Materials and energy : a story of linkages

Kleijn, E.G.M.

Citation

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

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

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 CO_2 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 CO_2 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 CO_2 emissions by about 80-90%. If comparable reductions were achieved in other sectors the 450-490 ppm stabilization goal for atmospheric CO_2 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 CO_2 (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 polices 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.