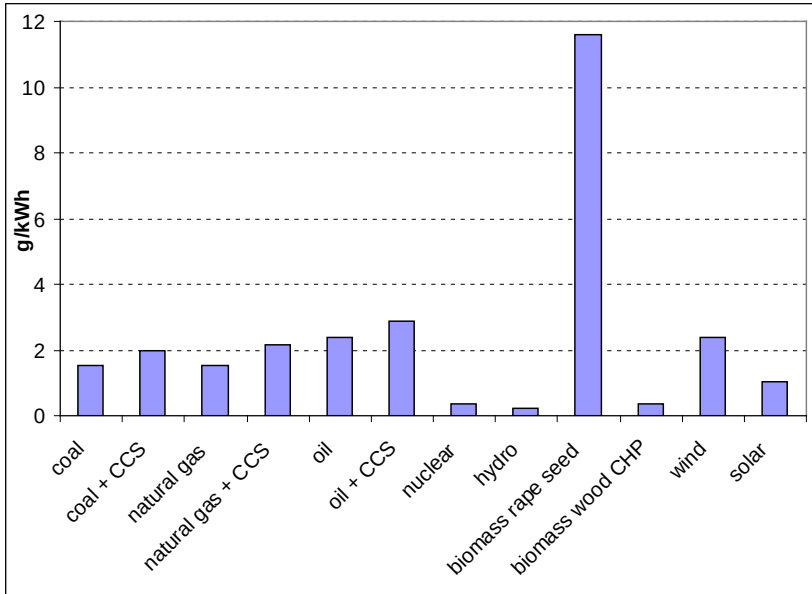


Figure 4-2: Iron requirements in different power generation technologies

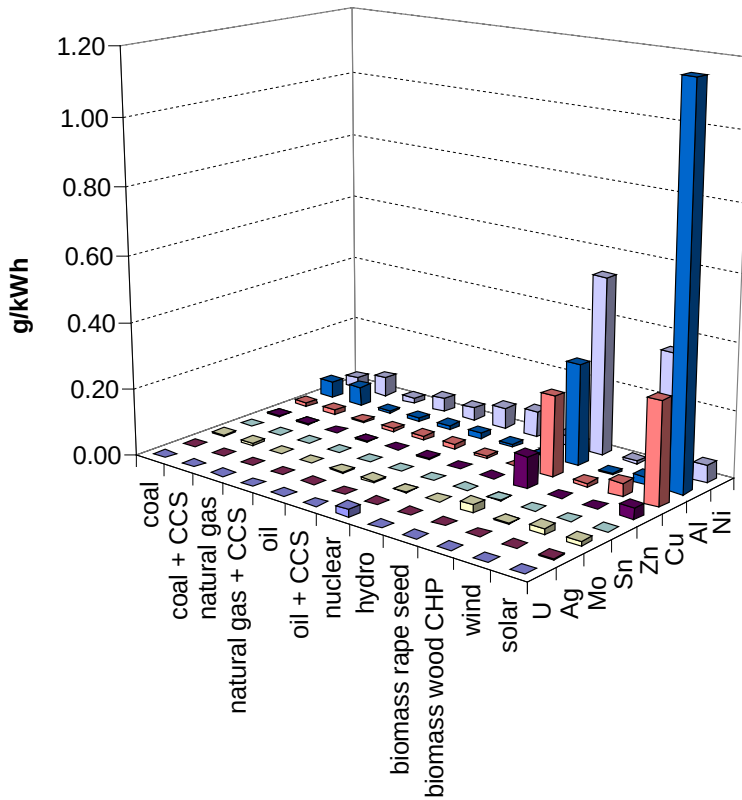


Figure 4-3: Requirements of selected metals in different power generation technologies

With regard to the metal requirements it is clear from Figure 4-2 and 4-3 that CCS will increase the demand for iron and nickel substantially. For coal fired power plants, the increase is about 30% for iron and 75% for nickel. For gas fired power plants, it is about 40% for iron and 150% for nickel. This is caused by additional infrastructure, especially the pipelines and the additional capacity needed to compensate for the loss in efficiency. Wind requires 20% more iron than coal plus CCS and solar is in the same range as natural gas power plants. Biomass energy based on rape seed oil requires about five times as much iron per kWh electricity produced than regular fossil fuel based energy. The reason for this lies in agricultural production of the biomass, which requires substantial inputs like fertilizers and capital goods per unit biomass produced. The intensity for other metals is given in Figure 4-3 and is especially high for the all new non-fossil technologies like rape seed based biomass, PV-solar and wind. For biomass the reason is again the high amounts of fertilizers and capital goods required. For wind and solar it is metal intensive turbines and solar panels and their production.

In Figure 4-4 the material demand of different technologies is given relative to the metal demand of the current electricity mix. It is clear that requirements for most metals are higher in the case of CCS, but much more so in the case of non-fossil technologies.

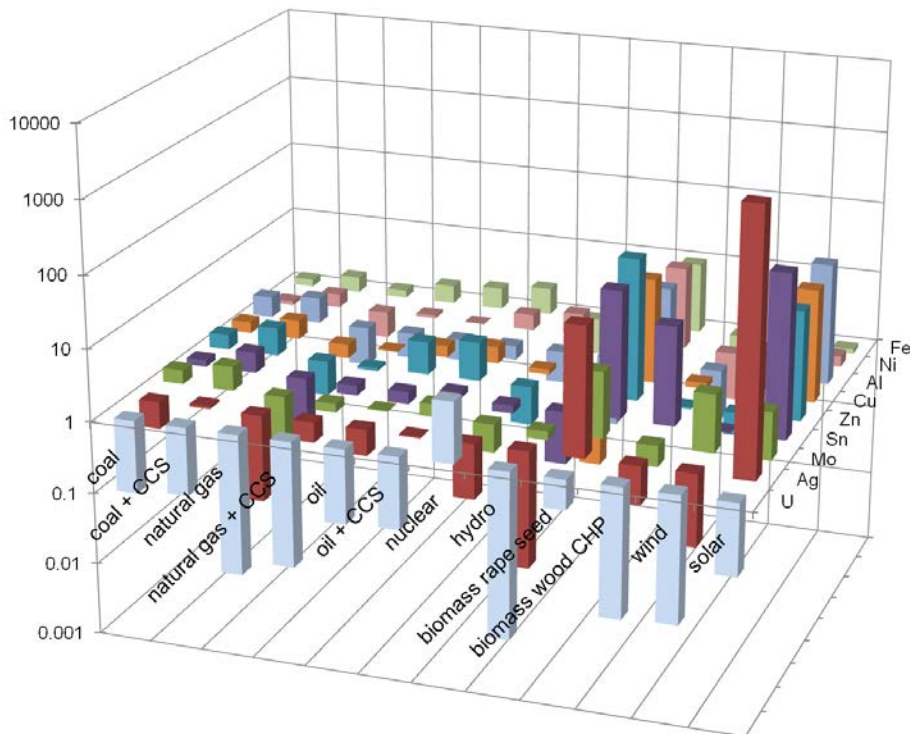


Figure 4-4: Requirements of selected metals in different power generation technologies relative to the metal demand of the current mix

4.5.2 Analysis of the CO₂ emissions and metal requirements at world scale implementation – the three cases.

In Figure 4-5 the CO₂ emissions of the three different cases and the reference case are given. The 11.6 Pg of annual CO₂ emissions from power generation compares well with the 11.9 Pg/a which is given by the IEA (International Energy Agency 2009c). However, in contrast to the IEA figures, the emissions we calculated are "life-cycle" emissions which means that the emissions of the production of the fuels and capital goods and all other upstream processes are included in the 11.6 Pg/a. Since over 90% of the life cycle CO₂ emissions from gas and coal based electricity originate from the power plants themselves and less than 10% from the background processes this still means the bottom-up figures we calculated are in correct order of magnitude. At an assumed 90% capture rate at the power station, CCS reduces the life cycle emissions to around 17% of the emissions in the current mix. The non-fossil case reduces the emissions just a little extra to about 10% of the current mix. The IEA BLUE Maps scenario is about as effective as the other two cases. All three cases are thus more or less equally efficient in reducing CO₂ emissions. All three fall well within the range of emission reductions (50-85%) that are necessary to stabilize atmospheric CO₂ concentration to levels around 450 ppm.

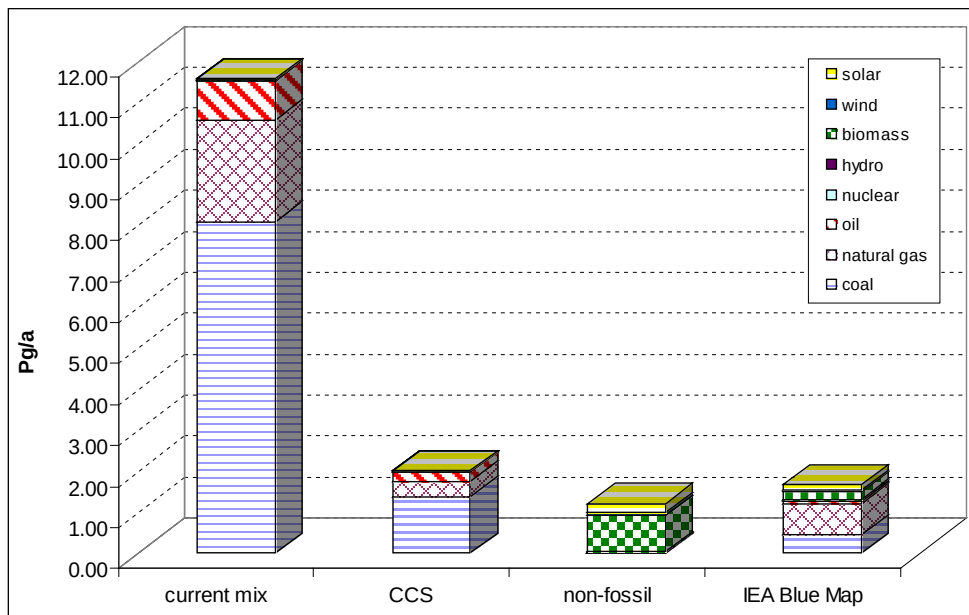


Figure 4-5: CO₂ emissions in the different power mix cases

Figure 4-6 and 4-7 show the metal requirements for the CCS, non-fossil, IEA BLUE maps cases in relation to the current mix. The CCS case requires an annual input which is 10% (silver) to 40% (nickel) higher than that in the current mix. For uranium the annual requirement remains constant as the nuclear fraction in the mix remains constant in this case. The non-fossil case requires far more metals than the current

mix: between 1.5 times (uranium) and almost 800 times (silver) the amount in the current mix.

Whether these increases are important becomes more clear, when the requirements for power generation are compared with current annual mine production. Figure 4-8 shows the annual metal requirements in the three cases and reference case, given as a fraction of the 2009 world mine production of these metals. From this analysis it is clear that the increases of metal requirement of iron, tin, and zinc are relatively insignificant when compared to current mine production. However, the increases in requirements in the non-fossil case for aluminum (1% to 15%), nickel (50% to 250%), molybdenum (30% to 100%) and silver (0% to 44%) but also uranium (130% to 190%) would have a significant impact on the mining of these metals. In the CCS case the material requirements are less but still significant. Nickel demand would go from about 60% to over 80% of the annual production and for molybdenum from about 30% to 40%. In the IEA BLUE maps case the material requirements are in between as expected.

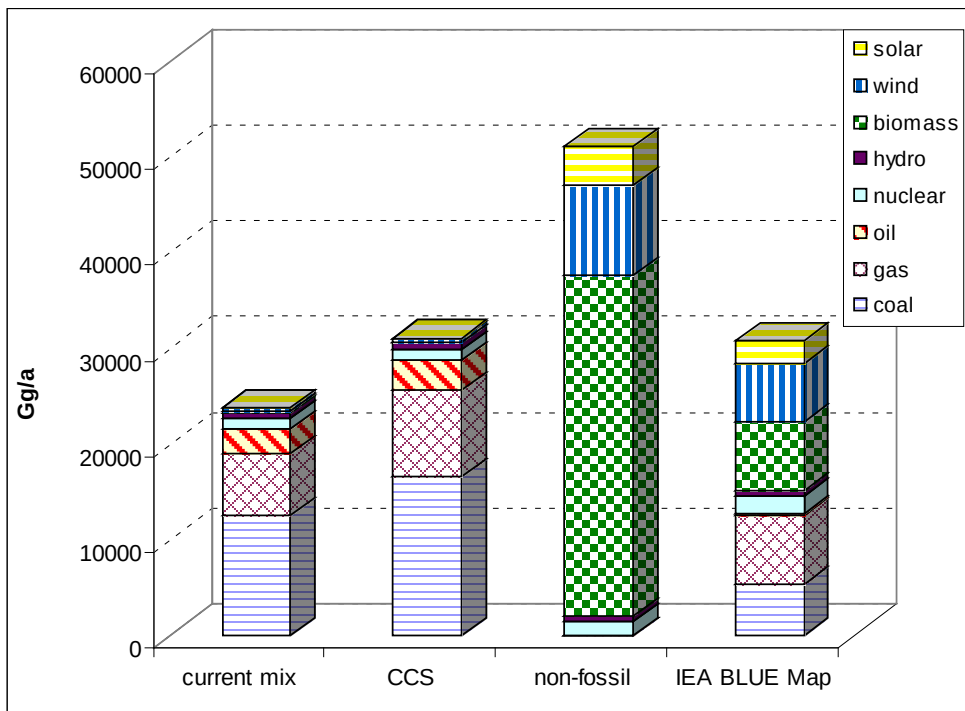


Figure 4- 6: Iron requirements in different power mix cases

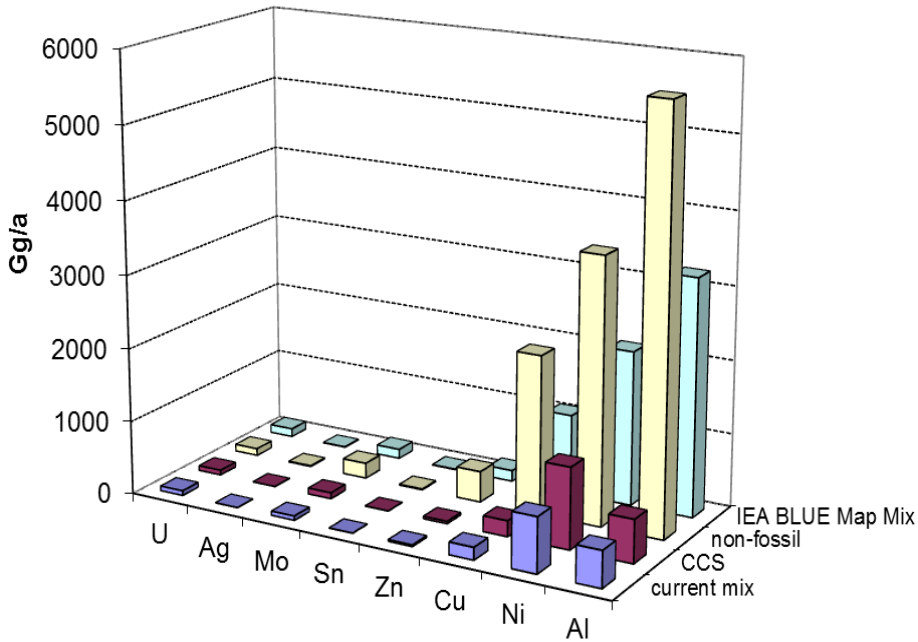


Figure 4-7: Requirements of selected metals in different power-mix cases

4.6 Conclusions and discussion

About 40% of global CO₂ emissions originates from the production of power. In this paper, we have analyzed to what extent these emissions can be reduced, by the use of low-carbon technologies (CCS, nuclear and renewables) and what the consequences would be with regard to the metal requirements. All three electricity mixes presented here (CCS, non-fossil and IEA BLUE Maps) result in a reduction of about 80-90% of CO₂ emissions, if comparable reductions would be achieved in other sectors the 450-490 ppm stabilization goals could be realizable. However, in all three cases presented here this comes at a cost of higher metal requirement.

The addition of CCS to the current electricity mix, would influence the annual demand for nickel and molybdenum substantially. Applying CCS requires 10 to 30% percent more metals than the current electricity mix (Figure 4-8). This is a result of the additional infrastructure that is needed to capture, transport and store CO₂ (specialty steels), in combination with a reduced efficiency of the power plants.

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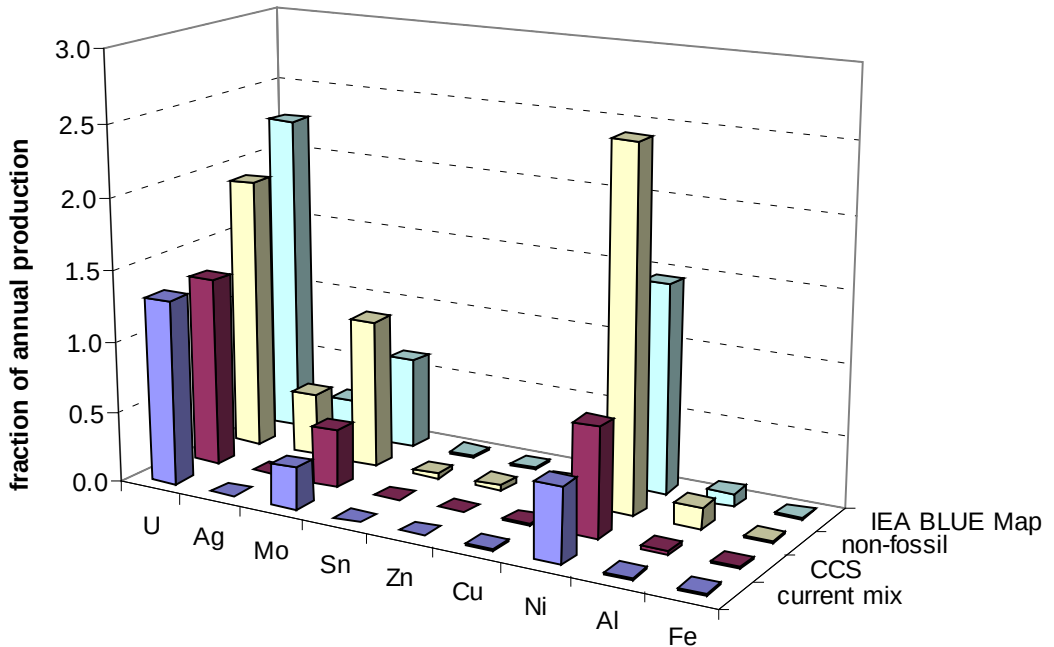


Figure 4-8: Requirements of selected metals in different power mix cases compared with world annual mine production of these metals.

The switch to a non-fossil electricity mix would result in a much higher demand for nickel, uranium, silver, molybdenum and, to a lesser extent, copper and aluminum. For PV-solar, non-waste biomass and wind the increase in metal use ranges from a few percent to a factor thousand. This means that mining of these metals would have to be scaled up considerably in order to fulfill the demand for these new electricity technologies (Figure 4-8). Not all non-fossil technologies are more metal intensive than fossil fuel based power. Nuclear power, hydropower and waste biomass have a relatively low metal intensity. PV-solar, non-waste biomass and wind, however, are much more metal intensive than the current mix. For PV-solar and wind the increase is related to the relatively high metal intensity of PV solar cells and wind turbines. For non-waste biomass it is related to the need for relatively material intensive agricultural processes including the production of agricultural machines and the production of fertilizers.

The last couple of decades a trend of decreasing material intensity per unit of GDP produced has been found in many developed countries (Moll et al. 2005; van der Voet et al. 2005). However, when climate change forces these economies to switch to alternative energy sources, for the energy sector, this trend is broken.

The type of material demand in different technologies depends strongly on the specific technologies that are chosen. For example, the extremely high demand for silver in solar electricity is related to the choice for mono-crystalline silicon PV cells. However, other PV solar technologies have material demand issues of their own (Kleijn and van der Voet 2010b; Wadia et al. 2009). Current thin film CdTe and CIGS will run into scarcity issues long before they will contribute significantly to the global power generation (Kleijn and van der Voet 2010a). The 2 MW off-shore wind turbine with a geared generator that we used in this study does not require neodymium based permanent magnets. However, the new, more efficient and low-maintenance direct-drive turbines use about 150 kg Nd per MW (Polinder et al. 2006; Kleijn and van der Voet 2010a). Scaling up these technologies to the level of tens of GW would require a dramatic increase in the production of this rare earth metal.

Next to PV solar, wind and biomass electricity other renewable technologies like ocean renewables and PV thermal are available as well. Some first results show that ocean renewables have an even higher metal intensity than the technologies discussed here. The amount of iron needed in the equipment itself (excluding the life-cycle) for wave and tidal energy is between 8 and 10 g/kWh (Kluts 2009), which is four to five times as high as the life-cycle iron intensity for wind turbines.

We did not analyze any changes in the grid related to the different technologies. However, it is clear that the CCS options would require little or no changes to existing transmission and distribution infrastructure, while the large scale introduction of PV and wind would require substantial changes in the electricity infrastructure. Roof PV relocates electricity production to the electricity consumers and it will thereby reduce the transmission load in the network. In contrast, centralized PV and wind power, especially off-shore, will relocate and probably increase the infrastructure needed for transmission. This will increase the metal requirements of these technologies considerably, especially for copper and aluminum.

The analysis presented here is a static analysis in which the dynamics of the transition to a low-carbon electricity system are not discussed. However, if climate goals are to be met a fast transition to a low-carbon power sector is needed. If the power sector will be transformed in the next two or three decades, based on current technologies, it is clear that this will cause a significant peak in metal demand. Uncertainties about the long term climate policy and technology choices will make it difficult for mining companies to anticipate such a peak. Further research is needed to explore the dynamics of the metal demand connected to the energy transition.

In this work we only looked at the electricity sector. However, the energy transition will also lead to increased material demand in other sectors. One of the most important ones will be the automotive sector. Hybrids and plug-in hybrids, full electric vehicles and fuel cell vehicles will all require metals in high tech parts like batteries, electro motors (including permanent magnets) and fuel cells (Kleijn and van der Voet 2010b). At the same time the introduction of these vehicles will considerably increase the demand for electricity.

Whether or not material requirements induce material scarcity will depend on a host of things, but specifically also on the possibilities for substitution (Goeller and Weinberg 1976; Ayres 2007). In many of the technologies described here, material substitution may potentially reduce the requirement of specific metals. Silver in PV-solar cells might be replaced by other metals. PV solar cells can be made on a completely new basis e.g. FeS cells. Nickel and molybdenum containing steels might be replaced by steels containing other alloys or by new strong and inert composite materials. Concrete might be used to substitute for the steel towers of wind turbines. Aluminum can substitute copper as a conductor. Extensive agriculture which produces high cellulosic biomass might substitute for the highly intensive oil producing agriculture. However, there is a limit to which this substitution is possible. It is not likely that completely new carbon based materials will replace basic materials like steel and other metals in the near future. There is a limited number of elements available and at the moment almost all of them have useful applications. Shifting from one to the other will therefore in many cases simply shift the problems of material availability from one sector to another. In addition, substitution that is forced by looming scarcity – in contrast to substitution induced by product improvement – could very well slow down the energy transition and reduce overall efficiency, as material choices are forced by scarcity and the technically “optimal” solutions cannot reach their full potential.

Energy and mining are linked to each other in two directions: not only are materials needed for building (new) energy infrastructures but, the other way around, huge amounts of energy are needed during mining, reduction and refining of metals. Increased mining will lead to additional energy use. Dwindling ore grades and the use of less accessible resources will increase energy demand per kg of metal (Norgate 2010). This will result in considerably higher CO₂-emission levels providing a less optimistic picture of GHG benefits of low-carbon energy pathways.

Until now technological developments in mining and processing of metals have more than compensated for the dwindling ore grades and increasing demand, keeping metal prices relatively low (Radetzki et al. 2008; Radetzki 2008; Gordon 2009; Solow 1974). The peaks we have seen in metal prices in the past can almost always be explained by peaks in demand that outpaced the capability miners and processors to increase supply. However, there are indications that the latest mismatch between demand and supply, the 2002–2008 metal boom, was at least partly caused by more fundamental problems at the supply side (Mudd 2010; Humphreys 2010).

The transition to a sustainable energy system is a prerequisite for a sustainable future but there are hurdles, some of which are not that obvious. In the end, changing the world's energy system to reduce GHG-emissions is a huge operation with huge implications for the world's material system as well. There are all kinds of feedback mechanisms and dynamics involved that make it difficult to oversee all implications. This paper shows, at least, that using diffuse energy sources instead of concentrated sources substantially increases metal requirements for harvesting the energy. It also

shows that adding emission reduction technologies to the existing fossil fuel based energy systems increases metal requirements, be it to a lesser extent. Whatever the future energy system will look like, at least we can be sure that the days of “easy”, i.e. material-extensive, are over. It is very important to explore all the implications of such a change to support the transition to a new energy system, in order to make it a sustainable system and catch any drawbacks in an early stage.

References

- Ayres, R. U. 2007. On the practical limits to substitution. *Ecological Economics* 61(1): 115-128.
- Fluor and Statoil. 2005. *Study and Estimate for CO₂ Capture Facilities for the proposed 800 MW Combined Cycle Power Plant -Tjeldbergodden, Norway* CB2005-0022
- Fouquet, R. 2008. *Heat, Power and Light*. Cheltenham: Edward Elgar.
- Frischknecht R., A. H.-J., Doka, G., Dones, R., Heck T., Hellweg, S., Hischer, 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.
- Global Wind Energy Council. 2009. Global wind power boom continues despite economic woes. [http://www.gwec.net/index.php?id=30&no_cache=1&tx_ttnews\[tt_news\]=247&tx_ttnews\[backPid\]=4&cHash=1196e940a0](http://www.gwec.net/index.php?id=30&no_cache=1&tx_ttnews[tt_news]=247&tx_ttnews[backPid]=4&cHash=1196e940a0). Accessed February 7, 2010
- Global Wind Energy Council. 2010. Large scale integration of wind energy into electricity grids. <http://www.gwec.net/index.php?id=146&L=0>. Accessed.
- 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.
- Guang, Y. and H. Wenjie. 2010. The status quo of China's nuclear power and the uranium gap solution. *Energy Policy* 38(2): 966-975.
- Hammond, G. P., S. S. O. Akwe, and S. Williams. 2011. Techno-economic appraisal of fossil-fuelled power generation systems with carbon dioxide capture and storage. *Energy* 36(2): 975-984.
- Heijungs, R. 2010. CMLCA: Scientific Software for LCA <http://www.cmlca.eu/>. Accessed February 8, 2010.
- Humphreys, D. 2010. The great metals boom: A retrospective. *Resources Policy* 35(1): 1-13.
- International Atomic Energy Agency. 2009. *Nuclear Technology Review*. Vienna: IAEA.
- International Energy Agency. 2008. *Energy Technology Perspectives*. Paris: EIA.
- International Energy Agency. 2009a. *World Energy Outlook 2009*. Paris: IEA.
- International Energy Agency. 2009b. IEA Statistics Online. <http://www.iea.org/stats/>. Accessed February 2, 2010.
- International Energy Agency. 2009c. *CO₂ emission from fuel combustion, 2009 edition, Highlights*. Paris: IEA.
- Kammen, D. M. and S. Pacca. 2004. Assessing the costs of electricity. *Annual Review of Environment and Resources* 29(1): 301-344.
- Kintisch, E. 2010a. Other Siting Problems. *Science* 329(5993): 789-.
- Kintisch, E. 2010b. Out of Site. *Science* 329(5993): 788-789.
- Kleijn, R. and E. van der Voet. 2010a. Resource constraints in a hydrogen economy based on renewable energy sources. *Renewable and sustainable energy reviews* 14(xxx).

- Kleijn, R. and E. van der Voet. 2010b. Resource constraints in a hydrogen economy based on renewable energy sources: An exploration. *Renewable and sustainable energy reviews* 14(9): 2784-2795.
- Kluts, I. 2009. Material use of ocean renewable energy technologiesthes, CML, Leiden University.
- Kramer, G. J. and M. Haigh. 2009. No quick switch to low-carbon energy. *Nature* 462(7273): 568-569.
- Lior, N. 2008. Energy resources and use: The present situation and possible paths to the future. *Energy* 33(6): 842-857.
- MacKay, D. J. C. 2009. *Sustainable Energy - Without the hot air*. Cambridge: UIT Cambridge Ltd.
- Metz, B., O. R. Davidson, P. R. Bosch, R. Dave, and L. A. Meyer, eds. 2007. *Technical Summary. 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. New York: Cambridge University Press.
- Moll, S., S. Bringezu, and H. Schütz. 2005. *Resource use in European countries*. Wuppertal: Wuppertal Institute.
- Mudd, G. M. 2010. The Environmental sustainability of mining in Australia: key mega-trends and looming constraints. *Resources Policy* In Press, Corrected Proof.
- 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.
- Odeh, N. A. and T. T. Cockerill. 2008. Life cycle GHG assessment of fossil fuel power plants with carbon capture and storage. *Energy Policy* 36(1): 367-380.
- Polinder, H., F. A. van der Pijl, G.-J. de Vilder, and P. J. Tavner. 2006. Comparison of Direct-Drive and Geared Generator Concepts for Wind Turbines. *IEEE Transactions on energy conversion* 21(3): 8.
- 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.
- Ramezan, M. and T. J. Skone. 2007. *Carbon Dioxide Capture from Existing Coal-Fired Power Plants*. DOE/NETL-401/110907. National Energy Technology Laboratory.
- Raugei, M. and P. Frankl. 2009. Life cycle impacts and costs of photovoltaic systems: Current state of the art and future outlooks. *Energy* 34(3): 392-399.
- REN21. 2009. *Renewables Global Status Report 2009 update*. Paris: Renewable Energy Policy Network for the 21st century.
- Schiermeier, Q., J. Tollefson, T. Scully, A. Witze, and O. Morton. 2008. Energy alternatives: Electricity without carbon. *Nature* 454(7206): 816-823.
- Solow, R. M. 1974. The Economics of Resources or the Resources of Economics. *American Economic Review* 64(2): 1.
- Spath, P. L. and M. K. Mann. 2004. *Biomass Power and Conventional Fossil Systems with and without CO₂ Sequestration – Comparing the Energy Balance, Greenhouse Gas Emissions and Economics*. NREL/TP-510-32575. National Renewable Energy Laboratory.
- U.S. Energy Information Administration. 2010. Electric Power Industry 2008: Year in Review. http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html. Accessed February 8, 2010.
- U.S. Geological Survey. 2010. *Mineral Commodity Summaries 2010*. U.S. Geological Survey.
- van der Giesen, C. 2008. Metals Matter, Assessing life cycle material demands of carbon capture and storage MSc thesis, Institute of Environmental Sciences (CML), Leiden University, Leiden.

Chapter 4

- van der Voet, E., L. van Oers, S. Moll, H. Schütz, S. Bringezu, S. de Bruyn, M. Sevenster, and G. Warringa. 2005. *Policy Review on Decoupling: Development of indicators to assess decoupling of economic development and environmental pressure in the EU-25 and AC-3 countries*. Leiden: Institute of Environmental Sciences (CML), Leiden University
- Wuppertal Institute for Climate, Environment and Energy
CE Solutions for Environment, Economy and Technology
- 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.

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.

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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 cropland². 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.

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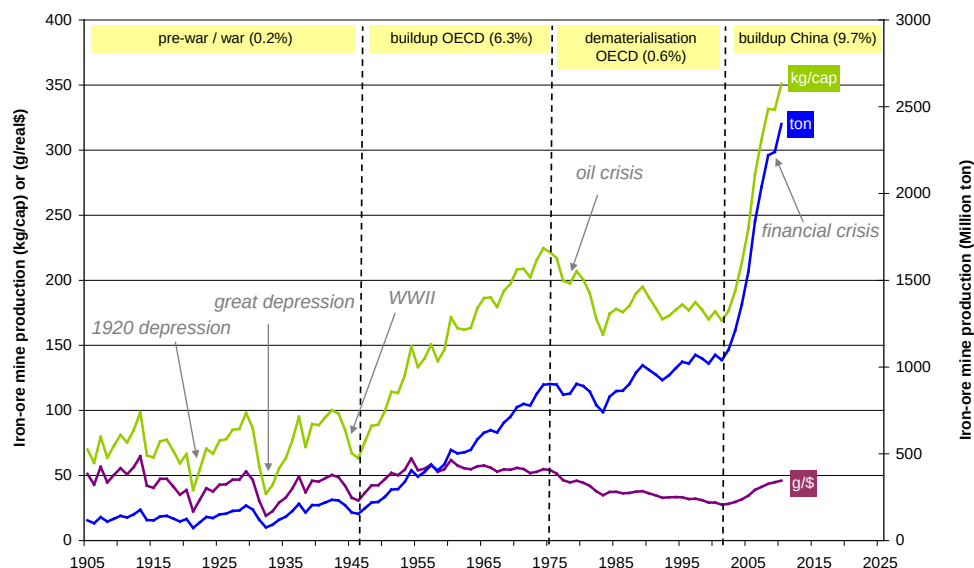


Figure 5-1: Global trends in mine production of iron-ore, 1905-2010. Population and GDP data from Maddison (Maddison 2011) and metal mine production data from USGS (U.S. Geological Survey 2011)

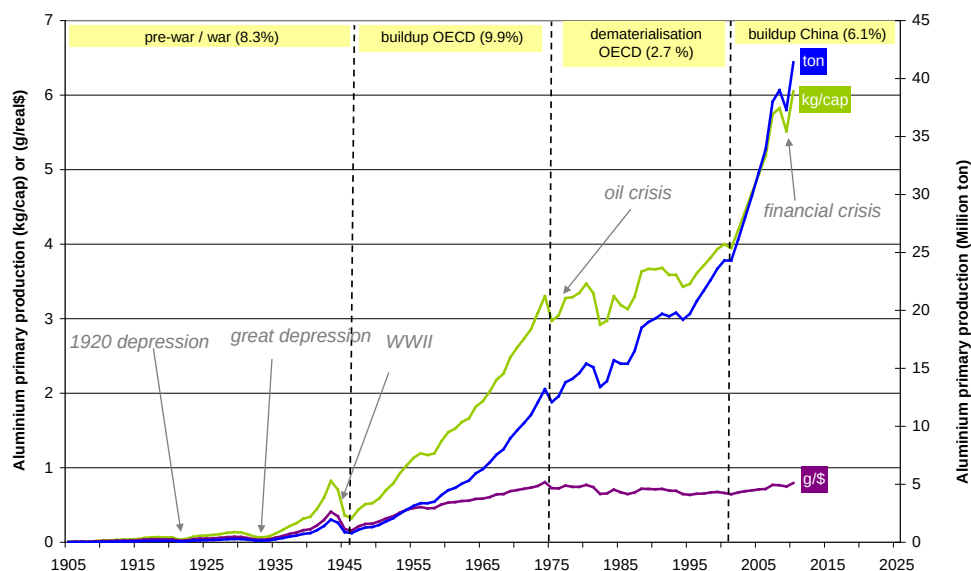


Figure 5-2: Global trends in mine production of aluminium, 1905-2010. Population and GDP data from Maddison (Maddison 2011) and metal mine production data from USGS (U.S. Geological Survey 2011)

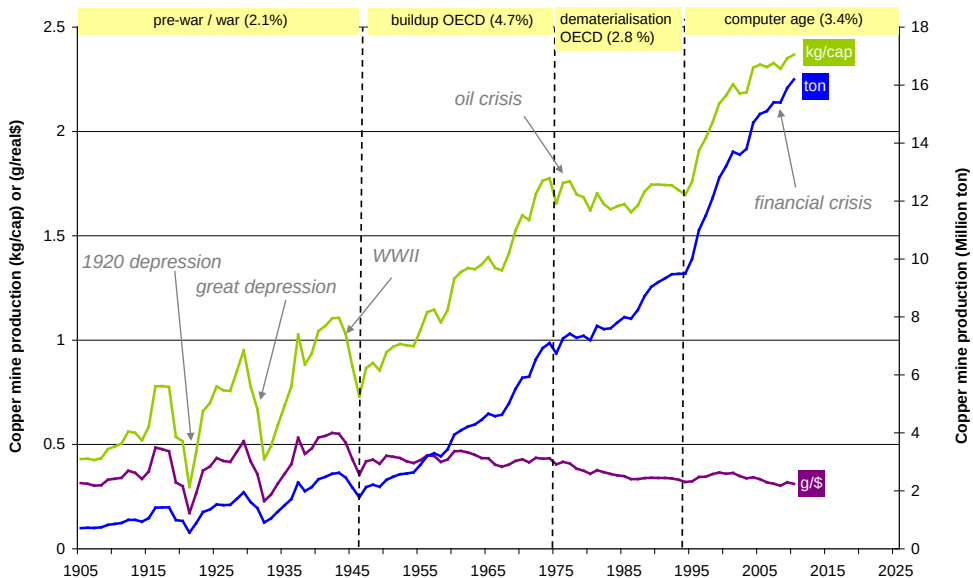


Figure 5-3: Global trends in mine production of copper, 1905-2010. Population and GDP data from Maddison (Maddison 2011) and metal mine production data from USGS (U.S. Geological Survey 2011)

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 China³ 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 large⁴. 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).

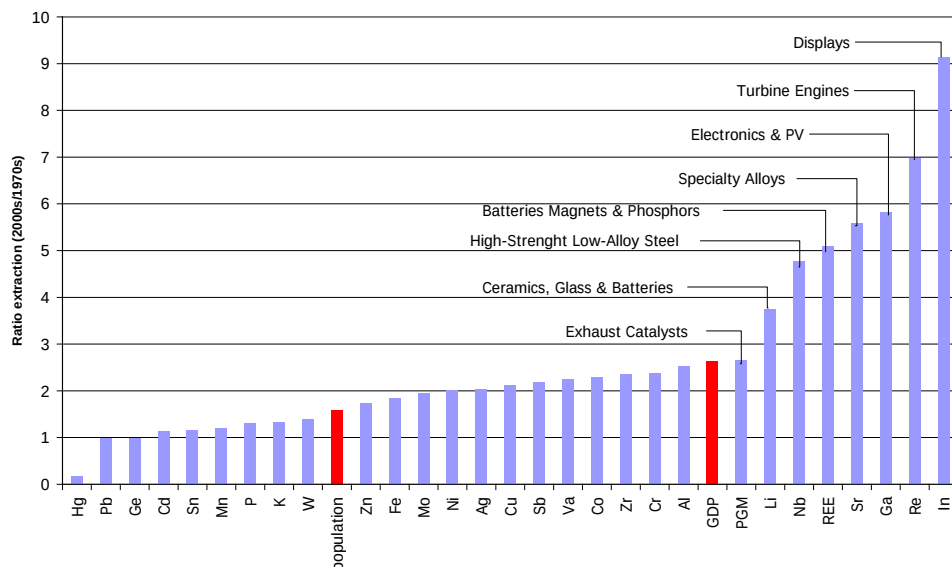


Figure 5-4: Ratio of global mineral mine production (2000-2009 / 1970-1979). GDP and population data from Maddison (Maddison 2011) and metal mine production data from USGS (U.S. Geological Survey 2010). Main applications are given for elements for which the mine production grew faster than GDP. (GDP=Gross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

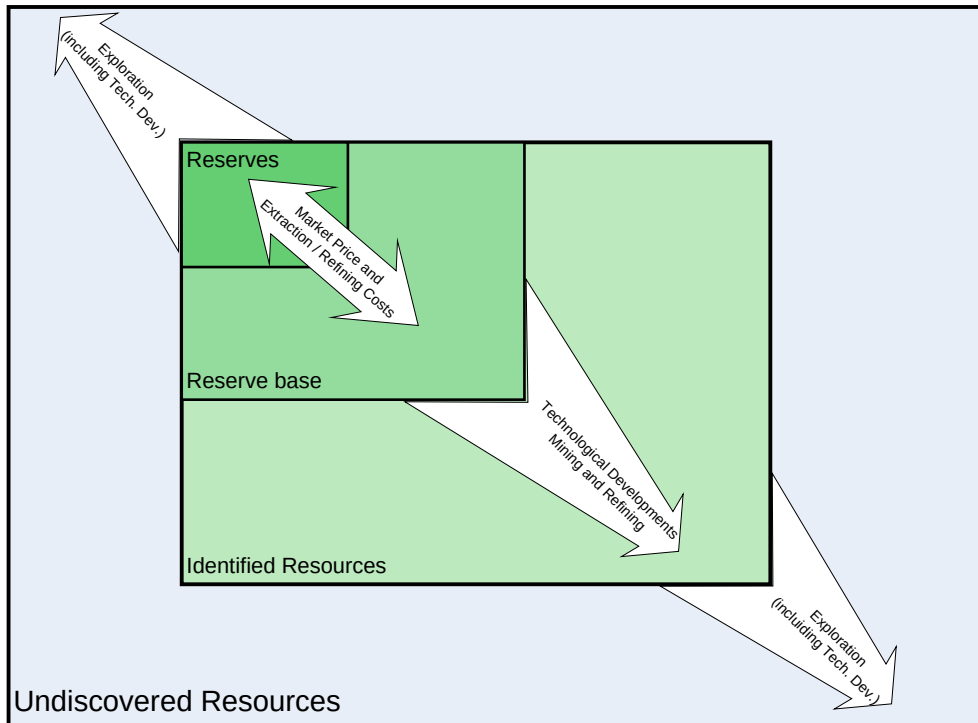


Figure 5-5: The relation between economic and technical reserves and resources. This is a simplification of a more detailed qualification system used by the USGS (U.S. Geological Survey 2010) The term Reserves is used for resources that can be economically extracted today. The term Reserve Base is used 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 assess 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 too 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" (Diederer 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 produced⁵. 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 and 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 g Cu/kWh		energy use for copper production kWh/g Cu		copper return on investment 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 change 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: Fraunhofer.
- Frischknecht R., A. H.-J., Doka, G., Dones, R., Heck T., Hellweg, S., Hirschier, 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.E.N.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.

- 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 precious metal recovery 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 Urbanization 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.

Chapter 6

The need for combining IEA and IE tools: The potential effects of a global ban on PVC on climate change

Abstract

Over the last decades the concepts of Integrated Environmental Assessment (IEA) and Industrial Ecology (IE), both claiming to provide analyses and solutions for sustainability issues, have been developed separately as they emerged in response to questions from different policy-fields. In both fields, specific tools are used to support national and international environmental policy. The focus of IEA and IE tools, however, is different. IEA tools focus on one or a limited number of specific environmental issues. They often model the chain environmental processes with high spatial (and temporal) resolution, but have a low resolution for the material structure of the economy and only partly take into account indirect effects that occur via physical and socio-economic linkages. IE tools take into account all environmental issues related to a specific substance or product. They have a high resolution for the material structure of the economy and take into account indirect effects that occur via physical linkages, however, their environmental modelling is very limited. Both IE and IEA tools have proven to be very useful and neither is superior to the other. However, a combination of both can provide additional information that can be used for more effective policy making. We use the case of a hypothetical world wide ban on PVC to show that a measure that is not directly related to climate change could still have significant climate effects. This indirect effect is a result of the linkages of material flows in society. We show that IEA tools are not well suited to include these types of effects and that IE tools can fill this gap partially. What is really needed is a broader systems perspective that takes into account the full range of possible side-effects of environmental policy measures.¹

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6.1 Introduction

Integrated Environmental Assessment (IEA) and Industrial Ecology (IE) are important concepts in the realm of sustainability and environmental sciences. Both concepts use a systems perspective to analyse similar environmental and sustainability issues. Therefore both concepts are quite comprehensive if one looks at the definitions that are used by their advocates (for Integrated Environmental Assessment see e.g.: Hettelingh et al. 2005, Van der Sluijs 2002; Rotmans and Dowlatabadi, 1997; for Industrial Ecology: Lifset and Graedel 2002; Allenby 1999). Although the definitions of the concepts are overlapping to a large extent, the tools that

¹ An update on this issue is given in Chapter 7.

practitioners in the fields use are distinct both in their structure as well as in the questions they answer. To our knowledge this is the first attempt to illustrate the differences between these two concepts when applied to a specific case and to highlight the possibilities for combining them in a more comprehensive analysis.

Integrated Environmental Assessment tools are often used for scenario analysis, to calculate future trends in emissions and related environmental issues. These calculations are made on the basis of socio-economic indicators at the macro-level, such as developments in GDP and population. Current IEA tools are built around specific, large-scale environmental issues such as climate change and acidification. Although existing Integrated Environmental Assessment tools contain complex dynamic models of the economy, the resolution in terms of material flows in society is rather low (Figure 6-1).

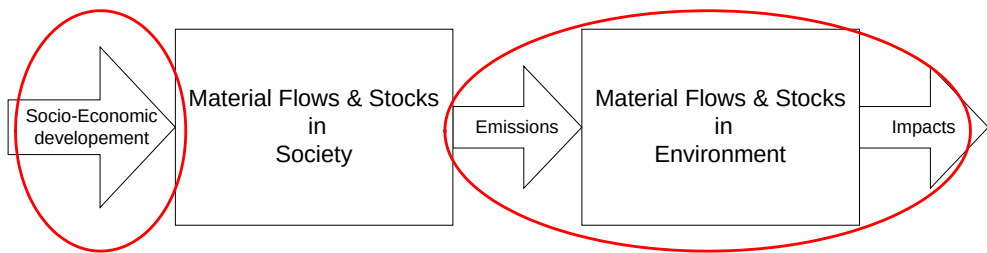


Figure 6-1: *The main focus of Integrated Environmental Assessment tools*

The emissions are calculated on the basis of the dynamic development of a few highly aggregated economic sectors. Interconnections between material flows within society are not systematically accounted for. However policy measures aimed at reducing environmental issues mostly have a number of widely different impacts, often also outside the realm of the environmental issue they address (Raadschelders et al., 2003). Examples are: economic accumulation, relocation of pollution, substitution of one emission by another, dilution of emissions and co-recycling of contaminants (Raadschelders et al., 2003). Studies in the emerging field of Industrial ecology have clearly shown that side-effects of environmental policy measures are often caused by changes in the closely interconnected material flows in society (e.g. Ayres & Simonis 1994; Ayres & Ayres, 1996; Baccini & Bader 1996; van der Voet et al., 2000; Bourg & Erkman, 2003). Because of this interconnection, problem shifting from one substance to another, from one environmental problem to another, or shifts in time and space often occurs as a result of policy measures. Co-benefits and co-damages of policy measures that occur via the interconnections of material flows in society can easily be overlooked by IEA tools.

The aims of Industrial Ecology are, as indicated above, quite similar to those of IEA. In contrast, the tools connected with this concept are quite different. Industrial Ecology tools are mainly used to analyse and assess the environmental effects of

changes in material flows in society. Material Flow Analysis (MFA) and Substance Flow Analysis (SFA) are used to analyse the flows of materials or specific substances in society and their interconnections.

The resolution of IE tools is high in terms of material flows in society and their interconnections, for example linked to product life cycles, and in how these material flows result in emissions (Figure 6-2). In the environment, on the other hand, the resolution is low: environmental impacts are modelled roughly or not at all like in MFA/SFA, or in terms of potential impacts with low spatial resolution like in LCA. Furthermore, the link with macro-economic drivers is weak. The result of most LCAs is only valid if the differences that are described are marginal from a macro-economic point of view. MFAs and SFAs describe also non-marginal changes but they are not systematically linked to socio-economic developments.

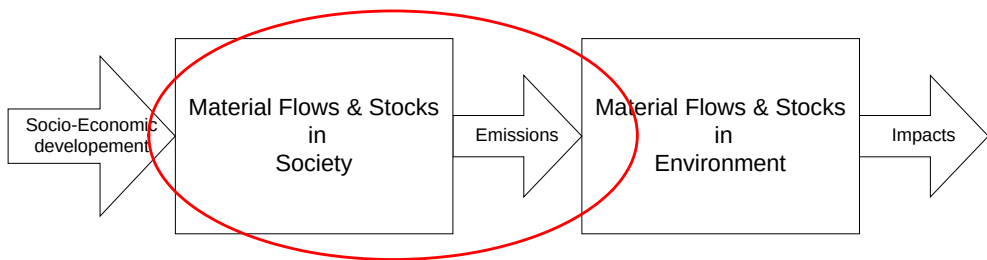


Figure 6-2: The main focus of Industrial Ecology tools

Our hypothesis is that the systems perspective on material flows in society that is provided by Industrial Ecology tools can be used in addition to Integrated Environmental Assessment tools, (1) to detect and therefore prevent different forms of problem shifting, or in other words to identify co-benefits and co-damages of environmental policy measures, techniques, transitions etc., and (2) to identify potential environmental impacts of policy measures aimed not at specific environmental issues, but at materials and products in society.

In this article we will show that tools related to Industrial Ecology analysing material flows in society can provide important additional information compared with IEA tools. In order to illustrate this we will use the example of a hypothetical world wide ban on the production of PVC. This example is chosen for several reasons. First of all, it refers to a long-standing and still ongoing environmental debate. For that reason, PVC has been subject to policies both on the national (VROM, 1997) and on the European level (Commission of The European Communities, 2000 and European Parliament, 2001). Secondly, phasing out PVC implies a large-scale change which cause far reaching changes in industrial sectors and thus possibly also in the environmental flows, both directly and indirectly. In the third place, it aims at changes in material flows in society and therefore is suitable as a case to illustrate the value of using Industrial Ecology tools in addition to an Integrated Environmental Assessment approach. In Section 2, a brief description is provided of the PVC and chlorine

debate. Section 3 describes the above mentioned tools of Integrated Environmental Assessment and Industrial Ecology. In Section 4, the tools are applied to assess the impacts of a hypothetical PVC ban. Section 5 generalises these findings and treats the need for a wider perspective. Conclusions are presented in Section 6.

6.2 The PVC and chlorine debate

Chlorine and chlorinated compounds have been an important part of the chemical industry since the early 1940's. DDT was found to be very useful because its acute human toxicity is extremely low, and therefore it was thought of as a very safe pesticide. The same holds true for CFCs as aerosol. PVC has become one of the major plastics because of its inertness and because its properties can be manipulated relatively easily by adding all sorts of additives. Furthermore, chlorinated compounds have become very popular intermediates in chemical industry. It is relatively easy to replace hydrogen by chlorine in a hydrocarbon compound while this chlorine in turn can relatively easily be replaced by other functional groups.

Environmental concerns around chlorinated compounds started with concerns about the ecotoxicological impacts of DDT and Drins (a group of pesticides) in the late nineteen sixties. Later, the ozone depleting impacts of CFCs were discovered and PCBs were added to the list of toxic and persistent chlorine compounds. With the discovery in the nineteen eighties of the fact that in many processes unintended production of extremely persistent and toxic dioxins occurred, the use of chlorine in the chemical industry became strongly debated. Many of the compounds that are nowadays on the list of most hazardous substances are chlorinated compounds. Environmental NGOs, supported by a number of scientists and GOs, have been calling for a complete ban of chlorine from the chemical industry. PVC has been in the centre of this discussion because it is the only bulk polymer (next to neoprene) that contains a substantial amount of chlorine (up to 56% on weight basis) and because of the fact that dioxins are produced when incomplete combustion of PVC occurs. Another argument against PVC was put forward recently, concerning the additives. Toxic phthalates are used as a plasticiser in flexible PVC, which for example was often used in baby-toys. Still another argument that is used against the use of PVC is the adverse effects of PVC on the recycling of mixed plastics. Both the chlorine and the additives interfere with the recycling process. Although toxicity issues have been the driver of the PVC/chlorine debate in the early days, nowadays it is clear that other environmental issues are involved as well. Climate change is introduced as an issue in the assessment of plastics in general, for example when comparing fossil fuel-based plastics with bio-based alternatives. Acidification is also an issue, specifically related to PVC, because of the formation of hydrochloric acid in waste incineration. Finally public safety is now an important issue in the chlorine debate, mainly connected to the transport of chlorine by train through densely populated areas.

There are many sides to the issue of PVC, or, more broadly, chlorine. The stalemate in the societal debate seems to center around a difference in basic starting points (Tukker 1999, Kleijn et al., 1997). The NGO's take the point of view that there are alternatives to all chlorine applications, consequently they argue that a ban on chlorine is possible and should be effected in view of all certain and uncertain adverse impacts. In contrast, the industry starts from the wide usefulness of chlorine, and argues that substitution is only useful if the alternative is proven to have less impacts. It could be useful, therefore, to assess the impacts of a measure such as a complete ban on PVC. What would be the environmental benefit? Are the alternatives functionally equivalent, and is their impact on the environment indeed less? The PVC case is used here to illustrate the differences between the IEA and IE approaches, single out their strong points and limitations, and say something about the way they could be improved and mutually benefit from each other.

6.3 IEA and IE Tools

6.3.1 Integrated Environmental Assessment tools

There are many Integrated Environmental Assessment tools. In Figure 6-1 the main focus of Integrated Assessment tools is illustrated. For practical reasons we will use the Climate Change tool IMAGE (IMAGE team, 2001) and the acidification tool RAINS (Amann et al., 2001; Hettelingh et al., 2005) as examples here. Both tools have been very successful in supporting policy on both the national and the international level.

RAINS has been developed by IIASA (Alcamo, 1990; Amann et al., 2001; Hettelingh et al., 2005) as a tool for the integrated environmental assessment of alternative strategies to reduce acid rain deposition. RAINS is an abbreviation of 'Regional Air Pollution INformation and Simulation'. RAINS Europe, which was developed on the basis of the original RAINS, expanded its scope from acidification to eutrophication and ground-level ozone. Recently the scope of RAINS was further broadened to include fine particulate matter (Schöpp et al, 1999). The tool consists of five modules:

1. developments in energy use, agricultural and other productive activities, delivering emissions of acidifying compounds;
2. and 3. two modules on emissions and control costs;
4. atmospheric dispersion;
5. environmental impacts (environmental effects in RAINS terminology).

Any changes in the flows of materials in society have to be translated in terms of the first module. In this module, emissions of three acidifying compounds (sulphur dioxide, nitrogen oxides and ammonia), VOC and fine particulate matter are calculated by using the characteristics of different energy sources and agricultural activities. This is done on the basis of a database on energy use and agricultural activities for 38 European countries and regions, 21 energy sources and 6 economic sectors. Locations of emissions and depositions are specified and the output of the tool can be given as a map consisting of grid cells with different colours that correspond with the level to which critical loads are exceeded.

RAINS Europe was used to provide scientific support for the negotiations under the Geneva Convention on Transboundary Air Pollution in Europe (Overseas Environmental Cooperation, 2000). The European commission has decided that IIASA's RAINS tool will serve as the core Integrated Environmental Assessment tool in the framework of the 'Clean Air For Europe' (CAFE) programme (IIASA, 2003).

The Integrated Model to Assess the Global Environment (IMAGE) tool has been developed by RIVM (IMAGE team, 2001) as a tool for the integrated environmental assessment of global change. IMAGE 2.2 consists of three modules:

1. The Energy Industry System (EIS), which calculates regional energy consumption, energy efficiency improvements, fuel substitution, supply and trade of fossil fuels and renewable energy. On the basis of energy use and industrial production emissions are calculated.
2. The Terrestrial Environment System (TES) which calculates land-use changes on the basis of data on developments in agriculture and forestry. Furthermore it calculates emissions from land-use changes, natural ecosystems and agricultural production systems, and the exchange of CO₂ between terrestrial ecosystems and the atmosphere.
3. The Atmospheric Ocean System (AOS), which calculates changes in atmospheric composition using the data from the EIS and TES modules, and taking oceanic CO₂ uptake and atmospheric chemistry into consideration. Subsequently, AOS calculates changes in climatic properties by resolving the changes in radiative forcing.

IMAGE and other IEA climate change tools have been used as a basis to support the discussions in the Intergovernmental Panel on Climate Change (IPCC) (de Vries et al., 2001). The IPCC, in turn, provided policy makers with scientific assessments that were used as an input for the development of international conventions like the United Nations Framework Convention on Climate Change and the Kyoto protocol that resulted from that.

The starting point for calculating the impacts of a ban on PVC obviously is the EIS module, and more specifically TIMER (the Targets IMage Regional simulation model). TIMER is used as a sub-module within the EIS module and simulates the global energy system on the basis of data on 17 world regions. The main objectives of TIMER are to analyse the long-term dynamics of energy conservation and the transition to non-fossil fuels, and to explore long-term trends for energy-related greenhouse gas emissions (de Vries et al., 2001). TIMER will also be used in future versions of RAINS.

The perspective of these IEA tools is limited because:

1. the thematic character of the tools: they only address a specific environmental issue. For example impacts of an energy oriented measure on toxicity are outside the scope of climate change tools;

2. the resolution of the economic driver modules is low. Small scale measures, for example aimed at specific industries, are out of sight because their influence on the economic development of the aggregated sector will be small;
3. material flows in society and their linkages are absent. Therefore these tools are blind for effects that occur via product and material chains and lifecycles. One example of this is the PVC case which is described in this article.

There may be different ways to address the limitations of these tools. To detect side-effects to other environmental issues, the different thematic IEA tools could be linked. To resolve the low resolution problem, for example, more detail may be brought into the economic driver module. Other tools might be used in addition to IEA tools to provide a more complete picture. Here we focus on the combination of IEA tools with IE tools

6.3.2 Industrial Ecology tools

Similar to Integrated Environmental Assessment, there are many different analytical tools in the field of Industrial Ecology. In Figure 6-2 the main focus of Industrial Ecology tools is illustrated. Again for practical reasons we have chosen two tools that will be applied on the case of PVC: Substance Flow Analysis (SFA) and Life-Cycle Assessment (LCA). Both tools have been used frequently to analyse the societal metabolism of certain substances (SFA) and societal material flows connected to products and services (LCA).

Environmental Life Cycle Assessment is an IE tool that can be used to compare the potential environmental impacts of productsystems. A product system consists of all processes in the lifecycle of a product or services: from extraction of raw materials via the production, to use, recycling and final waste disposal. (e.g. Guinee et al. 2002; ISO 14040). It can be used, therefore, to compare PVC applications with certain PVC free alternatives. LCA is by nature a static tool in which 'ceteris paribus' conditions will normally be used for the calculations, although more advanced types of LCA are being developed (Wrisberg et al., 2002). Like SFA, LCA is a tool that, in principle, can be applied to all products and services. The first phase therefore is the definition of the specific research question(s) and selection of the products or services that are being compared. In the next phase, the inventory analysis, the relevant process data are collected and the emissions, extractions and possibly other interventions of the whole product system are calculated. In the impact assessment phase these interventions are translated into potential contributions to selected environmental issues. In the impact analysis so-called characterisation factors are used to indicate the potential environmental impacts of the specific emissions and extractions. If possible internationally accepted factors like Global Warming Potentials and Ozone Depletion Potentials are used as characterisation factor. One way in which IEA and LCA are linked is the use of these factors which can be seen as a result of IEA tools. IEA tools are also more and more used to generate spatially differentiated characterisation factors (e.g. Potting, 1998 et al. and Potting, 2000). In some cases the results are

weighted and added to one single environmental score. Nowadays LCA types of analysis are used increasingly for larger systems, e.g. to compare different systems for the energy supply in a certain region or country.

Substance Flow Analysis (SFA) has been developed as a quantitative analytical tool to keep track of the flows of a certain substance or substance group in society. SFA can be used for different purpose: As an accounting system, large flows or accumulations can be signalled that may cause environmental issues in the future. If repeated regularly, trends in certain flows can be detected. As a static or steady state model, it can be used to trace back environmental issues to their origins: the flows of substances in society. The steady state model can also be used to study the effectiveness of policy measures. SFA as a dynamic model can be used to estimate future flows and stocks. In dynamic SFA societal stocks are included and time is thus entered as a variable in the model, and dynamic scenario analysis is made possible (Kleijn et al., 2000, Elshkaki et al., 2005). The framework of SFA can be applied to any (group of) substance(s) and on any geographical level or region. The starting point for an SFA is often a specific environmental problem. The substances contributing to this problem are identified and the geographical and temporal system boundaries are set. SFA is obviously suitable to describe and analyse societal flows and stocks of PVC, and the changes therein as a result of policy measures. The consequence for the environment are more difficult to address since the focus is limited to the substance(group) which is studied.

Not only the scope, but also the policy implications of Industrial Ecology tools are different compared with the IEA tools. Integrated Environmental Assessment tools are used to support policies on specific environmental issues while the IE tools are used in product policy and chemicals policies both in the private sector and by governmental agencies. In addition Life Cycle Assessment (LCA) is sometimes use to support environmental labelling and certification (Guinée et al, 2002). SFA has been used to analyse the societal material flows which cause certain specific environmental issues (Van der Voet et al., 2000, Hansen and Lassen, 2000). Potting (2000) has shown that the IEA tools can be used to introduce spatial differentiation in LCA.

6.4 Applications of IEA and IE tools on the case of PVC

Before applying any analytical tools, we must have a rough idea on what would happen in case of a world-wide ban on PVC. A simplified schematic overview of the production and use of PVC is given in Figure 6-3. PVC is produced via the polymerisation of vinyl chloride monomer (VCM) which in turn is produced from ethylene dichloride (EDC). EDC is produced via a combination of direct chlorination (with chlorine) and oxy-chlorination (with HCl) of ethene. The main applications of PVC are in profiles for construction (pipes, window frames etc), insulation material (electrical cables), flooring and packaging. At first glance, a ban on PVC would result in:

- the dismantling of PVC production facilities (or transformation in order to produce other products which in this case is not very likely);
- a drop in the demand for the raw materials for the production of PVC;
- a substitution of PVC by other materials in products in which PVC is used at the moment.

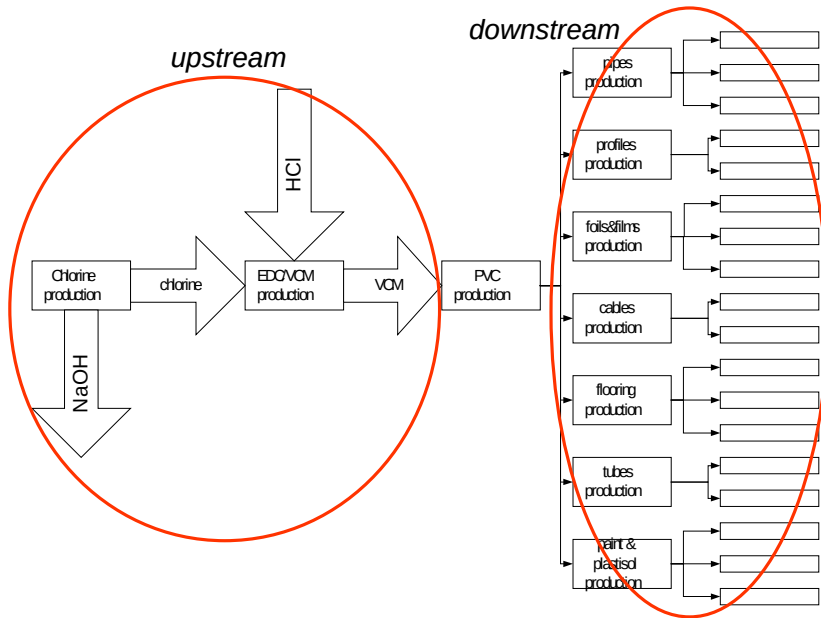


Figure 6-3: A simplified schematic overview of the production and use of PVC.

Of course all these effects would result in changes in material and energy flows through society. This in turn would affect extractions and emissions and thus environmental impacts. Emissions of e.g. phthalates, dioxins and other chlorine compounds, and extractions of fossil fuels would change. However a ban will also result in changes in greenhouse gas and acidifying emissions. Half of the mass of the PVC polymer is determined by chlorine, therefore if PVC is replaced by pure hydrocarbon plastics such as polyethylene (PE), more fossil fuels will be needed to

produce the same amount of plastic. On the other hand, if PE-waste is incinerated with energy recovery, a part of the energy in the fossil fuels used to produce the PE will be recovered. Naturally, the drop in PVC related impacts will coincide with an increase of impacts related to the alternatives for PVC. The question is, which of these and other direct and indirect impacts will become visible when applying the IEA and IE tools. This is treated below.

6.4.1 Application of IMAGE on the case of PVC

In terms of IMAGE a ban on PVC should be translated in terms that can be used as a change in the Energy and Industry System. In this system there are two modules that are of interest in this case: the Energy & Industry emissions and the Energy Demand & Supply module (TIMER). The Energy & Industry module contains lists of industrial sectors together with emission factors for non-energy greenhouse gas emissions. Economic data on the development of these sectors is used to calculate the greenhouse gas emissions from these sectors over time. The feedstock or chemical manufacture sectors are in principle relevant for this case, but the resolution of these sectors is too low to distinguish a single polymer like PVC. Therefore there is little opportunity to use this module for the calculation of the effects of this ban on PVC. The introduction of the ban on PVC in the Energy Demand & Supply module is also problematic. On first sight a ban on PVC does not result in a large change in the global energy demand. One example is the substitution of PVC by PE as a plastic. Since the substitution of PVC by PE will result in an increased demand for fossil fuels as feedstock (PVC consists for about 50% of chlorine while PE comes for 100% from fossil fuels) this can be translated in a change of demand for fossil fuels. For this, the ban on PVC would have to be translated in a change of certain variables in TIMER that would result in changes in greenhouse gas emissions. However, since the resolution of TIMER is very low if it comes to the use of fossil fuels as feedstock, again it is not straightforward how a ban on PVC could be translated in terms of IMAGE.

It is clear that IMAGE can not be used directly to calculate the changes in emissions of greenhouse gas (GHG) emissions connected to a ban on PVC due to the fact that neither the EIS nor the TIMER module have the appropriate resolution. Of course it would be possible to first calculate the changes in greenhouse gas emissions by other means, and to use the obtained reduced greenhouse gas emissions as an input for IMAGE. However, this solution is not optimal since for every measure a separate analysis would be needed. Another solution could be to increase the resolution by, for example, distinguishing not 5 but 500 sectors of industry, similar to the resolution in current Input-Output Analyses. The PVC producing industry then could be one of those sectors. A measure such as phasing out PVC would then be translated in the decline of the PVC industry and the concurrent growth of, for example, the PE producing industry. It is very likely that the changes in GHG emissions resulting from this change as calculated in TIMER would be minor, and that the measure could indeed be considered too small to be relevant. Moreover, indirect effects as well as side-effects to other environmental issues would still be out of sight.

6.4.2 Application of RAINS on the case of PVC

When attempts are made to translate the phase-out of PVC into terms of changes in inputs for RAINS, similar problems do occur. Like in IMAGE, the resolution on the material flows in society in RAINS is relatively low although emission reduction technologies are quite specified. The economy is divided in 6 economic sectors and 21 energy sources. A measure like the phase-out of PVC is again too small to be implemented in RAINS as such. Like in IMAGE, it would of course be possible to first calculate the changes by other means and then to use the results in terms of changes in emissions as an input for RAINS. Adding more resolution could be another option here as well, with similar implications as described in section 4.1. An additional interesting point is that the incineration of PVC generates HCl which contributes to acidification. A phase-out of PVC would thus reduce the HCl emissions and thereby acidification. HCl emissions are not included in RAINS, therefore these changes are invisible. This could be repaired, however, by adding HCl as an acidifying substance. All in all it is clear that, because of the low resolution of RAINS if it comes to material flows in society, a measure like a phase-out of PVC is a measure too small for RAINS to handle.

In the next sections, we apply Industrial Ecology tools to see whether indeed phasing out PVC is a small, non-relevant measure. We will focus mainly on the changes in emissions of climate change and acidifying compounds via indirect routes, including substitution and effects based on the linkages of material flows within the relevant sectors. Side-effects on other environmental issues will also be visible, but we consider this self-evident and it will not be the main focus. The interesting question is: can changes in the emissions that do not come forward in IEA tools, either due to a lower resolution or to indirect effects, be detected with IE tools?

6.4.3 Application of LCA on the case of PVC

When a ban on PVC would be implemented PVC would be replaced by other materials. LCA can be used to calculate the potential environmental impacts of the substitution of PVC with alternatives like polyethylene (PE) and polypropylene (PP). In LCA the whole life cycle is considered so all processes of the lifecycle, from the extractions of resources such as salt and crude oil to the final waste treatment of the products, are included.

Many of such LCAs have been made for PVC products and their alternatives. Although there are some good reasons why LCAs cannot cover all details of the discussions on toxicity related to the PVC lifecycle (Tukker, 1998), they can still be used to get some indication of the relative impacts of PVC products on many other environmental issues like climate change. A simple qualitative meta-analysis was made of existing LCAs of PVC products and alternatives. 22 studies were considered of which 8 were part of other meta-studies (PVC LCAs: Reusser, 1998; Richter et al, 1996; Potting and Blok, 1994; Intron, 1995; de Baere et al., 1994; Verspeek et al., 1992; Beenen and Eygelaar, 1993, Tötsch, W. and H. Polack 1992, FKS, 1995; Albrecht and Langowski, 1997; meta studies: Krahling 1999; Finnveden et al., 1996).

All studies give answers to the question whether or not replacing PVC by alternatives in specific applications would be beneficial for specific environmental issues. The alternatives depend on the applications but consist of other (HD)PE, PP in different applications, aluminium and wood in window frames, linoleum and wool in carpets, glass and paper in packaging etc. (Table 6-1).

Table 6-1: Results of LCAs of PVC and alternative materials in different products (in relative ranking, 1=least impact)

	product (reference)	compared materials	energy use	waste	global warming potential	acidification	nutrification	photochemical smog formation	toxicity	abiotic depletion
1	potable water pipeline systems (Reusser, 1998)	PVC	2		1	3	2			
		HDPE	3		2	2	3			
		cast iron	1		3	1	1			
2	sewage pipeline systems (Reusser 1998)	PVC	2		1	3	3			
		HDPE	3		1	2	2			
		stoneware	1		2	1	1			
3	windowframes (Richter et al, 1996)	PVC	2	3		4		4		
		aluminium	4	4		5		3		
		steel	5	5		3		5		
		stainless steel	6	1		7		6		
		non-ferrous+B84 metal	7	2		6		7		
		wood/Al	3	6		2		2		
		wood	1	7		1		1		
4	flooring (Potting & Blok, 1994)	cushion PVC	3	2	2	3	2	3		
		linoleum	1	1	1	1	1	1		
		woollen carpet	2	4	4	3	4	4		
		polyamide carpet	4	3	3	2	3	2		
5	sewage pipelines (Intron, 1995)	PVC (3 layers)	3	3				3	3	3
		concrete	1	1				1	1	1
		gres (stoneware)	2	2				2	2	2
6	bottles for non-sparkling water de Baere, et al., 1994)	PVC	2	3	1	3	1	1	2	2
		PET	3	2	3	1	2	3	2	1
		glass	1	1	2	2	3	2	1	3
7	blisters for medical tablets de Baere, et al., 1994)	PVC-Al	1	2	1	2	2	1	2	3
		PP-Al (BUWAL)	2	1	3	1	1	2	1	1
		PP-Al (PWMI)	3	1	2	3	3	1	3	2

	product (reference)	compared materials	energy use	waste	global warming potential	acidification	nutrification	photochemical smog formation	toxicity	abiotic depletion
8	potable water pipelines (Verspeek et al, 1992)	PVC	2						2	1
		asbestos cement	1						1	1
		cast-iron	4						1	2
		steel	5						5	1
		glassfiber/polyester	2						3	1
		glassfiber/epoxy	3						4	1
9	ring binders (Beenen & Eygelaar, 1993)	PVC	5	5					4	
		PVC glued	3	4					3	
		PP	2	1					1	
		PP glued	4	2					2	
		cardboard PP lam.	1	3					5	
10	blisters (Tötsch and Polack, 1992)	PVC	1						1	
		PET	2						2	
11	blisters for medical tablets (Tötsch and Polack, 1992)	PVC/Al	1						2	
		PP/Al	2						1	
12	wounddrain bottle (Tötsch and Polack, 1992)	PVC	1						2	
		PET	2						1	
13	main sewage pipes (FKS, 1995)	PVC (recycled)	1	1					2	3
		Gres (stoneware)	3	2					3	1
		concrete	2	3					1	2
14	flooring resilient (Albrecht & Langowski, 1997)	PVC	4	5	5	4				
		PVC cushion	2	4	4	3				
		polyolefine	3	2	1	2				
		linoleum	1	1	6	1				
		rubber	5	3	3	5				
		parquet	7		7					
		textile	6		2					

The relative ranking of the impacts of consequences for the different environmental issues that were included in each study was determined (Table 6-1). PVC scores relatively good on climate energy use and climate change. This is due to the fact that only half of the weight of PVC comes from fossil fuels, contrary to other plastics. The scores are however influenced by assumptions that are made for waste treatment. If a waste treatment is assumed with an efficient energy recovery system, the advantage of PVC over PE and PP is reduced. PVC is worse than PE if it comes to acidification because hydrochloric acid is produced during the incineration of PVC waste. PVC also scores worse on toxicity impacts. This is caused partly by the emissions during production and use, and partly by dioxin emissions during waste treatment.

In order to draw some strong conclusions on the basis of a meta study differences in methodologies, assumptions and quality of the LCA studies should be considered. However, on the basis of this very rough survey it seems that replacing products containing PVC with alternatives that are free of PVC might reduce toxicity problems and acidification, but on the other hand could increase the problem of climate change.

It is clear that these LCA studies can be used to compare the environmental impacts of PVC products with its alternatives. The methodological limitations of such studies should however be kept in mind. The product system of PVC, or process tree, is built up out of processes that are linked to each other in a linear way. Since standard LCAs use the assumption of *ceteris paribus* the effects of replacing 1 kg of PVC by e.g. 1 kg of PE can be assessed. However, the effects of replacing the total PVC production and consumption chain by a PE chain would need more than a standard LCA. The effects of changes in the market for chlorine and other intermediates and the possible dismantling of chlorine production plants are not included. To answer that type of question LCA is not the right tool. LCA is more suited to answer *smaller* questions like: *what material, from an environmental point of view, would be best to use in a specific product?* Although a standard LCA does not answer the question: *what would be the environmental impacts of a ban on PVC*, it can still be used to answer a part of this question: *how does PVC compare environmentally to its alternatives in specific applications?*

6.4.4 Application of SFA on the case of PVC

In case of a world-wide ban on PVC, the SFA region is defined as the world as a whole and the material is PVC. An SFA of PVC as a substance would result in an overview of PVC flows and stocks in the world. These PVC flows can then be connected to environmental problem flows like those of phthalates and heavy metals which are used as additives (Tukker et al. 1997, Tukker et al., 1998). Although this is interesting when one wants to highlight the most important flows in the total metabolism of a material it does not answer the question *what would be the environmental impacts of a ban on PVC?* The answer to this question on the basis of an SFA of PVC is that all the flows, thus also all the problematic flows, would gradually disappear as the stocks in society will decrease over time. Any alternatives or shifting of problems via other materials or processes is out of sight.

If one would broaden the scope of the SFA by choosing chlorine as the substance for the analysis, the interconnections of PVC to the rest of the chlorine chain become visible. Several of these studies have been done on different geographical levels (Tukker et al., 1995; Ayres, 1997; Ayres and Ayres 1997; Ayres, 1998; Kleijn et al., 1997; Kleijn and Van der Voet, 1998). These studies show the quantitative relationships between PVC and the rest of the chlorine chain. These quantitative relationships can be used to assess the changes in chlorine chain as a result of a ban of PVC. Practically the only use of VCM is the production of PVC and its co-polymers. A ban on PVC would therefore make the VCM production obsolete. To a lesser extent the same is true for EDC: although there are some other applications, the bulk of the EDC production is used for the production of PVC. One step further upstream

the SFA studies on chlorine show that PVC is by far the most important single end-use of chlorine. In 1992, 38.6% of the produced chlorine in Western Europe was used to produce vinyl chloride monomer (VCM) which is almost totally used for the production of PVC (Kleijn and Van der Voet, 1998). In that same year, 32% went to the production of PVC in the US (Ayres and Ayres, 1997). Thus in the end a ban on PVC would result in a strong reduction of the demand for chlorine (Figure 6-4).

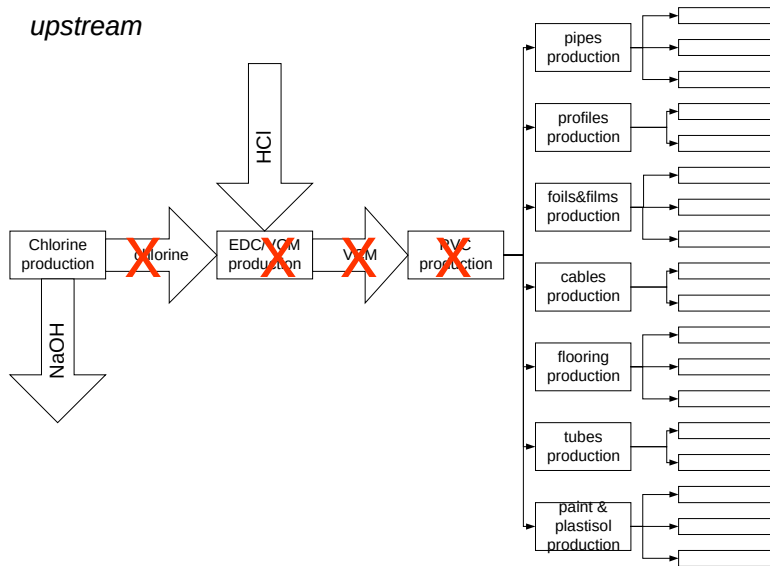


Figure 6-4: A ban on PVC would result in a strong reduction of demand for chlorine.

Furthermore the production of PVC is linked to other parts of the chlorine chain via the use of hydrochloric acid (HCl) in the production process. A substantial part of the chlorine used to produce PVC comes from HCl. Nowadays many of the products of the chlorine industry do not contain chlorine. Instead, chlorine is used during the production process and (partly) returned either as chloride salts or as HCl. A time series SFA would show a gradual shift from chlorine containing end-products to chlorine-free products using chlorine as an intermediate in the production process. This by-product HCl can be regarded as an inevitable and undesirable by-product and it is not so easy to deal with. The most favourable and in fact most wide-spread option is to use this HCl again in the production of chlorinated compounds, especially PVC. In case of a world-wide ban, this sink for HCl would no longer exist. This in turn would stimulate the use of HCl/chlorine recycling loops (see textbox/endnote) which in turn would cause a sharp decline in the demand for chlorine and, together with the reduction in primary demand for chlorine, could make the chlorine production obsolete (Figure 6-5).

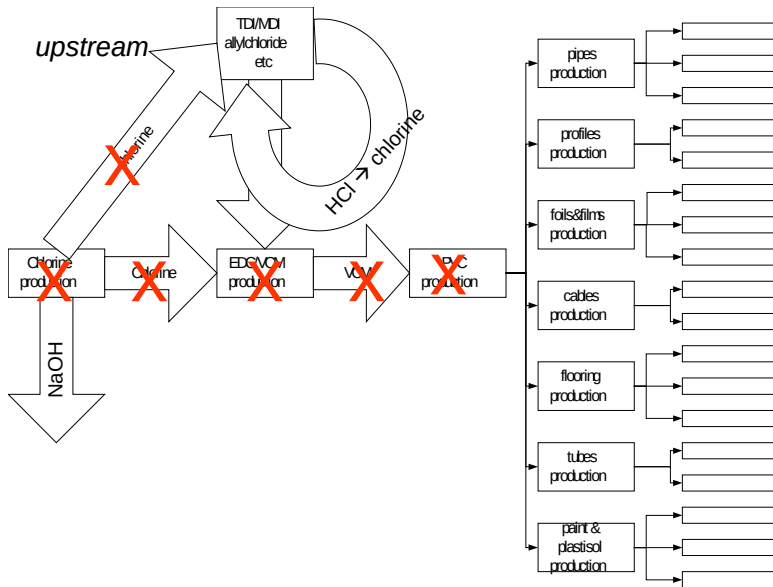


Figure 6-5: A ban on PVC would stimulate the use of HCl/chlorine recycling loops which in turn would cause a sharp decline in the demand for chlorine and, together with the reduction in primary demand for chlorine, could make the chlorine production obsolete.

Although an SFA of chlorine shows and quantifies the interconnections between PVC production and the rest of chlorine chain it too has a limited focus: it focuses on flows of chlorine only. A drastic change in the chlorine production would also affect other non-chlorine industries that are connected to the chlorine industry. One very straightforward example of this is the linked production of chlorine and caustic soda (Kleijn et al. 1993). The electrolysis process in which chlorine is produced in fact produces 1.1 kg of caustic soda (NaOH) for every kg of chlorine. If chlorine production would stop, another source would have to be found for caustic soda. This link, and other links, are invisible in an SFA on chlorine.

HCl as a key substance in the chlorine industry

HCl is a key substance in the chlorine industry. It is produced as a by-product in the production of products of the chlorine industry that contain less chlorine than the starting materials or no chlorine at all themselves. Its single most important use is the production of PVC via the oxy-chlorination process. In most processes HCl is produced in its pure form, as a corrosive gas, but in some processes it is produced in the diluted form of hydrochloric acid. There are three major options to get rid of HCl as a by-product: HCl can simply be diluted and/or neutralised and discharged as chloride into waste water streams, it can be diluted and sold on the market as hydrochloric acid or it can be used to make other chlorinated compounds, including chlorine. Discharging in the form of chloride is an option when the production units are located near an ocean but it would be a problem at locations more inland. In the production of TiO_2 (a white pigment) chlorine is completely converted to a 30% solution of hydrochloric acid. However, because this acid is contaminated with silicates it is often simply neutralised with lime to produce calcium chloride which can either be disposed in a nearby ocean or dumped at a solid waste disposal site (e.g. http://www.chemlink.com.au/caustic_oz.htm). Selling HCl on the market is not always an economic option because of limited demand, transport costs and costs of the demineralised water which is needed to dissolve the HCl gas and the costs of removing traces of organics from the HCl gas (Motupally et al., 1998). Re-using HCl in the production of chlorinated chemicals like PVC is often the most favourable option.

The main sources of HCl in Europe are the production of the isocyanates MDI and TDI (precursors of polyurethane (PUR) foams) potash fertiliser, allyl chloride, monochloroacetic acid (MCA) and of chloromethanes (Kleijn and Van der Voet, 1998). Before 1995 another important source was the production of (H)CFCs but this production has been banned almost completely at this time. Another source of HCl is the incineration of chemical waste from the chlorine industry (light and heavy ends).

In general the processes in which HCl is being produced grow faster than the processes in which HCl can be used. Thus HCl supply is larger than the demand and this imbalance will continue to grow in the near future. A ban on the main process in which HCl is used, the production of PVC, will have a heavy toll on the production processes that produce HCl as a by-product. Since this problem is already occurring even without the ban, the industry is looking for alternative ways to get rid of the excess of HCl. One of the options is to convert HCl back into chlorine, the feedstock of many of the processes in which HCl is the by-product. Two routes for this process have been available for some decades. The first option is the Uhde electrolysis in which HCl is absorbed in water and then electrolysed to hydrogen and chlorine. The main disadvantages of this process are that a small amount of oxygen is being co-produced which leads to corrosion of the cell components and that the produced chlorine contains 1-2% water which has to be removed. The second option that has been available for some time is the Deacon process in which HCl together with oxygen is catalytically converted to chlorine and water. The main disadvantage of this process is that it is very energy intensive (the process is operated at 400-450 °C) and the co-production of water demands an extensive separation step. Since these two existing processes have important drawbacks which makes them economically less favourable new processes are being developed. One of those processes is a direct electrolysis of gaseous anhydrous HCl patented by DuPont (Trainham et al., 1995). With this process both the absorption step and the water separation step can be skipped. Furthermore, the diffusion coefficients in the gas phase are much higher than those in aqueous solutions which increases the overall efficiency of the process. It can be expected that other processes will be developed in the near future. This is an interesting development from an industrial ecology perspective because this opens the opportunity to close the loop for processes in which chlorine is used and HCl is produced as a by-product. For example the production of MDI and TDI can be done in a closed system in which chlorine is continuously recycled from HCl to Cl_2 that would make the input of new chlorine obsolete.

6.4.5 Need for a broader perspective

In the previous paragraphs a description is given of the results of the application of different existing IEA and IE tools on the case of a ban on PVC. It is clear that a combination of IEA and IE tools can give a more complete analysis of the environmental impacts of a ban on PVC than either could give individually. IMAGE and RAINS would either need a much more detailed module to calculate emissions from industry in order to be useful at all in this case, or must be supplemented by other information. IE tools offer some insight in environmental impacts, each in a different way. They even could generate some input for the IEA tools. An LCA could be used to spot differences in energy use, greenhouse gas emissions or emissions of acidifying compounds as a result of the substitution of PVC by other plastics. An SFA quantifies the links of PVC to the rest of the chlorine industry and thereby could deliver some input to calculate the changes of energy use on that basis. But still each of these tools would only put the spotlight on a part of the total effects of such a ban. All tools proclaim to use an encompassing systems approach but in fact they are only partial and all have blind spots for certain kinds of effects. To get the complete picture, a broader approach is needed.

6.5 Application of a broader systems perspective

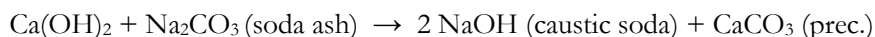
In the end, we come to the question which should have been the start: *what would really happen in case of a world-wide ban on PVC, apart from any specific tools to analyse it?*

In order to get a realistic answer to this question one has to start with a broad systems analysis which is not hindered by any constraint that is laid down by individual tools i.e.: the limitation to one substance in SFA; the limitation to bulk materials in MFA; the limitation to one product(system) and marginal linear changes in LCA; the limitation to one environmental problem in RAINS and IMAGE; the limitation to very aggregated material flows in society in IEA tools etc. One has to start with a general system description of the actual situation including all types of interconnections in society and the environment in qualitative way. This qualitative system description can then be extended with quantitative information from the different available tools. As an example we will now do this exercise for the PVC example.

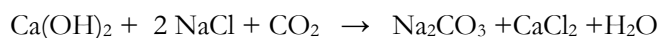
SFA has shown that a combination of a ban on PVC and the introduction of processes that would make the production of chlorine from HCl economic would decimate the traditional production of chlorine from salt. In traditional chlorine production caustic soda, an important industrial chemical, is a co-product. For every mole of chlorine a mole of caustic is produced. Caustic is used in many different applications of which the most important are the chemical processing industry, as a reactant or pH regulator, the pulp and paper industry for dissolving lignin and bleaching, the food industry and in the production of textiles (Kleijn et al., 1993). If the traditional production of chlorine would be decimated because of a ban on PVC

there are two options for the industries that are now using caustic: dramatically reduce the amount of input of caustic by efficiency improvement or substitution or to find alternative routes to produce caustic.

Substitution of caustic is possible in some applications. Alkaline substances like hydrated lime (Ca(OH)_2) and soda ash (Na_2CO_3) can be used as alternatives in pH regulation and in the pulp and paper industry, although they have some disadvantages of their own (e.g. lime has a very low solubility in water, less than 1.5 g/l and soda ash, when used in an acidic environment will lead to formation of CO_2 gas). Alternative routes for the production of caustic are rare. One known process is the production from soda ash and hydrated lime (CaCO_3):



Soda ash can be produced from hydrated lime and common salt (NaCl) via the Solvay process. The aggregated chemical equation of the Solvay process is:



Combining these processes, caustic soda can be produced from hydrated lime and common salt. Hydrated lime is produced by adding water to quicklime ($\text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2$) and quicklime is produced via the calcination of limestone which is used for example in cement kilns ($\text{CaCO}_3 + \text{heat} \rightarrow \text{CaO} + \text{CO}_2$). Caustic soda can thus be produced from limestone and common salt, two minerals of which large reserves exist (Figure 6-6). The mining of these minerals however has important detrimental impacts on the landscape. An interesting point from a climate change perspective is that CO_2 is produced in this process and that the energy need of the calcination process is high (temperatures higher than 500-600 °C are needed). The most commonly used fuel for this process is coal (USGS, 2002), resulting in high CO_2 emissions from the energy use.

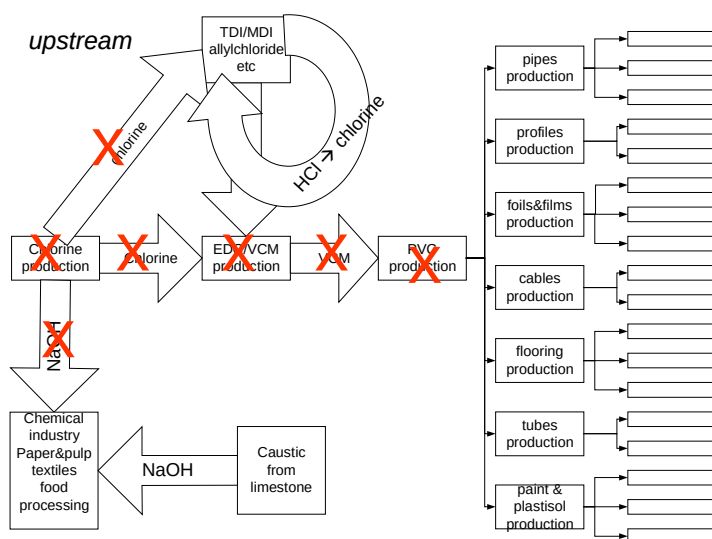


Figure 6-6: If the chlorine production would disappear other production routes for caustic soda would be needed. The most obvious known route would be the production from limestone.

Table 6-2 shows the contribution of lime and cement production as a fraction of the global CO₂ emissions. The production of lime and cement together accounted for a CO₂ emission of more than 9% compared to the CO₂ emissions from fossil fuels. About half of these emissions come from the chemical process while the other half comes from the use of fossil fuels in these processes. In Table 6-3 an overview is given of the chemical processes that are used in this alternative route for caustic soda production. For every mole of caustic soda 0.5 mole of CO₂ is released via the chemical process (thus excluding CO₂ from fuels). However, for the production of caustic soda via the electrolysis of common salt energy electricity is needed too, which in turn will lead to CO₂ emissions. In Table 6-4 a comparison is made of the CO₂ emission of the traditional NaCl electrolysis route for the production of NaOH (System 1) and the route via lime (System 2). In this calculation the emissions of CO₂ per kg of NaOH are calculated by adding up the emissions from the production of the different starting materials and the emissions from the chemical process itself (only in System 2). This calculation shows that a transition to the production of caustic soda via limestone will increase the CO₂ emission of caustic production by more than a factor two: for every kg of caustic produced more than a kg of CO₂ *extra* will be emitted. In Table 6-5 the additional CO₂ emission is given when the total world production of caustic would shift from the electrolysis route to the limestone route. It is shown that global CO₂ emissions would increase by around 0.2 % if this transition would take place.

Although one can discuss whether the total chlorine industry would really completely disappear when PVC would be banned and it is questionable that the current caustic soda production capacity would still be needed in such a situation this analysis clearly

shows that a ban on PVC can substantially increase global CO₂ emissions, via an indirect route.

Table 6-2: Contribution of lime and cement production to the total CO₂ production.

year	lime production (10 ⁹ kg)	cement production (10 ⁹ kg)	CO ₂ from lime production (10 ⁹ kg C)	CO ₂ from cement production (10 ⁹ kg C)	world CO ₂ production from fossil fuels (10 ⁹ kg C)	lime CO ₂ as % of world total from fossil fuels	cement CO ₂ as % of world total from fossil fuels
1963	68	378	29.7	129	2797	1.1	4.6
1964	82	416	35.8	142	2952	1.2	4.8
1965	75	433	32.7	148	3087	1.1	4.8
1966	78	464	34.0	158	3243	1.0	4.9
1967	82	480	35.8	164	3347	1.1	4.9
1968	85	515	37.1	176	3518	1.1	5.0
1969	90	543	39.3	185	3728	1.1	5.0
1970	97	572	42.3	195	3997	1.1	4.9
1971	100	590	43.6	201	4143	1.1	4.9
1972	102	661	44.5	225	4305	1.0	5.2
1973	107	702	46.7	239	4538	1.0	5.3
1974	110	703	48.0	240	4545	1.1	5.3
1975	105	702	45.8	239	4518	1.0	5.3
1976	108	735	47.1	251	4776	1.0	5.2
1977	117	797	51.1	272	4910	1.0	5.5
1978	120	853	52.4	291	4962	1.1	5.9
1979	118	872	51.5	297	5249	1.0	5.7
1980	120	883	52.4	301	5177	1.0	5.8
1981	117	887	51.1	302	5004	1.0	6.0
1982	109	887	47.6	303	4959	1.0	6.1
1983	110	917	48.0	312	4942	1.0	6.3
1984	117	941	51.1	321	5113	1.0	6.3
1985	123	959	53.7	327	5274	1.0	6.2
1986	124	1,008	54.1	344	5436	1.0	6.3
1987	127	1,053	55.4	359	5558	1.0	6.5
1988	134	1,118	58.5	381	5774	1.0	6.6
1989	139	1,042	60.7	355	5879	1.0	6.0
1990	136	1,043	59.3	356	5939	1.0	6.0
1991	133	1,185	58.0	404	6025	1.0	6.7
1992	133	1,123	58.0	383	5922	1.0	6.5
1993	123	1,291	53.7	440	5914	0.9	7.4
1994	118	1,370	51.5	467	6050	0.9	7.7
1995	120	1,445	52.4	493	6182	0.8	8.0
1996	121	1,493	52.8	509	6327	0.8	8.0
1997	118	1,547	51.5	527	6419	0.8	8.2
1998	117	1,547	51.1	527	6401	0.8	8.2
1999	116	1,603	50.6	546	6366	0.8	8.6
2000	118	1,643	51.5	560	6480	0.8	8.6

Source: lime and cement production from USGS online database (<http://minerals.usgs.gov/minerals/pubs/commodity/>), world CO₂ emission from Worldwatch Insititue (Signposts 2002). CO₂ emission connected to cement production is calculated as follows: per ton CaO 0.85 ton (non-fuel) CO₂ is produced. This 0.85 is the average of the range of 0.79-0.91 that is given by www.ghgprotocol.org. Furthermore, 0.75 ton CO₂ per ton cement is produced from the fossil fuels used in this process (BuildingGreen.com). CO₂ emissions from lime production are calculated as 0.785 ton CO₂ per ton CaO (chemical) (Winebrake and Laden, 1998) and 0.75 ton CO₂ per ton CaO from fuels with the assumption that the energy needs are similar to those of cement production.

Table 6-3: Chemical route to produce caustic soda from limestone and common salt

	amount of lime needed to produce caustic
	$\text{Ca(OH)}_2 + 2 \text{NaCl} + \text{CO}_2 \rightarrow \text{Na}_2\text{CO}_3 + \text{CaCl}_2 + \text{H}_2\text{O}$
	$\text{Ca(OH)}_2 + \text{Na}_2\text{CO}_3 \text{ (soda ash)} \rightarrow 2 \text{NaOH (caustic soda)} + \text{CaCO}_3 \text{ (prec.)}$
Sum	$2\text{Ca(OH)}_2 + 2 \text{NaCl} + \text{CO}_2 \rightarrow 2\text{NaOH} + \text{CaCl}_2 + \text{CaCO}_3 + \text{H}_2\text{O}$
	$\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$
	$\text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2$
Sum	$\text{CaCO}_3 + \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2 + \text{CO}_2$
	$2\text{Ca(OH)}_2 + 2 \text{NaCl} + \text{CO}_2 \rightarrow 2\text{NaOH} + \text{CaCl}_2 + \text{CaCO}_3 + \text{H}_2\text{O}$
2x	$\text{CaCO}_3 + \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2 + \text{CO}_2$
Sum	$\text{CaCO}_3 + 2 \text{NaCl} + \text{H}_2\text{O} \rightarrow 2\text{NaOH} + \text{CaCl}_2 + \text{CO}_2$
	to produce 2 moles of caustic 1 mole of CO ₂ is produced
	to produce 2 moles of caustic 2 moles of lime is needed

Table 6-4: Additional CO₂ emissions when caustic soda would be produced via limestone.

Year	world caustic production (10 ⁹ kg)	lime needed to produce caustic (10 ⁹ kg)	CO ₂ from caustic via lime minus electrolysis (10 ⁹ kg C)	world total CO ₂ emissions from fossil fuels (10 ⁹ kg C)	additional CO ₂ from caustic via limestone as % of world total from fossil fuels)
1995	40.7	60	11.8	6182	0.19
1996	41.1	61	11.9	6327	0.19
1997	43.6	64	12.6	6419	0.20
1998	43.4	64	12.6	6401	0.20
1999	44.4	66	12.9	6366	0.20
2000	45.6	67	13.2	6480	0.20
2001	47.3	70	13.7	6553	0.21

Source: lime production from USGS online databases, world CO₂ emission from Worldwatch Insititue (Signposts 2002). Caustic soda production from CMAI, 2001. Additional CO₂ emissions from production of caustic via lime 0.29 kg C per kg caustic see calculations in Table 6-4.

Table 6-5: Comparison of CO₂ emissions from caustic production via two routes: via electrolysis of common salt or from limestone and common salt

	mole (-)	M (g/mole)	mass (kg)	normalized per kg NaOH	CO ₂ emission from the production of starting materials (kg/kg)	kg CO ₂ / kg NaOH
System 1: NaOH from electrolysis of NaCl					$2NaCl + 2H_2O \rightarrow 2NaOH + Cl_2 + H_2$	
Inputs						
NaCl	1.00	58.4	0.0584	1.46	0.0940	0.137
H ₂ O	1.00	18.0	0.0180	0.451		
Outputs						
NaOH	1.00	40.0	0.0400	1.00		
Cl ₂	0.50	70.9	0.0355	0.886		
H ₂	0.50	2.02	0.0010	0.0252		
Emission of CO₂ from energy use in this process						0.688
Total CO₂ emissions (kg CO₂)						0.825
Total CO₂ emissions (kg C)						0.225
System 2: NaOH from limestone					$CaCO_3 + 2 NaCl + H_2O \rightarrow 2NaOH + CaCl_2 + CO_2$	
Inputs						
CaCO ₃	0.50	100	0.0501	1.25	0.00614	0.00768
NaCl	1.00	58.4	0.0584	1.46	0.0940	0.137
H ₂ O	0.50	18.0	0.0090	0.225		
Outputs						
NaOH	1.00	40.0	0.0400	1.00		
CaCl ₂	0.50	111	0.0555	1.39		
CO ₂	0.50	44.0	0.0220	0.550		0.550
Emission of CO₂ from energy use in this process						1.19
Total CO₂ emissions (kg CO₂)						1.89
Total CO₂ emissions (kg C)						0.515

Source: Emissions from energy use of the electrolysis process (System 1) are taken from ETH LCA database (ETH, 1996), together this is 0.825 kg CO₂ per kg NaOH of which 0.137 kg CO₂ per kg is related to the production of NaCl. Emissions from the production of the starting materials of the limestone route (System 2) are also taken from the ETH database. The emissions from the chemical process itself are based the fact that for every mole of NaOH one mole of CaO is needed (Table 6-3) and the CO₂ emissions related to this given in the note below Table 6-2.

6.6 Discussion and conclusions

Our hypothesis was that IE tools can be used in addition to IEA tools to identify potential environmental impacts of policy measures aimed not at specific environmental issues, but at materials and products in society. In the example the virtual ban on PVC we show that this hypothesis holds. We also show that this combination of tools can be used to detect and therefore prevent different forms of problem shifting (from PVC related issues to climate change) or in other words to identify co-benefits and co-damages (disappearance of the chlorine industry and increase in lime kiln activities) of environmental policy measures (a ban on PVC).

IEA tools cannot look outside the scope of the specific environmental issues they are made for. Moreover, their resolution in the economic driver modules is too low to enable analysing a quite extensive measure like a complete ban on PVC. This could in part be repaired by increasing the resolution of the economic driver module by distinguishing a higher number of economic sectors. This would indeed constitute to a better picture but there is more to it than that. Not only the resolution, but also the impossibility of detecting indirect effects is a problem. Due to the significant impacts of a ban on PVC on global CO₂ emissions, be it in an indirect manner and via a number of steps, it can be concluded, that the argument that such a measure is too small to be detected is not applicable. IEA tools are not suitable to analyse the effects of measures not affecting their object directly.

Because the resolution of IE tools is much higher for material flows in society they do a little better in this case. Since they look, in different ways, at society's metabolism it is possible to detect changes as a result of a PVC ban. With LCA, a picture emerges of the changes in a wider number of environmental issues as a result of a substitution of PVC with other materials. With SFA, the implications for the chlorine chain become apparent. However, the scope of tools like LCA and SFA is also limited, and their assessment of environmental impact is limited. They show part of what might happen. Also the picture they show remains fragmented and incomplete. Moreover, their analysis of what happens in the environment is limited compared to the outcomes of IEA tools.

IEA tools and IE tools are clearly complementary when looking at their main focus. In our PVC example we have shown that IE tools can indeed provide input for the IEA tools. LCA can provide data on changes in emissions and waste flows resulting from substitution of one product or material to another. SFA can be used to show the connections between different industrial processes. Thus, the combined tools deliver a more complete picture than any of the single tools. How such a combination could be further implemented in practice is a question for further research. For SFA, this may be easier than for LCA. SFA is time and location specific and analyses flows in a geographically demarcated area, just as IEA tools do. SFA can also easily be tailored to the same compounds as the IEA tools. For LCA, a translation step is necessary to make the connection but it could be worthwhile to make the attempt.

However, even a combination of IEA and IE tools is, as can be seen from Section 5, not sufficient to capture all effects. There is a need for a broader systems analysis which can be used for the analysis of what actually can be expected to happen, preceding the selection of the specific tools. The format of the broader systems analysis could range from a material and product flowchart to a true dynamic quantified systems analysis. Only when, on the basis of this analysis, there is an idea of what really happens has the time come to select and apply specific tools - IEA tools, IE tools or a combination of both - to quantify the effects.

References

- Albrecht G., Langowski H.-Ch., 1997. Life Cycle Assessment Study on Resilient Floor Coverings. *International Journal of LCA* 2 (2) 73-80.
- Alcamo J., Shaw R., and Hordijk L. (Eds), 1990. The RAINS Model of Acidification. Science and Strategies in Europe. Dordrecht, Netherlands: Kluwer Academic Publishers.
- Amann, M, Johansson M., Lükewille A., Schöpp W., Apsimon H., Warren R., Gonzales T., Tarrason L., Tsyro S., 2001. An integrated assessment model for fine particulate matter in Europe. *Water, Air and Soil Pollution* 130: 223-228
- Ayres, R.U., 1997. The Life Cycle of Chlorine: Part I; Chlorine Production & the Chlorine-Mercury Connection, *Journal of Industrial Ecology* I (1): 81-94.
- Allenby, B.R., 1999. *Industrial Ecology, Policy Framework and Implementation*. Prentice Hall, NJ.
- Ayres, R.U. and Ayres L.W., 1997. The Life Cycle of Chlorine: Part II; Conversion Processes & Use in the European Chemical Industry. *Journal of Industrial Ecology* I (2): 93-115.
- Ayres, R.U., 1998. The Life Cycle of Chlorine: Part III: Accounting for Final Use. *Journal of Industrial Ecology* II (2): 65-89.
- Ayres, R.U. and Ayres L.W., 1996. *Industrial ecology, Towards Closing the Materials Cycle*. Edward Elgar, Cheltenham, UK.
- Ayres R.U. and Simonis U. E. (Eds.), 1994. *Industrial Metabolism. Restructuring for Sustainable Development*, Tokyo: United Nations University Press.
- Baccini P., Bader H.-P., 1996. *Regionaler Stoffhaushalt*, Spektrum Akademischer Verlag, Heidelberg Berlin Oxford.
- Baere, de V., Huijbrechts D., Wouters G., 1994. Milieubalans van kortcyclische PVC-verpakkingen, Eindrapport: Tekst / Tabellen en Figuren, VITO, Mol, Belgium.
- Beenen, J.H., Eygelaar K.H., 1993. De ecobalans van ringbanden, een eerherstel voor de vinylringband., *Kunststof en Rubber*, No 1, 10-13.
- Bourg, D., Erkman S. (Eds.), 2003. *Perspectives on Industrial Ecology*. Greenleaf Publishing, Sheffield, UK.
- CMAI, 2001. 2001 World Chlor-Alkali Analysis, Volume I&II, Chemical Market Associates, Inc., Houston, Texas, USA.
- Commission of The European Communities, 2000. Green Paper, Environmental issues of PVC. COM(2000) 469 final. Commission of The European Communities, Brussels.
- Elshkaki, A., van der Voet, E., van Holderbeke M., Timmermans V., 2005. Dynamic stock modelling: A method for the identification and estimation of future waste streams and emissions based on past production and product stock characteristics. *Energy* 30(8): 1353-1363.
- European Parliament, 2001. European Parliament resolution on the Commission Green Paper on environmental issues of PVC (COM(2000) 469-C5-0633/2000).

- R. Frischknecht (Ed.), 1996. Okoinventare von Energiesystemen. Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in ökobilanzen für die Schweiz (Life-cycle Inventories of Energy Systems), ETH. Zürich.
- Finnveden, G., Gunnar Lindfors, L.-G., Wennberg L., 1996. Alternativa Material till PVC. Inventering och analys av genomförda livscykelanalyser m.m. avseende jämförelser av PVC och alternativa material för olika produktgrupper. (Alternative Materials to PVC. Listing and analysis of LCA's, etc., carried out regarding comparisons of PVC and alternative materials for different product groups.) Institute for Water and Air protection Research (IVL) Report 1232. Stockholm, Sweden.
- FKS, Vereniging van Fabrikanten van Kunststof Leidingssystemen, 1995. Rapport milieuprofiel beton, gres en PVC in hoofdriolering (Report Environmental profile of concrete, gres and PVC). FKS, Amsterdam.
- Guinée, J.B., Gorée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleswijk, A., Suh, S., Udo de Haes, H.A., de Bruijn, H., van Duin, R., Huijbregts, M.A.J., 2002. *Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards*. Kluwer Academic Publishers, Dordrecht, 692 pp.
- Hansen, E. and Lassen C., 2000. Paradigm for Substance Flow Analyses - Guide for SFAs , Report Prepared for the Danish EPA, Copenhagen: the Danish Environmental Protection Agency.
- Hauschild, M., Wenzel, H., Alting, L., 1998. Environmental Assessment of Products. Vol. 1. 1998: Chapman and Hall.
- Hettelingh, J.P., de Vries, B., Hordijk, L., 2006. Integrated Assessment. In: Boersema, J.J. , Reijnders, L. (Eds.) *Principles of Environmental Science*. Kluwer Academic Publishers, Dordrecht/Boston MA.
- IIASA, 2003. RAINS homepage at IIASA, <http://www.iiasa.ac.at/rains/research.html?sb=4>, consulted at 7-2-2003.
- IMAGE team, 2001. The IMAGE 2.2 implementation of the SRES scenarios: A comprehensive analysis of emissions, climate impacts in the 21st century. RIVM CD-ROM publication 481508018, National Institute for Public Health and the Environment, Bilthoven. The Netherlands, July 2001.
- Intron, 1995. Milieuprofiel en milieumaten van een buitenriolering van PVC en gres in vergelijking met beton, rioleringstechniek, Vol.6, No. 2, 483-494.
- ISO International Standard 14040, 1997. Environmental management - Life cycle assessment - Principles and framework. International Organisation for Standardisation (ISO). 1997E. Geneva.
- Kleijn, R., Huele, R., van der Voet, E., 2000. Dynamic substance flow analysis: the delaying mechanism of stocks, with the case of PVC in Sweden. *Ecological Economics* 32, 241-254.
- Kleijn, R., van der Voet, E., 1998. Chlorine in Western Europe. Materials Accounting as a Tool for Decision Making in Environmental Policy. EC Programme Environment and Climate 1994-1998, ENV4_CT96_0230.
- Kleijn R., Tukker, A., van der Voet, E., 1997. Chlorine in the Netherlands: an overview, *Journal of Industrial Ecology*, Vol. 1 No. 1, 91-112.
- Kleijn, R., van der Voet, E., Udo de Haes, H.A., 1993. Controlling Substance flows: The case of chlorine. *Environmental Management*, Vol. 18 No. 4, 523-542.
- Krähling, H., 1999. Life Cycle Assessments of PVC Products: Green Guides to Ecological Sustainability. In *LCA Documents*, Vol. 6. Eco-Informa Press, Landsberg, Germany.

- Lifset R., Graedel, T.E., 2002. Industrial Ecology: goals and definitions. In: R.U. Ayres L.W. Ayres (eds.) *A Handbook of Industrial Ecology*. Edward Elgar Cheltenham, UK.
- Potting, J., Blok K., 1994. Life-cycle assessment of four types of floor covering, Department of Science, Technology and Society, Utrecht University.
- Potting, J., Schöpp, W. , Blok, K. , Hauschild, M., 1998. Site-dependent life-cycle impact assessment of acidification. *Journal of Industrial Ecology*. Vol 2 Issue 2, 63-87.
- Potting, J.M.B., 2000. Spatial differentiation in life cycle impact assessment : a framework, and site-dependent factors to assess acidification and human exposure. PhD thesis Universiteit Utrecht, Faculteit Scheikunde.
- Raadschelders, E., Hettelingh, J.-P. , van der Voet, E., Udo de Haes, H.A., 2003. Side-effects of categorised environmental measures and their implications for impact analysis. *Environmental Science and Policy* 6, 167 - 174.
- Reusser, L., 1998. Life Cycle Assessment of Pipeline systems - A case study on the setting up of the potable water supply and sewage disposal for a detached family house development. Summary report, EMPA: St Gallen, Swiss.
- Richter K., Künniger, T., Brunner, K., 1996. Ökologische Bewertung von Fensterkonstruktionen verschiedener Rahmenmaterialien (ohne Verglasung) EMPA Dübendorf, Swiss.
- Rotmans, J , Dowlatabadi, H., 1997. Integrated Assessment Modeling, in *Human Choice and Climate Change*, Vol.3, eds S Rayner and E L Malone, Battle Press, Columbus, OH, 291–377.
- Schöpp, W., Amann, M., Cofala, J., Heyes, C., Klimont, Z., 1999. *Environmental Modelling & Software*, 14(1): 1-9.
- Van der Sluijs, J.P., 2002. Integrated Assessment, Definition of. Volume 4 Responding to global environmental change, 249–250. Edited by M. K Tolba in *Encyclopedia of Global Environmental Change* (ISBN 0-471-97796-9) Editor-in-Chief T. Munn John Wiley & Sons, Ltd, Chichester.
- The Overseas Environmental Cooperation Center, 2000. Development of an Integrated Assessment Tool for Acid Deposition in Asia: Training, Model Validation and Upgrading. RAINS-ASIA Phase II. Final report submitted to the World Bank.
- Tötsch, W. , Polack, H., 1992. PVC und Ökobilanz. *UWSF-Z. Umweltchem. Ökotox.* 4 (2).
- Trainham, J. A., Law, C. G. , Newman, J. S. , Keating, K. B. , Eames, D. J., 1995. U.S. Patent 5,411,641.
- Tukker A., Kleijn, R. , Jasser, A.S., 1997. Material Suppliers and Industrial Metabolism. *Environmental Science and Pollution Research*. Res.4 (2), 113-120.
- Tukker, A., Kleijn, R. , van Oers, L., Smeets, E.R.W., 1998. Combining SFA and LCA: The Swedish PVC Analysis. *Journal of Industrial Ecology*, Volume 1, Issue 4, p. 93-116.
- Tukker A., 1999. Frames in the Toxicity Controversy: Based on the Dutch chlorine debate and the Swedish PVC debate. Kluwer Academic Publishers, Dordrecht.
- USGS, 2002. USGS Mineral Industry Surveys: Lime in the United States 1950 to 2001.
- Verspeek, F.A.B., Kramer, J.E. , van den Hoven, Th.J.J. , Stellard, D.A., 1992. Milieu-effecten van leidingsystemen van asbestcement, PVC, gietijzer, staal en glasvezel versterkte kunststoffen. (Environmental impacts of piping systems of asbestos cement, PVC, cast iron and plastics enforced with glass fiber). KIWA. Nieuwegein, Netherlands.
- van der Voet, E., Guinée, J.B., Udo de Haes, H.A. , (Eds.), 2000. *Heavy Metals: A Problem Solved? Methods and Models to Evaluate Policy Strategies for Heavy Metals*. Kluwer Academic Publishers, ISBN: 0-7923-6192-X.
- de Vries, B.J.M., van Vuuren, D.P. , den Elzen, M.G.J. , Janssen, M.A., 2001. The Targets IMage Energy Regional (TIMER) Model. Technical Documentation. RIVM report 461502024 2001. RIVM, Bilthoven, Netherlands.

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- VROM, 1997. Beleidsstandpunt PVC. Letter from the Minister of Housing, Spatial Planning and the Environment to the Dutch Parliament (ICB97113155), Ministry of VROM, The Hague.
- Winebrake J.J., 1998. State Greenhouse Gas Emission Inventory for the Commonwealth of Virginia. James Madison University, Integrated Science and Technology Program, Harrisonburg.
- Wrisberg, N., Udo de Haes, H.A., Triebswetter, U., Eder, P., Clift, R., 2002. Analytical Tools for Environmental Design and Management in a Systems Perspective. The Combined Use of Analytical Tools Kluwer Academic Publishers, Dordrecht.

Chapter 7

Overarching conclusions, general discussion and research agenda

This Chapter presents the conclusions to be drawn from the material presented in the preceding chapters, a general discussion of the results of this dissertation and a proposal for a future research agenda.

7.1 Conclusions on the history of metal use and scarcity

Research questions:

1. How did the use of metals co-evolve with human progress and what was the role of metals scarcity in that process?
2. What was the nature of scarcity in previous eras and what was its nature perceived to be at the time? And how does the current scarcity situation and scarcity debate differ from those in the past?

Until some 6000 years ago the use of metals was limited to the few that occur in their metallic form on Earth (mainly gold and copper). Although metals were rare, they were not scarce because their importance was also limited to ornaments with at most symbolic value. With the start of the Bronze Age (~4000 BC) and their application in tools, weapons and armour, metals acquired a utilization value. At certain times and in certain locations, scarcity of the main ingredients of bronze, notably copper and tin, will have occurred, while the use of the wood (charcoal) required to free the metals from their ores led to deforestation. The use of the much more abundant iron (~1000 BC) solved the issue of local shortages of copper and tin, but it further increased the scale of deforestation. Between the 16th and the 18th century the scarcity of wood became a constraint in Europe, not only for metal smelting but also for heating and shipbuilding. This link between biotic and abiotic resources was broken by the introduction of coke made from abundant coal.

The material basis of societies has shifted many times during the course of human history. The main drivers for substitution are scarcity and innovation. While innovations often occur independent of scarcity issues, scarcity can lead to innovations that both solve the scarcity issue and lead to improved performance. The substitution of bronze for copper and wrought iron for bronze illustrate this point. The technological breakthrough that allowed the substitution of firewood (charcoal) by coal (coke) alleviated the scarcity of wood in the late 18th century. Steel alloys like manganese, nickel, chromium and molybdenum steels can often replace one another without loss of performance. Until the mid-18th century humans used fewer than 10 metals, while at present practically all the metals that exist are used in industry. Metals like iron, aluminium, zinc and copper are the foundation of our cities and

infrastructure. Over 60 elements are used in the production of the microchips to be found in many everyday products. As Figure 5-4 in Chapter 5 shows, the trend over the last few decades is that the mined output of many relatively scarce elements is growing faster than GDP. While of less abundant metals can often be substituted by more abundant ones (Al, Fe, Ca, Na, Mg, K and Ti), this often leads to loss of performance. The opportunities for substituting scarce metals by other scarce metals are limited because all these metals are essential for one or more applications. (Chapters 2 and 5)

7.2 Conclusions on the future of metal use and scarcity

Research questions:

3. What are the metal requirements of the transition to a low-carbon energy system and will these requirements constrain the scale-up of individual technologies or constrain the pace of the energy transition as a whole?
4. Will these metal requirements, combined with other types of demand, lead to significant scarcity in the short- and medium-term future?

Today, after two centuries of rapid exponential growth, the limits to the production of fossil fuels are starting to emerge. Not only is production struggling to keep up with demand, but the related emissions are now an eminent threat to society. The transition to a low-carbon energy system required to tackle climate change implies a steep increase of the metals intensity of the energy system, which in turn implies a substantial increase in the demand for metals (by a factor 2 to 100). At the same time, declining ore grades will result in a substantial increase in the use of energy, water and land and in the production of waste per kg of metal produced. Today's metals scarcity is therefore not an isolated issue, but one of many interconnected issues in a world where planetary boundaries for all of these issues are in sight.

The introduction of Carbon Capture and Sequestration in fossil-based power production would increase the metals intensity of power generation: by 30% for iron and 75% for nickel at coal-fired plants, and by 40% for iron and 150% for nickel at gas-fired plants. There are two main causes: the efficiency of power production is reduced because energy is needed to capture and transport CO₂; and additional infrastructure is needed in the form of capture installations, pipelines, pumps and injection wells. A full transition of the current generation system to a non-fossil electricity mix would require a substantial scale-up of the mining and refining of many metals including nickel, molybdenum, uranium, silver and, to a lesser extent, aluminium and copper. When a business-as-usual economic growth scenario (SRES A1) is combined with a complete transition to renewable energy (65% PV solar from the deserts, 15% PV solar from rooftops, 15% wind and 5% others) by 2050, the metals requirements for this transition would be very high. The equivalent to several to hundred times current annual world production would be needed to build the

required grid, wind turbines and hydrogen pipelines. For certain technologies it is highly likely that materials requirements will hinder their scale up to significant levels (hundreds of GW worldwide) in the time frame available to address climate change (three to five decades). This is certainly true for thin-film CdTe and CIGS solar cells (ten to a hundred times current annual production); new efficient and low-maintenance direct-drive wind turbines and electro motors that contain permanent magnets with Nd and Dy (tenths of times current annual production for 100 GW installed capacity and 10% of produced cars); PEM fuel cells that use Pt as a catalyst (more than current annual production of Pt for 10% of annual car production); cobalt-containing Li-ion batteries for electric cars (all current annual Co production for 10% of produced cars). The conclusions above are based on the upscaling of current technologies. In many cases alternative technologies are either available or being developed that are less likely to run into material constraints when scaled up to substantial levels. However, in many cases this might come at the cost of functionality or efficiency. Examples are neodymium-containing wind turbines and electro motors, In- en Te-containing thin-film PV cells and copper-containing HVDC power lines. (Chapters 3 and 4)

Economists tend to point to technological progress and innovation as the process that will provide a virtually limitless supply of metals in the foreseeable future. Innovation can indeed be employed to resolve scarcity issues by increasing the efficiency of use of metals or, in other words, decreasing the metals intensity of processes and products. Although this process of relative decoupling will lead to a reduction in the amount of metals used per unit of GDP, in practice this has seldom led to an absolute reduction in the amount of metals produced. The Iron Age did not reduce the production of copper and tin, nor did the introduction of aluminium and titanium lead to a reduction in iron or copper production. Economic and population growth have always annihilated the efficiency gains delivered through innovation and technological progress. However, these processes did manage to increase the global reserves of many metals and thereby kept reserve / production ratios relatively constant. However, since the mining output of almost all metals continues to grow exponentially, technological progress and innovation need to proceed at an ever increasing pace in order to keep up. (Chapters 2 and 5)

Hall and Klitgaard investigate the role of energy and energy return on investment (EROI) for economic growth (Hall and Klitgaard 2012). They analyse the essential role of an ample supply of high EROI energy sources for economic development. Their thesis is that we are entering an age where the EROI for society as a whole will significantly decrease due to a lack of easy oil, and later gas which will hamper economic growth. This is very much in line with conclusions of this study that it is not a lack of metal ores in Earth's crust and oceans that will cause problems for society but the increasing costs related to their mining and production both in monetary terms and in terms of required energy and water and environmental impacts. In Chapter 5 of this dissertation it is concluded that due to current trends in mining and refining not only the energy requirements per unit of metal produced will increase but

also the metal requirements i.e. the metal return on investment. Three major long term trends will compete with the decreasing ore grades and less accessible deposits: the technological progress in mining and refining; the slowdown in demand with higher per capita income levels (“S-curve”); and the increasing role for recycling. For energy, Hall and Klitgaard conclude that it is highly likely that economic growth, as measured in GDP, will stagnate because of the decreasing declining EROI and thus declining surplus of energy. Ayres and Warr draw a similar conclusion: economic growth cannot be sustained if we fail to find an alternative source of cheap energy (Ayres and Warr 2009). However, from a sustainability perspective this might actually be a good thing as is discussed by Hall and Klittgaard but also by Jackson and other de-growth economists (Jackson 2009).

7.3 Conclusions on methodology

Research question:

5. What are the possibilities and limitations of Industrial Ecology and other analytical tools when it comes to including the real complexity of material flows in societies in sustainability analyses?

The case of a virtual ban on PVC shows that even within a limited subset of the industrial system, the chlorine industry, the complexities in the system can have a substantial impact on the outcome of an analysis of the environmental impacts of such a ban. Integrated Environmental Assessment (IEA) tools lack the resolution in their description of material flows through society to capture the changes that occur as a result of such a measure. Industrial Ecology (IE) tools have a much higher resolution, but they only partially capture the changes that would occur within the chlorine industry. With LCA, a picture emerges of the changes in a wider number of environmental issues as a result of substituting PVC by other materials. With SFA, the implications for the chlorine chain become apparent. However, the scope of tools like LCA and SFA is limited, and their assessment of environmental impact is generic. The picture they show remains fragmented and incomplete. (Chapter 6)

Combining different tools will help capture a larger part of the true complexities of the material metabolism of society but is still insufficient to capture them all. Any sustainability analysis should therefore start with a broad description of the system. From this description research questions should be formulated that can be quantitatively answered using tools like LCA and SFA that have a high resolution for the material flows in society. Broader tools like Environmentally Extended Input Output analysis (E-IOA) and IEA tools can then be used to track and quantify possible macro-scale consequences. (Chapters 4 and 6)

When it comes to the analysis of the metals requirements of the future energy systems presented in this dissertation, the following observations can be made on the

limitations of LCA. First of all, the *ceteris paribus* assumption that is used in regular LCAs does not hold for the system-wide changes that will occur as a result of a major transition in the energy system. Secondly, this transition will take place somewhere in the future, which means that the background processes of e.g. steel production and transport cannot be assumed to be similar to those that are valid today. Finally, LCA databases lack the level of detail with regard to the use of minor metals that is needed to quantify them over the life cycle. There is a clear need for tools that can be used to assess the sustainability impacts of large-scale changes without losing the life-cycle perspective. These tools are currently being developed under the heading *Life Cycle Sustainability Analysis*. (Chapters 4 and 6)

7.4 General discussion

Over the ages, the primary sector (agriculture, fishery and mining) has steadily declined in importance and now accounts for less than 5% of GDP in most rich market economies. 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, the undeniable physical reality remains that the products of mining and agriculture are the ultimate foundation of our prosperity. Ecologists have pointed out that classical economics fails to acknowledge this by mislabelling 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 represents but a small fraction of GDP, the global interconnectivity of the economy and the complexity of material services provision mean that disruptions of supply may be more damaging now than at any time in the past.

Over time, the input of materials in society as a whole has exponentially increased and in the future supply will struggle to keep up with demand. The production of the materials needed to double the extent of urban infrastructure and triple per capita income in the coming decades will require more and more energy, water and land and thereby cause substantial environmental impacts. At the same time, global use of water, land, energy and environmental services are fast reaching planetary boundaries. In earlier ages, humanity could consider the planet as effectively infinite, while now we are entering an age in which we are exceeding the safe operating space of our planet in many respects (Rockstrom et al. 2009). Paul Crutzen has named our present age the Anthropocene (Crutzen 2002).

This dissertation has focused on the link between metals and energy production. Climate science tells us that if we fail to act within the next decade irreversible and possibly catastrophic climate change will set in. In order to avoid collapse we will need to shift our current production and consumption pattern to a much less energy and

material intensive direction. In general, the outlines of a sustainable society are clear and can be phrased in terms of three major transitions:

1. a transition from fossil fuels to renewable energy sources;
2. a transition from linear material flows, from raw materials to waste, to a closed-loop materials economy;
3. a transition from the exploitation of nature and biodiversity to its protection.

Only a combination of these three major transitions will direct humanity in the direction of a truly sustainable society. It is important to recognize that both the physical and the symbolic aspects of society are interconnected through complex linkages. In order to study and implement these transitions these linkages should be taken into account in our assessments of future technologies and policy measures. In this thesis, I have used tools from the research field of Industrial Ecology to do that.

Industrial Ecology is a young field of science in which societal metabolism (the physical part of society) is the object of study. Several tools and methods have been developed that can be used to analyse societal metabolism from a natural-science, engineering-science and social-science perspective. The core element uniting these tools is that they all start out from a systems perspective in which the linkages between physical and symbolic aspects of society are (partially) taken into account. The sustainability of processes, production plants and products are always analysed as part of the broader socio-economic system. This systems perspective is essential when designing solutions for sustainability issues, because it prevents problem-shifting from one product to another, from one environmental problem to another, from one location to another, from one resource to another, etc. However, Industrial Ecology tools are based on models of the real world and are therefore by definition a simplification of reality. In an attempt to overcome these simplifications and retain the overall systems perspective, different routes are being explored. One of these routes is the connection of traditional Industrial Ecology tools like Life Cycle Assessment (LCA) and Substance Flow Analysis (SFA) with Agent Based Models (Bollinger et al. 2011; Davis et al. 2009). Another route is the development of Life Cycle Sustainability Analysis (LCSA), a life cycle-based framework that is applicable for triple P sustainability analysis of large-scale transitions (Guinée and Heijungs 2011). These methodological developments are essential if future IE tools are to capture the true complexity of societal metabolism.

In this dissertation the issue of material scarcity has been addressed with a specific focus on the metals used in energy technologies. Metals have clearly been a key ingredient in the development of complex societies. It is unlikely that the views of resource optimists about ever-increasing resources and ever-decreasing prices will retain their validity over the coming decades. In the next few decades developments in emerging economies will lead to a tripling of the global average income per capita. The acquired affluence will be spent on products familiar from the Western lifestyle: cars, meat, electronics and so on. Billions of people will move to cities, thereby doubling the global urban population. This means that the equivalent of all the cities

in existence today will be built over the next few decades. The newly produced products and urban infrastructure will drive up demand not only for materials but also for energy, water, agricultural produce, etc. At the same time we will need to stay within the safe operating space of the planet, which effectively means that we need to decarbonise our energy system. In this dissertation it has been shown that this would require even more metals than would be the case for conventional energy. Mining and exploration efforts already find themselves confronted with environmental and physical constraints and are struggling to keep up with demand. An ample supply of metals is not only important for producing our favourite gadgets. It also plays a vital role in providing sustainable energy, food and shelter for the 9 billion of us that will be around in 2050. It is hard to imagine how this can be achieved without either a reduction in growth or the decoupling of growth from material and energy requirements.

Whether or not the material requirements of the energy transition, if implemented, will induce materials scarcity will depend on a number of factors, but specifically also on the possibilities for substitution. The periodic table comprises a limited number of elements and at the moment almost all of them have useful applications. Shifting from one to the other will therefore in many cases simply shift the problems of material availability from one sector to another. The substitution by abundant elements forced by looming scarcity – in contrast to substitution induced by product improvement – could very well slow down the energy transition and reduce overall efficiency, as material choices are forced by scarcity and the technically “optimal” solutions cannot achieve their full potential.

While metals scarcity in itself may be a problem that can be resolved, the relationship with other constraints such as climate change, energy supply, biodiversity/nature conservation and time makes it one of the key issues for the coming decades. There are two main directions that might be used to address this issue: innovation and abandoning the growth paradigm. Although some economists are working on de-growth scenarios, mainstream economics and politics are still directed towards economic growth measured mainly in terms of GDP (Martínez-Alier et al. 2010; Jackson 2009). Innovation, for its part, can help by:

- *closing metal cycles*: although recycling can, by definition, be of only 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;
- *dematerializing the economy*, which also has its limitations, but we need to shift 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 for metals 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.

If policies are put in place that would significantly stimulate a combination of the innovations mentioned above this may ensure a sufficient material supply in next four

decades for the energy transition that is needed to tackle climate change. However, there is clear need to assess 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 extraction, and here, as we have argued, there is less reason for unbridled optimism. This does not mean that physical metals scarcity will necessarily lead to future economic scarcity. There are a range of technical options for addressing the issue, but alongside technological development we will need a change in materials policies, product design and business models in order to achieve sustainable global metal metabolism.

7.5 Research Agenda

To obtain a better understanding of the implications of the issues raised in this dissertation, additional research is needed. Below the most important directions for future research are described.

Dynamic analysis of metals metabolism

Further in-depth and dynamic analysis is needed to assess the material needs of a transition to renewables-based energy systems. Some of the dynamic mechanisms have the potential to make the system spiral out of control. The increasing use of energy to produce the materials required to generate energy could be one such mechanism. Initial, rough estimates suggest that up to 40% of the global total primary energy supply might be needed for metal mining in 2050 (Graedel and van der Voet 2010). At the same time it has been suggested that the prime driver for economic growth is the availability of cheap energy (Ayres and Warr 2009). It is commonly assumed that the energy transition requires only a few percent of global national income (Stern 2007). While this analysis is superficially correct, if it is implausible that we will be able to mine enough metals to actually build it, we will be unable to complete the transition. In our free-market world this is most likely to mean that if the target is adhered to, the cost will be far higher (as a result of higher commodity prices stimulating mining). Further research is also needed to explore the precise dynamics of the metals demand associated with the energy transition. This will lead to more detailed and realistic estimates of materials requirements as a function of time in different scenarios. If the power sector is to be transformed over the next three to four decades, based on current technologies, this will clearly cause a significant peak in metals demand and associated emissions. Uncertainties about long-term climate policy and technology choices will make it difficult for mining companies to anticipate such a peak in demand. The associated emissions could have a significantly adverse effect on the success of climate policies.

More detailed and additional explorations of the energy transition

It would be useful to analyse the materials requirements of promising energy technologies that are still in the early stages of development and to add detail to the analysis of the technologies that have been discussed in this dissertation. The issues that need exploring include the following:

- The intermittent nature of solar and wind as energy sources will make some sort of buffering an essential part of the system. This may consist of high-capacity power lines, hydrogen pipelines, macro-scale capacitors and water reservoirs. All these buffering technologies would both decrease the total efficiency of the energy systems and increase their material requirements. This should be included in a more complete analysis of the materials requirements of the energy transition.
- Side-effects in the form of environmental impacts, such as land and water use, emissions of toxic substances, etc. For a more balanced assessment of alternative energy systems all these issues need to be investigated.
- Many of today's industrial processes depend on the input of fossil fuels. Thus steel production depends on coke as a reducing agent for iron ore (iron oxide), while production of plastics, artificial fibres and other organic compounds are based mainly on oil and natural gas. Furthermore, many processes are now based on fossil fuel as a source of energy. It is not clear how these processes would change in the event of an energy transition leading to a world in which electricity is the main energy carrier.

More detailed explorations of the supply of metals

Mining engineers have identified several important signs that mining will struggle to keep up with ever-increasing demand. Some of these, such as deteriorating ore grades, have been studied on a continental scale. Others, like decreasing sizes of newly discovered deposits, have been less well quantified. An overall picture of the different constraints for scaling up mining is not yet available. More complete analyses are needed to clarify the extent of the supply problems. Such analysis could focus on:

- global historic trends of discovery of resources, including their geographic distribution; this could be combined with Hubbert's peak-type analysis for minerals, as presented by (May et al. 2011);
- the energy requirements of different mining and refining technologies;
- the possibilities of upscaling deep-sea mining including the (life-cycle) environmental impacts and materials and energy requirements;
- developing a more complete picture of the interdependencies among the production of different metals. Minor metals that are important for high-tech products are often but not necessarily produced as by-products of more bulk metals. A start could be made through a data-mining exercise of large online databases such as developed by the USGS;
- creating cumulative supply curves (Yaksic and Tilton 2009) for all metals and minerals.

More detailed analysis of demand for metals

In the emerging economies, demand for primary metals is rapidly rising as infrastructure is built and consumption increases. In OECD countries, demand for bulk metals has stabilized and is decreasing per unit of GDP for many metals. Owing to the increased complexity of products, however, demand for high-tech metals is still booming. To obtain a better picture of future demand for metals, further research is needed to explore the relation between GDP per capita and metals use in more detail. This could also be done for minor metals on the basis of information about the way different technologies enter lifestyles at different levels of GDP. Such an analysis should include the distribution of wealth over the population.

Recycling and substitution

Recycling is an essential ingredient of a sustainable societal metabolism. However, in a scenario where demand for metals is rapidly increasing, recycling does not significantly reduce demand for virgin materials, nor does it significantly postpone the moment of true scarcity. Furthermore, it makes sense to reduce the amount of metals we use per unit of product, but recycling is both technically and economically more difficult when elements are dispersed in products in minute quantities. An analysis of the potential of recycling for increasing the sustainability of metal cycles is needed. Substitution is also potentially a solution for scarcity, but substituting one scarce element by another will simply shift the problem, since all the elements are used in important applications. The interesting question remains, to what extent we can substitute scarce metals by "the elements of hope". Is it possible to draw certain general conclusions about substitutability on the basis of the fundamental properties of different elements?

Designing a sustainable society

The growth paradigm is central to the world economy. Many of today's business models and consequently a large part of global economic growth are based on rapid replacement of material products. It is hard to envision a viable business model for a producer of razor blades with blades that will last a lifetime, even though this is technically possible. New smartphones are introduced ever few months and many consumers, including the author, have a hard time not buying the latest gadget. Many of the cheap products we buy, including clothing, furniture, toys and electronics, seem to be designed to break down or fail as soon as possible. In the business-to-business sector, important improvements have been achieved through the introduction of service-oriented rather than product-oriented business models for furniture, flooring and office equipment (Mont and Tukker 2006). The scope for introducing such business models for consumer products is an interesting topic for further research, especially since it is hard to imagine a sustainable metals metabolism grounded in the currently dominant replacement economy and linear metal flows. Decoupling of economic growth from material inputs and material inputs from environmental impacts has often been suggested as one of the routes to a more sustainable society. The question is, however, to what extent such decoupling is realistic. Society, even the virtual part, is undeniably based on a continuous inflow of materials. Shifting from products (CDs, DVDs, books) to services (MP3, video on demand and e-readers)

does not necessarily reduce the input of materials per unit of service and, even if it does, it will lead to extra consumption, which will increase material demand (the rebound effect). Degrowth scenarios are being explored in the academic world, but the consequences for the material basis of society still needs to be investigated.

Methodological development

Sustainability analyses should be taken into account the true complexity of societal metabolism. The present early attempts to define Life Cycle Sustainability analysis are an important step in this direction and this should be explored further. This is especially useful when assessing the future technologies needed for large-scale transitions such as the shift required in the energy system. The constraints of resources and climate and other environmental impacts are so interwoven that a framework for a broad systems analysis is needed to perform useful sustainability analyses. Resource scarcity considerations should be an integral part of such a framework as well as social and economic impacts.

References

- Ayres, R. U. and B. Warr. 2009. *The economic growth engine, how energy and work drive material prosperity*. Cheltenham, UK: Edward Elgar.
- Bollinger, L. A., C. Davis, I. Nikolić, and G. P. J. Dijkema. 2011. Modeling Metal Flow Systems. *Journal of Industrial Ecology*: no-no.
- Crutzen, P. J. 2002. Geology of mankind. *Nature* 415(6867): 23-23.
- Davis, C., I. Nikolić, and G. P. J. Dijkema. 2009. Integration of Life Cycle Assessment Into Agent-Based Modeling. *Journal of Industrial Ecology* 13(2): 306-325.
- Graedel, T. E. and E. van der Voet. 2010. *Linkages of Sustainability*. Edited by J. Lupp, *Strüngmann Forum Reports*. Cambridge: MIT-press.
- Guinée, J. B. and R. Heijungs. 2011. Life Cycle Sustainability Analysis. *Journal of Industrial Ecology* 15(5): 656-658.
- Hall, C. A. S. and K. A. Klitgaard. 2012. *Energy and the Wealth of Nations, Understanding the Biophysical Economy* New York: Springer.
- Jackson, T. 2009. *Prosperity without Growth, Economics for a finite planet*. London: Earthscan.
- Martínez-Alier, J., U. Pascual, F.-D. Vivien, and E. Zaccai. 2010. Sustainable de-growth: Mapping the context, criticisms and future prospects of an emergent paradigm. *Ecological Economics* 69(9): 1741-1747.
- May, D., T. Prior, D. Cordell, and D. Giurco. 2011. Peak Minerals: Theoretical Foundations and Practical Application. *Natural Resources Research*: 1-18.
- Mont, O. and A. Tukker. 2006. Product-Service Systems: reviewing achievements and refining the research agenda. *Journal of Cleaner Production* 14(17): 1451-1454.
- Rockstrom, J., W. Steffen, K. Noone, A. Persson, F. S. Chapin, E. F. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. J. Schellnhuber, B. Nykvist, C. A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sorlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J. A. Foley. 2009. A safe operating space for humanity. *Nature* 461(7263): 472-475.

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- Stern, N. 2007. *The Economics of Climate Change: The Stern Review*. Cambridge Cambridge University Press.
- 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.

Summary

In this dissertation frameworks and tools from the field of Industrial Ecology have been used together with a broader systems analysis to analyse problems related to metal scarcity, the energy transition and climate change.

Chapter 1 General introduction

Chapter one forms the introduction. It provides an overview of the broad debate on societal metabolism, with a focus on resource scarcity issues, and introduces the main research questions. These are:

1. What has been the significance of metals in human history ?
2. How has the debate on metals scarcity evolved over the course of human history ?
3. What are the metal requirements of the transition to a low-carbon energy system ?
4. Will these metal requirements, combined with other types of demand, lead to significant scarcity in the short and medium term future ?
5. What are the possibilities and limitations of Industrial Ecology and other analytical tools for including the true complexity of material flows in societies in sustainability analyses?

Chapter 2 A short history of the importance of metals for humanity and the debate on their scarcity

Metals that occur naturally in their metallic state (gold, silver, copper and iron-nickel alloys) are very rare and have been used as curiosities and ornaments since pre-historic times. On our planet pure metals are oddities of nature and very different from biotic materials and stone-like materials that formed the ubiquitous constituents of the environment of early man. Ever since the processes were developed to free metals from their ores, some 6000 years ago, metals have been important in the development of complex societies. Hunting, warfare, agriculture, industry and urban environments have all profited from the ample availability of metals. The development of the technology to produce bronze created a clear advantage in the production of effective tools, equipment and other gear of both soldiers and craftsmen. The fact that bronze was made from two or more different metals (mainly copper and tin) that differed in their geographical distribution increased the need for trade over longer distances and the dependence on foreign supply of materials. It also increased the incentive to conquer lands that were rich in resources.

Both copper and tin are relatively scarce elements compared with iron, which by mass accounts for about 90% of all current metal mining. The importance of metals for society therefore rose significantly when the technology to produce useful iron from iron ore was developed some 3000 years ago. During this period, however, the material basis of societies was still dominated by renewable resources and silicon-based building materials, with wood serving as the main source of energy. Both during

the final stages of the Roman empire (200 CE) and from the 16th to 18th century CE in the United Kingdom and other European countries the availability of fuel wood became a constraint for metals production (mainly iron, copper and tin). With the introduction of coal as a cheap and abundant source of energy during the industrial revolution and the rapid development of new technologies that followed, all this changed.

The invention of the coke production, which facilitated iron production using coal as a fuel and reduction agent rather than wood-derived charcoal is an example of a technological breakthrough that resolved an early scarcity issue. This technology was one of the main breakthroughs that led to the industrial revolution, which in turn spawned a period of rapid economic expansion and globalization. This expansion coincided with a huge increase in the consumption of base metals like iron, copper, zinc, tin and lead. These metals were needed to build the new infrastructure, railways, bridges and modern cities but also for steam engines, trains, ships and, later on, cars. At the same time these new inventions and infrastructure provided the heavy equipment and industry that was needed for large-scale mining and refining. Steam-powered ships and trains provided cheap bulk transport that made it economical to transport food, textiles and other medium-value commodities over large distances, both on land and overseas. In the late 19th century the large-scale introduction of electricity facilitated the liberation from its ore of the only metal that is more abundant in Earth's crust than iron: aluminum.

About a century after the start of the industrial revolution the issue of fast depleting (national/continental) resources, biotic, mineral and environmental, came to be recognized by governments and scientists. This resulted in a strong movement of conservationists, led amongst others by Theodore Roosevelt, which in the United States resulted in legislation on the use of natural resources and the creation of national parks. During the same period economists like Gray (1914) and Hotelling (1931) developed the first theoretical economic frameworks of so-called exhaustion theory.

In the OECD, World War II was followed by a another period of rapid economic development associated with urbanization, infrastructure expansion and the rise of mass consumption. The availability of low-cost energy sources combined with rapid technological advances led to ample availability of cheap consumer goods. This in turn led to increased demand for the mineral resources required to produce these newly developed goods.

However, the supply of mineral resources was hampered by the dwindling quantities available in developed countries, the weakening or severing of colonial ties and the disruption of normal trade patterns caused by the start of the Cold War. During this period of rapidly expanding demand for mineral resources and unstable world politics the US government commissioned the Paley Committee (1951) to assess the problem of material scarcity and make recommendations for a comprehensive policy on

materials. In their seminal report the Paley Committee laid down the basic principles of the material scarcity debate, including the formulation of possible policies and research agendas. It framed the depletion problem as a problem of resources that are harder to retrieve rather than a problem of absolute depletion. The committee recognized that materials scarcity would start to be problematic long before the last gram of ore was mined, simply because the economic, environmental and social costs would become prohibitively high. The committee took a strong stand against self-sufficiency as a leading principle for securing supply. In contrast, it propagated the Least Cost Principle as leading: the main aim of any resource policy should be to supply the US industry with the cheapest resources available. It therefore also focused on international free trade and investing in resource-rich countries as something that should be promoted by policy makers. Although the Paley report was a landmark in the debate on resource depletion, after the Korean War commodity prices relaxed and a period of relatively little concern about materials scarcity followed until the oil crisis of the 1970s. One of the reasons for the fall in commodity prices was the Suez crisis of 1956-1957, which triggered the development of bulk carriers. Bulk carriers made long-distance transport of commodities even cheaper, thereby facilitating the globalization of flows of cheap bulk products like iron ore and coal.

In 1968 the Club of Rome was founded and in 1972 their report "The Limits to Growth" was published. About a year later, in October 1973, the first oil crisis was a fact and the resource dependency that had been described by the Club of Rome moved from a merely academic exercise to an event that disrupted daily life in many parts of the world. It demonstrated the interdependence of world economies and the vulnerability of resource-importing countries to supply disruptions. As with the Paley report, the Club of Rome triggered a debate about materials scarcity and much of the debate of the 1970s can be readily translated to the debate we see today. In February 1976 an entire issue of *Science* was dedicated to materials, with a focus on resource scarcity. Many of the topics discussed in that issue can be more or less directly translated to ongoing debates today. Supply security, strategic stockpiling, self-sufficiency, recycling and dematerialization were back on top of the political agenda. Again, however, this period of high commodity prices was followed by a period of relative abundance of cheap resources. Bulk carriers were still growing ever larger and combined with low fuel prices this led to a period extremely low transport costs. The scaling up of mining also provided economic advantages that pushed metal prices down despite annual growth rates in mine production of around 3%. Metal prices remained low until what is referred to as the 'great metals boom' that started in 2002. This boom was caused by a sharp increase in demand that resulted mainly from the rapid expansion of emerging economies, most notably China. During that period the prices of non-fuel commodities almost doubled in real terms. Although the global financial crisis that started at the end of summer 2008 caused a significant price decrease, prices never reached pre-2002 levels. Prices peaked again in February-March 2011 at a level almost 20% higher than that of the 2008 peak. After that the European sovereign debt crisis again caused concern about the global economy, which led to a fall in commodity prices. In November 2011 non-fuel commodity prices were back at

the level of the 2008 peak. In the period between 2002 and 2011 a number of publications by authors well familiar with the mining industry expressed concerns about the supply of metals, with degrading ore grades, decreased deposit size of newly found deposits, constraints in the supply of water and energy and increased local and global environmental concerns all being cited as causing cracks in supply lines.

As a result of the 2002-2008 metals boom and recent constraints on the supply of certain rare (earth) metals, many governmental organizations, NGOs and research organizations have issued reports defining critical materials for the local and global economy. All the world's major economies are now assessing the possible impact of metals scarcity and policy measures including the mechanisms of the WTO to ensure free commodity trade, national stockpiles for strategic materials and bilateral agreements with supplying countries. The establishment of the UN Resource Panel is a clear sign that the international community regards resource-related issues as a major concern for the coming decades.

Chapter 3 Resource constraints in a renewables-based hydrogen economy

There are many linkages between the various resources used in modern society. The energy system is closely linked to the use of materials in two ways. First of all energy is needed to mine and process mineral resources in such a way that they become useful materials and secondly materials are needed for the mining of energy carriers, their transformation (e.g. oil refineries, power plants, transformers) and their transport (bulk carriers, pipelines and power lines) and for harvesting energy from diffuse sources (e.g. wind turbines, solar cells and hydropower reservoirs).

In Chapter 3 a quantitative systems analysis is made of the resources that would be needed for a worldwide transition to renewable energy in the year 2050 with hydrogen and electricity as the two major energy carriers and based on current technologies. The amount of renewable energy that is available is not the limiting factor for a renewables-based energy system. Even in an extreme growth scenario the total primary energy demand of about 1300 EJ/a in 2050 could be supplied through current-technology wind power (15%) and photovoltaic solar (80%), leaving 5% for other renewables. In order to limit the amount of infrastructure needed for harvesting the available energy it is important to choose locations where the circumstances for harvesting are optimal. For solar energy, especially, these locations are often far from the locations where the energy is to be used. Extensive transmission networks are therefore needed to carry the energy to the right place.

The choice of technology has a strong influence on the resource requirements of energy technologies. In three crucial parts of the system relatively scarce materials are show-stoppers for specific technologies: tellurium and indium in thin-film solar cells, neodymium in direct-drive permanent magnet wind turbines and electro motors, and platinum in electrolysis and fuel cells. Resource constraints prevent these technologies from being upscaled to substantial levels (hundreds of exajoules). In all cases

alternative technologies are available, be it sometimes at the cost of efficiency and/or economics.

The amount of steel required in this scenario for both wind turbines and hydrogen pipelines is very high: for wind turbines around six times the world's current annual output of iron and for hydrogen pipelines 40% of this amount. If current-technology stainless steel is used for the pipelines, about 45 times the current annual output of nickel would be needed and 5500 times the annual output of chromium. If electricity is adopted as a carrier, the amount of copper that would be needed in the system is equivalent to 70 times current annual world production. Wind turbines would require an additional 4 times the current annual world copper output.

Chapter 4 Material requirements of low-carbon power generation

About 40% of global CO₂ emissions derive from the production of electrical power. In Chapter 4 an analysis is made of the metal requirements of low-carbon power generation. Based on a Life Cycle Assessment approach, the CO₂ emission reductions and metal requirements of low-carbon power sources like wind, PV solar, biomass and fossil generation with Carbon Capture and Sequestration (CCS) were calculated. All three electricity mixes presented (CCS, non-fossil and IEA BLUE Maps) result in a reduction of CO₂ emissions by about 80-90%. If comparable reductions were achieved in other sectors the 450-490 ppm stabilization goal for atmospheric CO₂ concentrations would be achievable.

However, in all three cases this comes at the cost of higher metals requirements. The addition of CCS to the current electricity mix would have a substantial impact on annual demand for nickel and molybdenum, requiring 10-30% percent more metals than the current configuration. This is down to the additional infrastructure required to capture, transport and store the CO₂ (specialty steels), in combination with reduced efficiency of the power plants themselves. A switch to a non-fossil electricity mix would result in much higher demand for nickel, uranium, silver, molybdenum and, to a lesser extent, copper and aluminum. For PV solar, non-waste biomass and wind the increase in metal use ranges from a few percent up to a factor thousand. This means that mining of these metals would have to be scaled up considerably in order to fulfil demand for these new electricity technologies. Not all non-fossil technologies are more metals-intensive than fossil-fuel based power, though. Nuclear power, hydropower and waste biomass have a relatively low metals intensity with the exception of uranium for nuclear. In the case of PV solar and wind the increase is related to the relatively high metals intensity of PV solar cells and wind turbines. For non-waste biomass it is related to the need for relatively materials-intensive agricultural processes, including the production of agricultural machinery and fertilizers.

Over the last several decades a trend of decreasing materials intensity per unit GDP has been recorded in many developed countries. However, when climate change forces these economies to switch to alternative energy sources, in the energy sector

this trend will be broken. The type of materials demand occurring in various technologies depends very much on the specific technologies adopted. For example, the extremely high demand for silver in solar electricity is related to the choice for mono-crystalline silicon PV cells. However, other PV solar technologies have material demand issues of their own. Current thin-film CdTe and CIGS will run into scarcity issues long before they contribute significantly to global power generation. The 2 MW offshore wind turbine with a geared generator that is used in the calculations in Chapter 4 does not require neodymium-based permanent magnets. However, many of the new, low-maintenance direct-drive turbines use about 150 kg neodymium per MW. Scaling up these technologies to the level of tens of GW would require a dramatic increase in the annual production of this rare earth metal, which currently stands at about 18000 tonnes. The Chinese government has recently announced that the installed capacity of wind power is to be increased to 1000 GW by 2050. If these turbines were all based on direct-drive, permanent-magnet generators this would require over 30 times the world's total current annual output of neodymium, leaving little for other countries and applications.

Chapter 5 Metals scarcity: imminent threat, eternal problem or red herring?

In Chapter 5 the various aspects of future metals supply and demand are surveyed and in combination with the results of the earlier chapters we can now turn to the question of whether the metals requirements of the energy transition, in tandem with other types of demand, will lead to significant scarcity in the short and medium term.

Although Earth is finite, until the present the magnitude of current resources has not constrained the production of metals. Although ore grades are deteriorating, reserves of lower-grade ores have until now almost always exceeded those of rich ores. Ultimately, backstop reserves exist in the form of ocean water and common rock. Therefore, reserves of almost all minerals have increased rather than decreased over the last century, despite, or perhaps because of, the exponential growth in extraction. However, this does not automatically mean that metals production can keep up with exponentially growing demand over the coming decades.

The pure scale of materials extraction is now far larger than it ever was in the past. Globalization, driven partly by cheap bulk transport, has opened up virtually every remote corner of the world for exploration and mining. However, globalization generates no more than a one-off gain. Remaining undiscovered deposits exist mainly in regions where exploitation will be difficult and under a cap of a kilometre or more of common rock. Moreover, the cost of bulk transport may already have reached its lowest possible plateau owing to limitations on the upscaling of bulk carriers and rising fuel costs.

The rate at which minerals can be extracted is a limited, similar to the case of conventional oil. The rate of extraction 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 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. While in the current globalized world rapidly increasing demand is still a major factor, it is now insecurity of supply that has become a global issue. Today this is combined with cracks in the supply lines. Mining companies have great difficulty keeping up with demand for a whole raft of reasons, including deteriorating ore grades, smaller and deeper deposits and environmental constraints.

Furthermore, for the first time in human history we are truly experiencing the linkages between resources 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 to tackle climate change. Water use, land use and environmental impacts are additional constraints that are interlinked with energy and metals production. These mutually enhancing constraints will pose new challenges for future generations. We will need to pick our technologies carefully, avoiding obvious material constraints.

Demand for metals will continue to grow exponentially for decades to come. This demand will increase as a result of the rapid urbanization projected for the years ahead, leading to a massive expansion of cities and their accompanying infrastructure. Furthermore, economic growth in emerging economies will lead to the production of more and more complex products, which will in turn lead to ever-increasing metals demand. The transition to a low-carbon energy system will require vast amounts of materials. For certain metals this means that current production will need to increase several times over. The most crucial issue of all, though, is that we need these materials in the next few decades, if they are to still be relevant for tackling climate change.

It is unlikely that resource optimists' views about ever-increasing resources and ever-decreasing prices will retain their validity over the coming decades. If the long-term projections of urban development prove true and if climate change is properly addressed, over the next four decades we will build the equivalent of all the cities in existence today, triple the global average income per capita and build a global low-carbon energy system from scratch. Mining and exploration efforts find themselves confronted with environmental as well as physical constraints and are already struggling to keep up with demand. An ample supply of metals is not only important for producing our favourite gadgets. It also plays a pivotal role in providing sustainable energy, food and shelter for the 9 billion of us that will be around in 2050.

Chapter 6 Combining IE and IEA tools: the case of PVC

In Chapter 6 a case study of a virtual ban on PVC is used to show that even within a limited subset of the industrial system, the chlorine industry, the complexities in the system can have a substantial impact on the outcome of the analysis. Neither Integrated Environmental Assessment (IEA) tools nor Industrial Ecology (IE) tools fully include the linkages existing within the chlorine industry.

With LCA, a picture emerges of the changes in a wider number of environmental issues as a result of a substituting PVC by other materials. With SFA, the implications for the chlorine chain become apparent. However, the scope of tools like LCA and SFA is limited, and their assessment of environmental impact is generic. The picture they show remains fragmented and incomplete.

All the tools and models we use are a mere reflection of the real world and are by definition less detailed than the real thing and therefore do not include all the complexities. This means that not all the linkages that exist in reality can also be taken into account in the analysis for which these tools and models are used. Even a combination of tools is insufficient to capture all effects. There is a need for a broader systems analysis that can be used for analysing what can be expected to actually happen, prior to selection of specific tools. The format of the broader systems analysis could range from a material and product flowchart to a truly dynamic, quantified systems analysis. Only when such an analysis has yielded a picture of what in reality is likely to occur has the time come to select and apply specific tools - IEA tools, IE tools or a combination of both - to quantify the impacts of policies and activities. This is different from simply choosing the right model or tool and correct model parameters, and it cannot be done in any general manner. It needs to be done on a case-by-case basis, as a tailor-made holistic analysis. Current developments under the heading of Life Cycle Sustainability Analysis can be regarded as a step in this direction.

Chapter 7 Overarching conclusions, general discussion and research agenda

In this chapter the results are presented in the form of a set of conclusions. The most important reflect back to the central questions of Chapter 1 and deal with the importance of metals throughout human history, the development of the debate on resource scarcity with a focus on metals, the material requirements of the energy transition and the usefulness of Industrial Ecology tools for analysing the environmental impacts of large-scale transitions. This dissertation then concluded with a general discussion and a proposal for an agenda for further research.

Samenvatting

In dit proefschrift zijn methoden en technieken uit het veld van Industriële Ecologie samengebracht met een bredere systeemanalyse om de problemen te analyseren die gerelateerd zijn aan schaarste van materialen, de energietransitie en klimaatverandering.

Hoofdstuk 1 Inleiding

Hoofdstuk 1 is de inleiding. Het geeft een overzicht van het brede debat over het metabolisme van de maatschappij, met een focus op de schaarste van natuurlijke hulpbronnen. Ook worden in dit hoofdstuk de onderstaande onderzoeksvragen gedefinieerd.

1. Hoe belangrijk zijn metalen geweest voor de ontwikkeling van de mensheid ?
2. Hoe heeft het debat rondom de schaarste van metalen zich door de eeuwen heen ontwikkeld ?
3. Wat is de metaalbehoefte van een transitie naar een koolstofarm energiesysteem ?
4. Leidt deze metaalbehoefte, samen met de vraag naar metalen voor andere toepassingen, tot een significante schaarste op korte en middellange termijn ?
5. Welke mogelijkheden en beperkingen bieden de methoden en technieken uit de Industriële Ecologie en aangrenzende vakgebieden om de werkelijke complexiteit van materiaalstromen mee te nemen in duurzaamheidsanalyses?

Hoofdstuk 2 Een korte geschiedenis van het belang van metalen voor de mensheid en het debat over de schaarste van deze metalen

Metalen die in hun metallische vorm voorkomen op aarde (goud, zilver, koper en ijzer-nikkel legeringen) zijn zeer zeldzaam en worden al sinds de prehistorie gebruikt als curiosa en sieraden. Op onze planeet zijn metalen een vreemde eend in de bijt en zeer verschillend van het biotische en steenachtig materiaal dat de belangrijkste ingrediënten vormden van het milieu van de vroege mens. Sinds er processen werden ontwikkeld om metalen uit hun erts te onttrekken, circa 600 jaar geleden, zijn metalen belangrijk geweest voor de ontwikkeling van complexe samenlevingen. De ruime beschikbaarheid van metalen heeft belangrijke voordelen opgeleverd voor de jacht, oorlogsvoering, landbouw, industrie en stedenbouw. Samenlevingen die de technologie beheersten om brons te maken hadden daarmee een belangrijke voorsprong in het maken van beter gereedschap en een betere uitrusting van zowel soldaten als ambachtslieden. Het feit dat brons gemaakt wordt uit twee verschillende metalen (voornamelijk koper en tin) met een verschillende geografische spreiding, vergrootte het belang van zowel de handel over grotere afstanden als de afhankelijkheid van buitenlandse toevoer van grondstoffen. Het versterkte daarmee ook de drang naar het veroveren van grondstofrijke gebieden.

Zowel koper als tin zijn relatief schaarse elementen vergeleken met ijzer, dat op dit moment ongeveer 90% van alle gewonnen metalen vertegenwoordigt. Het belang van

metalen werd daarom aanzienlijk groter toen zo'n 3000 jaar geleden de technologie werd ontwikkeld om bruikbaar ijzer te produceren uit ijzererts. In deze periode werd de materiële basis van de samenleving echter nog steeds sterk gedomineerd door op silicium gebaseerde materialen, met hout als belangrijkste bron van energie. Aan het einde van het Romeinse rijk (200) en in het Verenigd Koninkrijk en andere Europese landen in de periode van de 16^e tot en met de 18^e eeuw werd de beschikbaarheid van hout een beperkende factor voor de metaalproductie (voornamelijk ijzer, koper en tin). Dit veranderde gedurende de industriële revolutie en de periode van snelle technologische ontwikkeling die volgde met de introductie van kolen als een goedkope en overvloedige energiebron.

De uitvinding van de techniek om cokes te produceren, zorgde ervoor dat kolen als brandstof en reductiemiddel kon worden gebruikt in plaats van houtskool dat was afgeleid van hout, is een voorbeeld van een technologische doorbraak die een eerder schaarse probleem oploste. Deze technologie was een van de vele doorbraken tijdens de industriële revolutie, welke gezamenlijk gezorgd hebben voor een periode van snelle economische groei en globalisering. Deze groei ging gepaard met een enorme groei in de consumptie van metalen zoals als ijzer, koper, zink, tin, en lood. Deze metalen waren nodig voor de nieuwe infrastructuur zoals spoorwegen, bruggen en moderne steden maar ook om stoommachines, treinen, schepen en later ook auto's te produceren. Tegelijkertijd leverden deze nieuwe uitvindingen en infrastructuur de apparatuur, machinerie en industrie die nodig waren voor grootschalige mijnbouw en opwerking. Stoomschepen en treinen zorgden voor goedkoop bulktransport zowel over zee als over land van voedsel, textiel en andere goederen. In de late 19^e eeuw maakte de grootschalige introductie van elektriciteit het mogelijk om het enige metaal dat nog rijkelijker in de aardkorst aanwezig is dan ijzer, aluminium, vrij te maken uit het erts.

Ongeveer een eeuw na het begin van de industriële revolutie werd uitputting van biotische en abiotische grondstoffen door overheden en wetenschappers als probleem erkend. Dit resulteerde in een sterke beweging van natuurbeschermers, onder andere geleid door Theodore Roosevelt, en welke in de VS leidde tot wetgeving op het gebied van het gebruik van natuurlijk hulpbronnen en het oprichten van nationale parken. In diezelfde periode ontwikkelde economen zoals Gray (1914) en Hotelling (1931) het eerste theoretische raamwerk van de zogenaamde "exhaustion theory"

In de OECD volgde na de Tweede Wereldoorlog een nieuwe periode van snelle economische ontwikkeling en de daaraan gekoppelde urbanisatie, uitbreiding van infrastructuur en de opkomst van massaconsumptie. De beschikbaarheid van goedkope energie gecombineerd met snelle technologische vooruitgang leidde tot een overvloedige beschikbaarheid van goedkope consumentenproducten. Dit alles zorgde voor een snel groeiende vraag naar minerale grondstoffen die nodig waren om deze goederen te produceren.

De aanvoer van deze grondstoffen werd echter gehinderd door de beperkte beschikbaarheid van grondstoffen in de ontwikkelde landen, de verzwakte koloniale banden en de verstoring van de normale handelspatronen als gevolg van het begin van de koude oorlog. Gedurende deze periode van snel groeiende vraag naar grondstoffen en instabiele wereldpolitiek werd door de Amerikaanse regering in 1951 de Paley Committee opgericht om het probleem van schaarse grondstoffen te duiden en om aanbevelingen te doen voor een alomvattend grondstoffenbeleid. In hun baanbrekende rapport heeft deze commissie de hoofdlijnen van het schaarste debat beschreven, met inbegrip van mogelijke beleidsopties en onderzoekslijnen. Ze beschreef het schaarste debat in termen van grondstoffen die steeds lastiger te winnen zijn in plaats van een probleem van absolute uitputting. De commissie onderkende dat materiaal schaarste een probleem zou worden lang voordat de laatste gram erts gewonnen zou zijn, simpelweg omdat de economische, ecologische en sociale kosten te hoog zouden worden. De commissie was verdere sterk gekant tegen zelfvoorzienendheid als leidend principe om een stabiele aanvoer van grondstoffen te garanderen. De commissie koos daarentegen voor het "Least Cost Principle": het belangrijkste doel van het grondstoffenbeleid zou moeten zijn om de industrie in de VS van zo goedkoop mogelijke grondstoffen te voorzien. Ze legde de nadruk daarom ook op internationale vrijhandel en het investeren in grondstofrijke landen als zaken die door beleidsmakers zouden moeten worden nagestreefd. Hoewel het Paley rapport een mijlpaal was in de discussie rondom uitputting van grondstoffen volgde tussen de Koreaanse oorlog en de oliecrisis in de jaren 70 een periode waarin de grondstofprijzen daalden en waarin er relatief weinig aandacht was voor schaarste. De dalende grondstofprijzen werden deels veroorzaakt door de ontwikkeling van mammoetschepen die werd getriggerd door de Suez crisis van 1956-1957. Deze enorme vrachtschepen zorgden ervoor dat de prijzen van transport van goederen nog verder daalde hetgeen de globalisering van de handel in goedkope bulkproducten zoals ijzererts en kolen vereenvoudigde.

In 1968 werd de Club van Rome opgericht en in 1972 verscheen hun rapport "Grenzen aan de Groei". Ongeveer een jaar later, in oktober 1973, was de eerste oliecrisis een feit en de afhankelijkheid van grondstoffen zoals deze werd beschreven in het rapport verschoof daarmee van een wetenschappelijke exercitie naar een gebeurtenis die in veel delen van de wereld het dagelijks leven ingrijpend veranderde. De oliecrisis toonde de onderlinge afhankelijkheid van economieën en de kwetsbaarheid van grondstof importerende landen bij problemen in de aanvoer aan. Net als het Paley report, initieerde het rapport van de Club van Rome een debat over schaarste en veel aspecten van dit debat kunnen direct vertaald worden naar het huidige debat. In februari 1976 was een heel nummer van het wetenschappelijke tijdschrift Science gewijd aan materialen, met een focus op schaarste. Veel van de onderwerpen die hierin werden besproken kunnen ook weer min of meer direct worden vertaald naar de huidige discussie. Leveringszekerheid, de aanleg van strategische voorraden, zelfvoorzienendheid, recycling en dematerialisatie waren hiermee terug op de politieke agenda. Deze periode van aandacht voor schaarste werd echter opnieuw gevolgd door een periode met een relatieve overvloed aan goedkope

grondstoffen. Mammoetschepen werden steeds groter hetgeen gecombineerd met historisch lage brandstofprijzen leidde tot extreem lage transportkosten. De opschaling van de mijnbouw zorgde voor dalende prijzen van grondstoffen ondanks een jaarlijkse groei in productie van rond de 3%. De prijzen van metalen bleven laag tot wat wordt aangeduid als de “great metals boom” die begon in 2002. Deze periode van sterk stijgende prijzen was het resultaat van een sterke groei in opkomende landen, met name China. In deze periode stegen de inflatie gecorrigeerde prijzen van ‘non-fuel’ goederen bijna met een factor twee. Hoewel de financiële crisis van 2008 een significante daling in prijzen veroorzaakte zijn ze nooit meer teruggekomen op het niveau van voor 2002. In februari-maart 2011 piekte de prijzen nogmaals op een niveau dat 20% hoger lag dan de piek in 2008. Vervolgens veroorzaakte de Europese monetaire crisis nieuwe zorgen over de wereldeconomie waarna de grondstofprijzen weer daalden. In november 2011 waren de prijzen van ‘non-fuel’ goederen weer terug op het niveau van de piek in 2008. In de periode tussen 2002 en 2011 uitten een aantal auteurs die zeer bekend zijn met de mijnbouw bezorgdheid over de aanvoer van metalen. Afnemende ertskwaliteit, kleinere nieuwe vondsten, beperkingen als gevolg van water- en energiegebruik en zorgen over lokale en mondiale milieueffecten van de mijnbouw werden allemaal genoemd als oorzaken van problemen in de aanvoerlijnen.

Als een reactie op deze periode van hoge metaalprijzen en de recente toevoerproblemen van bepaalde zeldzame (aard)metalen, hebben veel overheden, NGO's en onderzoeksinstellingen rapporten uitgebracht waarin materialen worden aangewezen als kritiek voor de lokale en mondiale economie. Alle belangrijke wereldeconomieën zijn op dit moment bezig met onderzoek naar de mogelijke gevolgen van metaal schaarste. Ook worden de verschillende beleidsmaatregelen tegen het licht gehouden waaronder de WTO mechanismen om vrije internationale handel te garanderen, het aanleggen van strategische voorraden en het maken van bilaterale afspraken met exporterende landen. De oprichting van het ‘Resource Panel’ door de Verenigde Naties is een duidelijk signaal dat de internationale gemeenschap zaken gerelateerd aan natuurlijke hulpbronnen een belangrijk onderwerp vinden voor de komende decennia.

Hoofdstuk 3: Materiaalgebruik als beperkende factor voor een op hernieuwbare energie gebaseerde waterstofeconomie.

In een moderne maatschappij zijn er vele complexe verbanden tussen het gebruik van verschillende natuurlijke hulpbronnen. Het gebruik van energie en materialen is in twee richtingen met elkaar verbonden. Ten eerste is er energie nodig voor mijnbouw en opwerking van ertsen om deze om te zetten in bruikbare materialen. Ten tweede zijn materialen nodig om fossiele brandstoffen te winnen en op te werken (bijv. olie raffinaderijen, elektriciteitscentrales en transformatoren), ze te transporteren (mammoetschepen, pijpleidingen en bovenleidingen) en om energie te winnen uit diffuse bronnen (bijv. windturbines, zonnecellen en waterkrachtcentrales).

In Hoofdstuk 3 wordt een kwantitatieve analyse gemaakt van de grondstoffen die nodig zijn om in 2050, uitgaande van huidige technologieën, een mondiaal

energiesysteem te hebben dat volledig is gebaseerd op hernieuwbare energie, met elektriciteit en waterstof als de twee belangrijkste energiedragers. De hoeveelheid beschikbare energie is geen beperkende factor voor een energiesysteem gebaseerd op hernieuwbare energiebronnen. Zelfs in een extreem groeiscenario van het energiegebruik tot circa 1300 EJ/jaar in 2050 zouden huidige technologie wind- (15%) en zonne-energie (80%) toereikend zijn, hetgeen 5% over zou laten voor andere hernieuwbare energie.

Om het aantal benodigde zonnecellen en windturbines te minimaliseren is het belangrijk om locaties te kiezen waar de omstandigheden optimaal zijn. Met name voor zonne-energie zijn deze locaties vaak ver verwijderd van de locaties waar de energie gebruikt zal worden. Daarom zijn uitgebreide transmissie netwerken nodig om de energie naar de juiste plaats te transporteren.

De keuze voor een (energie)technologie is zeer bepalend voor de hoeveelheid en het type grondstof dat nodig is. In drie cruciale delen van het systeem zijn relatief schaarse elementen cruciaal voor specifieke technologieën: tellurium en indium in dunne-film zonnecellen, neodymium in direct-drive windturbines en elektromotoren met permanente magneten, en platina in elektrolyse en brandstofcellen. De hoeveelheid benodigde grondstoffen zorgt ervoor dat deze technologieën nooit een substantiële bijdrage kunnen leveren aan de energievoorziening (honderden exajoules). In al deze gevallen zijn alternatieve technologieën denkbaar maar deze zijn vaak kostbaarder en/of minder efficiënt.

In dit scenario zijn ook grote hoeveelheden staal nodig voor zowel windturbines als waterstofpijpleidingen: voor windturbines ongeveer zes keer de huidige jaarlijkse wereldproductie en voor pijpleidingen ongeveer 40% van de huidige jaarlijkse productie. Als voor de pijpleidingen roestvrij staal zou worden gebruikt zou daarvoor 45 maal de huidige jaarlijkse nikkelproductie en 5500 maal die van chroom nodig zijn. Wanneer elektriciteit wordt gebruikt als belangrijkste energiedrager zou ongeveer 70 maal de huidige jaarlijkse productie nodig zijn terwijl voor de benodigde windturbines nog eens 4 maal de huidige jaarlijkse productie nodig zou zijn.

Hoofdstuk 4: Metaalgebruik in koolstofarme elektriciteitsproductie

Ongeveer 40% van de wereldwijde emissie van CO₂ komt vrij bij de productie van elektriciteit. In Hoofdstuk 4 wordt een analyse gemaakt van het metaalgebruik van koolstofarme elektriciteitsproductie. De CO₂ emissies en het metaalgebruik van elektriciteit uit wind, PV, biomassa en fossiele brandstoffen met CO₂ afvang en opslag zijn bepaald met behulp van een LCA benadering. Alle drie gepresenteerde elektriciteitsmixen resulteren in een vermindering van de CO₂ emissie van ongeveer 80-90%. Als in alle andere sectoren een vergelijkbare emissiereductie zou worden gerealiseerd zou de doelstelling om het CO₂ niveau in de atmosfeer te stabiliseren op 450-490 ppm haalbaar zijn.

In alle drie de gevallen zal dit echter gepaard gaan met een hoger metaalgebruik. Het toevoegen van CCS aan de huidige elektriciteitsmix zou de jaarlijkse vraag naar nikkel en molybdeen met zo'n 10-30% vergroten. Dit is een logisch gevolg van de additionele infrastructuur die nodig is voor het afvangen, het transport en de opslag van de CO₂ (speciale staalsoorten), in combinatie met lager rendement van de centrales zelf. Het overschakelen naar een elektriciteitsmix gebaseerd op niet-fossiele energiebronnen zal een veel grotere vraag naar nikkel, uranium, zilver, molybdeen, en in mindere mate, koper en aluminium tot gevolg hebben. Voor PV, biomassa (op afval na) en wind zit deze vergroting in de range van een paar procent tot een factor 1000. Dit betekent dat de winning van deze metalen sterk zal moeten worden uitgebreid om aan de vraag te kunnen voldoen. Niet alle niet-fossiele technologieën zijn metaalintensiever dan fossiele brandstof gebaseerde elektriciteit. Voor kernenergie, waterkracht en biomassa afval zijn relatief weinig metalen nodig, met uitzondering van uranium voor kernenergie. In het geval van PV en wind zijn de metalen met name nodig voor de productie van de PV zonnecellen en windturbines zelf. Voor gecultiveerde biomassa komt de vraag naar metalen vooral voort uit de materiaal intensieve landbouwprocessen, waaronder de productie van landbouwmachines en kunstmest.

De afgelopen decennia was in veel ontwikkelde landen een trend zichtbaar van een afnemende materiaalintensiteit per eenheid BNP. Wanneer klimaatverandering deze landen dwingt om over te schakelen op alternatieve energiebronnen, zal deze trend in de energiesector worden doorbroken. Het soort materiaal dat nodig is hangt sterk af van de keuze voor specifieke technologieën. Zo wordt de hoge zilverbehoefte in PV met name veroorzaakt door de keuze voor mono-kristallijne silicium cellen. Andere PV technologieën kennen echter weer hun eigen materiaal gerelateerde problemen. De huidige dunne film CdTe en CIGS gebaseerde cellen zullen geconfronteerd worden met de schaarste van de benodigde grondstoffen lang voordat ze een significante bijdrage leveren aan de elektriciteitsproductie. De 2 MW offshore windturbines met een versnellingsbak die gebruikt wordt in de berekeningen in Hoofdstuk 4 bevatten geen neodymium gebaseerde permanente magneten. Echter, veel van de nieuwe direct-drive turbines die weinig onderhoud vergen, bevatten zo'n 150 kg neodymium per MW. Het opschalen van deze technologie tot een niveau van tientallen GW zou een geweldige opschaling vergen van de huidige jaarlijkse productie van dit zeldzame aardmetaal die op dit moment 18000 ton per jaar bedraagt. De Chinese overheid heeft recent aangekondigd dat de te installeren capaciteit van windenergie in 2050, 1000 GW zou moeten bedragen. Wanneer al deze turbines op de direct-drive technologie gebaseerd zouden zijn, zou hiervoor 30 maal de huidige jaarlijkse wereldproductie van neodymium nodig zijn waardoor er weinig zou overblijven voor andere landen en toepassingen.

Hoofdstuk 5: Metaalschaarste: acute dreiging, eeuwigdurend probleem of dwaalspoor

In Hoofdstuk 5 worden de diverse aspecten van vraag en aanbod van metalen geanalyseerd. In combinatie met de andere hoofdstukken wordt de kwestie besproken of de metaalbehoefte van de energietransitie, gecombineerd met gebruik in andere sectoren zal leiden tot een significante schaarste op korte en middellange termijn.

Ondanks het feit dat de planeet Aarde eindig is, is de omvang van de voorraden nog geen beperkende factor geweest voor de productie van metalen. Hoewel de ertskwaliteit achteruit gaat zijn de voorraden metaal in laagwaardige ertsen tot nog toe steeds groter gebleken dan die in de hoogwaardige ertsen. Uiteindelijk zijn er altijd nog ultieme reserves in de vorm van oceaanwater en veelvoorkomende gesteenten. Tot op heden zijn de beschikbare voorraden van vrijwel alle metalen in omvang gegroeid in plaats van gekrompen, ondanks, of misschien wel juist vanwege, een exponentiële groei in winning. Dit is echter geen garantie dat de productie de komende decennia de exponentiële groei in vraag kan blijven bijhouden.

De schaal waarop materialen aan het milieu worden onttrokken is groter dan ooit. Globalisering, deels gedreven door goedkoop massatransport, heeft vrijwel elke uithoek van de wereld toegankelijk gemaakt voor exploratie en mijnbouw. Globalisering is echter eindig. De overgebleven onontdekte voorraden liggen vrijwel allemaal in gebieden waar de mijnbouw moeilijk zal zijn of onder een laag van één of meer kilometer gesteente. Bovendien lijken de kosten van massatransport hun laagste punt te hebben bereikt als gevolg van beperkingen in de opschaling van mammoetschepen en stijgende brandstofkosten.

De snelheid waarmee metalen kunnen worden gewonnen is beperkt, analoog aan conventionele olie. De snelheid van winning wordt beperkt door de beschikbaarheid van geschoolde arbeiders, de benodigde energie en, niet onbelangrijk, de milieugevolgen van de winning. In de twee periodes in het recente verleden waarin de prijzen van metalen hoog waren (jaren 50 en 80) werden deze hoge prijzen veroorzaakt door een snel groeiende vraag gecombineerd met onzekerheid over de toevoer naar de OECD. Hoewel in de huidige geglobaliseerde wereld de snel groeiende vraag nog steeds een belangrijke factor is, is de geopolitieke onzekerheid over de toevoer nu een mondiaal probleem geworden. Daarnaast zijn er op dit moment ook problemen zichtbaar bij winning. Mijnbouwbedrijven hebben grote moeite om de vraag bij te houden om allerlei redenen, waaronder teruglopende ertskwaliteit, nieuwe ertslagen die kleiner zijn en dieper liggen en milieueisen.

Daarnaast leven we in een tijd waarin we voor het eerst echt op wereldschaal worden geconfronteerd met de verbondenheid van de verschillende natuurlijke hulpbronnen. Als de ertskwaliteit achteruit gaat, is er meer energie nodig om metalen te winnen uit de ertsen terwijl we tegelijkertijd meer metalen nodig hebben voor de energietransitie die nodig is om het klimaatprobleem het hoofd te bieden. Watergebruik, ruimtelijke ordening en milieueffecten leggen additionele beperkingen op aan de productie van

metalen. Deze elkaar versterkende grenzen aan de groei zullen een uitdaging vormen voor toekomstige generaties. Als we voor de hand liggende beperkingen als gevolg van materiaalschaarste willen voorkomen, zullen we onze technologieën zorgvuldig moeten kiezen.

De vraag naar metalen zal de komende decennia exponentieel blijven stijgen. Een van de belangrijkste oorzaken is de snelle verstedelijking welke zal leiden tot een massale groei van steden en bijbehorende infrastructuur. Bovendien zal de economische groei in de opkomende economieën leiden tot de productie van steeds meer complexe producten, en daarmee groeiende vraag naar metalen. De transitie naar een duurzame koolstofarme energievoorziening vraagt ook een omvangrijke stroom materialen. Voor sommige metalen zal dit betekenen dat de huidige productie enkele malen zal moeten worden opgeschaald. Het meest cruciale aspect is echter dat we al deze metalen in de komende decennia nodig hebben om klimaatverandering het hoofd te kunnen bieden.

Het is zeer onwaarschijnlijk dat de optimisten doctrine van steeds maar groeiende voorraden en dalende prijzen de komende decennia waar zal blijven. Wanneer de voorspellingen voor verstedelijking bewaarheid worden en wanneer klimaatverandering substantieel wordt aangepakt, zullen we de komende decennia het equivalent bouwen van alle steden die er nu zijn, zal het gemiddelde inkomen per capita met een factor drie toenemen en bouwen we vanuit niets een geheel nieuw duurzaam energiesysteem. Mijnbouw en exploratie worden op dit moment al geconfronteerd met beperkingen als gevolg van milieueffecten en water-, land- en energiegebruik en hebben daarom nu al moeite om de vraag bij te houden. Een ruime beschikbaarheid van metalen is niet alleen nodig voor de productie van onze favoriete gadgets, het is ook onmisbaar om in 2050 negen miljard mensen van voedsel, onderdak en duurzame energie te voorzien.

Hoofdstuk 6 Het combineren van IE en IEA methoden: de PVC case

In hoofdstuk 6 wordt een case studie van een fictief verbod op PVC gebruikt om aan te tonen dat zelfs de complexiteit in een beperkt onderdeel van het industrieel complex, de chloorindustrie, een substantiële invloed kan hebben op de uitkomst van de analyse. Noch de methoden van de Integrated Environmental Assessment, noch die van de Industrial Ecology zijn in staat de connecties die binnen de chloorindustrie bestaan volledig in beschouwing te nemen.

Met LCA ontstaat een beeld van veranderingen in een grotere groep milieuaspecten wanneer PVC wordt vervangen door andere materialen. Met SFA wordt het belang van de chloorketen duidelijk. De reikwijdte van methoden zoals LCA en SFA is echter beperkt omdat de analyse van de milieueffecten in deze methoden generiek is. Het beeld blijft gefragmenteerd en onvolledig.

Alle methoden en modellen die we gebruiken zijn slechts een beperkte afspiegeling van de werkelijkheid en dus per definitie minder gedetailleerd. Dit betekent dat niet alle verbanden kunnen worden meegenomen in de methoden en modellen die worden gebruikt.

Zelfs een combinatie van deze methoden is ontoereikend om alle effecten in beschouwing te nemen. Er is duidelijk behoefte aan een bredere systeemanalyse die kan worden gebruikt om de daadwerkelijke gevolgen van een verbod op PVC te analyseren, nog voordat specifieke methoden voor nadere analyse worden gekozen. De vorm van deze bredere systeemanalyse kan variëren van een materiaal- en productstroombiagram tot een dynamische en gekwantificeerde analyse. Pas nadat een dergelijke analyse duidelijk heeft gemaakt wat er waarschijnlijk in de praktijk zal gebeuren is de tijd gekomen om specifieke IEA, IE methoden of een combinatie daarvan te selecteren om de gevolgen van beleid en/of activiteiten te kwantificeren. Dit is niet hetzelfde als het simpelweg kiezen van de juiste methode of het juiste model en of de juiste parameters. Een brede systeemanalyse kan niet worden gestandaardiseerd, deze verschilt van geval tot geval en is een op maat gemaakte holistische analyse. Recente ontwikkelingen op het gebied van *Life Cycle Sustainability Analysis* kunnen gezien worden als een stap in deze richting.

Hoofdstuk 7 Overall conclusions, algemene discussie en onderzoeksagenda

In dit hoofdstuk worden de resultaten gepresenteerd in de vorm van een reeks conclusies. De belangrijkste reflecteren op de centrale onderzoeksvragen uit Hoofdstuk 1 en hebben betrekking op het belang van metalen in de menselijke geschiedenis, de ontwikkeling van het debat over grondstofschaarste met een focus op metalen, de metaalbehoefte van de energietransitie en de bruikbaarheid van Industrial Ecology methoden om de milieugevolgen van grootschalige transitie te analyseren. Dit proefschrift wordt afgesloten met een algemene discussie en een voorstel voor een onderzoeksagenda.

Curriculum Vitae

René Kleijn was born in 1964 in Naaldwijk, The Netherlands. He graduated from secondary school Thomas More College in 1982 (HAVO). From 1982 to 1986 he studied applied chemistry at 'De Haagsche Analisten School' (HLO, BASc). In 1986 he joined the military for a year of compulsory service. In 1987 he continued his study of chemistry at Leiden University from which he graduated in 1990 (MSc). During his studies in Leiden he came in contact with the Institute of Environmental Sciences (CML) where he found an inspiring atmosphere for his further professional career. He was appointed as a researcher at CML in September 1990. At first, his work focused on substance flow analysis and environmental risk assessment. In the 1990s he worked on many projects related to the chlorine industry and agriculture, including life cycle assessments. In 1996 he became a member of the Steering Committee of ConAccount, a European funded concerted action which served as a scientific home for researchers involved in substance flow analysis and material flow accounting. In 2000 he became a member of the Steering Committee that established the International Society for Industrial Ecology. From 2003 to 2006 he served as a member of the Council of this society. In November 2001 he co-organised the first international conference of the Society that took place in Noordwijkerhout. From 2001 to 2006 he acted as a subject editor for the International Journal of Industrial Ecology. From 1990 to present he was a researcher and project leader in many European projects on topics ranging from the application of material flow analysis in small villages in developing countries to the development of indicators to measure eco-innovation. Together with colleagues from Leiden University, Delft University of Technology and Erasmus University he initiated the interuniversity MSc programme Industrial Ecology that started in 2004 as a track within the Leiden Chemistry program, and is now a full master programme of Leiden University and Delft University of Technology. Since 2004 he is a teacher and course coordinator in the MSc Industrial Ecology. In 2009 he was appointed as an assistant professor at CML. In 2003 he started a sustainability assessment of a transition to a hydrogen economy. This drew his attention to the amount of material resources that would be needed for such a transition. This work led to the idea to write a PhD thesis, presently before you, on the topic of the material requirements of a transition to a sustainable energy system. Currently his research is focused on the linkages between the use of natural resources and mineral scarcity.