Scarcity: a story of linkages of sustainability

Authors: Rene Kleijn & Ester van der Voet, Department of Industrial Ecology, Institute of Environmental Sciences, Leiden University

Essay for the Conference: Enriching the Planet, Empowering Europe - Optimising the use of natural resources for a more sustainable economy, The Hague, 26 & 27 April 2010, cf: http://www.clingendael.nl/resourcescarcity

1. Introduction

In this essay we explain how technological improvements and substitution have saved us in the past from resource scarcity and how the linkages between different resources will make this a lot harder in the not-so-distant future.

One could argue that the economic importance of resources is very limited and has decreased over time. Some of the most important resources, such as water, air and biodiversity, are often not priced at all. In developed countries the share of the primary sector (agriculture, fishery and mining) to national GDP is between 1 and 5 %.[1] Hence, 95-99% of the economic added value comes from manufactured products and services. However, this economic reality does not contradict the physical reality that the materials we produce via mining and agriculture are the foundation of our welfare. Although we are more and more living in cyberspace, we cannot eat bits, nor can we live inside computer chips. We still have to nourish, build houses and infrastructure, and manufacture the products that make our lives comfortable. Even cyberspace only exists within material products like servers and PC's which are fed by a continuous and substantial supply of fossil fuels. If the supply of materials would fail, society as we know it, including cyberspace, would come to a grinding halt.

The world economy is not only large in monetary terms but also in terms of the material throughput. At this moment the global economy consumes a little over 1 Gton of metals, 6 Gtons of food, 12 Gtons of fossil fuels and 4,500 Gtons of water annually. The amount of nitrogen that is fixated by humans is larger than the amount fixated in nature. For more than half of the elements in the periodic table humans mobilize more than 50% of the total (natural an anthropogenic) mobilised amount. The scale of the human activities is in many cases now comparable or larger than the scale of natural processes. This means that we have a substantial impact on our environment which is illustrated by the environmental problems that we face today.

Although technological development and substitution have saved us from worldwide resource scarcity until now, this does not mean there is no scarcity in our world today. As a result of unequal distribution of wealth and resources, a large proportion of the human population is still deprived of access to clean water, food and other basic material needs. Though this unequal distribution is clearly one of the main issues human society will have to address, we will not discuss it further in this essay. Here we will review the historic and current debate on resource scarcity and discuss how the linkages between different resources may aggravate individual scarcity issues.
The history of resource scarcity

2. The history of resource scarcity

Several authors have described the role of the availability of resources in the collapse of civilizations.[2-4] In these historic studies a lack of big game, forests, fertile land and water (often caused by climate change) was one of the factors that contributed to the collapse of societies. Since the industrial revolution, mineral resources joined the list of resources that are crucial for a flourishing society.

Worries about the supply of basic commodities are as old as the human race. From the extinction of large mammals for hunters and gatherers, the availability of fertile land in the time of Malthus, the availability of fuel wood at the break of the industrial revolution, the projections of the Club of Rome in the 1970s, to the worries about peakoil and the 2003-2008 metals boom in current times, scarcity of resources has frequently been a hot topic. Time after time human ingenuity through technological innovation has solved the problem of scarcity, mainly by replacing natural capital by human capital. Sedentary agriculture with domesticated animals substituted game, artificial fertilizers, substituted fertile land and fossil fuels substituted fuel wood and animal and human labour. These substitutions of key resources marked major transitions in the development of human society. This underlines the importance of the material basis of society.

Since the industrial revolution resource use has exploded. If water is excluded, fossil fuels dominate resources use in both mass and value, followed by bulk metals and fertilizers. Although the work of the Club of Rome in the 1970s was heavily criticised, it made clear that exponential growth in resource use is, by definition, unsustainable. The scientific and public debate after WWII focused on scarcity issues related to fossil fuels and non-fuel minerals. In 1952 a report was published by the US President's material policy commission (Paley commission): "Resources for Freedom" in which material scarcity was addressed. The strongest scientific debate on mineral depletion between resource economists and environmentalists occurred in the two decades between 1960 and 1980. Economists like Solow and Nordhaus took the position that economic principles, technological progress and substitution will prevent the depletion of resources. Others like Georgescu Roegen, Daly and the main environmentalists of that time like Ehrlich and Meadows, emphasize that exponential growth will inevitably lead to the depletion of resources[5].

If real (inflation corrected) prices are used as an indicator for scarcity, the view of the resource optimists is clearly supported by the empirical data. Resource prices have decreased the last 200 years or so. Decreasing prices show that new discoveries, technological innovation and substitution have outran increased demand and degrading ore quality. However, the fact that the optimists have been right so far does not necessarily mean that their predictions will hold in the future. Next to the economic reality of the resource economist there is a physical reality in which we are now reaching some fundamental boundaries of the exponential growth in resource use. These boundaries can be found when one has a closer look at the factors that caused resource prices to decrease over the past centuries. A second important limiting factor can be found when one analyses in the linkages between the different scarcity issues

3. Why resource prices decreased in the past and why this trend will not continue in the future

Several factors have caused real resource prices to decrease in the past, despite exponentially growing demand. Globalisation has made it possible to tap into new remote resources. Global trade in commodities and resources has been made possible by a sharp decrease in the long distance transport costs that occurred in two major waves. Before 1850, the production and consumption of commodities like food, fibres, fossil fuels and minerals was largely a national or continental affair.[6] After 1850 the introduction of steam power facilitated the large scale deployment of railways and steamships for bulk transport. This development made long distance transport of bulk goods a lot cheaper. At the time, this caused major problems for European farmers because of imports of cheap textiles and foodstuffs. The second wave of reduction of costs of bulk transport took place between 1956 and 1970 and was triggered by the Suez crisis. In this time period specialised bulk carriers and deeper sea ports and specialised harbour infrastructure was developed. The introduction of bulk carriers made it possible to transport relatively low-price commodities like coal and iron ore over extremely long distances e.g. from Australia to Europe. This led to a crisis for European miners, again caused by cheap imports. These two waves of scaling up long distance transport reduced bulk transport costs by 90% (in real terms) between the 1870s and the 1990s.[1,6] The introduction of bulk carriers included a substantial positive feedback: bulk carriers made long distance transport of crude oil cheaper which in turn made oil consuming transport cheaper.

A second factor that supported the downward trend of resource prices was the scale-up of mining operations. Soon after pre-historic people started collecting minerals from the Earth's surface, subsurface mines were created to follow the mineral veins. For a long time, subsurface or underground mines were the major source for minerals. During the last century a shift has taken place from subsurface mines to large surface mines. In the US 98% of the metals is now mined from surface mines. Mining from surface mines is more efficient than mining from subsurface mines because much larger equipment can be used and no subsurface infrastructure is needed. The scale-up of mining operations is also linked to globalisation which made it possible to expand mining operations to large remote deposits.

Both globalisation and the scale-up of mining operations thus facilitated the downward price trends and increased the availability of commodities. However, for both trends, it is hard to envisage further developments in that direction. Globalisation is a one-off affair, there is only one globe and the effects seem to be decreasing. Scaling up bulk carriers much further than its current size is hard to imagine. A factor two size increase may be conceivable but a factor ten seems out of reach, not only because of the limits to construction but also because of the increased size of harbours and harbour infrastructure that would be needed[7,8]. The scale-up of mining operations also seems to have reached its practical limits. The size of newly discovered deposits is decreasing and new deposits are often found in deeper layers which are less accessible via surface mining.[9] The mechanisms that provided us with ample cheap resources are about to become obsolete. On top of this, the linkages between different resources increase the supply constraints.

4. Scarcity and linkages of sustainability

Resources are linked to each other in different ways. Land, energy and water are needed to produce mineral resources while surrounding biotic resources are being degraded through emissions, waste flows and physical destruction. Metals and land are needed to produce wind turbines and PV solar cells while the building and installation of this equipment also affects local climate and local flora and fauna. The production of food requires fertile land, ample water supplies, mineral inputs in the form of fertilizers and diesel for agricultural machines while biotic resources are being degraded through nutrient leaching, pesticide emissions and physical destruction, including the initial land use transition from nature to agriculture.

In a recent publication[10] the links between the different resources have been analysed and, where possible, quantified. The main conclusions of this comprehensive work will be summarized below.

4.1 Mineral resources

Although direct land use of mining is limited, mining affects large land areas indirectly by its waste flows and emissions. One of the major challenges in the mining industry is the reduction of this impact and the practical implementation of land reclamation. Another problem is the access to land, not only for the actual mining, but also for exploration. Exploration of oil and gas can be done with relative few seismic measurements, while non-fuel minerals can only be detected from a few hundred metres of the outer limits of the ore body. For new deposits, which are often deeply buried, access is required to a land area that is a factor thousand bigger than that of the area that will actually be mined. At the same time, large land areas are not available because they are already in use for other purposes e.g. urban areas and nature reserves.

Water and energy are essential resources in the mining of mineral resources. After the rich and easy accessible deposits are depleted, mining will continue with lower grade ores, more fine grained deposits and less accessible e.g. deeper deposits. This will have a substantial impact on the amount of water and energy needed per unit of resource produced. For oil, the difference in inputs between conventional oil from the Middle East and Canadian tar sands forms a good example. For the production of one barrel of oil from tar sands, 2 barrels of water are needed (net)[11]. In the Athabasca river basin the extraction of water is limited through governmental regulations to 370 million cubic meters per year (6% of the total water flow) which is equivalent to three million barrels of oil per day (3.5% of current global production and about three times the current output in the area). Furthermore, between 6.5 (strip mining) and 26 cubic meters (in situ) of natural gas is used for the production of one barrel of oil from tar sands. This is equivalent to 5 to 20% of the energy content of the produced oil.[11]

For non-fuel minerals the mining and grinding of lower quality ores also increases the energy and water needs. For copper and nickel, energy demand will dramatically increase when ore grades drop below 1%. This is mainly caused by the additional waste material which must be handled and processed. Water needs for metal production extraction could increase by a factor 30. More energy is also required for the exploration and identification of future resources that will likely be found at greater depth. If the extra energy needs are extrapolated to all mineral resources the energy required to produce metals could approach 40% of global energy supply by 2050, if current technologies are applied. When considering the constraints on energy resources this is clearly not possible. It will become unavoidable to move to mining technologies that are much less energy intensive than current practice or to reduce our consumption of primary metals.

4.2 Energy resources

In order to produce fossil fuels and uranium, water and energy are needed as described in 4.1. Furthermore, there is a need for non-fuel minerals which are needed to build the infrastructure and equipment that is needed for mining, refining and transport of these fuels. Moving from conventional fossil fuels to non-conventional fuels, such as heavy oil, tar sands, shale oils, coal-bed methane and gas hydrates, will increase the demand for equipment and infrastructure substantially. It will also increase the amount of energy that is needed to produce the fossil energy carriers. The same is true for the conversion of the more abundant fossil energy sources, coal and gas, to liquid oil-like carriers. For these conversions additional infrastructure is needed in the form of Gas-to-Liquids and Coal-to-Liquids installations and additional energy inputs will be needed. This means that, when a shift is made to non-conventional fossil energy sources, the total energy-efficiency of the global energy system will decrease while the material intensity will increase. If carbon capture and storage is applied as an add-on to fossil based system to mitigate climate change, the efficiency and material intensity will increase even further (20-30% of base materials[12]).

Renewable energy sources like wind and sunlight are clean, abundant and globally relatively evenly distributed. However, they are also diffuse, low-exergy energy sources. This means that relatively large amounts of high-tech equipment is needed to convert them into high-exergy energy carriers like electricity and hydrogen that can be used for transport, industry, household appliances, computers etc. Almost all renewable energy systems that convert renewable energy to high-exergy carriers, are much more material intensive than the current fossil fuel based systems[13]. Next to the extra use of bulk materials like copper, iron, aluminium and concrete, some specific issues arise related to minor metals that are used in these renewable technologies. New generation direct drive wind turbines are equipped with neodymium containing permanent magnets (about 150 kg/MWe). The same is true for the electromotors in hybrid and electric cars, which also often contain dysprosium. The use of neodymium and dysprosium in permanent magnets increases the magnetic strength per unit of mass and volume thus allowing for smaller and lighter motors and generators. In wind turbines the additional advantage of the direct-drive design is that the gear-box, which requires substantial maintenance, is not needed any more, making direct drive turbines the obvious choice for off-shore applications. However, current production of neodymium and dysprosium is very low (18000 and 500 ton annually respectively) and concentrated in China which currently controls 95% of the world market. The introduction of (hybrid) electric vehicles and direct-drive turbines will be strongly constrained by the supply of these rare earth metals.

At the moment, different solar cells are available, silicon based non-silicon thin film types. Amorphous silicon cells are cheap but have low efficiency, while crystalline silicon cells have high efficiencies but are also expensive and energy intensive to produce. Thin-film PV cells have been developed that can be produced at lower costs. The main thin-film technologies are cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS). Since these thin film cells use a combination of less common materials, the supply of these materials can be an issue of concern. Current reserves would not allow a substantial contribution to worldwide energy demand. All these thin film technologies would be limited to a maximum of less than 2% of current global energy consumption. Some, more unconventional, thin film PV technologies (especially FeS_2) look very promising from the perspectives of material constraints and can be scaled up to the level of twice the current global energy demand.[14] Considering these material constraints it seems that the use of current thin film cells based on rare materials will be limited. This illustrates the importance of the assessment of new technologies with regard to the possibility to scale them up to substantial levels. Large scale government funding for technologies that will remain marginal is not an efficient way to tackle the energy and climate crisis.

4.3 Water resources

Drilling for water, pumping filtering and purification requires energy and materials. Since the volume of water that is used is huge, 370 times the amount of fossil fuels, the amount of energy and materials that is needed for the handling is also large. At the same time, as described above, water is an essential resource in the mining of fossil fuels and non-fuel minerals. Water is also essential as cooling agent in the power sector. About 70% of total water consumption is used for agriculture. World food production is to a large extent dependent on the irrigation from surface water and fossil water sources. The latter is by definition not sustainable, although fossil water sources are often very large. Almost all of the water on this planet is seawater. In some locations, desalination is the best alternative for producing fresh water. Large scale cheap desalination would substantially increase the potential for agricultural production. However, although technologies are developing rapidly, desalination is still a very energy intensive process.

4.4 Land resources and agriculture

Agriculture is by far the most important type of land use by man. About one third of the ice free land is used for croplands (1/3) and pastures (2/3). This is equal to the surface area of all forests on the planet. Only about half a percent is used for built-up area. Next to the 20% of land that is used for pastures, 35% of all grain is fed to life stock. The efficiency of converting grain protein to meat protein depends on the meat product and is about 1:2 for chicken, 1:4 for pork and 1:10 for beef. This means that a shift from animal proteins to vegetable proteins would make it possible to feed more people with the same amount of crop production. Current trends point however in the opposite direction. Current agriculture is a very material, energy and water intensive process. The input of large amounts of mechanical labour, artificial fertilisers and pesticides has saved us from the food crisis that was looming just prior to the industrial revolution. However, all of these inputs however require large amounts of energy and materials. This is also one of the main reasons that first generation biofuels are not as beneficial for the environment as policy makers had hoped. Some of these inputs consist also of non-renewable resources like potash and phosphate. Although we still have phosphate reserves that will last for hundreds to thousands of years the dissipative use of a mineral resource is by definition unsustainable. Recycling is hardly possible and substitution is not an option since it is macro-nutrient that is essential for plant growth.

5. Conclusions, Discussion and Recommendations

World wide economic growth is still strongly coupled to growth in resource use. Emerging economies, and China in particular, are responsible for the growth in resource use that is coupled to the construction of urban areas, infrastructure and industrially. At the same time the internal markets of these countries grow rapidly and the demand for luxury consumer goods like cars, tv's, refrigerators and air conditioners is also growing rapidly. In developed countries, where the infrastructure is in place, the demand for basic resources like concrete, steel and other base metals has levelled off. However, because consumer products are becoming more and more high tech the demand for relatively scarce materials like indium for flat screens and tantalum for mobile devices is increasing rapidly. Next to that a transition is needed in the world wide energy system in order to address climate change. This transition will mean that we move to a more material intensive and also a more high tech energy system than the current fossil fuel based system. Since the energy system is one of the largest subsystems of the world economy the consequences in terms of material requirements will be substantial.

For all basic resources (energy, minerals, water and food) supply is struggling to keep up with the demand of the growing world economy. The fact that all these resources are needed to produce resources makes the potential scarcity problem a very complex one. Looking at resource scarcity issues individually while disregarding the links to the other resources will lead to underestimating the true scale of the problem and to problem shifting from one resource to another. Resource use is not just related to scarcity, but to environmental impacts: the production, use and disposal of these resources is by far the most important cause of the environmental problems that we are confronted with, including the loss of biodiversity, arguably the only true non-renewable resource.

It is clear that we will have to carefully manage the way we use the remaining resources. The European Raw Materials Initiative is aimed at giving European enterprises a fair access to raw materials from the world market, supporting the supply from European sources and improving resource efficiency and recycling rates. However, we also have to be careful to analyse potential solutions to existing problems from a systems perspective in which the linkages between the different environmental problems, resources and other issues are fully addressed. We will also have to find strategies that will solve the scarcity issue in relation to environmental issues. Moving to a more closed loop society seems one obvious way to address both the resource scarcity issue and to reduce the environmental pressure. Material accounting can help keeping track of materials from mining to manufacturing, end-use and disposal, and dynamic material models can help us understand future material requirements, including their linkages. Looking at different resources and environmental issues from a systems perspective will prevent the focus on partial solutions like first-generation biofuels that create other problems (in this case competition with food production, water use and increased pollution).

In principle the EU Resource Strategy takes this integrated approach and addresses resource issues as a set interlinked issues, from scarcity of minerals to the loss biodiversity. The challenge that lies ahead is to convert this general strategy into a set of concrete policy guidelines and policy measures. To start up the discussion we would like to propose the following:

- analyse all problems and proposed solutions from a systems perspective
- develop dynamic methods and models for that, targeted at individual resources as well as at the linkages between them, allowing to include these complex issues in scenarios for the future
- give incentives for increased resource efficiency in production processes and
- give incentives to close the loops of the main materials by improving collection and recycling and waste treatment
- start to discuss problems that will only occur in the distant future if there are no easy solutions and the consequences might be catastrophic (e.g. phosphate depletion)

References

1 Radetzki, M. A Handbook of Primary Commodities in the Global Economy. (Cambridge University Press, 2008).

2 Tainter, J. A. The collapse of complex societies. 250 (Cambridge University Press, 1988).

3 Ponting, C. A new green history of the world, the environment and the Collapse of Great Civilisations. (Penguin Group, 2007).

4 Diamond, J. Collapse, how societies choose to fail or survive. 572 (Penguin books, 2005).

5 Tilton, J. E. On borrowed time ? Assessing the threat of mineral depletion., (Resource for the future, 2003).

6 Lundgren, N.-G. Bulk trade and maritime transport costs : The evolution of global markets. Resources Policy 22, 5-32, doi:Doi: 10.1016/s0301-4207(96)00016-5 (1996).

7 UNCTAD. Review of Maritime Transport 2008. Report No. UNCTAD/RMT/2008, (UNCTAD Geneva, 2008).

8 Stopford, M. in Lloyds List Shipping Forecasting Conference 10 (2002).

9 Humphreys, D. Comment: Unravelling the causes of the mineral price boom. Resources Policy 34, 103-104, doi:DOI: 10.1016/j.resourpol.2009.02.003 (2009).

10 Graedel, T. E. & Voet, E. v. d. Linkages of Sustainability. (MIT-press, 2010).

11 Canadian National Energy Board. Canada's Oil Sands, Opportunities and Challanges to 2015: an update. 85 (National Energy Board, Calagary, Canada, 2006).

12 Kleijn, R., Voet, E. v. d., Oers, L. v. & Kramer, G. J. Metal use in low-carbon power-generation. (to be published).

13 Kleijn, R. & van der Voet, E. Resource constraints in a hydrogen economy based on renewable energy sources. Renewable and sustainable energy reviews submitted (to be publsished).

14 Wadia, C., Alivisatos, A. P. & Kammen, D. M. Materials Availability Expands the Opportunity for Large-Scale Photovoltaics Deployment. Environmental Science & Technology 43, 2072-2077, doi:10.1021/es8019534 (2009).