Materials and energy : a story of linkages

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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 GDP[1]. 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 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

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[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 has 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 Götenborg, 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 impacts[2]. 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.

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[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 CO_2 capture facilities are taken into account, but also all those used d 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.

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