Materials and energy : a story of linkages

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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 CO_2; 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 than 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 asses 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 a 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.

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