Geochemical Perspectives

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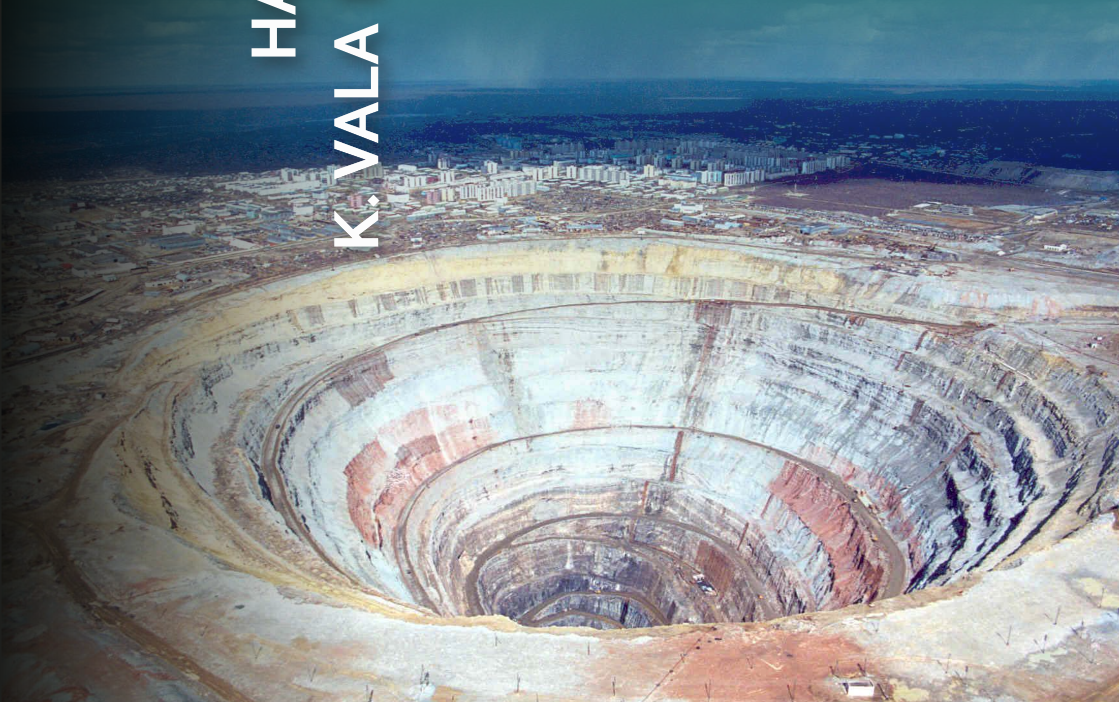
Natural Resources in a Planetary Perspective



Geochemical Perspectives

Each issue of ***Geochemical Perspectives*** presents a single article with an in-depth view on the past, present and future of a field of geochemistry, seen through the eyes of highly respected members of our community. The articles combine research and history of the field's development and the scientist's opinions about future directions. We welcome personal glimpses into the author's scientific life, how ideas were generated and pitfalls along the way. *Perspectives* articles are intended to appeal to the entire geochemical community, not only to experts. They are not reviews or monographs; they go beyond the current state of the art, providing opinions about future directions and impact in the field.

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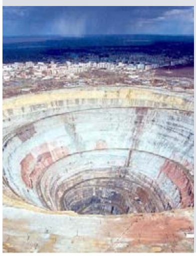

ABOUT THE COVER
Mir (or Mirny) abandoned open cast diamond mine in Siberia, Russia. At the time of its closing in 2004, the mine was 525 metres deep and 1,200 metres across – making it the second largest excavated hole in the world, after Bingham Canyon Mine in Utah. Source: amusingplanet.com

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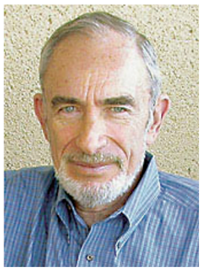
PREFACE

In this volume the authors would like to to show how the fate of our wealth and prosperity is linked to how we succeed in managing our resources over a very long time. So far, we appear to have been very successful with continuous growth in wealth and prosperity all across the globe. However, when we look beneath the surface, the picture becomes very different. This is not the work of us alone; in this we stand on the shoulders of giants, going far back in time.

Thomas Malthus was a British Professor of Political Economy. Already in 1798 he warned that continued growth would eventually outpace the availability of key resources, leading to major problems. *Malthus* was way before his time intellectually and far in advance of his contemporaries, and those coming after could not understand him. Many other people discussed these issues both before and after him, but in 1968 it had become evident that *Malthus* was not as mad as some had claimed. Then the Professor of biology at Stanford, *Paul R. Ehrlich* wrote his book *"The Population Bomb"*. There he pointed out the same issues as Malthus had done 170 years earlier, and that it was in the process of happening.


Source: Wikipedia.

Thomas Malthus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Paul R. Ehrlich

Source: The Cutting Edge www.thecuttingedgenews.com

Oil man *Marion King Hubbert* and the peak oil curve


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Aurelio Peccei, the first chairman of the Club of Rome

In 1956, *Marion King Hubbert*, a geophysicist working for Shell Oil Corporation in USA, developed a model for oil production and field exhaustion, that has since been referred to as peak oil. He predicted correctly an exhaustion date of early 1970s for the oil and energy reserves of the United States.


Source: Denis Meadows.

The Limits to Growth team. From the left: *Jørgen Randers, Jay Forrester, Donella Meadows, Dennis Meadows* and *Wilhelm Behrens III*.

In 1971, *Jay Forrester*, a famous MIT systems engineering professor from the WWII, developed a model for the future economy, showing that a resource crisis could be imminent. It started a chain of events, and eventually, *Aurelio Peccei* (Italian economist and industrialist), chairman of the Italian FIAT automobile company and the Concorde consortium, instrumental in rebuilding the Italian Industry after WWII, became aware of *Jay Forrester*´s work. He realised that a serious and comprehensive study would be needed to address the issues of global resources, population growth and potential industrial and economic crashes. The Club of Rome (*Peccei* was its founder and president) initiated the work that lead to the Limits to Growth study. *Jay Forrester*, assisted in the work, but kept in the background, and the limits to growth team was formed; it included *Donella Meadow* (American biochemist), *Dennis Meadows* (American systems engineer), *Jørgen Randers* (Norwegian physiscist) and *Willhelm Berents III* (American agronomist). They made the "Limits To Growth" study that had a huge impact on the world and is discussed in this volume.

More researchers in different disciplines have connected with that work and extended it to many different types of exhaustable resources. *Professor Charles Hall* (American ecologist), developed the concept of Energy Return on Investment (EROI), showing that as oil resources dewindle, so does EROI, because it costs more and more energy to get the oil out of the ground as the exploited reservoirs are deeper and deeper in the ground, and the refining costs rise because of low quality grades.

Charles Hall, Colin Campbell (British) and *Jean Laherrere* (French), both reservoir geologists, working for different large oil companies, and *Professor Kjell Aleklett* (Swedish physiscist) promoted the concept of peak oil, upsetting many people dependent on eternal growth for their income. Together, after their retirement they formed the Association for the Study of Peak Oil (ASPO) in 2001, as they were free of corporate policies constraints on what they could or could not say.

Photo credit: Kjell Aleklett.

Charles Hall

Source: The University of British Columbia.

Source: Colin Campbell.

Source: lemonde.fr/blogs

Kjell Aleklett, *Colin Campbell* and *Jean Laherrere*, where *Colin* demonstrates peak oil at an Irish pub to his friends. The full beer glass respresents oil resources in the year 1900, the half empty beer glass oil resources in the year 2000 and the near emply beer glass oil resources in the year 2100.

The peak resources issues took a new turn with people like *Richard Heinberg* (American journalist, Cultural geographer) and *Professor Ugo Bardi* (Italian physicist) who went to the public, giving lecture after lecture with the messages of a finite world in a series of popularised lectures, documentary films and books.

Source: richardheinberg.com

Richard Heinberg

Source: archivio.gonews.it

Ugo Bardi

The morale of our story is that complex issues need trans-disciplinary approaches, and international teams, in which each person needs to be devoted to the issue at hand, as well as being honest and persistent, and not put off by the criticism from a society that is inherently conservative and finds change unpleasant. Welcome to the world of finite and limited resources.

What you will see in this *Perspective* are a number of system dynamics model simulations. It is important to understand that models do not tell what the future will be, but they illustrate what may happen under a certain set of assumptions. They may be used to assess something about how likely the different scenarios are to occur. The use of models is important for preparing for different eventualities in case they really materialise. It is a way to have a foresight for the future and to be prepared. Please take note that the words « ton » and « tonne » have been used interchangeably throughout the text and figures of this *Perspective*; in all cases these refer to metric tons (1,000 kg).

ACKNOWLEDGEMENTS

Much of the work used for this *Perspective* on the long-term sustainability of resources was developed in cooperation with our long-term colleague, *Dr. Deniz Koca*, now at the Centre for Environmental and Climate Research in Lund University.

For *Vala*, work on natural resources started when she was wondering what a geochemist could do that would be of importance to sustainability of the world as a whole in the year 2000. *Vala* thanks *Dominique Weis* and other organisers of the Vancouver Goldschmidt Conference for inviting her to give a Plenary Lecture on resources in 2008 and the Nature Geoscience editor who asked her to write a Commentary in the November issue of the same year entitled Rare metals getting rarer.

We have been encouraged and motivated by very many people on the way in our efforts towards sustainability, and in our biographies we present who they were. Specifically we would like to thank *Dr. Ernst Weizsaecker* of the Club of Rome and the UNEP International Resource Panel, and *Dr. Ashok Khosla* of the International Resource Panel for their encouragement to go on, despite resistance. Also important in the development of ideas have been colleagues from the Schumacher Institute and the Balaton Group, including *Ian Roderick*, *Jenneth Parker*, *Alice-Marie Archer*, *Alan Atkinson*, *Alexander Chickunov* and *Karan Khosla*.

We would like to thank the European Commission Environment Framework 7 Programme for the funding of the first work that we undertook together on resources in the project CONVERGE (2009-2013). The theme was on sustainable communities and we decided that there was no way to establish such a framework, if there was no knowledge of resource availability for today and the future. The research presented in this issue was born then, enriched by discussions with CONVERGE colleagues from academia and non-government organisations in the UK, Sweden, Hungary, Iceland and India. The work has continued thanks to the German Government Funded project SIMRESS in collaboration with the Ecologic Institute, Berlin, European School of Governance, Berlin, and the Institute for Business Dynamics (GWS) in Osnabrück, Germany.

We are indebted to *Liane G. Benning, Eric Oelkers, Bruce Yardley* and *Robert Raiswell* for constructive reviews of this paper. We especially thank *Eric Oelkers* for the invitation to write this *Perspective*, for his engagement in these important issues, and for his expert editorial handling. The *Geochemical Perspectives* team, *Marie-Aude Hulshoff*, and *Juan-Diego Rodriguez-Blanco* are thanked for editorial help and patience.

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NATURAL RESOURCES IN A PLANETARY PERSPECTIVE

ABSTRACT

One of humankind's biggest challenges over the next century is to provide adequate resources for civilisation. Geochemistry plays a central role, from the processes that accumulate elements into ore bodies, to developing exploration techniques that are used to find them. Geochemistry is also important for the processes that win the resources and redistribute them with the accompanying risks of environmental contamination and threats for human health. As geochemists, it is useful to take a step back and look at the big picture of resources from a global perspective, to consider their place in history and to contemplate their importance. The future of our civilisation depends on their wise use and geochemistry lies at the centre – for ensuring adequate supplies and for minimising the risk of poisoning ourselves. This *Perspective* summarises the current and future availability of many natural resources. But the main focus is on the most important metals and on phosphorus. The metals are grouped into the big six (iron, chromium, manganese, aluminium, copper and zinc), with some shorter discussion of precious (gold, silver and platinum group metals) and other metals. These other metals are those needed for steel (niobium, vanadium, nickel, molybdenum), for technology (tantalum, zircon, indium, gallium, germanium),

for new technological developments in the renewable energy industry (europium, terbium, neodynium, lithium), and the chemical industry (platinum group metals, cobalt and rare earth elements).

The sobering common aspect for all of these resources is, that available data suggests that their production has either peaked already or will peak within the next 50 years. Throughout history, the major part of the economy of the world´s nations has been driven directly or indirectly by access to and use of natural resources, and this still remains so. Our main findings are that the world is heading towards a restricted access to the key resources that are used by humanity today and these restrictions will have a profound impact on the world economies and life styles of future generations. The challenge is to accept this knowledge, and to find the necessary solutions and adaptions for the future while we still have time and possibility to so. History will judge how well we responded to current resource challenges.

1. INTRODUCTION

1.1 The Authors

1.1.1 Harald-Growing up in Norway

The reason why I am writing about natural resources has to do with my background and goes back to Norway, where I grew up. The subjects of sustainability and the environment were early amongst my interests. I spent many summers as a child with my grandfather, *Torleiv Rasmussen* (1895-1991), in the Norwegian Rondane mountains, Norway's first National Park. We would walk the mountains and talk about how nature worked and how everything was interdependent. My grandfather was an eager sports fisherman, and he was an excellent bird hunter. He also had a keen interest in the environmental impacts of industry on nature. In 1948-50, he moved the family company out of Oslo, Norway, to the city of Hamar, 110 km north of Oslo, to be able to expand the business. The family company is a precious metal refining and processing plant that uses many mechanical and chemical processes. As part of the design, the facility was fitted with a sewage treatment plant and a metal recovery plant for taking precious metals out of sewage, so that every dust particle of precious metal that ended up on the floor or in the plant wastewater could be recovered. It was the first sewage treatment plant in Norway (1948), based on American know-how and design, and there was no other of its kind in Norway for many years.

My grandfather, *Torleiv Rasmussen* was educated as a Goldsmith Master in Schwäbisch Gemünd in the province of Baden-Würtemberg in Germany, but he had a sense for engineering. He would often tell me "*Nothing is too difficult to learn! ….just try harder if it is difficult*". To learn how to design the precious metal recovery unit for wastewater from the plant, he ordered books from the United States and Germany on the subject, and taught himself how to design it. And, then he built it…

Precious metals like gold, silver and platinum play a prominent role in this text as examples. These metals are very valuable, and society keeps very good track of them. Much data is available on these metals. My family's company, K.A. Rasmussen is a precious metal company, and thus, I grew up learning about how to work, refine, and never lose these metals. Precious metals are very valuable, and thus, great care in their handling is taken. Therefore the sewage treatment plant I mentioned earlier, through the recovery of precious metals, more than paid for itself.

I started school when I was 7 years old, and I remember that my mother, *Elise* (1928-1996), gave me a book she had from her father (1888-1932, the chief engineer at Norsk Hydro), who died when she was quite young. It was about the oil fields of Texas, issued by Texaco in 1927. I think it was called "Texaco, a pictorial story." It was full of black and white photographs, and not much text, like Figure 1.1. I read the book before I knew English (I read it anyway), fascinated with the pictures of drilling towers, refineries, petrol stations and office buildings. My father, *Rolv* (1928-1995) had a subscription to Scientific American from 1963 onward, and it came every month to our home in Norway. I avidly read everything in each issue. I still do, it is a wonderful way to stay updated.

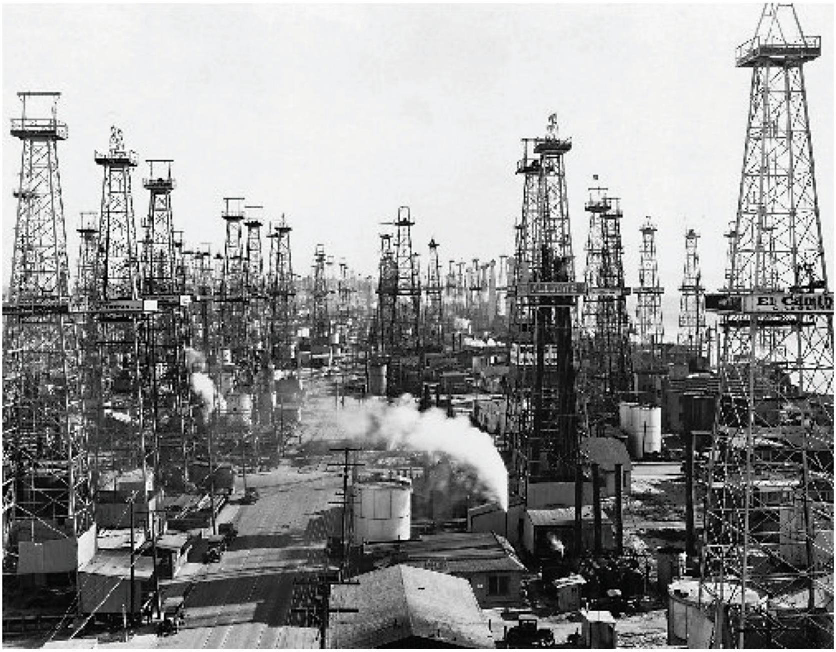


Figure 1.1 From the Texaco operations in Texas (about 1901).

Another defining moment for me personally was when the book *Limits to Growth* (Fig 1.2) by *Donella Meadows, Dennis Meadows, Jørgen Randers* and *Wilhelm Behrens*, came out in 1972. I was in my second year of gymnasium in Hamar, and I remember that I read the book twice just to be sure that I understood it and I experienced a great Ah-ha moment. I realised how everything is connected – what I learned in secondary school (I was in the natural sciences division) and from my grandfather, and how nothing should ever be lost in the precious metal business – everything resonated with the message of Limits to Growth. I realised there are limits to everything and that these limits are built into the fundamental foundations of our world. I have come back to that book and its follow-up books many times since (Meadows *et al.*, 1972, 1992, 2004; Randers 2012). What was outlined in there has become a part of my own research. The book received some scientific critique, but also detrimental political lobbying (Nørgård *et al.*, 2010). That is how slander and outright propaganda buried the important message in the book. Limits to Growth has, despite all the efforts to the contrary, stood the test of time and current data shows how the concept was spot on (Turner, 2012). As it now turns out, climate change is perhaps a small problem – the real challenge of today is the combination of conscious thought, human population and planetary limits. I am now a member of the Balaton Group, and get the pleasure of discussions with *Dennis Meadows'* aspects of Limits to Growth and on how we develop the next generation of models.

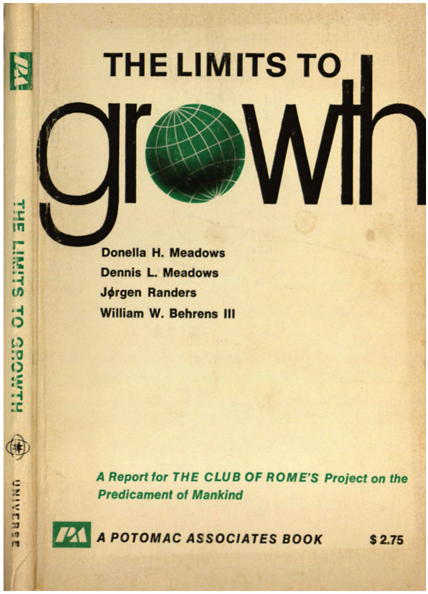


Figure 1.2 Book cover Limits to growth by Donella Meadows, Dennis Meadows, Jørgen Randers and Wilhelm Behrens.

1.1.2 Harald-Becoming a researcher

I went abroad to study Chemical Engineering at the ETH in Zürich, Switzerland and later for a PhD at Lund University in Southern Sweden. I ended up staying in Lund for 27 years. After completing my graduate education and starting my career in research, the environment, and sustainability of society came to be the pervasive themes of everything I worked on. Thus I came to spend time on subjects like: liming acid lakes, modelling acidification effects on soils and water, aquatic population dynamics in polluted lakes, sustainable forestry, predator-prey relationships, sustainable agriculture, chemical weathering components of silicate minerals as nutrients for trees and crops, business and economics systems dynamics, and modelling of large integrated and complex systems. Enginering and geochemistry was at the base of it all, but nothing is isolated. Other disciplines overlap but biogeochemistry is an important part of the bigger picture.

For engineers, the most important pathway to understanding a system's behaviour properly is to model it. This cannot be done without having a mental model as the basis for understanding. With a mental model, I mean a conceptual understanding in the mind. For this, systems analysis and systems dynamics are essential. *Richard Feynmann*, the brilliant American nuclear physicist, once wrote a book entitled "The Pleasure of Finding Things Out" (Feynman, 1999). I found the book very inspiring when I read it. Doing systems analysis on complex situations and problems and modelling them to create solutions, to me always becomes "the pleasure of finding things out." Thank you, *Mr. Feynman*! I have been asked several times about whether there are any limitations to this way of working, and after using it for 30 years, I have not found any yet.

In 1981, when I was travelling to the United States of America for the first time, I met two young Americans, *Douglas Britt* (Fig. 1.3) and *Jimmy Fraser*, working in a private consultancy in Reston, Virginia. I started to cooperate with them and in the process they became very good friends. They opened my eyes to a new world of thinking. I experienced together with them how to initiate a company the American way, starting with nothing but an idea and working your way up. I learned how we would search for clients with problems, and sell proposals on how to solve them. And we would win the proposals and do what we promised. I loved the American attitude of "everything is possible." We started many different companies, and we succeded in many endeavours, in environmental science, mainframe computer services, ecological restoration, geographical information services, environmental modelling, and restoration technologies. Finally the company moved on to space science and built systems for NASA for the life support for long distance space travel. On almost every Space Shuttle launched in the late 1980s and 1990s we had our cargo on the shuttle. We had a fantastic time, full of optimism working for the future. In the mid 1990s the American companies were sold and we moved on. My friends stayed there to pursue successfully their careers as businessmen, I went back into academia in Europe to continue work on biogeochemistry of terrestrial ecosystems, critical loads, modelling of biodiversity and sustainable societies, from sustainable food supply to the role of resources in the global economy, and as we will see, later also to business.

Source: NASA Image Exchange.

Figure 1.3 Douglas Britt.

In 1988, I was called in by the Swedish Environmental Protection Agency's research department, to participate in an effort referred to as "Critical loads for sulphur and nitrogen to mitigate acid rain." The effort resulted in the first research-based (actually evidence based) environmental policy in Europe. The Agency knew from earlier projects, which I had done with them that I was building environmental effects models, and that I was willing to develop new types of models. The kick-off event that mattered was the 1988 Skokloster Critical Loads Workshop

(Nilsson, 1988), where we went from traditional environmental problem-descriptions to formulate action plans for how to solve the air pollution problems. Scientists from all major countries in Europe participated, including Eastern Europe. We had no defined acid rain mitigation plans before that meeting in Sweden, but then a strategy was drawn up internationally (and nationally for Sweden) and scientists enlisted to work on it.

The research director at the Swedish Environmental Protection Agency at the time, *Dr. Jan Nilsson*, had the idea that Sweden would be one of the lead countries in the fight against acid rain and associated air pollution and that we needed to tackle the problem at the root cause, to reduce or eliminate the sulphur and nitrogen emissions. Liming lakes as I had done in the past was unsatisfactory as it was an "end-of-pipe" solution. In his work for the environment, *Jan Nilsson* always had a clear vision, a strategy and a plan. He told me:

"*We have three arenas we have to win to prevail in this battle! The battle is for the future environmental quality of Europe. We need to win the scientific arena, we need to win the media arena, and we need to win on the political arena. If we can make sure to win the scientific arena soundly, and overwhelm in the media arena, I am certain we will win the political arena as well.*"

He had developed a vision, a strategy and a plan for how to do this work. We were up against a substantial British and Central European industrial lobby, and the struggle was long and difficult. But as we now know, we (Swedish Ministry of the Environment, the Swedish Environmental Protection Agency, The Norwegian Environmental Authority, the Nordic Council, the Swedish Universities and research institutes) prevailed, we won and it worked! I was a student in Zürich, Switzerland, when the "Alpenblick" disappeared in smog in 1978, and experienced in a visit in 1998 how the Alps had re-emerged, again to become visible.

I was an ecosystems effects modeller and a systems analyst, and *Jan Nilsson* determined that I was to be one of the scientists in the team that should win the science arena. I just loved the work, the challenges, and what appeared to be unsolvable problems that we set about to solve. I had to work very hard and built up a large scientific network in those years to be able to win that arena. I was sometimes alone on the road, but most of the time with my PhD students and my European colleagues. *Jan Nilsson* urged me on, and funded my activity, the research, the travels, and the meetings. On behalf of Sweden, we formed unofficial coalitions with other European smaller countries, and this greatly helped the effort of creating a common understanding in Europe on these issues. The science coalitions I was able to build, were matched by *Jan Nilsson* and his colleagues on the project officer level throughout many European Environmental Agencies in the same countries as we were working in. My research group developed the computer modelling tools for determining the critical loads for Europe. We did it as an open source code and gave our biogeochemical models (SMB, PROFILE, SAFE) to everyone that wanted to use them (Sverdrup and Warfvinge, 1988a,b, 1995b; Sverdrup *et al.*, 1998, 2006; Sverdrup, 1990). The scientific tool development was coordinated with the Swedish Environmental Protection Agency, so that we targeted the models at the relevant issues, and provided assessments connected with the relevant policy proposals. Eventually the models, methods and policy development processes were adopted in 27 different European countries. I travelled to all 27 of them, established critical loads mapping teams and ecosystem modelling teams when they were not already in place, made sure they had the models running, taught them how to use them, and ensured that they delivered their results on time. My team reported progress and results back to *Jan Nilsson* in Sweden at the Environmental Protection Agency in Stockholm, keeping them well informed on the situation in every country. It meant visiting Parliamentary Committees, Environmental Agencies and Ministries to explain what critical loads mean, how they related to science and geosciences in particular, and why they were very good for both the national environment, the economy and industry in Europe.

The scientific teams, that *Jan Nilsson* had working for him, had frequent strategy meetings with his policy development team and the Swedish Ministerial team (*Dr. Lars Lindau* and *Lars Björkbom* to mention some). They did the actual international environmental negotiations, with people from the Swedish Environmental Agency and the Ministry of the Environment, relying on the scientists in the background, sometimes in the back room. The Nordic Council of Ministers was also brought in on the arena, to give more Nordic science attention, feed facts to the media and build political clout backed by science. A solid interface between policy development and science was built especially in Sweden, but also in the other Nordic countries. The major Swedish Universities were heavily involved (Lund, Uppsala, Gøteborg and the main environmental institutes (IVL[1], NIVA[2]). Different policy options were discussed, we tried out the ramifications in chains of models linking the source (combustion of fossil fuels and smelting sulphide ores), through the skies with the air down to lakes and forests in the Swiss Alps, the German Black Forest, Norwegian rivers and lakes or Swedish lakes, streams and forests. The models were tested out at home to pre-assess which policy option would work. *Jan Nilsson* and his negotiating team would take everything with them into the United Nations Economic Commission for Europe negotiations at Geneva. A special cooperation was started with Swiss Ministry of the Environment (*Beat Achermann, Beat Rihm, Daniel Kurz*). Since I spoke Swiss German fluently, that work flowed smoothly, leading also to a collaboration that lasted 20 years on the policy development level and coordinated work with European and National media. The Critical Loads UN/ECE-LRTAP[3] protocols of Oslo 1990, 1994, Århus 1998 and Gøteborg 1999 were the first examples of goal-oriented

1. Swedish Institute of Environmental Research, Gøteborg, Sweden. A key actor was their research director *Peringe Grennfelt*. He operated closely with research director Jan Nilsson at the Swedish Environmental Protection Agency on the International arena.
2. Norsk Institutt for Vannforskning, Oslo, Norway, where *Drs. Arne Henriksen, Richard Wright* and *Harald Dovland* played major roles.
3. United Nations Economic Comission for Europe – Long Range Transboundary Air Pollution

sustainability legislation[4,5,6,7]. The protocols were signed in the indicated years, and then ratified and implemented by the signatory countries in the years that followed; this often took 3-7 years or more.

For the first years, 1987-1990, it was only my colleague *Per Warfvinge* and I in my research group, but after 1990, the work expanded and we needed to have a larger workforce to do all the tasks we were given. The international work on environmental science support to the authorities also was the beginning of building a whole research group that would grow to be around 12 people for many years. In my group I had started with systems analysis and systems dynamics as a tool for bridging science domain boundaries. We invented what we called "causal link charts", only to later discover that we did not invent it, the systems dynamics group at MIT in Boston had done it before us! The natural continuity of that was to broaden the competences of my research group from only two engineers in a chemical engineering department. I realised that if we wanted to solve problems, we needed to pick the required knowledge from wherever it was found, ignoring that some of the knowledge would come from scientific arenas other reserachers would think they "owned." Problems know no boundaries and most academic boundaries set up in research are social constructs. In many scientific arenas we succeeded in finding very good trans-disciplinary cooperations (Sverdrup, 1999, 2002; Sverdrup and Svensson, 2003; Sverdrup and Guardans, 2008).

I enjoyed the company of many devoted and clever PhD students and assistants from many disciplines such as geology (*Anna-Karin Modin-Edman, Hördur Haraldsson*), geochemistry (*Johan Holmqvist*), theoretical ecology (*Mats Svensson*), chemical engineering (*Mattias Alveteg, Charlotta Walse, Liisa Martinsson, Per Warfvinge, Anja Danielsson, Andreas Barkman*), geography (*Cecilia Akselsson*), computer science (*Salim Belyazid*), plant ecology (*Gunnar Thelin, Ingrid Stjernquist*), chemistry, health and nutrition (*Ingegerd Rosborg*), environmental engineering and climate change (*Deniz Koca*). I worked closely with a very good friend, *Prof. Bengt Nihlgård*, also at Lund University, the best plant ecologist I know of on any continent, and his excellent research team (*Ingrid Stjernquist, Ulrika Rosengren* among many others). In addition came visiting scholars and people we cooperated very closely with from soil science, geology, geochemistry, agronomy, plant ecology, limnology, economics, social science, historical linguists, political science, forestry (*Prof. Kaj Rosen*, at the Agricultural University at Uppsala paved the way into the best soils and forestry databases) and policy development. Our group (then the Biogeochemistry Group at Chemical Engineering in Lund University) realised that trans-disciplinary research is great fun to do, and it is always full of surprises. Where others thought from a monodisciplinary point of view that no solution would be possible, we could find them with systems thinking and

4. http://www.unece.org/env/lrtap/fsulf_h1.html
5. http://www.unece.org/env/lrtap/hm_h1.html
6. http://www.unece.org/env/lrtap/multi_h1.html
7. http://www.unece.org/env/lrtap/status/lrtap_s.html

trans-disciplinarity! I think we could safely say that this also applies to geochemists that operate in trans-disciplinary settings, the geochemistry they do is often relevant to society and definitely fun to do.

In 1990-1992, I made some pilot studies on critical loads for acidic pollution in the United States of America, notably in Maryland. We mapped the whole state and made critical loads mapping and policy strategy development and effects assessments for both streams and soils (Sverdrup *et al.,* 1992, 1996). In the estimation process for critical loads, the weathering rate is needed. Then we made the first soil weathering and catchment weathering map for the Maryland state, based on calculations using the PROFILE model. The work with air pollution mitigation and the importance of robust weathering rates for critical loads and for forest sustainability, caused Sweden to fund the development of the mechanistic soil weathering rate model PROFILE. It was applied to map the weathering rate of soils across Europe; it does *a priori* soil weathering rates and does not require model calibration. It is field verified. It is a good example of how a transdiscipinary challenge outside of geochemistry created a major scientific development in geochemistry. The Maryland weathering map we published went under the radar of most American geoscientists at the time, and they only discovered that weathering map decades later (see Sverdrup *et al.,* 1992, 1996). However, we were far before our time, and the American government agencies were not ready for dealing with acid rain the European way using critical loads at that time. Since 2012, the interest and the need is there in America, the European success is obvious, and we are now participating in applying critical loads as an environmental method for the United States (McDonnel *et al.*, 2014; Phelan *et al.*, 2014). Critical loads and optimised reductions in sulphur and nitrogen emissions will be undertaken in the United States in the near future, with great benefit to industry and the environment.

The European air pollution work, "the sulphur wars" as we referred to it, was a life-changing experience for us who were deeply involved, and it gave me very many very good contacts and friends throughout Europe, among researchers and among policy makers. The working relationship was very close with people in Switzerland (*Beat Achermann, Dani Kurz*), Germany (*Heinz Gregor*) and the Netherlands (*Jean Paul Hettelingh* at the RIVM, *Wim de Vries, Hans Kros* and *Gerdt Jan Reinds* at ALTERRA), and former research competitors became allies in the struggle for the European environment. I became known for being willing to solve problems of any kind that could be modelled, to use models for science-based policy analysis, and that I never said anything was impossible.

I met the Rector (Vice Chancellor or President), *Prof. Boel Flodgren*, of Lund University on the plane to Stockholm in 1995. In our discussions on the plane I painted up a vision to create a trans-disciplinary master's programme focused on Environmental Science at Lund University, and what it would entail if I was given a free hand to design something different. I would shape it around systems thinking and solutions for creating sustainable world, using teacher-teams from many different sciences. The next morning I was called to the Rector´s office, and she told me to start at once, with programme start-up in 1996. I gathered up clever colleagues such as *Ingegerd Ehn, Marianne Sillen, Karin Bäckstrand, Mats Svensson* and many more at Lund University in the initial core team. It became LUMES[8] (Lund University Master of Environmental Science), and the first thing we did was to run a test version of the programme on ourselves. It had environment in the name, even if it at once was clear to us that environmental science is just a special case of sustainability, which is what it it becomes once we apply it to the whole world and generalise it. *Mats* and I designed up the first systems analysis and systems dynamics courses for the programme, the first in Lund University. We admitted students for the programme from all continents, from many ethnic, cultural and academic backgrounds, and welded them into effective student teams. We learned that if you make trans-disciplinary teacher-teams, selecting very good university teachers, who are good at cooperating and trust them to do a good job, creative dynamics is set in motion. That was for me a major eye-opener to see how creativity and teaching innovation could take off. How systems thinking can bridge cultural differences and unify thinking towards solving problems and finding solutions. Sustainability is the world's largest puzzle, and all must contribute for us to succeed. The world of finite resources and the feed-back between the social sphere and natural world became important, when we looked at all the issues coming up. The LUMES programme was focused on understanding problems of sustainability, ability to analyse them and develop solutions. The students were encouraged to go home to their countries and be sustainability change makers. They understood that we could send no solutions back with them, but that they would be able to develop what would be needed after graduating from LUMES. What is described in this *Perspective*, goes ideologically back to that moment when what we had learned was put into a masters degree programme of how to teach young people to to understand, conceptualise and solve problems. We shaped the future of those students, and in turn they changed the way we were thinking as teachers and researchers.

Throughout my carreer, I have been open to changing direction by absorbing information from neighbouring disciplines into my engineering basis and using it to find things out. I started early with geochemistry and limnology working with lake liming and calcite dissolution kinetics (1981-1990) and moved on to build fish population and phophorus dynamics models (1986-1995), for lake management as well as what are considered to be the best awailable soil and water acidification models (1987-present). We pioneered the modelling of soil acidification and how to undertake mitigation on many levels (1988-2014), building all the key models used for critical loads and and for adaptive policy development. As a natural evolution, it moved on to sustainability in a much more integrated way. Over time, I found myself working in forestry science (1996-2010) based on biogeochemistry and biology, and we developed a long-term-plan for sustainable forestry management in Sweden, ranging from physical forest management, integrated soils management, strategic planning, and economics of sustainability to proposals for policy changes in Sweden.

8. http://www.lumes.lu.se/

I worked for a long time on geochemical laboratory experimentation and geochemical modelling (1985-1995), and created mechanistic weathering rate models that are built on fundamental chemistry and physics under field conditions (1983-1992, 1996-2014). Their performance remains without parallel to the present day. Some of the first versions of the geochemistry models were made 1988, and were refined in several steps in the years after. They continue to pass rigorous field tests and are the only available generic tools for calculating weathering rates for soils based on site properties, without calibration against an already known result.

In retrospect, I have changed my scientific emphasis about every 5 years, then moving into a new field, where I work my way to the frontier, building up a research team, each time bringing a steadily broadened experience with us. More recently, I moved into full sustainability science (2000-present), linking social systems, economic systems, human behaviour and the physical world of resources in human society. Sustainability is the focus of this *Perspective*, and the prehistory was necessary to get here. Not only as a description of my involvement in geochemistry, but also my recent intimate involvement with metallurgy, and metal industry, and becoming an industrial leader of large companies. All these experiences were an important part of being able to analyse and propose how to solve resource-related problems and issues.

1.1.3 Harald – On to business

In 2007, time had come to move over to industry. The family precious metal business had struggled for years and needed somebody new to take its lead and give it a new start. I moved back to Hamar, Norway, taking up the challenges of the precious metals factory. Studying chemical engineering and my academic research in all those different topics had prepared me for this challenge. I redirected the company towards metal recycling and refining, and the business soon started to boom. It was noticed that the company grew substantially and I was named Norwegian Entrepreneur of the Year in 2012 and also awarded the title of “Best business leader in Norway” the same year.

During my time in the industry, I kept up with current research, continued to publish scientific papers and remained active in several research fields. I started the work on modelling supply of metals, first with the core metals for the business; gold and silver. This was not only academic research, it was applied systems thinking science and very beneficial for the business also. As I was leading a precious metal business, I was in a prime location for having access to information on gold and silver, way beyond what any researcher in academia would ever have. At the end of 2013 I left my leadership position in the family business, but have continued to, from time to time, to start new innovative companies[9].

9. Norse Metal Industries, a aluminium-bronze and specialty alloy company located at Elverum, Norway, or Sagatoon Films in Hamar, Norway, a company for full length computer animated films for youth and children.

1.1.4 Harald – Back to the grand cause

In 2014, I returned to academia and research, this time to the University of Iceland, as a professor of Industrial Engineering. Once back in the university world, my renewed focus is on the challenges of resource depletion and sustainability, how these things are coupled to the economy and the prosperity of nations. Also in focus for me is the fact that in spite of the imminent problems, almost no policy makers in any country are willing to lead the societal changes needed. I started working on this with my colleagues *Deniz Koca* and *Vala*, and we got up to speed fast. When we got awarded a new project in 2013 by the German Environmental Protection Agency at Berlin (SIMRESS), resource sustainability assessment modelling could take off. And, there is a lot to do…

1.1.5 Vala – the formative years

Sciences were always my favourite subjects at school, starting with maths in primary school, physics in middle school and chemistry in gymnasium. After spending a summer as a tour guide in the highlands of Iceland my chosen subject at University was geology with emphasis on geochemistry and petrology. I loved the challenges of these varied subjects, particularly the thermodynamics. After consulting with *Stefán Arnórsson*, my mentor from my undergraduate years in Iceland, the geochemistry of geothermal systems was what I chose for my PhD research at Northwestern University, Evanston, Illinois, USA. A part of my thesis was field based on the geothermal system at Svartsengi SW Iceland (the current location of the well known Blue Lagoon) relating the composition of the fluid with that of the altered rock using thermodynamics. This was the first study that demonstrated that fluids in modern geothermal systems are at equilibrium with their host fluids. But most of my PhD research was spent on dissolving minerals at high temperature and pressure in the laboratory. Solubility studies included that of corundum (Al_2O_3) and quartz (SiO_2), and how aluminium and silica moved in hydrothermal solutions (Ragnarsdottir and Walther, 1983, 1985; Ragnarsdottir *et al.*, 1984). The experimental work I learned from my supervisor *John Walther* at Northwestern, ended up being the focus of my work until the late 1990s.

1.1.6 Vala´s early career in industry

After finishing graduate school I had a short stint working for a consulting firm in Chicago in the mid 1980s. The focus of our work was evaluating the fate and transport of contaminants from industrial sites, generally referred to as Superfund Sites, due to priority funding given by the US Congress to clean up the environment. Again using thermodynamics we puzzled with the aqueous mobility of, for example, chromium from a logging operation, where chromium had been used as a wood preservative. During this time I not only learnt about detrimental environmental pollution, I also worked closely with toxicologists to evaluate the impact on health of the local population. But project management did not excite me; I wanted to do research and was lucky to be invited to the laboratory of *Claude Allègre* in Paris for a year, where I learned isotope geochemistry.

When back at Northwestern I obtained a grant from the Department of Energy in the US to investigate the dissolution kinetics of zeolites. I was lucky to learn how to set up fluidised bed reactors from *John Walther* and *Susan Carroll* and set forth to solve the puzzle of zeolite stability in a future possible nuclear waste repository at Yucca Mountain, Nevada. When I moved to the University of Bristol in the late 1980s my first PhD student, *Liz Bailey*, worked on the solubility of uraninite (UO_2) and thorianite (ThO_2). I had fun with my post-doc *Eva Valsami-Jones* studying the sorption of rare earth elements (REE) to apatite, only to discover in collaboration with *Andrew Putnis* in Münster that what was really happening was precipitation of REE phosphate, causing the dissolution of the calcium apatite (Valsami-Jones *et al.*, 1998). The REE thus acted as an apatite dissolution pump! In the years that followed I started working with *Eric Oelkers* and *David Sherman* on the structure and coordination of metals in high temperature aqueous solutions – including yttrium, antimony, tin and gold. To solve that puzzle we spent many a day and night at the Daresbury Synchrotron experimental facility in NW England, the armpit of the UK, as *Eric* "lovingly" called it. With PhD students we established the structure and behaviour of various sorbed metal complexes to mineral surfaces. The metals included uranium, cadmium, mercury, and gold. I also dipped into issues related to backfill materials for radioactive waste disposal, cement chemistry and stability, the link between soil trace elements and disease development (medical geology) with my friends *Jane Plant* at Imperial College, and the stability of pesticides in the natural environment. These studies were interdisciplinary involving amongst others biochemists, vets, medical doctors in addition to geochemists, of course. All these experiences were a firm foundation for the sustainability assessment focused on resources presented here, because sustainability science is truly trans-disciplinary.

1.1.7 A wakeup call

In the year 2000 I met the late *Richard St George* who was then the Director of the Schumacher Society. The society was founded in the memory of *E.F. Schumacher*, a German Economist, who lived in the UK. He is best known for writing *Small is Beautiful* (Schumacher, 1973) – a book that is hailed as the foundation of sustainability thinking in the 1970s. *Richard* and I discovered that we were both working on environmentally related issues, but I was working on environmental pollutants at the atomic scale whereas he was working on sustainability at the planetary scale. I felt that I had missed the big picture. Through our discussions I concluded that what I was doing was pretty worthless for the future of both mankind and the Earth. In retrospect I know that this was somewhat an overreaction. But I decided to switch my focus and start to work at a scale that included the whole Earth for the good of humanity and nature. It helped that around this time, I was invited by the United Nations Environment Programme on a Scientific Mission to Kosovo, to investigate the health and environmental risk due to the use of depleted uranium ammunition during the Balkan conflict. I was the only geochemist on the mission, chosen due to a book chapter that I had just completed with *Laurent Charlet*, Grenoble, on uranium biogeochemical behaviour in the environment. I then saw that I could contribute to the good of humans and nature. But the issue for me was, what could a geochemist really contribute to sustainability science, given that we know most of the problems, but have not found a way to change policies or our behaviour?

I found my sustainability niche first within societal sustainability action science, working with the people of Bristol through "sustainability café" discussions with colleagues, students and the public. These cafes became a lively part of city life and ended up having city government officers and politicians taking part. We discussed how a sustainable city might look like. We used visioning and back-casting to find steps from the sustainable future to the present. I went from being an unknown geochemistry professor in the city to being well-known by the public and policymakers alike. We started an internet discussion group which later was developed by one of my researchers, *Matt Fortnam*, into Ecojam (ecojambristol.org) that to this day links green thinkers in the city. It was both exciting and interesting to go from being a professor in geochemistry to being a facilitator and change maker in the sustainability realm. The City of Bristol applied to become the Green Capital of Europe in 2008, based largely on the vision from the cafes. After being short-listed a few times, the city is the Green Capital of Europe in 2015. This was the beginning of me thinking of science and science-based policy development.

1.1.8 The importance of resources

When working on city sustainability, several types of natural resources important for society caught my attention: water, soil, fossil fuels, metals and phosphorus. I decided to put my geochemistry expertise into soil science. Inspired by the definition of the Earth´s Critical Zone (the zone from treetop to the bottom of groundwater) by US colleagues in 2001, the Science special issue on soils in June 2004, and the call for Critical Zone research by my friend *Susan Brantley* at Penn State, I first joined forces with *Steve Banwart* at Sheffield and *Liane G. Benning* in Leeds to study the impact of fungi in weathering minerals. I then pulled together the disparate soil research community in the EU and colleagues from China and the US to develop research needs for soils as a system within the Critical Zone. This lead to a large EU funded project lead by *Steven Banwart*, where soil observatories were set up to integrate Critical Zone biogeochemical processes from plot scale to regional scale through modelling and up-scaling (www.soil-trec.eu). We also developed soil sustainability indicators and a framework for soil ecosystem services. Our work thus set a new vision for soil as an important resource and the results are being used by the European Commission to promote soil protection policies.

The year 2008 was important for furthering my development as a sustainability scientist. Then I was given the opportunity to introduce the subject of natural resource availability both orally and in writing. At the Goldschmidt Conference in Vancouver *Dominique Weis* invited me give a plenary lecture on

The role of geochemists in the era of peak everything – and subsequently I was asked to write a Commentary for Nature Geoscience on Rare metals getting rarer, based on Business As Usual calculations (BAU).

In 2009, I started working with *Harald Sverdrup* on resources, because I realised that Business-As-Usual resource burn-off calculations were not sophisticated enough and systems dynamics modelling was needed, so that recycling of resources and population influence could be included in the analysis. We had known each other long before that, but now serious cooperation started. Sustainability moved to become the main theme through everything we did together. We first tackled phosphorus and presented our findings using systems dynamics models for phosphorus production at the Geochemistry of the Earth´s Surface conference in Boulder in 2011 (Ragnarsdottir *et al.*, 2011; Sverdrup and Ragnarsdottir, 2011). I was then invited to write a book chapter, which I wrote with *Harald* and his colleague *Dr. Deniz Koca* and there we presented various scenarios for over 40 natural resources (Ragnarsdottir *et al.*, 2012) and came to the conclusion that unless recycling increased dramatically and population growth was curbed, most of these resources would become scarce this century. The natural resource work has since continued, with detailed systems analysis and systems dynamics modelling, and some of the results are presented in this *Perspective*. On a more personal front, *Harald*´s frequent visits to Iceland lead to us learning to know each other more personally and we married on New Years Eve in 2011.

1.1.9 A new community

Many of my colleagues have told me that they miss me coming only seldomly to geochemistry conferences. It is not that I would not like to go. My students and co-workers do, but there are only so many conferences and workshops each year where you can attend. Instead I have chosen to further my sustainability thinking through sustainability related groups that include the Schumacher Society, mentioned above, in addition to the Balaton Group and more recently the Club of Rome, all important sustainability think-tanks. The Schumacher Society lead environmental thinking in the UK from the 1970s and I was fortunate to work closely with them from 2000-2008, and their knowledge and leadership was very important in developing my thinking. The Balaton Group was founded by *Dennis Meadows* and *Donella Meadows* in 1982, the very authors of *Limits to Growth*. I came to meet *Dennis* for the first time in September 2008 and this meeting was an important inspiration to continue to work on resources. Our scientific contributions in this field lead to me being invited to become a member the Club of Rome in 2014, the club that commissioned the *Limits to Growth* study in the early 1970s.

1.1.10 Science policy interface

My sustainability science work has lead to me being invited to be involved in policy work at various levels. In Iceland I have advised government ministers, parliamentarians and the city mayor of Reykjavik on issues relating to sustainability and the environment. From 2012-2014 I advised the government of Bhutan on how to integrate their Gross National Happiness (GNH) indicator into the UN Sustainable Development Goals (SDGs – United Nations, 2014) being set for 2015-2030 (NDP Steering Committee, 2013; Ragnarsdottir *et al.*, 2014b). This work lead me and others to thinking about new development indicators beyond GDP (Gross Domestic Product) (Costanza *et al.*, 2013, 2014; Ragnarsdottir *et al.*, 2014a) and the establishment of Alliance for Sustainability and Prosperity. I have also been involved in policy work relating to the new economy in the UK (Green Econonomy Calition) and Germany (Federal Environment Ministry of Germany – UBA), for a research council in Sweden (MISTRA), and a green investment group in China (DeTao Institute of Green Investment). Currently I am working with the European Academies Science Advisory Council on developing advice for the EU on the Circular economy and with the Club of Rome on a Strategy for economic system change. And the latest research grant that I have been awarded with *Harald* by the EU is to train 12 PhD students in Adaptation to a new economic reality with colleagues in Stockholm and Clermont-Ferrand, France.

When I started working as a geochemist in the 1970s I never dreamt of having an influence on world development policies, or the green new economy! My journey from geochemistry to world development has been very exciting. Not only that. I am now considered an expert in sustainability science, a field that did not exist when I was a student. I am never happier than when I learn something new and all my life I have striven to learn something new every day.

1.1.11 A new story is needed

Our current development story has lead to environmental destruction, resource depletion and inequality. Inequality is on the rise within nations (Wilkinson and Pickett, 2011) and between nations (de Vogli, 2013). Eighty people own as much wealth as the poorer half of humanity, or 3.6 billion people (Oxfam, 2014). Now sustainability scientists of all genres must link together with governments and the world´s population to develop a new story that works both for the Earth and 100 % of humanity. I am proud to be a part of that new story.

1.2 Natural Resources in a Planetary Perspective

1.2.1 Introduction

The ecological footprint[10] is a measure of human demand on the Earth´s ecosystems. The footprint is a standardised measure of demand for natural capital that is contrasted with Earth´s ecological capacity to regenerate (Wackernagel and

10. http://ecologicalfootprint.com/

Rees, 1996). It represents the amount of biologically productive land and sea area necessary to supply the resources the human population consumes and to assimilate associated waste. Globally we are now having an impact corresponding to an ecological footprint that would require more than one and a half Earths to sustain (WWF, 2014). The consequence of careless exploitation and consumption of our Earth´s resources has lead to global warming that is likely to result in 2 m sealevel rise this century (Jevrejeva *et al.*, 2014) – putting most coastal cities on Earth under water. We have come to understand that the world is not only running into environmental limits but also into resource and energy limits. In this world the wealth is very unevenly distributed within and between nations (Kennedy, 1987; Wilkinson and Pickett, 2011; de Vogli, 2013; Piketty, 2014). This has lead to a plethora of societal problems and a poor quality of life for people across the world. These are very important sustainability issues. But in this *Perspective* we focus on natural resources and their imminent availability to society. Geochemistry is central to where we find resources and reserves, how we find them, how we extract them and why they are there. At the same time, to be socially relevant, these essential parts of geochemistry and geology must be assimilated with other knowledge such as that found in economics, engineering, sociology, political science and policy development. Geochemistry in integration with other sciences is thus very important for society for participating in solving sustainability problems. Natural scientists and engineers have one thing in common; they do know that you cannot negotiate with mass balance or thermodynamic principles, and if you try, huge trouble will follow.

The importance of resources is close to our hearts, and forms a part of the grand puzzle of Earth's sustainability. Geosciences offer an important expertise to this field; geological knowledge is needed to understand that on one Earth with a large population and with slow biogeochemical processes relative to a human life- span, there are resource limits.

1.2.2 Scope

In this *Perspective* we focus on resources that are related to geological processes and deposits including:

1. Resources required for food production; notably phosphorus from rocks and soils. These come from geological endowments with insignificant to zero regeneration rates.
2. Energy resources; oil, gas, coal, peat, low grade carbon fuel sources, nuclear fuels including thorium and uranium; these come from geological sources with insignificant to no regeneration rates.
3. Materials required for infrastructure, such as metals, sand, gravel, and stone, these come from geological sources with insignificant to no regeneration rates. Cement relies on carbonate and clay containing rocks, as well as energy from oil and coal.

4. Soils have a very slow regeneration rate; they are sensitive to human management that leads to degradation of its quality and to physical erosion. At present Business As Usual, the soil erosion rates are from 10-1,000 times greater than the regeneration rate (Brantley *et al.*, 2007), leading to a steady net loss of soils. Soil degradation is closely linked to food security.

We have not included renewable resources such as fish, biodiversity, and forests for the sake of space. However, these resources are only renewable as long as they are carefully managed – if not, they will be finite resources. Many forests and fish supplies are currently being consumed with limited understanding for the long-term outlook (Marchak, 1995), and thus every day the recovery potential from these resources decreases, for example:

1. Forests can yield energy from burning wood, and structural materials such as building materials and paper products. Forest have a large regeneration capacity, but are easily destroyed by overexploitation and incompetent management. Forests live off dissolved solids from soils and nutrients provided by the biogeochemical process of the weathering of the underlying rocks and soil minerals. Thus, sustainable forestry has a strong geochemical perspective. Sustainable forestry is well researched, and understood. It can easily fill a book on its own; *Harald* has written forestry books, and interested readers are asked to consult these (*e.g.,* Sverdrup and Stjernquist, 2002; Sverdrup *et al.*, 2005). Sustainable forestry is partly or fully practised in some parts of the world (for example Sweden), however, in many regions forestry is poorly managed (for example Brazil or Indonesia) to the extent that we are perhaps irreversibly destroying our landscapes (Marchak, 1995). The shortcomings in forest management are not lack of knowledge, money or tehnology, but derive from lack of will because greed and profits come first. This field is outside the scope of this study, and is not further addressed here.
2. Fishing in the global oceans has lead to the decline of over 80 % of all fish species (FAO, 2010, 2011): 17 % are overexploited, 52 % are fully exploited and 7 % are depleted. Only 3 % are underexploited and only 1 % are recovering from depletion (Lövin, 2007). There is a huge need for sustainable fishery policies, but is not the scope of this *Prespective*.
3. Renewable energy has several components:
   a. Hydropower is a long-term sustainable energy source when designed and managed properly. The amount of energy that can be produced this way is large, and the need for finite resources like metals are minimal. However, the supply of water in many mountaineous areas of the world, depends on glacial melting. Global warming is likely to change this supply in many places, including the Himalayas.

b. Harvesting of solar heat is important, but has a narrow geochemical perspective so is not discussed here in detail. It can use passive systems, and needs very little resources if designed for that objective.

c. Harvesting of solar energy with photovoltaic technology is dependent on certain metals and elements being available and will be discussed from this perspective. The energy collected is renewable, but the materials in the technology are not. Thus, we refer to this as semi-renewable energy.

d. Biofuels are important and may be seen as an output from ecosystems like forests. Forests are in many aspects the best source of wood bioenergy, which when used reasonably, is sustainable in the long-term and has a reasonable energy return on investment (EROI). This is considered below when discussing fossil enegy dependence. Biofuel production may even net sequester CO_2 if it is done correctly (Sverdrup and Stjernquist, 2002).

These resources are under certain conditions renewable, even if many are unsustainably exploited today. A re-newable resource that is mined implies that the extraction rate widely exeeds the regeneration rate.

Figure 1.4 **(left)** The snake goddess of Crete, possibly an ancestor Goddess to Athena. Statue from Knossos Museum, Crete, Greece. **(right)** Picture by Gabriel Dante Rosetti, Cassandra's prophecy of impending disaster is spoken but not heeded.

Systems thinking and systems analysis, a short primer

One of the basic methods used to bind knowledge from any field into whole connected systems is called systems analysis. Since this is central to the topics discussed here we will take some time to explain how causal loop diagrams, the basis for systems analysis, work. Using systems analysis, we create the construction drawings for computer simulations models, which are referred to as systems dynamics models. As the reader will soon see, we use causal loop diagrams as defined by Senge (1990), Senge *et al.* (2008), Sterman (2000), Sverdrup and Svensson (2002, 2004), and Haraldsson and Sverdrup (2004) throughout this *Perspective* when we want to explain and show complex systems. The problem is analysed using systems analysis methods, and clarified using causal loop diagrams. The main tool is called the causal loop diagram. Imagine we have a CAUSE that gives an EFFECT. It makes a basic causal loop diagram (Fig. 1.5):

The diagram in Figure 1.5 shows that the CAUSE creates the EFFECT. The plus (+) on the arrow says that the more cause we have, the more effect we get. It is not sufficient that CAUSE and EFFECT are correlated, there must be a real casualisation. After drawing an arrow from CAUSE to EFFECT we ask: does EFFECT have any feedback on CAUSE? If it does, we need to draw another arrow, from EFFECT to CAUSE. If more EFFECT gives more CAUSE, we mark the line with (+), if it is less it will be a (-).

When this is done, we ask again, is there something else that is affected? Normally there is an effect on something else. And then we draw an arrow from CAUSE to SOMETHING ELSE, naming it what it really is (Fig. 1.6a) and is an extension of Figure 1.5 shown above.

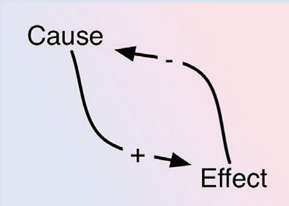


Figure 1.5 A very simple causal loop diagram. This will give a non-linear response.

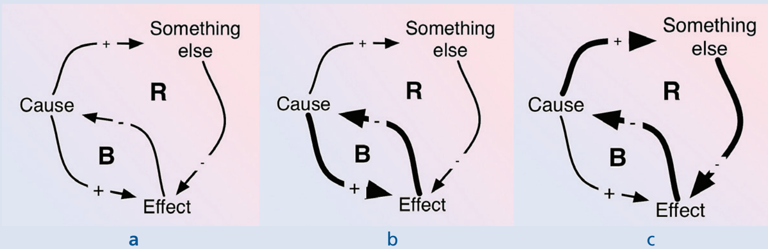


Figure 1.6 A complex causal loop diagram. This will give a non-linear response and sometimes oscillations. Most natural systems look like this or multiple versions of it.

And then we ask more or less and put the (+) or (-) signs on the arrow. And if SOMETHING ELSE has any effect on the EFFECT parameter, it could be as shown in the figure above. In the Causal Loop Diagram (CLD) we have two closed loops, one marked with B and one other marked with R.

If we follow the B loop (Fig. 1.6b), starting at CAUSE, then if it has an uneven number of (-) signs, an increase in CAUSE will come back and cause less increase in CAUSE (CAUSE gives more EFFECT, more EFFECT gives more CAUSE). We call this a Balancing Loop (B). For the other loop, an increase in CAUSE will cause an increase in EFFECT, but and increase in EFFECT will cause a decrease in CAUSE.

We may follow the R loop in similar fashion (Fig. 1.6c). More CAUSE gives more SOMETHING ELSE, more SOMETHING ELSE gives less EFFECT, and less EFFECT gives more CAUSE. An increase comes back as an increase, and is a Reinforcing Loop (R). You can find this explained in detail for larger systems in books like Senge (1990), Sterman (2000), Haraldsson and Sverdrup (2004), Sverdrup *et al.* (2013a).

We also use flow charts as a complementary tool to causal loop diagrams. Flow charts are what one could call “plumbing diagrams” of a system. They show how things flow, from where to where. Thus, a simple flowchart for iron would look like this:

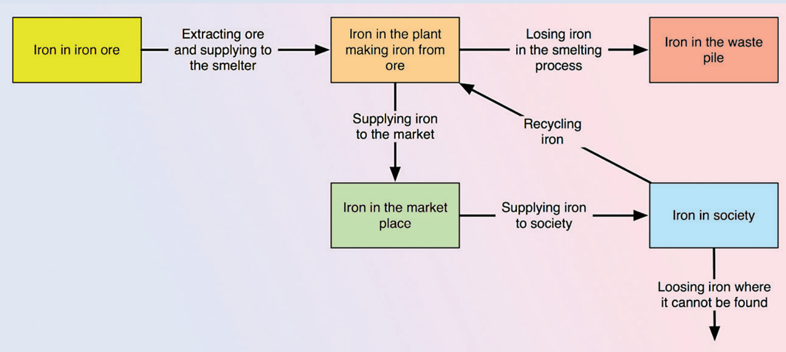


Figure 1.7 Example of a simple flow chart for iron in society.

Iron is stored in each box in Figure 1.7, thus, everywhere we only count iron in and out of boxes. The arrows are the fluxes (flows) between the boxes (stocks), how iron goes from one box to the other. Preferably, the flows/arrows are expressed with verbs, and those verbs should appear in the causal loop diagrams. We should be able to name what is kept in a box with a noun. For every commodity or countable entity we handle in our system, we make a flowchart. Together, the flow chart and the causal loop diagram uniquely define the computer simulation model we build afterwards, independent of which software or programming language we use. The systems diagrams are the graphical pictures we use to describe our mental model.

1.2.3 Cassandra's prophecies – All the early warnings not heeded

Humans are by constitution opportunistic, and thus also optimistic when it comes to problems. History has shown that humans are not likely to take predictions seriously, but rather improvise as they go and hope for the best – hence easily ignoring warnings and only listening to what confirms their wishes. This human trait is epitomised in the ancient legend of *Cassandra.* In Greek mythology, *Cassandra* was the daughter of *King Priam* and *Queen Hekuba* of Troy, the city of the Illiad by *Homer*. That would place her life around 1260-1210 BC. A version of her story is that *Apollo* gave her the power of prophecy to seduce her, but when she refused him, he gave her the curse of never being believed. In an alternative version, she fell asleep in a temple, and snakes licked her ears so that she was able to hear the future, a divine gift. Snakes as a source of knowledge are a recurring theme in Mycaenean or Minoan mythology (Fig. 1.4), although sometimes the snake brings understanding of the language of animals rather than an ability to know the future. Below we will explore some of the historical early warnings of resource depletion, that have been ignored by society and have lead us to the resource exhaustion crisis we face today.

1.2.4 Malthus

Thomas Robert Malthus (1766-1834) was an English scholar, influential in the fields of political economy and demography. He thought that the dangers of population growth precluded progress towards an utopian society and that sooner or later population would be checked by famine and disease – leading to what is referred to as a Malthusian catastrophe (also referred to as the Malthusian check). This catastrophe was his prediction of forced return to subsistence-level conditions once population growth had outpaced agricultural production. In *Malthus´* own words "*The power of population is indefinitely greater than the power in the Earth to produce subsistence for man*" (Malthus, 1798). *Malthus* argued that two types of checks hold population within resource limits: positive checks, which raise the death rate (*e.g.,* hunger, disease, war); and preventative ones (*e.g.,* later marriages), which lower the birth rate (Malthus, 1798). *Malthus* argued against the possibility that agricultural improvement could expand without limits as he realised that the world was finite. *Malthus* was a very controversial figure in his lifetime and certainly few were listening to his warnings against resource limits and population growth. He was way before his time. During our education as geologist and engineer, *Malthus'* insights were never discussed.

1.2.5 Hubbert´s Peak Oil

Marion King Hubbert (1903-1989) was a resource geologist at the multinational oil company Shell. In 1956, he published an oil production curve which came to be known as Hubbert´s model. It was a simple procedure for estimating the total volume of oil in a well to predict the rise in production, peak production rate and decline in production as the reservoir was emptied. The Hubbert curve and Hubbert peak theory laid the foundation for his prediction that is known today as peak oil production or Peak Oil. *Hubbert* first produced a bell shaped oil production curve in 1956. He went on to use it regularly for reliable production estimates for oil, and later also for uranium and coal. At first his model became appreciated for its reliable service in resource production estimates, but as time went by, and talk of resource limitations became politically less opportune, attempts were made to discredit Hubbert´s method. However, the method is easy to use and it is very easy to prove that it works on field data, and oil companies continue to use it internally (Al-Husseini, 2009; Aleklett *et al.*, 2012; Bardi, 2013; Campbell, 2013).

Vala became first aware of Peak Oil when she was introduced to the work of oil geologist *Colin Campbell* (Campbell and Laherrere, 1998; Campbell, 2004, 2013). *Campbell* founded the Association for the Study of Peak Oil (ASPO) in the year 2001. ASPO has organised annual conferences since 2002 and has gained recognition over the past decade. *Campbell* is given the credit for convincing the International Energy Agency in 2004 of the coming Peak Oil. He went on to publish an atlas of oil reserves, providing all his knowledge of oil reserves collected over 40 years into the public domain for all to see. It is now accepted from production data published by the major oil companies, that the production peak for conventional oil occurred in 2005-2007, and unconvential and exotic reserves are now keeping the production up (Al-Husseini, 2009; Aleklett *et al.*, 2012; Campell, 2013; Bardi, 2013; Ragnarsdottir *et al.*, 2014a). *Dr. Ugo Bardi* of University of Firenze, Italy, verified the peak behaviour of other types of oil and for other natural resources such as metals (Bardi, 2011). The Peak Oil phenomena is not something anyone has the liberty to believe in or not, it is a physical fact of extraction from any finite source and mass balance, and does not lend itself to belief. As will become evident as you read further, we have in this volume used Hubbert peak curves to represent observed and predicted resource extraction for oil, coal, metals, phosphorus and other resources.

1.2.6 Limits to Growth – We have followed the standard run

The systems dynamics pioneer *Jay Wright Forrester* (1918-), Professor of Systems Engineering at MIT in Cambridge, USA, wrote a book entitled *World Dynamics* in 1971 where he used systems analysis and systems dynamics computer models to investigate the interaction of population growth with resource use. The Club of Rome[11] noted his work and commissioned the research that lead to the Limits to Growth Report in 1972. The Club of Rome funded *Dennis Meadows*, who was then a PhD student with *Jay Forrester*, to develop the principles, to programme the model and run detailed world scenarios. *Dennis* assembled a team of scientists to work with him, including *Donella Meadows*, *Jörgen Randers* and *William Behrens III*. Their report was published in 1972 (Meadows *et al.*, 1972) and presented at a

11. http://www.clubofrome.org/

meeting of the Club of Rome. Their main message was that a limited planet will run into resource depletion, which in turn will lead to economic decline, and if unchecked, the depletion would occur soon after the year 2000 with economic decline following early in the 21st century. The report was followed up with a full documentation (Meadows *et al.*, 1974) and subsequent updates (Meadows *et al.*, 1992, 2004). At first it received a lot of attention (*e.g.,* Kanninen, 2013) but soon the doubters from the school of infinite resources won the debate, leading to the study being largely ingored (*e.g.,* Nørgård *et al.*, 2010). We argue, that the major reason why the Limits to Growth report was not taken as a warning was, that very few people understand systems analysis, let alone can build system dynamics programmes. The report was heeded as the report without numbers, but what people did not realise was that systems analysis maps out causes and effects and every component is linked with mathematical equations that are limited by laws of physics. Therefore the Limits to Growth scenarios were based on fundamental science. Through time, observations have shown that the "standard run" scenario of Limits to Growth, that was built on Business As Usual behaviour, has been followed (Meadows *et al.*, 1992, 2004; Turner, 2008, 2012, 2014; Bardi, 2011, 2013; Sverdrup *et al.*, 2013a). Field tests thus have shown that humans were wrong in ignoring the major recommendations of the Limits to Growth report: curb population growth, limit resource use and halt environmental degradation (Fig. 1.8).

Through participation with *Dennis Meadows* in the Balaton Group, we learned what an immense undertaking the Limits to Growth study actually was. Huge amounts of scientific work were put into the basis for the model, and this is documented in one of their least read books, that is 800 pages long (Meadows *et al.*, 1974). The Limits-to-Growth team got access to the MIT large mainframe computer at night where they carried with them a huge number of boxes of punch cards, and scenarios in their World3 programme took weeks to run. Computational resources in the 1970s were not as they are today. *Dennis Meadows* once told us that he very much regrets that the World3 model lumped together natural resources and fossil fuels, making it difficult for people to see the looming energy crisis that we have reached today, even if the Limits to Growth team was very aware of it in 1972. But they had to limit complexity to have a model that would be executable in a reasonable timeframe with the computers available.

We can contrast World3 (Meadows *et al.*, 1972) with our WORLD (beta version) model (Sverdrup *et al.*, 2013c), which is much more detailed and can be run on a laptop in minutes. This is due to the enormous advances in computing power in 40 years. WORLD has much in common with the World3 model and takes a lot of inspiration and actual parts from the earlier work. As in World3 the work presented here is built on systems dynamics submodules that are linked together in WORLD, and different scenarios are made to investigate possible outcomes. In the new WORLD model, every resource is taken individually as a sub-module and therefore it is possible to see the interaction of every one of them with rising population, the economy and the interplay between resource prices, supply and demand.

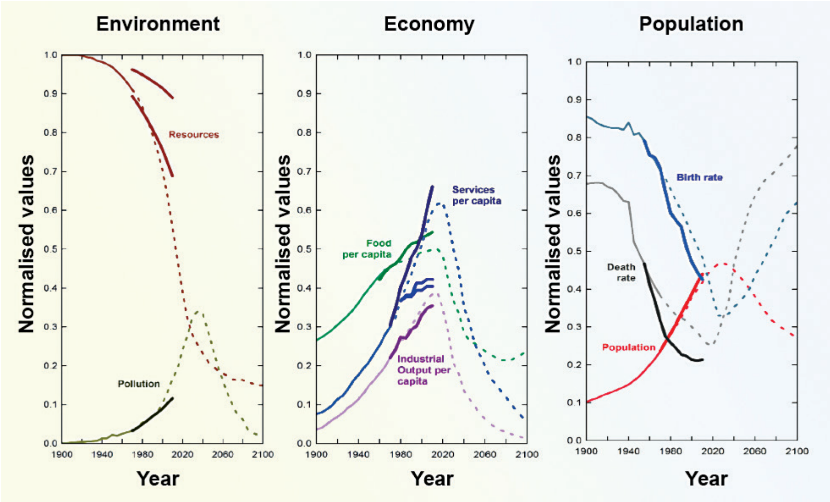


Figure 1.8 Testing Cassandra's prophecy. Comparison of the standard run from the 1972 *Limits to Growth* study by Meadows *et al.* (1972), published by Turner (2008, 2014). The dashed lines correspond to the predictions, the bold solid curves to the observations made since the predictions. When compared to data gathered over the past four decades, we see that the authors of *Limits to Growth* prediction were right.

As outlined above, the *Meadows* team encountered fierce resistance soon after publishing the *Limits to Growth* report. It was evident that they had stirred up strong forces that felt threatened by the concepts of a world that was not endless. Their work was attacked and significant efforts were made to discredit it, using largely rhetorical and political arguments. Afterwards, when we scrutinise the criticism, it stands out how scientifically weak the arguments used were and how political and ideological the argumentation was (Turner, 2008, 2014; Bardi, 2013). Further support for their 1972 outcomes is that World3 outputs compare well to data gathered over the 40 years since the study was completed (Fig. 1.8; see Turner, 2014 for more information). To understand the fierceness of the criticism, it is important to understand how limitless resource extraction has bestowed privileges and power on certain groups and people, and that a world of limits also implies limits to those privileges and power. No wonder there was a lot of noise.

In 40 years, however, the world has not changed in many respects when it comes to acceptance of limits. Many economic activities are based on the concept that the world is endless and limitless. Even if many engineers, geochemists and geologists know that this is wrong, there are many others in banking, finance, law or policy that do not. Therefore raising awareness is important, and in this *Perspective* we show how we may come to notice the limits of our finite resource in our life-times. We believe that we, as geochemists and engineers, must be ready to stand up for the foundation of science and defend that mass balance and the laws thermodynamics cannot be negotiated.

1.2.7 New Scientist and Nature Geoscience

In 2007, the *New Scientist* brought the looming resource depletion to the forefront in an article entitled *Earth´s natural wealth: an audit*. This article caught *Vala*'s attention, and she followed up with an invited commentary in *Nature Geoscience* (Ragnarsdottir, 2008). In writing her article, she wanted to bring Earth scientists to think about resources as the fundamental basis for our society. This quest was also at the centre of *Vala*´s *Geoscientist* article (Ragnarsdottir *et al.*, 2014a). But the issue of sustainable resource supply to society has been a serious concern long before *Vala*´s papers and before and after the *Meadows* and co-workers (Meadows *et al.*, 1972, 1992, 2004) studies. Studies before *Limits to Growth* include Malthus (1798), Hubbert (1956), Pogue and Hill (1956), and Forrester (1971) and studies after include Tainter (1988), Costanza and Daly (1992), Daily and Ehrlich (1992), Daily *et al.* (1994), Cohen (1995), Campell and Laherrere (1998), Heinberg (2001, 2005, 2011), Bardi (2005, 2007, 2008, 2009a,b, 2013), Costanza *et al.* (2005), Diamond (2005), Hirsch *et al.* (2005), Aleklett (2007), Cohen (2007), Ehrlich and Goulder (2007), Bardi and Pagani (2008), Brown (2009b), Jackson (2009), Rockström *et al.* (2009), Morrigan (2010), Nashawi *et al.* (2010), Ragnarsdottir *et al.* (2011), Sverdrup and Ragnarsdottir (2011), Graedel *et al.* (2011), Graedel and Erdmann (2012), Randers (2012), Sverdrup *et al.* (2013a,b,c, 2014a,b), Nuss *et al.* (2014), and Stanway (2014). These studies have hitherto unfortunately shared the fate of *Cassandra*. The studies are well documented and researched, and are supported by data, strongly telling us that there is reason for collective concern, and that natural resource limitations should receive wide attention and be further studied. Hence this *Perspective.*

1.3 Historical Perspectives on Natural Resource Use

1.3.1 The beginning of metals

When humans started to use metals for making tools, everything changed, eventually leading to modern society (Champion *et al.*, 1984; Rostoker and Bronson, 1990; Reardon, 2011; Murr, 2014). Two metals started it off; gold and copper. Metals were known as rarities earlier, but about 6,000 BC, these began to be mined in volume. The age of metals had begun. From the very beginning, gold was used as a measure of value and copper was used for tools that could not be made from stone or anything else.

The first metal man discovered and learned to use was probably gold. In caves from the Palaeolithic with habitation traces in France and Spain (some of them have the famous cave paintings from this age and later), small lumps of gold have been found, obviously brought there in or around 40,000 BC (Vronsky, 1997). It was, however, not handled in any amounts until about 7,000-6,000 BC when gold objects of status emerge in significant amounts. Gold was discovered early because it occurs as a native metal in nature. Gold occurs in the oldest city developments in Europe – Varna in Bulgaria is a good example as well as Sitagroi and Lerna in Greece (Champion *et al.,* 1984). There gold is found that originated maybe as early as 8,000 BC, and gold is associated with the growth of the first cities in Europe, which were seats of centralised power. In South America gold was known since 2,100 BC, always as ceremonial objects and jewellery – in Peru, Ecuador, Colombia and Bolivia. Gold was from the very beginning considered to be a bearer of value (Keatinge, 1988; Hosler, 1999; Horz, 2000). It was found to be indestructable, rare and to have the same colour as the sun. It became a symbol of wealth of kings and nobles, and the first money of the world was cast in gold.

Copper, was discovered around 6,000 BC. The technology to extract copper was developed somewhere in the Balkans-Anatolian area, but the metal was named after the island of Cyprus. Copper was the first metal to be used for tools, for which it is quite suitable. From around 6,000 BC pure copper was used; hammering of copper rendered it harder because mechanical changes occurred in the crystal structure and tools were made of it. By 4,000 BC copper sheet was produced, by 2,500 BC it was sometimes naturally alloyed with arsenic, tin or lead to make bronze. By 2,000 BC, tin ore deposits were discovered and tin was smelted and used to make standard bronze alloy. By 4,000-3,600 BC copper was smelted in Levant and Anatolia and worked on an industrial scale. The copper-bronze age started in the Nile Valley in North Africa, in southern Spain and in Anatolia (the modern territory of Turkey), marking the beginning of a metal-based economy. By 2,500 BC, copper tools were available throughout society (Champion *et al.*, 1984; Renfrew, 1994). Bronze working appears about 1,900-1,850 BC in China as a fully developed technology, from where it probably arrived by cultural diffusion. Copper started about 1,400 BC in the Andes in South America, based on smelting and hot working of the metal. Arsenic bronze makes especially good weapons, and occurred naturally from some of the ores that were mined. Copper extraction reached industrial scale with the Moche civilisation in Peru (200 BC-600 AD). Tumbaga was a commonly used alloy (80 % copper, 15 % silver and gold 5 %). It was leached with acid to create a golden surface, by first removing the copper, and then the silver. The Tumbaga alloy technology spread slowly north, reaching Costa Rica by 800 BC. Copper, silver and gold metallurgy spread to all of South America by 1,000 BC (Keatinge, 1988; Bruhns, 1994; Horz, 2000). Tin was first discovered around 2,000 BC, in Mesopotamia and the Zagros mountains. Tin is a rare metal and it was always in short supply, and expensive. It was necessary for making bronze out of copper, bronze being harder than pure copper and easier to work, and with a slightly lower melting point, making it easier to cast. Zinc was discovered around 600 BC in India. Brass became an important substitute for bronze because it did not need tin, which was scarce.

Brasses are based on zinc (copper-zinc alloy, brass) and lead (copper-lead alloy, billion). Brass occurs in Judea (1,000 BC) and Greece (700 BC), implying that zinc was used in alloys before being aware of it as a metal on its own.

Silver was discovered not long after gold (6,000-5,000 BC); it also occurs as native metal in nature, and this was how it was first found. The old production method was to extract it from lead, and the oldest dated silver-lead slag heaps in the Aegean are from about 4,000 BC. Silver like gold became a measure of value, and served as a medium for payment long before the first coin was made. Copper, silver and gold are unique in the sense that they represent the first kind of money, even before it was minted. Silver mining on a limited scale started at the same time as copper in South America (1,400 BC).

Lead was discovered around 3,500 BC in Egypt. It is easily reduced from sulphide ore with charcoal and melts and settles in the bottom of a fire. It contains silver in small amounts, and was among the first silver ores to be exploited (Laurion in Attica, Greece, archaeological finds suggest that lead mining here may go back to this time). The Romans used lead pipes for water supply, in cups and storing vessels and it has been suggested that lead poisoning was a contribution to the decline of the Romans. In the 20th century, it was found to be very toxic, and in Europe and the United States, legislation has been passed to phase it out of industrial use. One day in the future, we will probably no longer use it.

Iron was known in small amounts from meteorites (from about 3,500 BC in Egypt). Where the first meteorite was found is not known, but the etymology of the word for it is derived from an ancient word for star. Meteorites are the only source of iron in metallic form. Smelting of iron from oxide ore was first discovered in Anatolia and produced in some amounts through smelting by the Hittites from about 1,500-1,200 BC. From then on it became a bulk commodity and replaced other metals for weapons used in warfare. With the coming of the iron-age (1,300 BC to 700 BC), iron became the metal for making tools and was produced in large amounts (Champion *et al.*, 1984; Rostoker and Bronson, 1990).

Mercury was probably discovered in Italy around 1,600 BC, but it took until about 800 BC for it to be produced in significant amounts. It was used in gold and silver mining, as these metals dissolve in mercury. In 400 BC, mercury distillation was discovered. It is very toxic and is to be completely banned for all use by 2020 in Europe (UN/ECE-LRTAP; Nilsson, 1988).

1.3.2 The beginning of fossil fuels

Peat was the first fossil fuel to be widely used, starting in early prehistoric times. The first people to use coal were the Chinese, but the British were the first to use it on an industrial scale. Coal has been known since 200 AD in China. Marco Polo, the Italian traveller, tells how the Chinese burn black stones to get intense heat and use it for steel production (da Pisa about 1300, reprinted 1958). From about 1680, the use of coal for steel making and to power machines picked up as the British industrial revolution started. Three things made the fossil fuel age take off. Firstly it was the spread of the shareholder company in a secular free market, subject to rule of impartial law and abolishment of guilds and monopolies. Secondly it was the invention of steam and combustion engines, converting heat to motion, greatly increasing military power, transportation mobility and increasing human workforce efficiency (Kennedy, 1987; Diamond, 1997; Acemoglu and Robinson, 2013). Thirdly was the development of efficient state institution, including an impartial stystem of justice protecting ownership and intellectual rights (Fukuyama, 2011, 2014). This became the foundation of the British Industrial Empire, where the primary energy source was coal. From 1840, the industrial revolution started throughout Europe.

The use of oil goes all the way back to before antiquity. Oil has been known since 3,000 BC in Mesopotamia. The Greek historian Herodotos relates how the city walls of Babylon were glued together with tar instead of cement, and how the streets had asphalt surfaces at the time of the great Persian kings (650 BC). This oil originated from local sources where oil came to the surface. In China, oil was also used industrially very early, and the first oil wells were drilled down to a depth of 240 metres as early as in 347 AD. The oil was transported in bamboo pipelines to nearby salt refineries (Shen Kuo, 1088; Bodde, 1991; Al-Hassani, 2008).

The industrial oil age started in 1870s. It was not until oil was discovered in the United States in the 1860s that it became a major global source of energy for industry and propulsion of ships, trains, cars, and most recently aircraft. It provided the driving force of the American industrialisation and buildup of the American Empire. Cheap energy is a must for building up Empires, and once that is no longer available, then empires tend to contract or dissolve (Kennedy, 1987; Diamond 1997). After the British Empire experienced peak coal in 1890, the decline of the British Empire came gradually. The British Empire was dismantled in 1945, or about 50-60 years after the peak production of coal. The American Empire went through peak energy in 1970-1980, and therefore by analogy we could expect the American Empire to contract around 2020-2030, unless new, long-term sustainable energy sources are developed.

1.3.3 The issue of what is long-term and what is sustainable

In this *Perspective*, we will relate metals to what they are needed for, what the planetary capacity for delivering them would be, and discuss possibilities of what could happen if those planetary capacities are challenged. Alternatively, considering how important metals are for human civilisation, what would it take to make them last? History goes both ways. We learn about the past when we go to elementary school, and read about it as adults, and what we learn from history can inform us about the future. Humans have the ability to plan for the future but we are not good at planning for the long-term future. Sustainability demands very long-term planning because it concerns the present as well as the future that belongs to future generations. Any assessment must go beyond all delays in the system to be scientifically serious. Thus, we must discuss what those delays are and how long they are.

1.3.4 Future generations, time aspects and what constitutes a proper time horizon

By over consuming the Earth´s resources we are robbing future generations of possibilities for a good life. Closing our eyes will not make the issue go away. In what follows we will use the term "doomsday" for the point after which society will not have, or will not want to have access to any metals, and thus will be in deep trouble. It is a troubling concept for many, as it has complicated and challenging ethical implications and large ramifications for generations to come. We have experienced that many people get upset or angry when such issues are brought up, but in our view being angry is not a very scientific argument. We have personally experienced that this discussion is willingly avoided by many colleagues (discussed by Carter and McCrea, 1983; Gott III, 1993, 1994; Boetteke, 1997; Leslie, 1998; Hall *et al.*, 2001; Ainsworth and Sumaila, 2003; Greer, 2008; Hall, 2008; Morrigan, 2010; Heinberg, 2011 among others; see also Sverdrup and Svensson (2002, 2004) for a discussion of time and sustainability). Discussing future metal, materials or energy shortages raises questions many colleagues often find disturbing or unpleasant to discuss.

Sustainability should thus be determined by first thinking over how long it is envisioned that we intend society to last with access to resources and intact supporting ecosystems. Do we want our society to exist and prosper for the next 3, 10, 100, 1,000 or 10,000 years? For whatever we choose, the planning horizon must be long. If shorter periods are chosen, for example 200 years, then that implies that we do not care about the consequences after those 200 years have passed ("doomsday" might arrive, but we do not care). The most usual justification given is "...we cannot make predictions with any accuracy for more than 100 years, and who knows, by the way, what kind of political system will rule then....". Just taking for granted that in 200 years "someone smart" will have come up with a solution to fix all problems arising from what we do now, is a bad excuse for not taking full responsibility for our own actions.

When it comes to the time perspective, we may take reflections from several authors on what is long-term (Renfrew, 1989, 1994; Daily and Ehrlich, 1992; Daily *et al.*, 1994; van Andel, 1994; Sverdrup, 1999; Gibbard and van Kolfschoten, 2004; MacDougall, 2004; Kukla, 2005; Raynaud, *et al.*, 2005; Fagan, 2008). Their main take on long-term is that it must, from a systemic perspective, include 3 times the length of the longest significant delay in the system. History shows us that these are on the order of magnitude of centuries. This includes time to build a city or grow a forest, length of a human life, time to turn over carbon in the soil, or deplete the local copper mine. Denmark has existed as an identifiable country for 1,600 years, and a good house will last 300 years. Thus long-term is never shorter than 300 years, but normally very much longer.

1.3.5 On technology

Experience (common sense we could say) shows that sustainability must be planned on the basis of what we do, and not what we know today, and without basing our continued existence on wonders that we hope will occur in the future and without ruining the resources for those that come after us. This is what the history lessons in school really were about. Possibilities about getting metals from asteroids, natural gas from Jupiter or Saturn, nickel from the Earth's core or copper from the oceans are only excuses for inaction, basing our hopes on naïve dreams. These proposals are made by people that lack the understanding of geochemistry and geology. They lack understanding about how ores are formed and how long the processes take that concentrate them, and they lack the ability to realistically assess the energy balance of such proposals.

1.4 More on Sustainability and What It Means

1.4.1 Environmental limits and sustainability

Many talk about sustainability, but very few know what it stands for. *Harald* started thinking about it early in the 1990s and tried to publish articles on how sustainability was to be defined and how to make quantitative estimates for it. However, it soon became apparent that the academic community was not ready for it. *Harald* remembers how in his youth, his father *Rolv* would throw trash out of the car window while driving and replying to him when he protested: "*Son, get it, the world is endless*!" In elementary school in Norway in the mid 1960s, we were taught about environmental pollution and protecting the environment, but to our parent's generation this was something they never had received any teaching in. They were probably taught that the world was endless, and in many ways it was endless at that time.

Until very recently, this was also the mindset of scientific journal editors and many of our colleagues, and the whole sustainability discussion was seen as being "new age", "unscientific speculations" and "far out." As one editor of a well-known Swedish scientific journal asked: "*Why should a chemical engineer worry about sustainability, and is it at all necessary*?" The attitude was surprising to us then, but it occurred so many times after that, that it would be dishonest to deny that it happened. *Vala,* similarly was told by uneasy colleagues in the UK at the beginning of this millennium: "*It is not in my job contract to save the world*." In this context it is interesting to note that many of the advances in sustainability science have not come from academia, but from mavericks and NGO's. This becomes evident when we investigate when sustainability academic journals were founded. *Sustainability Science* was launched in 2006, *Journal of Sustainable Development* in 2008, *Sustainability* in 2009 and *Journal of Sustainability Science and Management* in 2009. Therefore it has been difficult for researchers to get established in this new scientific field.

In Scandinavia, two issues were important in raising the awareness of environmental issues by the middle of the sixties. The first issue was the pollution of waterways and lakes with sewage from cities and farms, leading to eutrophication. This included nutrients (nitrogen and phosphorus) from sewage piped to the nearest stream or lake, the use of detergents containing phosphates, and the practice of spreading cow manure on fields in the spring. These activities collectively polluted lakes and rivers so badly that eutrophication was widespread. The affected lakes turned into something that looked like yellow soup, and they smelled bad. The bathing season was ruined by the stink of the polluted waters. The yellow stuff was algal blooms, fish died and this made the public aware that humans had large-scale effect on the environment. In *Harald*´s home town Hamar, on Norway's largest lake Mjøsa, the authorities were very reluctant to undertake an investigation and carry through needed remedies, such as building sewage treatment plants and pass necessary regulations on farming. Spontaneously, a majority of the housewives all around Lake Mjøsa created the "Mjøsaksjonen" informal network through telephoning (this was before the internet). They boycotted the use of phosphate detergents to the degree that their sales in the shops collapsed, and the companies making them had a major surprise when they could no longer sell their product. The "Mjøsaksjøen" made it to the national news headlines. This woke up the regional community, shocked the local politicians that now worried about the next election, and then things started to happen fast. *Harald*´s mother was on the "Mjøsaksjonen" informal organising committee, and there was a lot of talk about it at the dinner table home in Hamar (1970-1973). It affected *Harald* – he could see the pollution in the lake, and that his mom acted as an activist to fight against it. *Harald*´s father was flabberghasted, but *Harald* was proud of her. The Lake Mjøsa pollution made environmental damage real to normal people. It showed him the need for action, and that when people unite, necessary change can happen in spite of politicians initially wanting to hush everything up.

The second issue was acid rain that caused the fish in upland lakes in Sweden and in salmon rivers in Norway to disappear, and it was discovered that the acid rain came from far away, from polluting industries of Great Britain, Netherlands, France and Germany. By the late 1960s and early 1970s, the damage to lakes and sport fishing was so widespread that the issue got scientific attention in Oslo, Gøteborg and Uppsala. Many of the famous Norwegian salmon rivers no longer had any fish due to acid rain. Scandinavians are outdoor people, fishing in lakes and rivers and outdoor hiking is serious business to us. This helped to put the environment on the National political agendas, and it was significantly helped by the fact that we, people in Sweden and Norway suffered, whereas the perpetrators were abroad (in Great Britain, France, Germany etc.). It is therefore no coincidence that the first UN Conference on the environment was held in Stockholm in 1972 – with a follow up of the foundation of the United Nation´s Environment Program (UNEP).

Harald encountered the pollution issue when he worked one summer during his gymnasium time (1971-1973) in Hamar for the Norsk Institutt for Vannforskning (NIVA) assisting in a follow up project for the rescue of Lake Mjøsa. At NIVA *Harald* also heard about lake and stream acidification problems. In Scandinavia, research programmes started to describe the issues, but only much later they attempted to try to find solutions. There were TV and newspaper coverages and the environment as a concept made its way into both researcher's and layman's minds. As with the discussion of health effects and tobacco smoking, there were always "skeptics" among the scientists that protested against humans having anything to do with environmental damage. But they isolated themselves with their closed minds from the new issues. With time environmental problems and sustainability issues have become so globally pervasive, that these attitudes have largely vanished and are no longer socially or academically accepted.

Large amounts of money were used for acid rain research, and the necessity of solving the problem lead to considerable geochemical innovations in soil chemistry modelling. Acid rain research, that *Harald* was actively involved with, helped frame new problems for geochemistry. The field was much advanced through the development of new models for soil chemistry, soil ion exchange processes, and soil water complexation reactions. *Harald* built a new type of system dynamics model for silicate weathering and the interaction of geochemical processes with biological processes of trees, plants, micro-organisms, fish and/or animals. Traditional geochemists were not always involved in this, but the field was moved significantly and quickly forward by occurring environmental problems being tackled by new types of trans-disciplinary research teams such as at the University of Lund.

There are different ways to define sustainability, and some even make a point of saying it is not definable. We think there are basically two definitions; the detailed one given in one of the first textbooks on *Sustainability Science* by Bert de Vries (2013) and the simple one. A simple definition was given by the Emperor Augustus of the Roman Empire in relationship to the engineering of the future Imperial Roman road network as we have related earlier. He defined a sustainable plan to be *"A plan that could be followed forever, without ruining the functions of the Roman Empire*." Our friend and sustainability trainer *Alan Atkinson* (Atkinson, 2008) defines sustainability as *"A set of conditions and trends in the given system that can continue indefinitely*." As a follow up, sustainable development is defined by *Atkinson* as *"A directed process of continuous innovation and systemic change in the direction of sustainability*." We have adopted the definition of *Atkinson* for both sustainability and sustainable development.

There are several terms for sustainability that are being used, and we need to consider which of those are adequate, inadequate, sufficient or necessary. Below we discuss the following five central concepts: sustainable society, sustainable growth, sustainable development, growth and de-growth, overshoot and contraction.

1. **Sustainable society**. This is a society that can go on for as long as we can reasonably foresee. It is not dependent on growth, but may persist and prevail at a steady level. It is achievable under certain conditions. There would be growth within the sustainability limits, accompanied by de-growth of what is in excess of the sustainability limits. Growth and de-growth would balance each other over the long-term, like waves that rise and fall (Fig. 1.9). Overall, the resource use stays within the sustainability limits (at or below the dotted line in Fig. 1.9). There are sustainability limits for the biophysical system, the social system and their interface, and correspondingly the economic system. For a sustainable system overall sustainability in all aspects of this complex system is required.

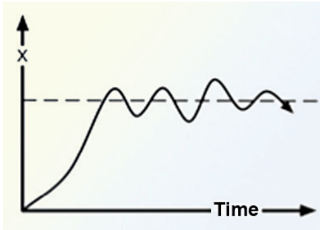


Figure 1.9 Resource use (line) rises to the carrying capacity (dashes) and oscillates at that level over the long-term.

2. **Sustainable growth**. There is no real consensus on how this concept is to be uniquely understood. Sustainable growth was a focus from the Brundtland Commission (United Nations, 1987), and is useful in starting the discussions about the unsustainability of the present civilisation. The Brundtland Commission defined sustainable growth as "*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*." It sounds great, but on closer inspection of the contents of the actual report text, how the definition was interpreted has some problematic features. It appears from the text that the authors of the report allow for continued growth in a finite world. It does not address the conflicts built into the definition. Perpetual growth is not possible in a finite world (Fig. 1.10). Such a system can readily overshoot. We would have problems covering the needs of the present, and we could not manage the transition to sustainability and we are likely to ruin the possibilities of future generations. The Brundtland definition was useful because it made the necessity of sustainability evident and pointed towards the need to come up with solutions. But the definition itself is no more than a starting point.

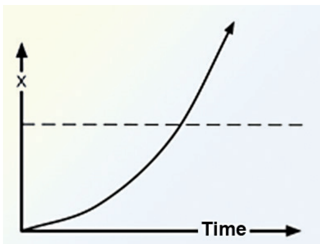


Figure 1.10 When there is unlimited growth, resource use (line) rises exponentially with time and exceeds the carrying capacity (dashes).

It is flavoured by political correctness, and implies unlimited growth. If it is interpreted to imply that we could have sustainable growth within sustainability limits, and de-growth of what is not sustainable, then it matches the definition under item 1 or 3. The physcicist *Arthur Allan Bartlett* is known for stating: "The greatest imperfection of mankind is that it does not understand the consequences of exponential growth."

3. **Sustainable development** is about developing within the sustainability frames that exist for society – or steps towards sustainability as defined by Atkinson (2008). It implies that there are quantifiable limits to physical consumption and to materials use losses, limits to natural system acceptable damage, and that development must be understood under such conditions. Sustainable development implies development within the sustainability boundaries (the dotted line in both Figs. 1.9 or 1.11). It can mean material and energy consumption contraction and convergence (as suggested for carbon; Meyer, 2000), and for societies in resource overshoot, contraction for all. It means that for some situations, we may be wise to be considering supplying sufficiency for many before affluency for a few. Sustainable development does not only have physical aspects, but also involves development of the social sphere and of society's structures (Costanza and Daly 1992; Costanza and Daily, 1992; Sverdrup and Svensson, 2003). In our CONVERGE project we also tackled the issue of equality in economic terms.

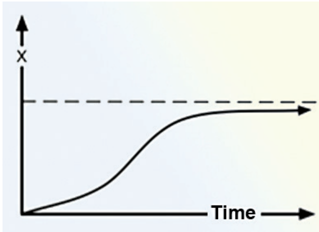


Figure 1.11 Sustainable development may be interpreted as growing resource use (line) up towards the carrying capacity (dashes), but staying below it. The further we stay below the carrying capacity, the more resilient the system will be.

4. **Growth and de-growth.** The world has had economic growth almost without interruption for almost 120 years. Many think this is the normal state of the world and think about decline, contraction or de-growth as a disaster. However, this is a misconception. Growth and de-growth are continuously present in society, as some business areas grow and some contract, as some countries have growth years and some have decline years because of population changes, their underlying resource is exhausted or other factors that can cause a local economy to temporarily decline. In a finite world, we can have periods of net total growth for a while, or total de-growth, or it can be intermixed, but both will always be there. In the pre-fossil fuel world this used to be the normal state. Net total growth means that there is more

growth than de-growth. Growth or de-growth have no direct value in themselves, they represent only ways for positioning society relative to the sustainability limits of society. When we jump out of the envelope into overshoot, we would need some net system de-growth to come back into the sustainability envelope; when we have extra carrying capacity, we can allow growth to get to full potential (Fig. 1.9). In the very long-term, net growth will always be compensated by more de-growth if the system has moved above the carrying capacity of the system.

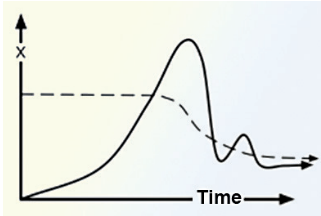


Figure 1.12 When resource use (line) overshoots the carrying capacity (dashes), then the carrying capacity may decrease because of the overshoot. Then it will be a race to catch up and eliminate the overshoot quickly.

5. **Overshoot and contraction** or overshoot and collapse, implies that we are far above the long-term carrying capacity. Overshoot means depleting reserves and the system's capacity for sustainability. In a world that realises this in time, the development will be as in Figure 1.12, a controlled contraction to within the limits. Staying in overshoot-mode erodes the sustainability potential in such a way that the longer we wait, the larger the long-term global contraction must be. If the overshoot is too large and the contraction too slow as compared to the resulting contraction of the sustainability potential, then a situation may arise where the sustainability potential approaches zero faster than the overshoot (Fig. 1.13). Most in-depth studies suggest that the world is in some type of overshoot with respect to environmental degradation, consumption of materials of all kinds, fossil energy and for population size. The world can at the moment produce sufficient volumes of food, but this is probably not sustainable in the long-term with respect to nutrients for crops, soil conservation and possibly water availability, unless something is changed.

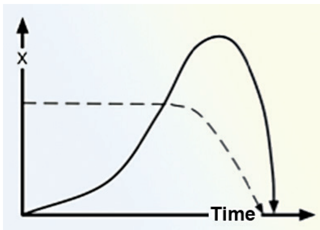


Figure 1.13 If we cannot limit the resource use (line) overshoot before the carrying capacity (dashes) crashes, there may be a system collapse.

6. **Convergence** is a concept that originates from *Aubrey Meyer´s* Contraction and Convergence (2000) concept for CO_2 emissions. This concept has been further developed by us in collaboration with the Schumacher

Institute, which is built on the ideology of *F. Schumacher*, a German economist and sustainability visionary who lived in Britain and is best know for writing the seminal book *Small is Beautiful* (Schumacher, 1973). It involves reducing large economic differences in society and improving equality in the world. The convergence concept has been applied by us to resources, suggesting that those that consume the most, reduce their consumption and those that consume the least are given room to consume more to close the equality gap in terms of standard and quality of living. Convergence is a concept still under development, and will be modified when resource limitations come into play. Many countries of the world are in resource use overshoot today, because of high per capita resource use combined with large numbers of consumers. All developed nations will have to contract their resource use in the coming century, and very few countries have resource consumption below the sustainability capacity. The sustainability limitation is for total amounts of global resources, and for countries with very many people, this inevitably leads to fewer resources per person. Since many of the resources are without regeneration mechanisms within generational life-times, the longer we want to have those resources, the more years we must make last what we have left.

Our work on resources caught the attention of the German government and the WORLD model is now being redeveloped, extended and applied to Germany inside a global context (Bleischwitz *et al.*, 2012; Meyer *et al.*, 2012). Germany is a large country, large enough to have a feedback and an influence on the whole world. The German economy is at present 5 % of the global economy approximately. The German resource policy must have several linked legs:

1. A domestic policy for:
   a. A financially sustainable economy, with respect to nature protection and in compliance with a long-term sustainable society.
   b. Using cutting edge knowledge to make German businesses more competitive and in a position to benefit from the challenges of sustainability.
2. A foreign policy for a sustainable society:
   a. To influence the world to create sustainable conditions, in which Germany can create a long-term society for itself.
   b. For taking care of Germany's share in the responsibility for the world, making sure that German activities do not affect the world in a way that makes it less sustainable.
   c. For Germany to take a leading role and teach others how to become sustainable.

The German government is working on this at present, but most other governments also need to have such goals and act on them. The countries that take a leading role will face many difficulties, but also have the advantage of being innovative and being involved in creating solutions. Germany is known for taking the initiative on developing solutions to pervasive problems, producing a business and financial advantage for the country. A good example is the development and building of coal plant air pollution technology that most European countries invested in to reduce sulphurous air pollution, when the opportunity arose to enter the EU in the early 1990s. For policy development, we have several options of how to improve resource efficiency. An increase in resource efficiency will allow us to:

1. Make more growth with a smaller growth in resource use (more growth-increase use – often referred to as Factor X – pioneered by German researchers)
2. Make slow growth with the same resource use (some growth-same resource use)
3. Make zero growth with less resource use (no growth-reduction in resource use)
4. Contract society with far less resource use (de-growth-large reduction in resource use)

Essential in this context, is that the amount of resources used must be at or below the long-term sustainable resource availablity – the carrying capacity – for society to be sustainable. We can do items 1 or 2 when we still have room inside the sustainability limits. We can do items 2, 3 or 4 when we are at the sustainability limit, and we must do 3 or 4 if we have an overshoot with respect to our sustainability limits (Fig. 1.9). So far, all gains in resource efficiency achieved went into consuming even more, thus little total resource use was saved.

Another important point is that the sustainable resource use rate is normally far below the maximum possible production rate. Just like the optimal speed for car driving in a city is normally far below the maximum speed the car can do. Not everybody grasps the difference conceptually (neither do some car drivers and many businessmen and politicians), but we need to be able to explain this clearly. In a finite world, there is a finite and quantifiable amount of resources. This sets a frame that the world will be forced to acknowledge and accept. An essential concept in this context is the Energy Return On Investment (EROI) or Resource Return On Investment (RROI). How much do we get back for each unit of resource value invested? As ore grades get lower and lower, or oil gets more and more expensive to extract because it is deeper in more difficult terrain or requires more expensive production technology, we will reach a point where we have to spend more in value than we get out. That is the case when we talk about mining in space, or digging ultra low-grade coal or copper ore, or mining the deep ocean, or tunnelling 6 km down to mine nickel. Then more effort may be spent than the usefulness we will gain by doing so. When energy (EROI) or resource (RROI) return is less than the resource investment, then extraction is at a loss that can never be covered.

The challenge of continuous and exponential growth is evident in a classic story from India (Fig. 1.14). Once upon a time, about 1,400 years ago, the *Maharadja Sharim* had a visitor to his court. *King Sharim* was a great enthusiast of games and challenged his visitor to a game of his choice. The visitor told him he had a new game to show, and asked the king to try it with him. To encourage the visitor to play seriously, *King Sharim* offered the visitor any reward he wished. The visitor answered with a modest request, to place one grain of rice in the first square, two on the next, four on the third and doubling until the board, which contained 64 squares, was filled. They played, and to *King Sharim*'s surprise, the visitor won. But *King Sharim* was very pleased with the game, and wanted to reward the visitor generously. When *King Sharim* ordered his servants to pay the visitor, he realised that the amount added up to far more grain than the he ever would possess, namely 2^{64}, *i.e.* $1.8 * 10^{19}$, grains of rice, corresponding to 210 billion tonnes, which is more rice than was produced in the whole history of the Earth until 1990 (Fig. 1.15). In one version of the story, the visitor then revealed himself to the king as the *Lord Krishna* himself and forgave the king's debt, provided he realised what he had just learned. Pilgrims feasting on Pall Paysam remember the king's debt by sacrificing rice at the temple. Constant growth and especially exponential growth eventually exceeds capacity. Yet, the world is consuming resources at exponential growth rates.


Source: www.historyforkids.org

Figure 1.14 The Mahradja Sharim playing chess with a stranger, who transpired to be Lord Krishna (National Museum, New Delhi, India).

When we plot the production of different metals (and materials) in a logarithmic diagram over time, such as in Figure 1.16, we can see that they form straight lines. They show exponential growth in the time from 1900 to at least 2010, with doubling times in production from 10-20 years on the average. This means 3.5-7 % growth in resource extraction per year. Each doubling in production represents more metal than all the previous doublings added up.

Source: www.thinkhumanmetrics.com

Figure 1.15 King Sharim playing chess; the visitor won the game and the king is discovering that he cannot pay an exponentially increasing reward.

If this resource extraction increase goes on much longer, the extraction will at some time in the near future exceed the total reserves, because the reserves are limited. It means that resource extraction growth is soon over. Whether it takes 10, 20, or 40 years is of minor importance, because it cannot continue much longer. *Harald´s* father told him it would not happen in his time, it was not his problem. But it will happen in our time, thus it is our problem and all of our contemporaries. Another important factor to note is that as we extract metals, the ore grade that we extract is decreasing with time (Fig. 1.17b), while the necessary effort for extraction is increasing, slowy also showing in the metal prices[12] (Fig. 1.17a). Therefore, the effort and cost that we are expending to obtain these resources is rising, eventually increasing to a level that the extraction of additional resources will become prohibitive. Of note is that price fluctions occur when political decisions interfere with the market, as appears to be occurring today where prices of fossil fuels are concerned.

When ore grades go down, production costs go up. When production costs go up, metal prices must go up, or production will go down. Why this is so, is explained by the causal loop diagram in Figure 1.18. When prices go up, the market may react with reducing demand, leaving more in the market and sending the price (and profits) down, and later, reducing mining. Reduced mining will imply less metal in the market, sending prices up at sustained demand. It is a dynamic system. The figure shows the dynamics of this interaction. R is the

12. Take note that our discussion of metal and material prices, stocks and fluxes are generic discussions in a scientific context and do not in any way whatsoever constitute any form of investment or trading advice or warning. Our predictions may serve as parts of the inputs to long-term policy development, but they serve this in the same way as weather predictions do. Predictions do not tell what the future will be, they tell what could be possible, sometimes with estimates of probability. Any one who acts based on our information, does so fully on their own responsibility.

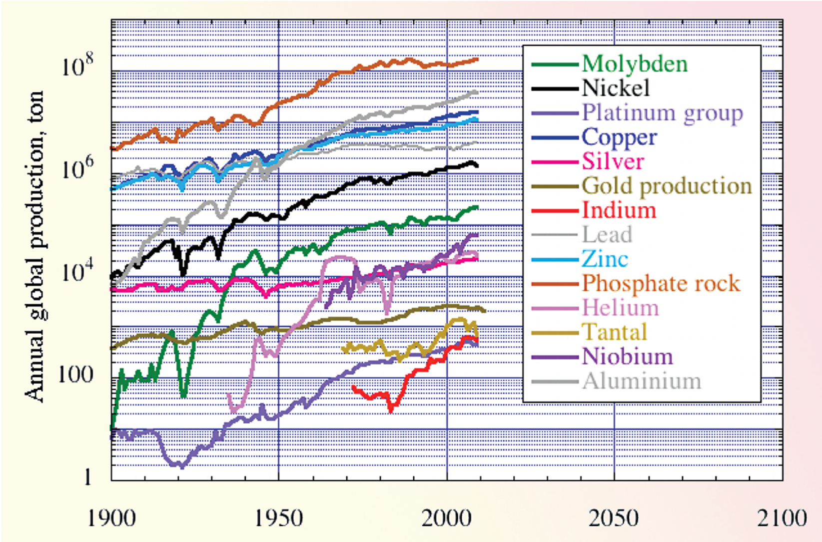


Figure 1.16 During the period 1900-2010, natural resource extraction from the world's mines increased exponentially (straight line on a logarithmic graph).

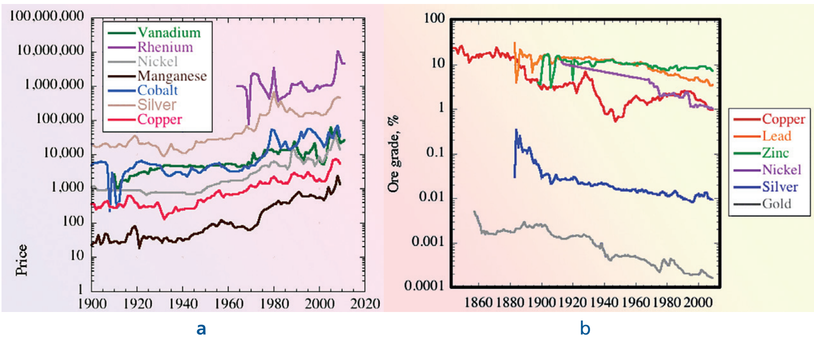


Figure 1.17 **(a)** Development of metal prices 1900-2010 in US dollars per tonne. Note that the scale is logarithmic, and that the metal prices (dollars per kg) are rising exponentially. **(b)** Development of ore grades with time, based on Australian data. All the metals have had a declining trend in ore grade since about 1880, when the first rich ores were depleted by industrial scale mining (Mudd, 2007, 2009, 2010). These are all strong signals suggesting that we are consuming our resources at a speed where demand is about to overshoot supply. This is evident by the observation that as ore grades go down, prices go up.

reinforcing loop of the mining business, which is profit driven. B are balancing or limiting loops, where an increase comes back as a decrease. More mining leads to less reserve. Less reserve leads to less ore grade since they move in the same direction (more reserve, more ore grade). Lower ore grade leads to higher mining costs, and higher costs to lower profit. Lower profit leads to less mining, and more profit leads to more mining.

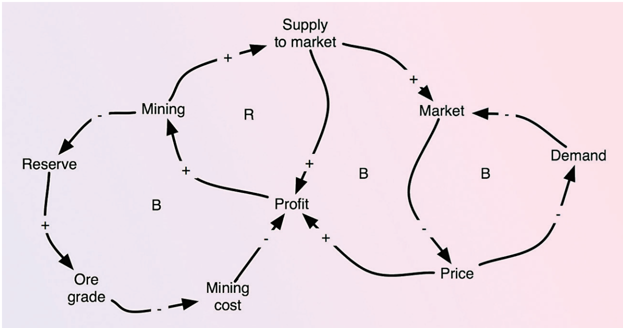


Figure 1.18 A simple causal loop diagram showing the dynamics of resource price, resource extraction, reserve size, and supply and demand, to explain why prices will show upward trends when a metal or material comes towards the end of the extractable reserves.

The rise in metal price is more than inflation, and in general, prices have gone up more than Figure 1.17a appears to show. Over time the inflation-adjusted curve has a U-shape, with high price before 1900, low prices 1930-1990, and increasing prices after 2000. Over the years the increased amount of work input required, caused by declining ore grades (silver, copper, nickel; see Mudd, 2007, 2009, 2010 for further discussion), and the increasing energy need has been to a large extent compensated for by increased technical efficiency and by moving the work to low wage countries with limited if any environmental regulations. We are at the end of that road now; technical efficiencies start to meet material balance limits and the extraction work has largely shifted from the industrialised, high wage countries to the lowest of the low-wage developing countries. As we have started to run out of room for further technical efficiency gains, and we lack even poorer people to be paid less for more mining, extraction cost increases will to a larger degree transfer straight to the metal price. As with gold and platinum (see below), the price will shoot up once the production peak has been passed.

2. CLASSIFICATION OF NATURAL RESOURCES

2.1 Introduction

Natural resources are derived from the environment. They form through biogeochemical and physical processes within the Earth and on the Earth´s surface where interaction between the atmosphere, hydrosphere, biosphere, geosphere and cryosphere takes place. A natural resource may exist as a separate entity such as sunlight, air, and fresh water, as well as living organisms such as birds or fish, or may exist in an a form that must be processed to obtain the resource – including metal and mineral ores as well as coal, oil, and gas. Because natural resources underpin our economic systems, there is much debate over natural resource allocation, and this is increasing with increasing scarcity due to the interaction between population rise, resource extraction, and economic development.

In our work, the US Geological Survey[13] is an important source of data. We work with all technically extractable ore content (below referred to as extractable amount) that is classified according to ore grade and extraction costs in our models. The terms reserves and resources are often misunderstood, and this sometimes confuses discussions. Regardless of what it is called, we work with the amount we can expect humans to find and dig up at some point in time, sooner or later, in this narrative (Wellmer, 2008). We divide up the metal and fossil fuel extractable amounts in this *Perspective* as follows: in reserves we include the amounts that are known and extractable at today's market prices and with today's technology. Under a regime of scarcity, the price will go up and a part of what is technically possible but not profitable at today's prices will be recovered when the price has gone up. Resources include all amounts that are classified as technically extractable, but it may sometimes exclude those estimated to be not extractable for other reasons. The reasons of this can be that they are practically or energetically

13. The text supplied by the USGS (2004) as definitions is**:** **Resource**: A concentration of a naturally occurring mineral in a form and amount such that economic extraction of a commodity is currently or potentially feasible. **Identified Resource**: Resources whose location, grade, quality, and quantity are known or reliably estimated. **Demonstrated Resource**: Resources whose location and characteristics have been measured directly with some certainty (measured) or estimated with less certainty (indicated). **Inferred Resource**: Resources estimated from assumptions and evidence that minerals occur beyond where measured or indicated resources have been located. **Reserve Base**: That part of an identified resource that meets the economic, chemical, and physical criteria for current mining and production practices, including that which is estimated from geological knowledge (inferred reserve base). **Reserves**: That part of the reserve base that could be economically extracted at the time of determination. **Marginal Reserves**: That part of the reserve base that at the time of determination borders on being economically producible. **Undiscovered Resources**: Resources whose existence is only postulated.

out of reach. This means that it will cost more energy to get them than what they can be worth, or that there are for all practical puposes insurmountable physical obstacles to get them (for example that they are at depths where we cannot go).

Table 2.1 Example of the relationship between copper ore grade, production cost and minimum supply price to society. Y is the metal yield when extracting ore (Sverdrup *et al.*, 2013c, 2014a,b).

Ore type	Metal content, %	Y %	Production cost, $/kg	Minimum price, $/kg
Rich grade, 400-50 kg/tonne	40	100	4	5
High grade, 50-10 kg/tonne	5	99	15	18
Low grade, 10-2 kg/tonne	1	98	63	76
Ultra low grade, 2-0.4 kg/tonne	0.2	91	278	334
Extra low grade, 0.4-0.1 kg/tonne	0.05	80	995	1,200
Trace amounts, 0.1-0.02 kg/tonne	0.01	22	1,600	2,000

Table 2.2 The extractable amounts set at the beginning of the COPPER model simulation in 1800, stratified with respect to ore metal content and relative extraction cost (Tilton and Lagos, 2007).

Ore grade	Million tonnes copper				% Average ore grade	kg Cu/tonne ore
	Known	Hidden	Extractable	Cumulative extractable		
Rich	15	5	20	20	40	400-50
High	10	20	30	50	5	50-10
Low	100	1,250	1,350	1,400	1	10-2
Ultra low	15	1,200	1,215	2,615	0.2	2-0.4
Extra low	15	1,100	1,115	3,730	0.05	0.4-0.1
Sum	155	3,575	3,730			

The result is that we will have ever rising cost as ore quality and extraction yields go down. We divide the technical extractable amounts into ore grade as shown for copper in Table 2.1: Rich grade, high grade, low grade, ultra low grade, extra low grade and trace amounts. Table 2.2 shows the reserves for copper (known, hidden reserves, cumulative reserves, average ore grade). Our approach is much more adapted to how the industry is actually acting to the impacts of demand, supply and market dynamics. How large the ultimately recoverable reserves (URR) are, is a dynamic variable, depending on how much the market is willing and able to pay.

2.2 Sunlight, Air and Water

Sunlight, air, and water are fundamental resources, and perhaps the most important of all. Resource use and extraction interact with these through consumption of oxygen, contamination of water through processing and disposal, but that is also another study that will fill a whole *Perspective* by itself.

2.3 Soil

Soil can be considered to be the second most important natural resource on Earth after water. It has been described as the most complex matter in Earth (*Science*, 2004) and it is of concern that we seem to know more about the surface of other planets than our own soil. Soil forms in the Earth´s Critical Zone (from treetop to the bottom of groundwater) due to biogeochemical and physical processes at the Earth´s surface where the geosphere meets the biosphere, hydrosphere, atmosphere and cryosphere (Anderson *et al.*, 2004). This is the zone that feeds the biosphere. Soil is a complex system of minerals, organic matter, water, air and microorganisms that form the habitat for rich and complex flora and fauna. Millions of microbes can reside in one teaspoon of soil.

Soil characteristically is composed of mineral particles and organic matter. These particles stick together forming aggregates that are the fundamental building blocks of the soil structure. The stability of soil aggregates is one of the most central issues for soil quality and stability (*e.g.*, Kemper and Rosenau, 1986; Lehtinen *et al.*, 2014a) and maintainance of organic matter in the soil is crucial to its stability. Soil organic carbon is extremely important in all soil processes. Organic matter in soils is derived from residual plant and animal material, synthesised by microbes and decomposed under the influence of temperature, moisture, and ambient soil conditions. The decline in soil organic carbon is recognised as one of the eight soil threats identified in the European Union and one of the key goals of the European Soil Strategy is to maintain and enhance soil organic carbon levels. Since soil contains twice as much carbon as the atmosphere and biosphere combined (Bellamy *et al.*, 2005), enhancing the stability of soil organic matter is crucial in combating global warming. A recent review of 39 studies of soil organic carbon and greenhouse gas emissions has demonstrated that crop residue incorporation is important for maintaining soil organic carbon (Lehtinen *et al.*, 2014b). For contaminated soils O´Day and Vlassopoulos (2010) outline the need for sustainable soil remediation using mineralogical and geochemical principles but show that each remediation needs to be site specific. This demonstrates the need for geochemists to engage in soil remediation issues (Hodson, 2010).

Soil formation is a slow process (about 10 mm per 100 years) that is worryingly slower than soil erosion (from about 100 to 1,000 mm per 100 years) in agricultural areas (Brantley *et al.*, 2007). This underlines the fact that soil is an unrenewable resource at the scale of one human generation. Data from

FAO (United Nations Food and Agriculture Organisation) show that we have reached the peak of tillable soil (Fig. 2.1). This puts a limit to food production (*e.g.*, Bindraban *et al.*, 2012) and by analogy also the population on Earth.

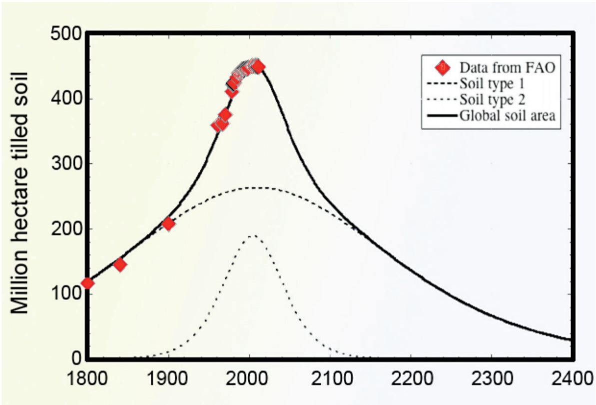


Figure 2.1 A plot of soil showing that "peak soil" was reached in the year 2000, fitted to a Hubbert's curve. Adapted after Sverdrup *et al*. (2013a). Data from FAO (2010, 2011). The diamonds represent millions of hectares of tilled soil.

Since it is now evident that our soils are under threat globally it is imperative that improved land management be adopted globally. Reports from soil experiments focusing on soil fertility are available from a variety of sources – including agroecology (Pimentel *et al.*, 1995; Gliessman, 2006; De Schutter and Vanloqueren, 2011) and the Rodale Institute (Rodale Institute, 2012). The former demonstrates an increase in yields and the latter that organic farming systems increase soil health by building rather than depleting soil organic matter, making it more sustainable. Organic land management matches conventional yields; outperforms conventional yield in years of drought; and may under the right circumstances use 45 % less energy and thus be more long-term resource efficient. Conventional systems often produce 40 % more greenhouse gases and organic farming systems are more profitable than conventional ones. Organic farming here means that the farming is conducted with no toxic chemicals such as pesticides and herbicides (which are pervasive sources of endocrine disruptors and persistent biotoxins), and is fertilised with manure and plant residuals as the main fertiliser. It is normally organised as a system with both plant and animal cultivation, and able to benefit from manure and nutrient recycling from the animals.

The most effective way of regenerating denuded soil and eroded land back to fertile land with regenerated soils, is to let the trees of a forest do the work. As almost every forester knows, a forest that is properly mangaged and carefully harvested will be able to build back soils from very poor conditions within

100-200 years (Sverdrup and Stjernquist, 2002). This is far faster than geological processes can achieve alone (centuries to millennia), and fertile soils need the cooperation of both geological processes and biological processes to be effective.

Forest management can produce more biomass products than sustainability limits permit, implying that management is not the limiting factor (Sverdrup and Stjernquist, 2002). When the sustainable harvest volume has been removed, the residual biomass is available for recycling into soil, building up the stocks of the ecosystem. In this way, sustainable forestry and sustainable agriculture hold the capacity to stop soil erosion and have considerable capacity for soil and landscape restoration. That demands, however, that the limitations of sustainability are respected, and that short-term considerations should be set aside for the long-term goal to be achieved. Commercialised and industrialised agricultural and forest practices are often short-term and opportunistic, doing considerable damage to system structures and functions (Marchak, 1995; Sverdrup and Stjernquist, 2002). The know-how to do sustainable agriculture, forestry and soil management is commonly available, and well documented, and thus reversing the trend requires a combination of political will to set policies and society's ability to change.

2.4 Metals

What is common to all the metals dealt with here, is that the rate at which they are formed today is vanishingly small compared to the rate at which we extract them. Many of them were created by very distinct geological events that occurred millions of years in the past, and the deposits we have is everything that is available, and no more will be produced over human scale timeframes. This means that we need to be able to deal with a finite amount of resources. The processes through which they formed is important for understanding where to find them and how much it is reasonable to think exists. But the amounts extractable are limited by ore grade and accessability. Detailed account of the metal formation processes is material for at least one other *Perspective*. Therefore only a rather simplistic representation of formation processes is presented here. For more detailed overview we refer to standard textbooks on ore deposits and natural resources (*e.g.*, Pohl, 2005; Robb, 2005; Pipkin *et al.*, 2013; Ridley, 2013; Walther, 2013).

2.4.1 The big six

Iron, chromium, manganese, aluminium, copper and zinc have the highest production rates of all the metals in the world. In this section the formation of these metal resources are outlined. There are many compositions of steel, depending on how it will be used in industry, but the most common components of steel are iron, chromium and manganese. Their formation history is outlined below.

Figure 2.2 Banded iron ore in Karijini National Park, Western Australia.

Iron has the highest production rate of all metals used by man. Three billion tonnes of iron ore are mined annually, leading to the production of almost 1.5 billion tonnes of iron and steel. Most iron ores were formed by sedimentary processes during the Precambrian (4.6 Ga to 541 million years ago), forming banded iron formations (BIF; Fig. 2.2) (*e.g.,* Ramanaidou and Wells, 2014). Vast quantites of banded iron formation sediments were deposited on the seafloor. Banded iron ores are often hundreds of metres thick and extend hundreds of kilometres along strike. These rocks are comprised of iron-rich (~20-40 % Fe) and silica-rich (~40-50 % SiO_2) layers that are commonly banded, from layers metres in thickness to submillimetre-thick laminae that might represent seasonal events (Trendall and Blockley, 1970; Taylor and Konhauser, 2011). Evidence suggests that the BIFs precipitated from an anoxic ocean water column, yet it is believed that the initial mineral phases were ferric (oxyhydr)oxides (Klein, 2005). There are three hypothesis for the oxidation of Fe^{2+} to Fe^{3+}: UV photooxidation at the ocean surface; reaction with oxygen produced by primitive cyanobacteria or their predecessors; and anaerobic photosynthesis where bacteria convert CO_2 into organic biomass, using Fe^{2+} as reducing power (Bekker *et al.*, 2010).

Significant amounts of atmospheric O_2 first appeared between 2.4 and 2.2 Ga ago, during a period referred to as the Great Oxygen Event (GOE), raising the levels of oxygen in the atmosphere from being a factor of 10^{-5} lower than today, to 8-15 % of present atmospheric levels (Canfield, 2005; Holland, 2006). There are several theories about the cause of oxygenation of the atmosphere; either there was a drop in CH_4 and subsequent cooling (Kasting and Ono, 2006), or there were pulses of mantle plume volcanism or rift-related volcanism (Melezhik, 2006; Eyles, 2008). Variations in $\delta^{13}C$ in marine carbonates deposited around this time, with values as negative as -12 ‰ suggest disturbances to the exogenic carbon cycle which in turn support the possiblity of changes in atmospheric greenhouse gas levels (White, 2013). Others suggest that volcanic gases became more oxidising through time as a result of subduction, which could account for the timing of the GOE (Kump *et al.*, 2001; Holland, 2009).

Oceanic iron deposition, whether by direct oxidation of iron or bacterially induced oxidation, can be represented as:

$$3\ Fe^{2+} + 3H_2O + 0.5O_2 = Fe_3O_4 + 6\ H^+ \quad (2.1)$$

$$2\ Fe^{2+} + 2H_2O + 0.5O_2 = Fe_2O_3 + 4\ H^+ \quad (2.2)$$

The largest banded iron deposits are found in the Great Lakes region of North America, NW Australia, and Brazil (Fig. 2.2). Other iron ores are magnetite ores (found within banded iron ores and currently mined in Minnesota and Michigan in USA), haematite ores (altered banded iron ores now mined in all continents except Antarctica with the largest intensity in South America, Australia and Asia), and igneous magnetite ores.

The banded iron formations story is also a story in which the evolution of one geochemical cycle (oxygen) negatively impacted another (iron; Taylor and Konhauser, 2011). As atmospheric and surface-ocean O_2 levels rose, ocean iron concentrations fell and banded iron formations disappeared from the geologic record. It is not clear whether the disappearance of banded iron formations is due to the reaction of Fe^{2+} with O_2 in seawater (Holland, 2006), or whether increased atmospheric oxygenation facilitated increased weathering of sulphide minerals, resulting in a greater supply of dissolved sulphate to the oceans. The sulphate, then allowed sulphate-reducing bacteria to generate dissolved sulphide in quantities sufficient to remove all the available iron from the oceans and form pyrite, FeS_2 (Vargas *et al.,* 1998). Geochemical modelling reacting basalt with chemical composition of rainwater as the present day, but with initial values of log f_{O2} = -70 and log f_{CO2} = -1.5 (Hessler *et al.*, 2004) and containing the volcanic gases H_2, H_2S, SO_2, CO_2 and CO (Zolotov and Shock, 2000; Catling and Claire, 2005), produced weathering minerals that include pyrite (FeS_2), kaolinite ($Al_2Si_2O_5(OH)_4$), chalcedony (SiO_2), siderite ($FeCO_3$), calcite ($CaCO_3$) and lizardite ($Mg_3Si_2O_5(OH)_4$). The iron in equilibrium with this mineral assemblage has the value of 10^{-3} mol l^{-1} or 3 ppm (Sverjensky and Lee, 2010). Thus significant quantities of Fe^{2+} could be produced during weathering and possibly transported in Archean rivers to the oceans. These thermodynamic calculations indicate that Archean near-surface rainwater, volcanic gases and basaltic rocks do not react to produce significant changes in oxidation state. The calculations suggest that production of O_2 by oxygenic photosynthsisis could proceed in the near-surface environment without any accumulation of O_2 in the atmosphere. In the shallow marine environment, a pulse of O_2 could have resulted in the deposition of a ferric hydroxide precipitate, contributing to the formation of banded iron formations (Sverjensky and Lee, 2010). They suggest that diversity of oxidised minerals could not be introduced until oxygenetic photosynthesis completely dominated reductants released to the near-surface environment from non-biological and biological sources, and that such domination was achieved by 2.0 Ga. As soon as the O_2 started to accumulate in the atmosphere and reached 1 % of the present atmospheric value, weathering reactions proceeded very similarly as they do today and siderite and pyrite were oxidised to iron oxides. Holland (2006, 2009) suggests that 90 % of the tonnage of all known iron formations was probably deposited between 1.9 and 2.6 Ga as banded iron formations. These formations represent the removal of dissolved Fe^{2+} from the shallow marine environment in response to the oxidation of the atmosphere. The main change in iron minerals after the GOE was the cessation of deposition of detrital siderite and pyrite and the end of riverine transport of Fe^{2+} to the oceans.

Banded iron formations re-appeared around 750 Ma in association with global glaciations, often referred to as a *Snowball Earth* event. It is suggested that these banded iron formations were caused by global freezing of the oceans, leading to water stagnation and build-up of dissolved iron. As the ice melted and ocean circulation became re-established, iron became oxidised and formed banded iron formations in the oxic zone of upwelling areas (Hofmann and Schrag, 2002). Of note is, however, that each of these banded iron formations is linked with extensive eruption of submarine mafic volcanic rocks, suggesting that iron depositon was the result of iron inputs from these eruptions (Bekker *et al.*, 2010). During the Phanerozoic (540 Ma to present) less spectacular banded iron formations and iron-rich deposition periods have occurred. These are generally in the form of oolitic ironstones, formed in shallow marine basins (especially during the Ordovician, Cretaceous and Jurassic) with mineralogy dominated by bethierine ($(Fe^{2+},Fe^{3+},Al)_3(Si,Al)_2O_5(OH)_4$) or chamosite ($((Fe^{2+},Mg,Al,Fe^{3+})_6(Si,Al)_4O_{10}(OH,O)_8)$) (Taylor and Konhauser, 2011). It is suggested that these oolitic iron formations are linked with periods of lowest or highest sea level and the presence of shallow-marine shelves. Under favourable circumstances large deposits are the result of multiple superimposed processes, as demonstrated by several generations of iron oxides (Hagemann *et al.*, 2008; Simonson, 2011).

Currently mined ores are mostly magnetite. Pure magnetite contains 72 % iron, but in nature the ore has normally between 60-65 % iron. Low grade magnetite ore, referred to as taconite, has an iron content of about 25-30 %. Other minerals mined are haematite, goethite ($FeO(OH)$), the hydrated form limonite ($FeO(OH)\cdot nH_2O$) and siderite ($FeCO_3$). Further iron deposits include the igneous deposits formed in granites (now mined in Malaysia and Indonesia), skarns where granites intrude carbonate rocks, metamorphic massive magnetite (*e.g.*, Savage River, Tasmania), and layered intrusions. The latter generally contain titanium and vanadium with the major iron mineral being titano-magnetite (Fe_2TiO_4).

To reduce iron oxides to Fe metal, an enormous amount of energy is needed and in the process CO_2 is produced because coal is oxidised while reducing iron in accord with:

$$Fe_3O_4 + 2\ C = 3\ Fe + 2\ CO_2 \tag{2.3}$$

Hence for each tonne of Fe, 0.5 tonnes of CO_2 are produced and 20-40 MJ/kg of energy are needed. The first iron ore to be mined, were not those with the highest contents, but those most accessible with primitive tools and low mechanisation. Often siderites were used from coal deposits and even earlier in historic times, bog iron was dug out of wetlands and lakes. Historically, the amounts extracted this way were small, and they have been ignored in the modelling we present in this *Perspective*.

Chromium: Current chromium mining is 16 million tonnes/year. Chromium deposits are generally found in layered igneous intrusions of which the Bushveld Igneous Complex is by far the largest (9 km thick and 66,000 km^2); this deposit was formed 2 billion years ago. The fact that the intrusion is 9 km thick is not only of academic interest. The world's deepest mines (gold and platinum mines) reach down to almost 3,900 m. Below that, the temperature is so high that it becomes very expensive to cool the mine sufficiently at that depth (where the rock temperature can be above 60 ^oC). Of note is that these formations are also important for extraction of platinum group metals (see below). Other layered intrusions include the Stillwater Igneous Complex in Montana and the Ring of Fire in Ontario. Igneous layered complexes have chromite layers which are largely formed by the mineral chromite ($FeCr_2O_4$) which belongs to the spinel group. Chromium rich garnet, uvarovite ($Ca_3Cr_2(SiO_4)_3$) is found in interbeded layers with chromitite (Guilbert and Park, 1986). Chromium is also mined from ophiolitic complexes (*e.g.,* Edwards and Atkinson, 1986). The largest chromium mining activities are in South Africa (44 %), India (18 %), Kazakhstan (16 %), Zimbabwe (5 %), Finland (4 %), Iran (4 %) and Brazil (2 %).

Manganese: Manganese production is 18 million tonnes per year. It is similar to iron in its chemical properties and often substitutes for iron in its divalent and trivalent form. Manganese, however also has a 4^+ valence state which gives rise to a plethora of Mn-oxide minerals that do not have Fe counterparts. Mn deposits are unevenly distributed over geologic time and cluster in three groups: Palaeoproterozoic (2,500 to 1,600 million years ago), Neoproterozoic (1,000 to 541 million years ago), and Cenozoic (66 million years ago to the present). The Palaeoproterozoic deposits are by far the largest and correspond to the major episode of banded iron ore formation, when the Earth's atmosphere oxygenated. The Neoproterozoic Mn deposits are also contemporary with iron ore formation but the Cenozoic (Oligocene – 34 to 23 million years ago) deposits are not associated Fe mineralisation. The largest Palaeoproterozoic Mn deposits are in the Kalahari desert of South Africa; the largest Neoproterozoic Mn deposit is in Brazil with many smaller deposits in China. The Oligocene deposits are centred around the Black Sea. Manganese ores are sediment hosted, volcanic hosted or karst hosted (*e.g.,* Edwards and Atkinson, 1986). The most common ores are in close spatial relation to iron ores and the minerals are, rhodochrosite ($MnCO_3$ – 32 %), braunite (Mn_7SiO_{12} – 24 %), cryptomelane (KMn_8O_{16} – 8.7 %), manganite ($MnOOH$ – 7.8 %), pyrolusite (MnO_2), hausmannite (Mn_3O_4 – 2.9 %) and romancheite ($BaMn^{2+}Mn_8^{4+}O_{16}(OH)_4$ – 3.9 %). Unexploited manganese resources are found on the oceanic floor as manganese nodules where they precipitate from seawater (Wang *et al.*, 2009). Manganese nodules are a mixture of manganese and iron oxides with small amounts of cobalt, copper, nickel and zinc. The nodules grow slowly in onion-like concentric spheres. The growth rate of these nodules has been estimated to be 49.5 mm Ma^{-1} using $^{230}Th/^{232}Th$ isotopic ratios (Huh and Ku, 1984; White 2013). Because of the depth to the oceanic floor and the present low price of manganese, any exploitation of this ore appears to be far in the future, though some dream about starting exploitation sooner. However, the exploitation is currently neither technically, economically, nor politically viable and also has environmental limitations.

Aluminium: Annual aluminium metal production from alumina (Al_2O_3) is now about 50 million tonnes per year. The formation of bauxites demands intensive weathering of rocks in the tropics where there is very good drainage. Bauxite consist of the minerals gibbsite ($Al(OH)_3$), boehmite (γ-AlO(OH)), and diaspore (α-AlO(OH)), mixed with the iron oxides goethite (FeO(OH)) and haematite (Fe_2O_3). Bauxites are classified into lateritic bauxites (containing silica and derived from silicate rocks) and karst bauxites (containing carbonate derived from limestone and dolomite), *e.g.*, Edwards and Atkinson (1986). Alumina is derived from bauxite ore through a chemical process where about 5 weight units of bauxite yield about 1-2 units of alumina. Thus to produce 50 million tonnes per year of aluminium, we need 100 million tonnes of alumina, which in turn needs 200-300 million tonnes bauxite per year. Thus, for every 50 million tonnes aluminium metal per year produced, we also produce about 150-250 million tonnes per year of waste, which is called "Red mud". Gibbsite is formed when kaolinite ($Al_2Si_2O_5(OH)_4$) is dissolved through weathering reactions:

$$\underset{\text{(kaolinite)}}{Al_2Si_2O_5(OH)_4} + 5\,H_2O = \underset{\text{(gibbsite)}}{2\,Al(OH)_3} + 2\,H_2SiO_4(aq) \tag{2.4}$$

Gibbsite, bohemite and diaspore are treated in sodium nitrate and sodium hydroxide solutions, resulting in massive red mud pools that are environmentally destructive, if not properly contained. Subsequently the alkaline treated ore is heated to produce alumina (Al_2O_3). Australia is the top producer of alumina from bauxite with almost one third of the world´s production, followed by China, Brazil, Guinea, and India. For each tonne of aluminium oxide that is reduced, energy is needed and CO_2 is released into the atmosphere via

$$2\,Al_2O_3 + 6\,C = Al_4C_3 + 3\,CO_2 \tag{2.5}$$

$$Al_4C_3 + 3\,O_2 = 4Al + 3\,CO_2 \tag{2.6}$$

The sum of these reactions is:

$$2\,Al_2O_3 + 6\,C + 3O_2 = 4\,Al + 6\,CO_2 \tag{2.7}$$

or

$$Al_2O_3 + 3\,C + 1.5\,O_2 = 2\,Al + 3\,CO_2 \tag{2.8}$$

For each metric tonne of Al produced, roughly 2.4 tonnes of CO_2 are released and 230-350 MJ/kg of energy are required. Because energy is cheap in countries like Iceland, alumina is shipped around the globe to be reduced in Iceland and then the aluminium metal is again shipped for further product development to another country. All of this is possible because fossil fuels are relatively cheap with respect to their compact energy content.

Copper: Annual copper production from ore is about 16 million tonnes. However, supply to society is 28 million tonne per year when including recycling. Copper is found in Volcanogenic Massive Sulphide (VMS) deposits, porphyry copper deposits and deposits associated with salt brines (Barnes, 1996).

VMS ore deposits host mainly copper and zinc and are associated with volcanic-associated hydrothermal events in submarine environments (Franklin *et al.*, 2005). In addition to the ancient VMS deposits that are being mined now, some are forming today along the oceanic ridges by black smokers. These formations are generally stratiform accumulations of sulphide minerals that precipitate from hydrothermal fluids on or below the seafloor. As the water is heated by magmatic intrusions on the oceanic ridges, oxygen, magnesium, sulphates and other chemicals from seawater are removed through chemical reactions with the basalt. The fluids also become more acidic with hydrogen sulphide (H_2S) from the underlying magma causing them to leach metals including copper from the rocks they flow through. The copper can be monovalent (+) and divalent (2+) and can be transported in hydrothermal fluids as a sulphide complexes depending on pH, fluid composition and temperature (Barnes 1996; Mountain and Seward, 1999):

$$Cu^+ + HS^- = CuHS^o \qquad (2.9)$$

$$Cu^+ + 2\ HS^- = Cu(HS)_2^- \qquad (2.10)$$

$$2Cu^+ + 3\ HS^- = Cu_2S(HS)_2^{2-} + H^+$$
$$\text{(only important at low temperature)} \qquad (2.11)$$

Chloride is also an important complexing agent for copper at high chloride concentrations and high temperatures (300 °C; Mountain and Seward, 1999):

$$Cu^+ + 2\ Cl^- = CuCl_2^- \qquad (2.12)$$

As the fluid rises and cools, the copper complexes become unstable and copper sulphide minerals form, notably chalcocite via

$$2\ CuHS^o = Cu_2S + HS^- + H^+ \qquad (2.13)$$

and

$$2\ CuCl_2^- + HS^- = Cu_2S + 4\ Cl^- + H^+ \qquad (2.14)$$

On the oceanic ridges, black smokers are rich in metal sulphides. The metals precipitate into sulphide mounds often as large as fifty metres or more across. Well known copper deposits of this type are found both on the island of Cyprus in the Mediterranean and in North Western Wales in the United Kingdom and are generally referred to as massive sulphide deposits (*e.g.*, Barrie and Hannington, 1999). Well-known copper sulphides are CuS (covellite), digenite (Cu_2S) and djurleite ($Cu_{13}S_{16}$) as well as with other metals such as iron and arsenic in chalcopyrite ($CuFeS_2$), bornite (Cu_5FeS_4) and energite (Cu_3AsS_4), and as cuprite (Cu_2O) in weathered ore. Copper is also found as native copper (Cu).

Porphyry copper desposits are found in zones around igneous intrusions. Their formation involves the entire lithosphereic column below explosive arc volcanoes, starting in the metasomatised upper mantle and then in the upper crust the hydrothermal fluid exolves and degassing occurs from an oxidised magma (Tosdal *et al.*, 2009). These changing physicochemical conditions coupled with external geological controls contribute to precipitation and the formation of deposits containing copper and other metals such as gold, occurs pervasively throughout the intrusion and the rocks (*e.g.*, Edwards and Atkinson, 1986). Ascent of such fluids hydrofractures the overlying rock, allowing magma to ascend as narrow dykes and plugs. Magma ascent is accompanied by a pressure drop, vapour loss and pressure-quenching, forming the characteristic aplitic groundmass of the phorphyry intrusions. Massive hydrofracturing of wall rocks and stocks form the pathways for ascent of magmatic fluids from the cupola (Tosdal *et al.*, 2009). The exolved, water-rich volatile phase at the top of the magma chamber contains water soluble components such as chloride and sulphide species. The salt rich fluid intersects the broad field of fluid immiscibility between 750 °C and the critical point for water (374 °C), leading to the separation of high-density brine from a larger volume of low-density vapour (Williams-Jones and Heinrich, 2005). Copper sulphites precipitate in the porphyry environment at around 400 °C as a result of decreasing stability of chloride complexes due to cooling in the presence of H_2S (Hemley and Hung, 1992). The precipitation of copper and other metals is enhanced by fluid-rock reaction, changes in pH and fluid speciation, brine-vapour unmixing (so-called boiling) and local fluid mixing (Seedorff *et al.*, 2005). With cooling to ~400 °C, most SO_2 in the hydrothermal fluid disproportionates via reaction with water in the rising fluid to form H_2SO_4 and H_2S, which promotes sulphide precipitation. Brine and vapour may separate with chloride and chloride-complexed species (*i.e.* Cu, Pb, Zn, K and some Au) concentrated in the brine and H_2S and bisulfide complexed species (*i.e.* Cu, Au, As) concentrated in the vapour. The fluid alters the rock to low-K calc-alkaline diorite to tonalite, high-K calc-alkaline quartz monzonite, and alkaline monzonite and syenite (Tosdal *et al.,* 2009).

Sediment-hosted copper deposits are stratabound, restricted to a narrow range of layers within a sedimentary sequence but do not necessarily follow sedimentary bedding. They are epigenic and diagenetic, formed after the host sediment is deposited, but in most cases, prior to lithification of the host (Cox *et al.,* 2007) and are independent of igneous processes. Sediment-hosted copper deposits are formed by fluid mixing in permeable sedimentary rocks. Two fluids are involved: an oxidised brine carrying copper as a chloride complex and a reduced fluid, commonly formed in the presence of anaerobic sulphate-reducing bacteria. Copper is leached from the source rock at moderately low pH according to:

$$Cu_2O + 6\ Cl^- + 2\ H^+ = 2\ CuCl_3^{2-} + H_2O \qquad (2.15)$$

The brine is often related to evaporite deposits (Davidson, 1965). Rose (1976) showed how reduced fluids, derived from organic-rich shales and carbonate rocks, cause precipitation of copper when contacting copper-rich brine:

$$2\ CuCl_3^{2-} + 2\ H_2O + C = 2\ Cu^o + CO_2 + 4\ H^+ + 6\ Cl^- \qquad (2.16)$$

In addition bacteria reduce sulphate to sulphide (Sweeney and Binda, 1989):

$$SO_4^{2-} + CH_4 = S^{2-} + CO_2 + 2\ H_2O \qquad (2.17)$$

Sulphide then reacts with the copper chloride complex to form chalcocite:

$$2CuCl_3^{2-} + S^{2-} = \underset{\text{(chalcocite)}}{Cu_2S} + 6\ Cl^- \qquad (2.18)$$

Sulphate is commonly abundant in brines derived from evaporites and may accompany copper-rich oxidised solutions such that:

$$2CuCl_3^{2-} + SO_4^{2-} + CH_4 = Cu_2S + CO_2 + 2\ H_2O + 6\ Cl^- \qquad (2.19)$$

Most sulphide ores are precipitated within 50 cm of the sediment-water interface. Deposits are most commonly situated at basin margins where fluid mixing is most likely to take place (Cox *et al.,* 2007). One of the major Cu provinces is the Central African Copper Belt. There the ores were formed in sedimentary sequences related to the movement of brines in response to tectonic deformation. Extracting copper from the sulphide ore involves heating to around 900 °C and producing cuprite:

$$Cu_2S + 2\ O_2 = 2\ CuO(s) + SO_2 \qquad (2.20)$$

The sulphur dioxide is converted into sulphuric acid (H_2SO_4) by reacting it with water. The cuprite is then reduced with coal, requiring 120-160 MJ/kg of energy per tonne copper produced via

$$2CuO + C = 2Cu + CO_2 \qquad (2.21)$$

For each tonne of copper produced, 0.3 tonnes of CO_2 is released into the atmosphere.

Zinc: Annual zinc production is 12 million tonnes per year. Many of the major zinc deposits are formed in sedimentary basins at depths of typically hundreds of metres, but sometimes shallower. Sediment-hosted Pb-Zn deposits can be divided into two major subtypes (Leach *et al.,* 2010).

The first subtype is clastic-dominated lead-zinc (CD Pb-Zn) ores that are hosted in shale, sandstone, siltstone, or mixed clastic rocks, or they occur by carbonate replacement, within a CD sedimentary rock sequence. This subtype includes deposits that have been traditionally referred to as sedimentary exhalative (SedEx) deposits. The CD Pb-Zn deposits occur in passive margins, back-arcs and continental rifts, and sag (trough-like) basins, which tectonic settings are sometimes transitional into each another.

The second subtype of sediment-hosted Pb-Zn deposits is the Mississippi Valley-type (MVT Pb-Zn) that occurs in platform carbonate sequences, typically in passive-margin tectonic settings (Lumpkin and Ewing 1985; Pardis *et al.,* 2007).

MVT deposits occur mainly in dolostone as open-space fillings, collapse breccias and/or as replacement of the carbonate host rock. They are typically in undeformed orogenic foreland rocks, commonly in foreland thrust belts, and rarely in rift zones (Leach and Sangster, 1993). The MVT deposits originate from saline basinal metalliferous fluids at temperatures between 75-200 °C. MVT account for approximately 25 % of the world´s zinc and lead deposits. The redox state of sulphur is one of the major controls on the transport, and deposition of Pb and Zn in sediment-hosted Pb-Zn ores and therefore can be considered a rock type that recorded the oxygenation of Earth's hydrosphere. The emergence of CD and MVT deposits in the geological record between 2.02 Ga and 1.58 Ga corresponding to a time after the Great Oxygenation Event (Leach *et al.*, 2010). Increased oxygenation of the oceans following the second oxidation event (550 to 542 Ma) led to an abundance of evaporites, resulting oxidised brines, and a dramatic increase in the volume of coarse-grained and permeable carbonates of the Palaeozoic carbonate platforms, which host many of the great MVT deposits. Not all zinc deposits are sedimentary. There are also deposits which host zinc together with copper, lead and similar base metals (Franklin *et al.*, 2005). These formations are generally stratiform accumulations of sulphide minerals that precipitate from hydrothermal fluids on or below the seafloor. The smelting and extraction of the zinc sulphide ore is similar to that of copper. Copper, zinc, lead and tin and other metals often form poly-metallic ores, and they are often extracted together.

2.4.2 Precious metals

Gold is found in deposits affiliated with the Late Archean (2.7-2.6 Ga; greenstone hosted deposits), Palaeoproterozoic (2.0-1.6 Ga: iron oxide-copper-gold and lode gold deposits), and Phanerozoic (0.6 Ga to the present: porphyry and epithermal deposits); these periods broadly correspond with phases of new crustal growth (Walshe and Cleverley, 2009). The two former types are sometimes modified into placer gold despoists (*e.g.,* Long *et al.*, 2011). They are associated with contractional and extensional tectonism where gold production involved the entire lithospheric colum, starting in metasomised upper mantle, then the upper crust where hydrothermal fluids exolve from oxidised magma, and higher in the upper crust changing physico-chemical conditions coupled with external geological controls contribute to precipitation and the formation of ore deposits (Tosdal *et al.*, 2009). Gold is transported in the crust as as a chloride complex ($AuCl_2^-$) at temperatures above 400 °C (Zotov and Baranova, 1989; Stefansson and Seward, 2003a, 2004; Williams-Jones *et al.*, 2009) and as sulphide complexes ($AuHS^o$) and $Au(HS)_2^-$ at temperatures below 350 °C (Benning and Seward, 1996; Gibert *et al.*, 1998; Stefansson and Seward, 2004). While some large native gold nuggets have been found (*e.g.,* Hugh *et al.,* 2009), gold is currently mostly mined from "gold-only" deposits. These include modified placer deposits (*e.g.,* Witwatersrand, South Africa, the biggest single deposit on the planet that originates from a nearby greenstone belt; Robb and Hayward, 2014) and "orogenic gold" deposits, associated with deformation zones in metamorphic rocks where fluid migration in deep crustal fault zones is driven by pressure fluctuations during seismic events (Goldfarb *et al.*, 2005). Gold is also mined as an impurity in silver, copper and zinc sulphide ores. Most of the gold production was dominated by South Africa, but now China has taken over (USGS, 2013). Gold mining is now widely distributed in many countries with smaller mines.

Silver is found in similar settings to gold (*e.g.,* Tosdal *et al.*, 2009). It is also transported as chloride complex ($AgCl_2^-$; Seward, 1976) and sulphide complexes ($AgHS^o$, $Ag(HS)_2^-$ and $Ag_2S(HS)_2^{2-}$; Stefansson and Seward, 2003b) in hydrothermal solutions. Similar to gold, silver is found in minor quantities as native silver (Ag) but more commonly it is deposited and mined as an impurity in sulphide ores containing gold, copper, zinc and lead, and a significant amount is produced as a by-product of production of these metals.

2.4.3 Other metals

In this section an outline is given for metals that are used in steel, technology, and the chemical industry. For specialty steel some metals are essential such as niobium. **Niobium** is generally found in association with pegmatite intrustions and in alkaline igneous complexes in the mineral pyrochlore ($(Ca,Na,Ce)(Nb,Ti,Ta)(O,OH,F)_7$) and in placer deposits as columbite-tantalite $(Fe,Mn)(Nb,Ta)_2O_6$) (Edwards and Atkinson, 1986). The columbite is so-named because the element niobium was formerly named columbium. The short name for columbite-tantalite (or niobium-tantalite) is coltan, the mining of which in recent years has become a major factor in the civil war in the People´s Republic of Congo and hence there has been considerable discussion about the ethics of the mining and using coltan from this source (Nest, 2011). Less common are the niobdates of calcium, uranium, thorium and the rare earth elements, examples of which are pyrochlore ($(Na,Ca)_2Nb_2O_6(OH,F)$) and euxenite ($(Y,Ca.,Ce,U, Th)(Nb,Ta,Ti)_2O_6$), which are often found in association with carbonatites (carbonate-silicate igneous rocks) (Lumpkin and Ewing, 1985).

Vanadium is found in 65 different minerals and in bauxite and fossil fuel deposits. Economically significant minerals are patronite (VS_4) and the secondary minerals vanadinite ($Pb_5(VO)_3Cl$) and carnotite ($K_2(UO_2)_2(VO_4)_2{\cdot}3H_2O$) that are generally mined from oxidised lead sulphide ore deposits. Vanadium is also extracted in association with iron processing. It is mostly mined in South Africa, NW China and Eastern Russia.

Nickel is found in magmatic iron-nickel-copper-platinum group ore deposits, formed in sulphide melts exolved from komatitic volcanics and can be found within magma chambers, sills, feeder dykes or lava channels. The most common minerals are pentlandite $(Fe,Ni)_9S_8$, millerite (NiS), but Ni is also found as a minor component in galena (PbS). In laterites nickel is found in nickeliferous limonite (Fe,NiO(OH)), and garnierite ($(Ni,Mg)_3Si_2O_5(OH)_4$). Nickel is mined in many countries, with the largest production in the Philippines, Indonesia, Australia, Russia and Canada. Nickel ore is also a source of palladium and platinum.

Molybdenum is used for specialty alloys for high performance machine parts and for tools. The most common molybdenum mineral is molybdenite (MoS_2) but it is also found in wulfenite ($PbMoO_4$) and powellite ($CaMoO_4$). Molybdenite is mined principally from porphyry deposits, and the oxide minerals from contact metamorphic deposits (powellite) and oxidised lead sulphide deposits (wulfenite) (Edwards and Atkinson, 1986). Molybdenum is mined as the principal ore and also as by-product of copper and tungsten mining. Molybdenum mining occurs mostly in China, USA, Chile and Peru.

Other metals are important for superalloys and special technical applications, such as **tantalum**. It is found in the same minerals and environment as niobium (see above). Most of tantalum mining is in the People's Republic of Congo and South Africa. **Zirconium** is most commonly found in the mineral zircon ($ZrSiO_2$) which is a trace mineral constituent of most granite and felsic igneous rocks. Due it its inertness, zircon persists in sedimentary deposits and is common constituent of sands. Zircon forms economic concentrations within heavy mineral sands from certain pegmatites, and some rare alkaline volcanic rocks. Eighty percent of zirconium mining is in Australia, Brazil, India, Russia, South Africa and the United States. **Indium** is rarely found as grains of free metal, and also occurs rarely as the minerals indite ($FeIn_2S_2$) and the secondary mineral dzhalindite ($In(OH)_3$). There are no purely indium mines. It is mined as a by-product of zinc and copper slimes that are derived from refining their ores. China is the leading producer of indium, followed by Canada, Japan and South Korea from from copper and zinc anode slimes. In nature **gallium** forms the rare mineral gallite ($CuGaS_2$). Gallium is extracted as a by-product from bauxite and the zinc sulphide mineral sphalerite (Zn,Fe)S. Most of the gallium production is in Chile from copper and zinc anode slimes. While some rare sulphite minerals of **germanium** can be found, including argyrodite (Ag_8GeS_6), briarite ($Cu_2(Zn,Fe)GeS_4$), germanite ($Cu_{26}Fe_4Ge_4S_{32}$) and renierite ($(Cu,Zn)_{11}(Ge,As)_2Fe_4S_{16}$), none are found in minable quantities. There are no purely germanium mines. Germanium is mined as a by-product of zinc-copper-lead-silver sulphide ore deposits and some unusually enriched coal seams. Most of the germanium production is at present in China from copper and zinc anode slimes, with minor production in Chile, Russia and USA.

Lithium has its highest concentration in granitic rocks and granitic pegmatites where spodumene ($LiAl(SiO_3)_2$), petalite ($LiAlSi_4O_{10}$), and lepidolite ($(K(Li,Al,Rb)_3(Al,Si)_4O_{10}(F,OH)_2$) contain the highest concentrations of lithium (Kamienski *et al.,* 2004). The major deposits for lithium mined at present are found in the dried evaporitic saltbeds of the Andes Mountains in South America where Chile, Bolivia and Peru meet. These formations have zones where lithium has become enriched. These are easier to extract than lithium bound in silicates. Tibet in the Himalayas has similar salt bed deposits but these remain relatively unexplored. The underground salt deposits in Central Europe may contain similar old buried evaporites with lithium in substantial amounts. Lithium is also found in bentonite, altered volcanic ash, as hectorite ($Na_{0.3}(Mg,Li)_3O_{10}(OH)_2$). Lithium mining is primarily in Chile, Bolivia, Peru and China (Tibet).

For chemical industrial synthesis, some metals are quite important. A special position is taken by the **Platinum Group Metals (PGM)** which include ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir) and platinum (Pt). PGM are some of the rarest elements in the Earth´s crust. They are primarily found in magmatic intrusions and extrusions where sulphuric melts containing chalcophile Ni-Cu-Co-PGM separate from the silicate component of intraplate komatiite and picritic magmas (Arndt *et al.*, 2005). The equilibrium concentration of all of the PGM is at least 10,000 times higher in sulphide melt than in coexisting silicate melt, because of the preference shown by the PGM for covalent bonding with sulphide ions (S^{2-}) in sulphide melts (Mungall and Naldrett, 2008). PGM ore deposits require the saturation of magma with immiscible sulphide liquid and the collection of that liquid in structural traps within magnatic systems. This occurs at the ultimate stages of sulphide-magma evolution, at temperatures between 200-700 °C where small volume sulphide melts evolve into mobile liquid solutions composed of PGM, Au, Ag, S, Te, Bi, Sb, As and Cl as major components. The final crystallisation products of these melts are composed primarily of platinum-group minerals such as PGM sulphides, intermetallic compounds and sulfosalts. PGM mining is primarily in South Africa and Russia, but smaller PGM deposits are also found in Canada, Russia and China. Platinum group metals are used as catalysts in many chemical processes, including production of pharmaceuticals and fertilisers. They are also important for fuel cells, where oxygen and hydrogen are combined to create electricity. Alternatives exist, but the performance of the platinum group metals is superior. **Cobalt** is found in sulphide ores in association with sulphur and arsenic in cobaltite (CoAsS), safforite ($CoAs_2$), skutterudite ($CoAs_3$), and glaucodot (Co,Fe)AsS (Holleman *et al.*, 2007). Cobalt is found in association with nickel in magmantic sulphide deposits, where it is a minor component in pentlandite ($(Fe,Ni)_9S_8$). Cobalt can also be found as a minor compound in copper sulphide minerals and also as cattierite (CoS_2). Where weathering of the sulphide ores has occurred, erythrite or cobalt-glance ($Co(AsO_4)_2 \cdot 8H_2O$) and spherocobaltite ($CoCO_3$) form.

Rare earth elements (REE) include the 15 lanthanides (often referred to collectively as Ln), scandium (Sc) and yttrium (Y). The lanthanides include lanthanum (La), cerium (Ce), praesodymium (Pr), neodemium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb) and lutecium (Lu). And they are actually not very rare, and small amount can be found almost everywhere. REE ores are primarily associated with magmatic carbonatites, rare volcanic rocks with >50 % primary carbonate minerals that originate in the Earth´s mantle, and peralkaline silicate rocks in intracontinental, anorogenic, extensional settings formed by pull-apart tectonics or asthenospheric upwelling (Chakhmouradian and Zaitsev, 2012). These magmas often form extensive igneous provinces associated with rifts, grabens, crustal lineaments and transcurrent fault systems. Carbonatites generally show enrichment in light REEs (LREEs) relative to heavy REEs (HREEs). Hydrothermal processes mobilise the REEs as fluoride and chloride complexes (LnF^{2+}, $LnCl^{2+}$), with the latter being more important (Willams-Jones *et al.,* 2012). There are over 40 types of REE minerals, but the most common include bastnäsite ($LnCO_3F$), and monazite ($LnPO_4$). Peralkaline granites and pegmatites often have xenotime ($(Y,Ln)PO_4$) that is rich in HREE. A further REE carbonatite mineral is loparite (Ln,Na,Ca)($(Ti,Nb)O_3$), which is also found in nepheline syenite intrusions and pegmatites such as the Kola Peninsula in Northern Russia. 97 % of the REE production is in China at present, from deposits formed both by hypogene and secondary processes (Kynicky *et al.,* 2012). They include the LREE enriched carbonatites from the Himalayan Mianning-Denchang orogenic belt, and metamorphosed carbonatite and polyphase mineralisation in the Bayan Obo deposit. In the Qinling orogenic belt the carbonatite REE patterns are flat, and there is HREE enrichement in residual clays in southern China.

2.5 Phosphorus

The annual production of phosphorus rock in 2013 is 210 million tonnes and is rising proportionally as global population increases. While minor concentrations of phosphorus bearing apatite ($Ca_5(PO_4)_3(F,Cl)$) are found in all igneous and sedimentary rocks, phosphorus is primarily obtained from ancient coastal sediments that have been uplifted to land. Phosphorus rich sediments form when upwelling of cold, low pH, PO_4-rich ocean bottom water occurs on coastal zones where it mixes on continental shelves with warmer river-fed Ca^{2+}-bearing coastal water that has a higher pH, resulting in the precipitation of hydroxyapatite; under these conditions its solubility is lower than at depth and phosphate precipitates via

$$3PO_4^{3-} + 5Ca^{2+} + H_2O = Ca_5(PO_4)_3(OH) + H^+ \qquad (2.22)$$

Significant amounts of phosphorus are associated with iron ore and rare earth ores, but these sources have high contents of heavy metals and need expensive treatment before use as a fertiliser. Many of the best reserves have already been mined, and extractable amounts that remain have significantly lower ore grade than earlier and a higher content of toxic contaminants like arsenic, cadmium, lead and traces of radioactive elements such as uranium. Current estimates suggest economic phosphorus supply may be severely depleted over the next 100 years (Cordell *et al.*, 2009, 2011a,b; Oelkers and Valsami-Jones, 2008) and phosphate rock is probably close to or at peak production at present (Ragnarsdottir *et al.*, 2011; Sverdrup and Ragnarsdottir, 2011; also see below) and therefore while half of the original resource is left, it is mostly at lower grade and has significant levels of heavy metal contamination. The consequence of phosphorus depletion is discussed later. Phosphorus is primarily mined in Morocco, which has by far the largest deposits. Other mines are found in USA, Russia and China.

2.6 Fossil Fuels

2.6.1 Coal

The annual production of coal is 7.3 billion tonnes. Coal is formed when peat is altered physically and chemically through a process often referred to as "coalification," where peat undergoes changes with time as a result of compaction, bacterial decay, temperature and pressure. Peat forms in a waterlogged environment where plant debris accumulates in peat swamps and peat bogs. Because of waterlogging, available oxygen is used up by the decaying process, resulting in a very slow anaerobic decay. Continued burial causes increased temperature and pressure, and with time complex hydrocarbon compounds break down and alter. The gasesous alteration products, including methane, are expelled from the deposits and the solids become more and more carbon-rich. The stages of alteration go from plant debris to peat (60 % carbon), lignite (60-71 % C), sub-bituminous coals (71-77 % C), bituminous coal (77-87 % C), anthracite coal (87-99 % C) to graphite (100 % C), which is a pure carbon mineral. Bitumious coal forms at a depth of 2.5 km and is stable to 170 °C; anthracite forms at a depth of 6 km and is stable up to 300 °C. The pressure and temperature to achieve graphite is ~500 MPa (5 Kbar) and 300-500 °C (*e.g.*, Ross and Bustin, 1990) and is the reason

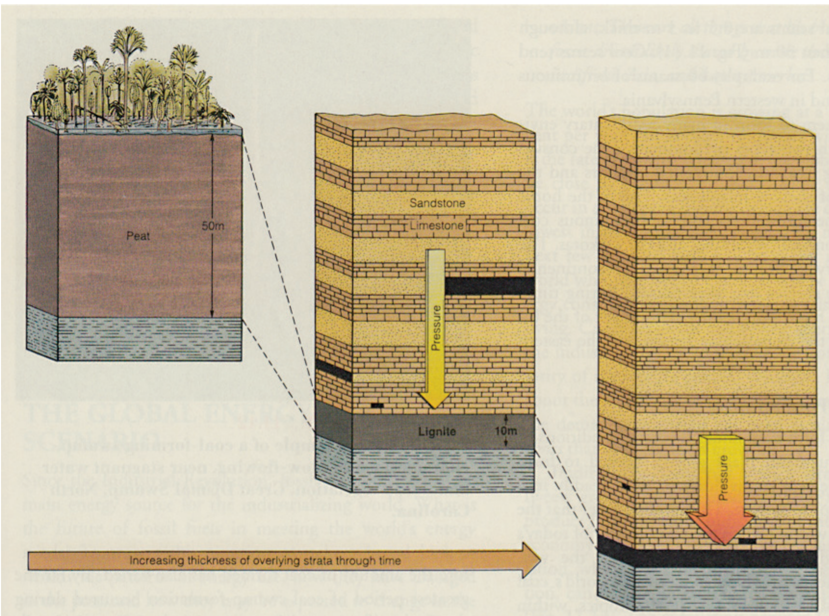


Figure 2.3 Schematic formation of coal from peat (after Murck *et al.*, 1996).

why graphite is very rare. Approximately 10 metres of peat result in 1 metre of bituminous coal. The coal formation process generally takes millions of years (Fig. 2.3). Major coal deposits have been formed in nearly every geological age since the Carboniferous (350-250 million years ago). Coal is energy dense, with a heating value of about 24 MJ kg^{-1}. When burning coal, CO_2 is formed and emitted into the atmosphere. Most of the world´s coal is now produced in Auatralia, China, USA, Russia and India.

2.6.2 Oil and natural gas

The annual oil production is 3,700 million tonnes. Oil and gas form when organic matter such as dead algae settle on the oceanic floor and get buried with sediments (Fig. 2.4). It is pressure and temperature that affects the proportions of oil and gas formed – as depicted in Figure 2.4 which shows the so called "oil window." Oil and gas forms in areas at temperatures of 50-130 °C and typically at depths ranging from 1,500 m to 6,000 m, depending on the temperature gradient.

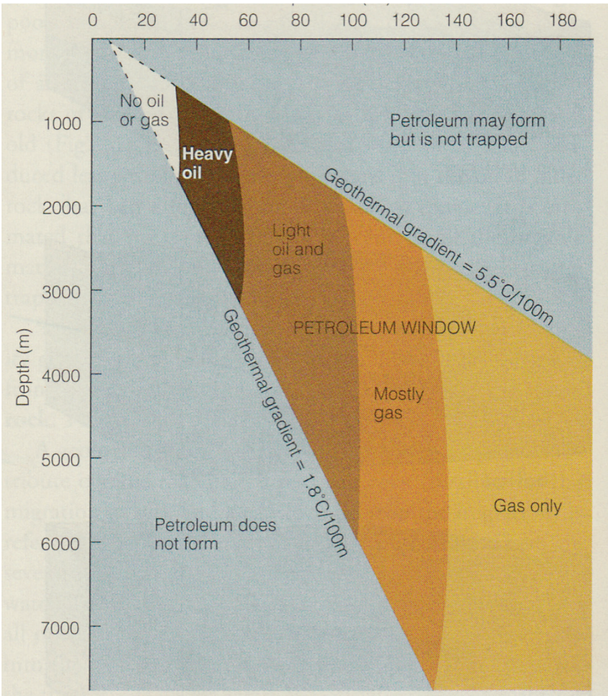


Figure 2.4 The "petroleum window" is the combination of depth and temperature within which oil and gas are generated and trapped (after Murck *et al.*, 1996). The X axis gives temperature in °C.

If the temperature is significantly higher, only gas forms. Oil and gas generally migrate upward until they are trapped beneath formations that have low permeability. It is from these formations that oil and gas can be mined by drilling into traps. The largest oil producing countries are Saudi Arabia, Venezuela, Russia, Canada, United States, Norway, Quwait, United Arab Emirates, Iraq and Iran. For oil reserves considered below we include oil, shale oil, tight oil, tar sands and shale oil, that are regarded as technically recoverable below 400 $/barrel oil equivalent. In gas we include similarly all qualities of natural gas; gas, sour gas, shale gas, coalbed gas, and tight gas (for which fracking is needed for recovery). Coal implies anthracite, hard coal, soft coal, brown coal and carbon shale.

2.7 Sand, Gravel and Rocks

Globally an enormous amount of sand, rocks and gravel is used to build the infrastrucutures in society, including housing, roads, and bridges. More than 15 billion tonnes of such material are moved annually. Man has become a geologic force that moves more than 10 times more material than all of the geological forces together (Hooke, 2000; Wilkinson, 2005). 70 % of the material moved is through agriculture, but the remaining meterials are the natural resources that are mined and many of them are addressed in this volume. You would think that sand resources are unlimited, but recent reports show that in some parts of the developing world, people sneak to the shore at night and dig up beach sand to sell to companies that are building infrastructure in other parts of the globe. On the Cape Verde Islands are examples of beach sand being mined in a clandestine manner, leaving the beaches rocky and unattractive.

2.8 Mining Meteorites and Other Planets

Nickel and cobalt are characteristic minor components of meteoric iron meteorites. When dreaming about obtaining resources for meteorites, the total amount of meteorites hitting the Earth annually needs to be compared with the current annual production. Total amount of metorites coming to Earth each year is 16,000 tonnes, of which iron meteorites are only a small fraction (20 %). This means the total iron is about 2,500 tonnes, nickel 600 tonnes and cobalt 100 tonnes. Compare this with the annual production rates of these metals of 1.4 billion tonnes of iron, 2 million of nickel and 68,000 of cobalt. Needless to say, meteorite mining will never keep up the current rate of mining on Earth. As for other planets, they are comprised of silicate rocks and nowhere has there been evidence of hydrothermal activity except perhaps on Mars. Mars is relatively close at 55 million km away from Earth, but with no fuelling stations on the way. The trip to Mars and the return takes 5-10 months on the shortest route, and there is no existing technology to return to Earth, let alone to carry the quantities of metals we currently mine, so another dream goes out the window.

3. ASSESSMENT METHODS

To determine the future of global resoures we need to determine the current availability and consumption rates.

3.1 World Resource Use

A schematic diagram of world resource use is depicted in Figure 3.1. Reserves are extracted, they are sold as market stocks, used in society, scrapped and lost or recovered. The fluxes were estimated using scientifically published sources together with less formal industrial information available to us. When *Harald* was a young engineer in Sweden, he learned about pollution cleanup and treatment. Today this is called end-of-pipe solution; it does not have the high status it once had. More recently, focus has moved on to pollution prevention by smart design and cleaner production; we have thus moved up the causal chain as illustrated in the causal loop diagram (Fig. 3.1). Even more recently, focus has been on cleaner production and design for less resource use. Less consumption, however, always ends up as more; even if everyone consumed less, as if consumer goods were produced more efficiently, demand keeps on going up faster than resource use, and therefore total consumption rises. Population size is a major driver in the system. Thus, the population of the Earth sets the total volume of resouces we use.

The impact of consumption on resource use is governed by a very simple equation by Ehrlich *et al.* (1992). The impact variable (I) of the Ehrlich-equation stands for "impact" or for the consumption rate in our version of it. We can then write:

$$I = P * A * (1-X_R) * E \quad (3.1)$$

The equation states that there are four different parameters we need in order to adjust the consumption rate to a sustainable level:

1. A is affluence or net consumption per capita,
2. P represents population or more specifically the number of consumers,
3. X_R stands for the degree of recycling of the amount supplied to society, and
4. E is the resource efficiency of producing the affluence A.

By recycling and improving efficiencies and yields (E), we may reduce net consumption per capita (A), however if that is less than the increase in population (P) or recycling (X_R), we are not conserving resources. The larger the efficiency, the lower the impacts. Our observation is that this is the case we can see in the world today. The improvements that can be made on recycling (X_R) and efficiencies (E) have clear limitations, whereas so far the population (P) has been steadily going up, to a point where the consumption volume has exceeded the planetary supply capacity. E can only move between 0 and 95 % in reality and it has linear impact on a system that can grow exponentially. X_R has a value for iron in the 25-50 % range, and values above 80 % have not been realistic except for precious metals that are very valuable and do not corrode. For iron, a substantial amount is lost irreversibly through corrosion. Zinc is a critical element for curbing corrosion of steel and iron by galvanisation, and if zinc were to become scarce, corrosion would have to be counted in at substantially higher rates. Thus, population management must be a part of sustainability policy and strategy, and any policy not dealing with population size will be insufficient. The FoF-model is an integrated population dynamics and phosphorus supply model that was used to prepare for the global population size scenarios underlying the demand calculations as below (Ragnarsdottir *et al.*, 2011; Sverdrup and Ragnarsdottir, 2011).

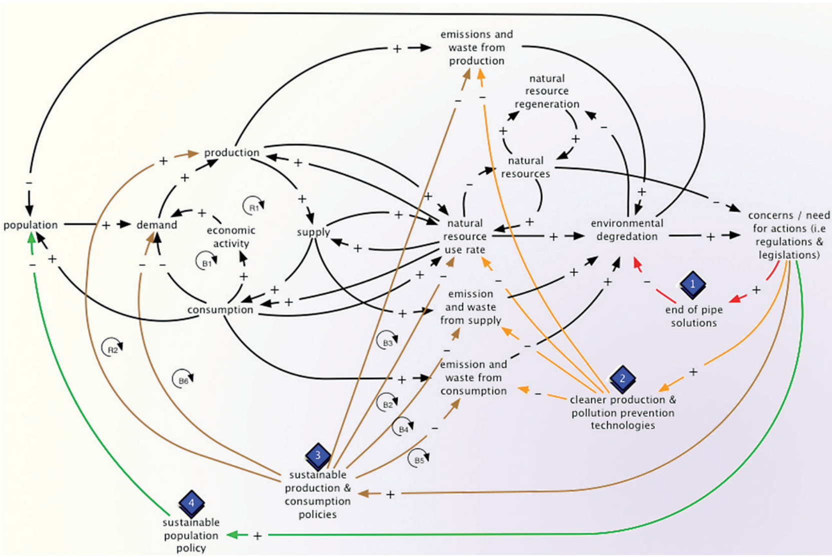


Figure 3.1 Sustainability of resource use has moved from end-of-pipe solutions (fighting pollution <1>) to the root cause (overpopulation <4>). Attention has over time moved from end-of-pipe solutions <1> to more focus on recycling and clean production <2>, slimmer consumption patterns and sustainable production <3>. Ultimately the issue of population size must be addressed <4>. B1-B6 are different balancing loops that can be introduced into the system by policies (Ragnarsdottir *et al.*, 2012).

The capacity to extract resources has increased with technological development. This has a deceiving effect by offsetting the feedback from exhaustion of the resource. The final result is that it looks as if the resource is increasing. Removing early warnings of exhaustion may cause exhaustion to apparently set in unnoticed. This has been observed in fisheries where the increase in catching technology has gone faster than fish stock decline. The result has been total near collapse of the fisheries without warning once the stocks were fully depleted. This is demonstrated in Dennis Meadow´s 2001 FishBanks© game which is widely used in systems dynamics teaching – for example by *John Sterman* at MIT (http://mitsloan.mit.edu/sustainability/profile/fishbanks).

There are delays in the system. A maximum in prospecting typically occurs about 40 years before the production peak (Sverdrup *et al.*, 2013a). Because of rising resource prices, the income revenue from resource extraction commonly occurs 10-20 years after the production maximum. The system collapses occur about 15-30 years later. Over time, sustainability of resource use moves from end-of-pipe solutions (fighting pollution) to the root cause (overpopulation; Fig. 3.1).

We have compiled earlier estimates of the Earth's ability to feed people. Many of the assumptions taken in these earlier studies violate the basic principles of living on a finite planet. We have made a large compilation, building on the compilation by Cohen (1995), and not re-listed all references here. Figure 3.2 shows estimates of the population the Earth can sustain using our total compilation; the estimates were made by researchers from 1675 and to the present. The diagram consists of their low (blue and open circles) and high (red dots and red line) estimates. The black line is the past record of the Earth's population, and beyond 2014 it is the UN Business As Usual estimate, made assuming endless food and resources. The figure demonstrates that the predicted trend for the carrying capacity is becoming lower and lower (Fig. 1.12). In contrast, the actual population is increasing. The three lines are the UN population estimate assuming no food limitation, our runs with the FoF model described later, with food limited by phosphorus, shows an earlier population decline. The lowest curve is the population curve from the *Limits to Growth* study. The data show that there is a long-term convergence for the predicted Earth population carrying capacity estimates; the sustainable global population is by many considered to be in the range between 1.5-2.5 billion people for the low estimate, and that the high estimates converge in the range of 4-6 billion people. We conclude that the world is at population overshoot, and therefore not much time is left to create the necessary change. Figure 3.2 suggests that there will be serious challenges in the near future (again, see Fig. 1.12). The population simulations from the FoF model, now a submodule in WORLD, was used to estimate demand in the assessments for metals discussed later.

Politicians across the world do not like to discuss the global population size issues; it would be fair to say that there is a taboo on population discussions. We have both been to many conferences to see that this is so, and the antagonism towards the question is real. At UN conferences the issue cannot be discussed because religious and conservative forces block every attempt. The reasons for this are several, but since global population size is such a central component in magnitude for resource use, at some point this issue must be tackled regardless of whether we want to or not. *Paul Ehrlich* (Ehrlich and Ehrlich, 2013) at Stanford University once said "either we deal with the issue, or it will deal with us."

Population can be influenced in many ways, one way that appears to work, within the frame of democracy, is giving women their full human rights and making sure they have access to education. Unfortunately, that issue is very difficult for many, as demonstrated by recent blocking by Saudi Arabia of the Swedish foreign minister, who intended to address human rights at the Arab League summit, resulting in a full blown diplomatic crisis between the two countries.

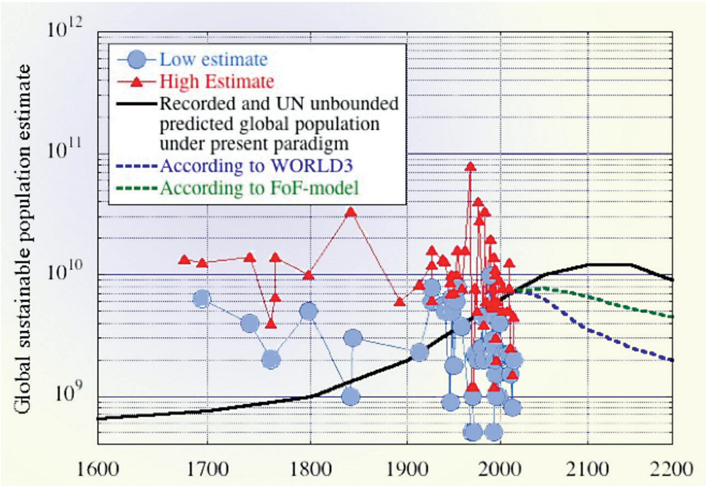


Figure 3.2 Estimates of the population the Earth can carry, made between 1675 and the present by different researchers as compiled into a diagram by the authors. The diagram consists of low (blue dots) and high (red triangles) estimates. The black line is the past record of the Earth's population and beyond 2014 is the UN Business-As-Usual scenario. The UN estimate (black line) is assuming no resource limitations.

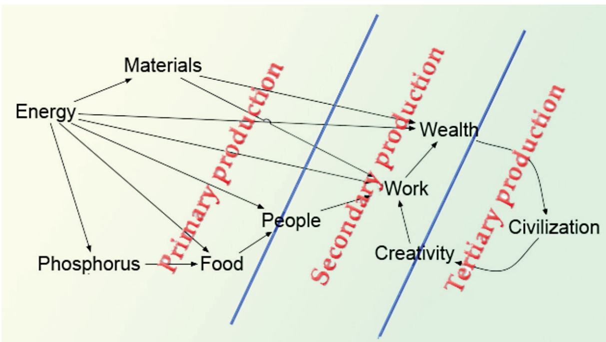


Figure 3.3 Trophic levels in societal systems are analogous to ecosystems. The upper levels depend causally on the levels below.

3.2 Efficiency versus Resilience

In recent years efficiency and resilience have become much discussed in the sustainability arena. Efficiency comes from technological development whereas resilience is a term from ecological research. Improved efficiency implies faster turnover, assumes no disruptions in the production chain and less stocks-in-waiting. Resilience implies that a system is resistant to changes and variations in key drivers and parameters. Such a system has buffers that can absorb changes for a while, as fall-back positions, stocks larger than the amount day-to-day operations require and that processing units are autonomous. This often comes at the cost of lower efficiency in the overall system, with larger stock-in-use and longer transition times. Thus, resilience normally comes as a trade-off against efficiency. Resilience is a part of long-term system sustainability, whereas efficiency is part of less resource use and short-term economic sustainability. The two concepts may sometimes offer goal conflicts.

The material and energy metabolism of society is like an ecosystem with different trophic levels. Resources are the nutrients of the human social ecosystem. This is illustrated in Figure 3.3. The human society is overlaid on a trophic chain, where the secondary trophic level depends on the primary production in the first level, and where the production of culture and complex services in the tertiary trophic level depends on the production on the second level.

Thus, "decoupling" in the meaning of disconnecting the trophic levels of the system is not possible as we can see from Figure 3.3. Increased efficiency of energy and mass transfer between the levels is possible, but is limited by constraints on the maximum possible efficiencies. For tertiary production to be sustainable, the underlying secondary production must be sustainable and show a surplus large enough to support the third trophic level. The secondary trophic level will be sustainable if the primary production level is sustainable and has a surplus large enough to support the second level. Third level resource consumption volume is thus less than the surplus in second level. The surplus in the first trophic level minus the second level volume, give maximum availability on the third trophic level. The second level is maximised by the surplus in the first trophic level. Figure 3.1 shows how measures to manage sustainability of resource use need to move from end-of-pipe solutions (<1>) to the root cause (sustainable population policy <4>). The conclusion from this analysis is that policy making cannot focus on one trophic level alone, but must see all three levels as one complex system.

3.3 Quantitative Methods

We have used four different methods of assessing resource availability throughout this volume. These are in order of increasing complexity: burn-off time (Business As Usual), peak discovery early warning, Hubbert´s model estimates, and system dynamics modelling; these are described below.

1. **The burn-off time** is a worst-case scenario, and gives an order of magnitude indication for how long the total extractable resource will last. It does not consider consumption, and neither growth nor market-price. The burn-off time is defined as the estimated extractable amounts divided by the present net yearly extraction rate. This is an underestimate in a world with a rising population, but a reasonable estimate in a stagnant economy, and an overestimate in a growing economy. The burn-off is defined as:

$$\text{Burn-off time} = \frac{(\text{Total extractable amount})}{(\text{Present production})} \qquad (3.2)$$

   The burn-off time is an indicator, rather than a robust time estimate, and should be used as such. Many metals and materials have over a number of years stayed at a burn-off time of about 50-100 years. The indicator gives us a sense of a time-frame until the particular resource is depleted, and is a diagnostic variable to evaluate the urgency of the situation at hand.

2. **Peak discovery early warning**. Earlier work has shown that there is a systematic shift of 40 years between the peak discovery and the production peak (Heinberg, 2001, 2005, 2011; Bardi, 2008; Ragnarsdottir *et al.*, 2012; Sverdrup *et al.*, 2013a):

$$\text{Peak production time} = \text{Peak discovery time} + 40 \text{ years} \qquad (3.3)$$

3. **Hubbert's model estimates** of peak production and time to scarcity. The oil engineer *King Hubbert* at Shell Oil Corporation, developed what is referred to as the "Hubbert curve" (Hubbert, 1956, 1966, 1972, 1982) to predict the lifetime of oil wells and oil fields. He showed, using observed production data for oil wells as well as uranium and phosphate mining, that all finite resource exploitation follows the distinct pattern of the Hubbert curve which has the shape of a normal curve. This shape has a scientific explanation, derived from the nature of a finite resource, as shown in Figure 3.4; *Hubbert* verified his model on field data several times over. The purpose of the figure is to show that despite the Hubbert curve being empirically determined, there is a mechanistic explanation for it. Each oil field has a fixed mass and volume, and it is given as the area under the curve (barrels or tonnes). A flow chart (Fig. 3.4A) is shown at the top of the figure with the corresponding causal loop diagram beneath it (B).

The system in Figure 3.4 is based on two stocks, one known resource, backed by a hidden resource that can be found by prospecting and finding more resource, converting "hidden" to "known". As the hidden resource, which is finite, dwindles, the "known" resource gets replenished for a short time until the "hidden" resource is exhausted. Thus as the extraction loop exhausts the "known" resource, it gets backfilled a few times by prospecting that brings more

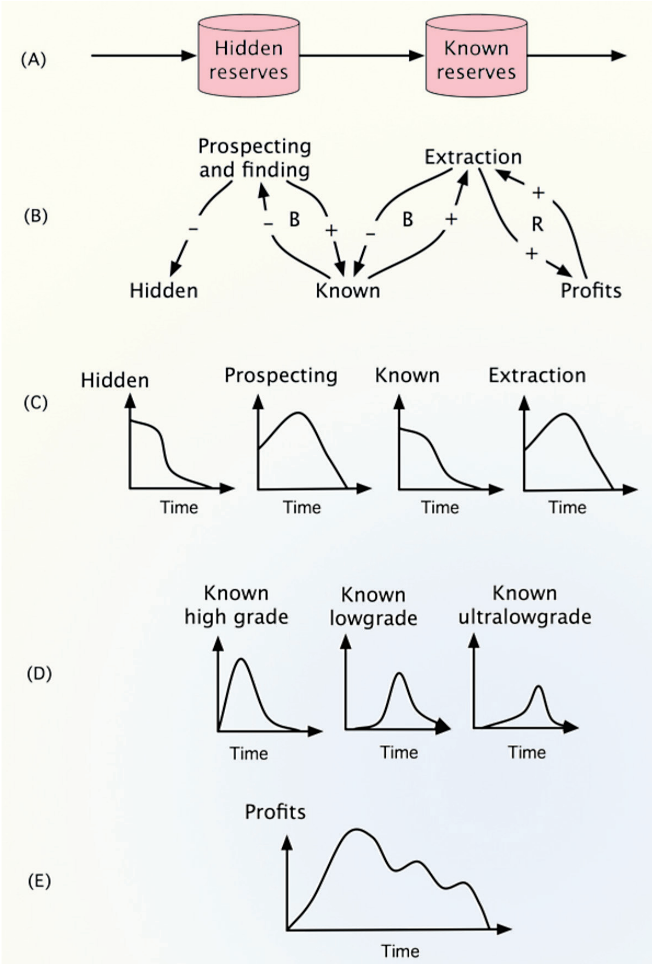


Figure 3.4 Flow chart and causal loop diagram that explains the normal curve-shape discovered by Hubbert (1956, 1982). The system is based on two stocks, one known resource, backed by a hidden resource that can be found by prospecting, so converting "hidden" to "known" **(A)**. As "hidden" dwindles, "known" does get replenished until "hidden" is exhausted. As the extraction loop exhausts the "known", it gets backfilled, overlying several individual "rise and fall" curves to yield the sum of several Hubbert curves. The causal loop diagram is shown in **(B)**. The behaviour of the components is depicted in **(C)**. If we consider three types of resources in the system; high-grade, low-grade and ultralow-grade, we get three peak behaviour curves **(D)**, which may be overlayed to show the final total production, expressed as profits **(E)**. The results of Hubbert curves and dynamic models, yield similar results for time to scarcity.

"hidden" resource over to "known" (B, C), and overlying several individual "rise and fall" curves (D) yield the typical Hubbert curve (E). The system is driven by profits, as mining leads to profits and more profits drives more mining, whereas the exhaustion of the finite stocks terminates it. The diagrams in Figure 3.4 show the relationship between the parameter at the arrow-head over time. The diagrams depict what happens with new resources becoming known after prospecting (D), the bottom diagram (E) (sum of several normal curves) shows the sum of all the small diagrams, showing extraction as a function of time. Some economists disagree with this approach (*e.g.,* Goklany, 2009), however, it is a robust consequence of mass balance, and field-tested against observed data from oilfield, phosphorus and uranium field exploitations with good success.

We have also been told several times that: *"….you should know, Hubbert's curves do not apply to metals!"* Somebody once told *Harald*´s grandfather *"You cannot smoke a pipe in a tuxedo!"* He retorted drily back *"I have tried, it worked!"* Our answer here is the same, we have tried the Hubbert's curves using data for extractable amounts for more than 40 metals, minerals and materials, and the tests on field data show us that Hubbert's curves work excellently on any non-renewable geological resources subject to independent mining from a deposit. For metals and materials that are dependent on primary metal or material extraction, the Hubbert' model must be a derivative of that of the mother substance. In science, successful field tests win the argument. We conclude that the arguments of "Hubbert skeptics" have been disproven by the evidence so many times and that it can be used to provide useful insights.

The Hubbert's curve is defined by the simple equation for production where t is time and t_{max} is the time of the peak production, URR (ultimately recoverable reserve) is the size of the whole resource that eventually is extracted, and b is the curve shape constant. The annual production is given by:

$$P(t) = \frac{2 * P_{MAX}}{1 + \cosh(b * (t - t_{MAX}))} \tag{3.4}$$

where P_{MAX} is the maximum production rate, and P(t) is the production at time t. If we can distinguish several independent deposits or groups of extractable resources in different deposits, these may be modelled individually and the results summed up. The curve will be consistent with the estimates of the extractable amount. The estimate of t_{MAX} is sensitive to the accuracy of the estimate of b. URR is given by:

$$URR = 4 * \frac{P_{MAX}}{b} \tag{3.5}$$

This may be re-written to yield an estimate for the time of the peak if we know the overall average b and the maximum production or the URR of the resource:

$$t - t_{MAX} = \frac{1}{b} * \ln\left(\frac{\left(4 * \frac{P_{MAX}}{P} - 2\right) \pm \sqrt{\left(4 * \frac{P_{MAX}}{P} - 2\right)^2 - 4}}{2}\right) \quad (3.6)$$

This can be used to estimate the time after the peak to scarcity, as we will do later. Once t_{max} and P_{max} have been empirically determined, then the predictions are both accurate and robust. The Hubbert's curve model has been verified on field data from oil, coal, phosphorus and metal mining, demonstrating that it works well (Hubbert, 1956, 1966, 1972; Greene *et al.*, 2003; Bardi and Yaxley, 2005; Hirsch *et al.*, 2005; Aleklett *et al.*, 2012; Sverdrup *et al.*, 2013a, 2014a, 2014b). In case n curves are used to generate the full cumulative production curve, we get:

$$m(t) = \sum_{i=1}^{i=n} m_i(t) = \sum_{i=1}^{i=n} \frac{URR_i}{1 + e^{-b*(t - t_{MAX.i})}} \quad (3.7)$$

and for the total URR:

$$URR = \sum_{i=1}^{i=n} URR_i = \sum_{i=1}^{i=n} \frac{4 * P_{MAX.i}}{b_i} \quad (3.8)$$

If we cannot set b accurately with one curve, then t_{MAX} can be graphically determined by curve-fitting. The composite curves drawn in this study are adjusted so that the amounts under the curves correspond to the best estimate of the Ultimately Recoverable Reserve (URR). Figure 6.3 later in this *Perspective* illustrates the curve for Norwegian oil that was constructed using a Hubbert's function several times and adding them up as is shown in the figure.

3.4 System Dynamic Modelling

System dynamic modelling was used to reconstruct the past for explanatory and testing purposes, to estimate the time to production maximum, and to study the rate of decline to resource scarcity after the maximum production rate has been passed. The flow pathways and the causal chains and feedback loops in the system are mapped using systems analysis, and then the resulting coupled differential equations describing these feedbacks are transferred to computer codes for numerical solution, using an environment such as STELLA®. The methods are those of systems analysis and systems dynamics, incorporating mathematical modelling of complex systems (Senge, 1990; Sterman, 2000; Senge *et al.*, 2008; Haraldsson and Sverdup, 2004; Meadows and Wright, 2008). For dynamic modelling, elaborate flow chart and causal loop systems analysis charts are needed.

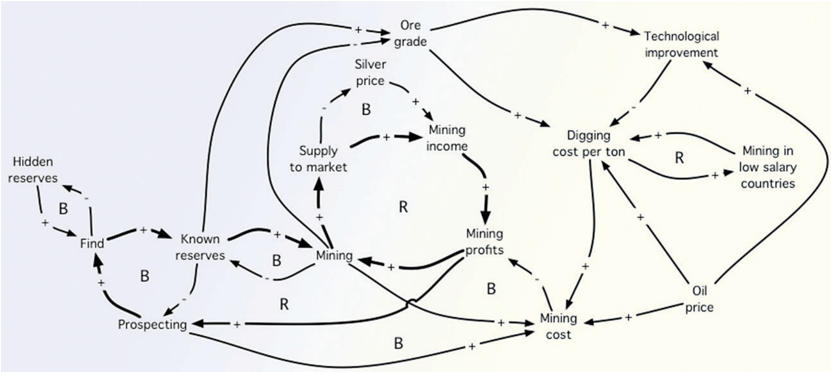


Figure 3.5 Causal loop diagram for the mining process. The mining process is mainly profit driven. The profit depends on product supply rate, supply costs and product price. For further description of the diagram see text.

When the basic assumption of constant boundary conditions is no longer valid, then static methods like methods 1-2 described above are no longer valid and cannot be used for predictions. Then fully integrated, process and mechanism-oriented dynamic models are required. An example of a casual loop diagram for mining is shown in Figure 3.5. The arrows represent causal links, between the cause and the effect. These diagrams are referred to as "causal loop diagrams" and are used when the system dynamics is analysed or the system is to be modelled. B implies a balancing loop, where an increase at one parameter comes back as a decrease. R is a reinforcing loop where an increase returns a further increase. Systems analysis of the price mechanism used here is given in Figure 3.6 for the Comodity Exchange in London. The figure shows how the prices of resources are determined by market forces as demand and price and production dynamics like supply, mining, recycling and resource size and quality (ore grade).

3.5 Scarcity of Resources

During extraction of resources, the best ore grades are extracted first, because this is the easiest and has the lowest cost. An effect of this is as extraction progress through the extractable amount, the ore grade will decline. Eventually, more and more effort must be put in to keep the extraction rate up, and at some point it will also decline. Then the resource may become scarce, as there will be more people wanting to buy larger amounts than the system can supply. Then the commodity price will go up as long as the use of the metal gives larger benefit than the cost of getting it. Only when the benefit no longer can warrant the price to be paid, the market will collapse and extraction will cease. Because of this, resource prices are diagnostic parameters that need to be monitored. Under such dynamic conditions, traditional econometric models are invalid and cannot be used for predictions. Then fully integrated, process- and mechanism-oriented dynamic models are required. However, econometric models may provide useful estimates of single internal components of a larger integrated dynamic model.

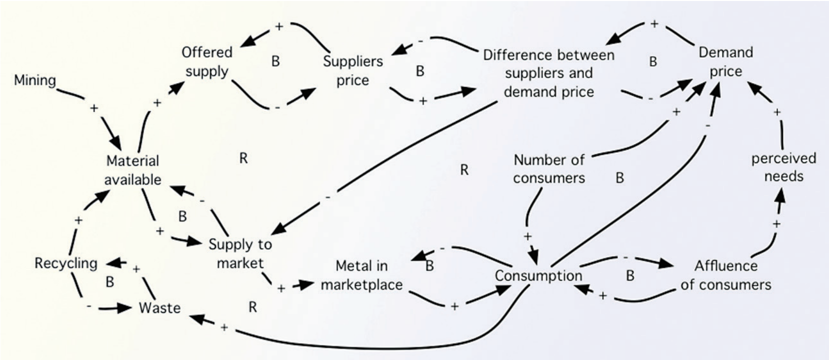


Figure 3.6 The price mechanism at the COModity EXchange (COMEX) in London, New York and Tokyo. Causal loop diagram for the basic price mechanisms as operated within the gold metal exchanges. Every day the demand proposals and supply proposals are compared, when they are not equal in amount, the price is increased when demand is larger than supply, or vice versa. When supply equals demand, the price is fixed. Throughout the day, this is done repeatedly. In a model, supply would be related to price with a characteristic price-supply curve and demand with a price-demand curve. R is a reinforcing loop, B is a limiting loop.

We have developed systems dynamics based sustainability assessment models since 1988 (Sverdrup and Warfvinge, 1988a,b, 1995a,b; Sverdrup *et al.*, 2005; Sverdrup and Ragnarsdottir, 2011; Kifle *et al.*, 2012; Sverdrup *et al.*, 2013a,b,c, 2014a,b). Exponential growth and market price mechanisms are incorporated in our process-oriented models. Basically, for all the metals, mass balance applies, requiring that:

$$\text{Flux through society} = \text{Mined} + \text{Recycled} \tag{3.9}$$

The mass balance for society is:

$$\text{Mined} + \text{Recycled} = \text{Accumulated} + \text{Recycled} + \text{Lost} \tag{3.10}$$

This can be rearranged into a classical differential equation for resource use with time where recycling is eliminated:

$$dM/dt = \text{Accumulated} = \text{Mined} - \text{lost} \tag{3.11}$$

Here we can see one very useful aspect to remember: societal services and benefits are related to both the accumulated resources and their flux through which it is mined plus recycled. The accumulated resource provides benefit when it is used in infrasructures. We then get for benefits:

$$\text{Benefit} = w * \int (\text{Accumulated} + \text{Recycled} + \text{Lost})\, dt \tag{3.12}$$

Where M stands for mass of the resource, w is a value function for the resource and t is for time. However, resource consumption is related to that mined minus the amount lost irreversibly:

$$\text{Consumption} = v * (1 - X_R) * \int (\text{mined} - \text{lost})\, dt \tag{3.13}$$

Where v stands for an efficiency factor and X_R is the fraction recycled. "Mined" is what we take from the reserves, that is the production of new metal from something that is not metal. "Accumulated" is metal kept in society and not lost, and "Lost" is what is lost in such a way that we cannot retrieve it again. "Recycled" are the metals we circulate in the system (Fig. 3.7). The more we recycle, the less we need to mine to keep the same amount in society. Finally, we need to address the issue of a far too large global consumption; one of the major causes of which is the size of the global population. Consumption is governed by a very simple equation:

$$\text{Consumption rate} = \text{Net consumption/capita} * \text{Number of consumers} * (1 - X_R) \tag{3.14}$$

The equation states that there are three different parameters we can elaborate to adjust the consumption rate. X_R, the degree of recycling of the material, number of consumers, and net consumption by consumers. The real flow to society becomes amplified by recycling, because part of the outflow becomes returned to the inflow (Fig. 3.7). The price in the market reflects several aspects and limitations. One is that the price will not go below the production cost for any extended period of time. This production cost depends on several factors:

The price of energy since production requires energy for mining, moving rock, crushing, smelting, processing, refining, transporting and fabricating metal into products.

The ore content of metal, indicating how much rock must be moved and processed in addition to the metal. The metal ore grade has been shown to be steadily decreasing historically (Mudd, 2007, 2009, 2010).

The amount and quantity of other metals that can be gained at the same mine. As ore grades go down other metals extracted simultaneously become more important for contributing towards income.

For a long time the oil price was so low that the first component was considered almost insignificant for mining operations, but with the combination of dwindling ore contents and increasing oil prices, it has become important. We may derive an estimate of the sustainable population from just mass balance. This leads to the equation given as the minimum for all the metals assessed in the study:

$$\text{Sustainable population size} = \min_i \left\{ \frac{\text{Sustainable Metal Use}_i * \left(1 - X_{R,i}\right)}{\text{Consumption per capita}_i} \right\} \tag{3.15}$$

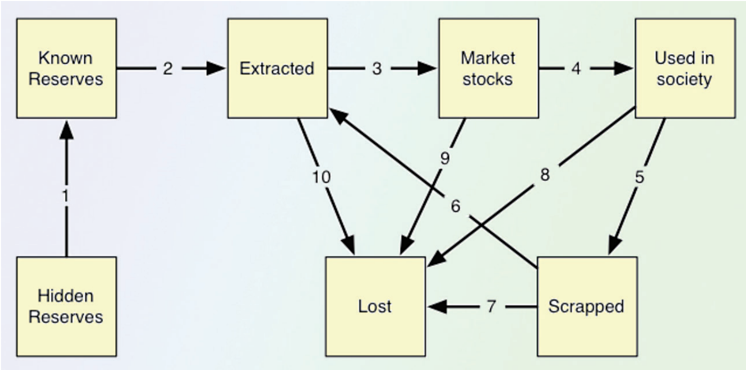


Figure 3.7 The flow of resources in society. Hidden reserves are where all non-renewable fossil resources originate. To become known they must be discovered, by chance or by prospecting (1). The known resource can be mined (2, 3), with some losses as no extraction is perfect (10) and put to the market, where it is transferred to society (4) or a part may be lost (9), with further losses (8). The resource is used in society, and depending on use, eventually scrapped (5). From the scrapped resource, we may recover part (6) or lose part (7). Here lost is meant lost in such a way that we cannot recover it again.

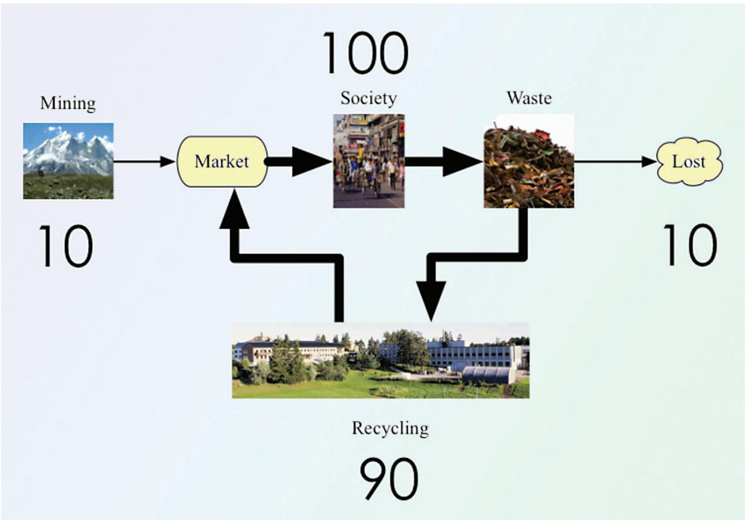


Figure 3.8 Recycling magnifies the net resource impact, getting "more bang for the buck." Instead of mining 100 % as an input to the market, only 10 % needs to come from mining if 90 % is from recycled resource.

In these equations the real flow to society becomes amplified by recycling (Fig. 3.8), because part of the outflow becomes returned to the inflow. Recycling will be one of the main policy tools as we will see later. The maximum sustainable mining rate is given by the size of the mineable material and how long it must last:

$$\text{Sustainable mining rate per year} = \frac{\text{Presently recoverable amount}}{t_{DOOM}} \qquad (3.16)$$

Where t_{DOOM} is the time to "doomsday" in years from now, implying after this point in time, the society does not have, does not want to or cannot get any natural resources, and thus will be in very deep trouble.

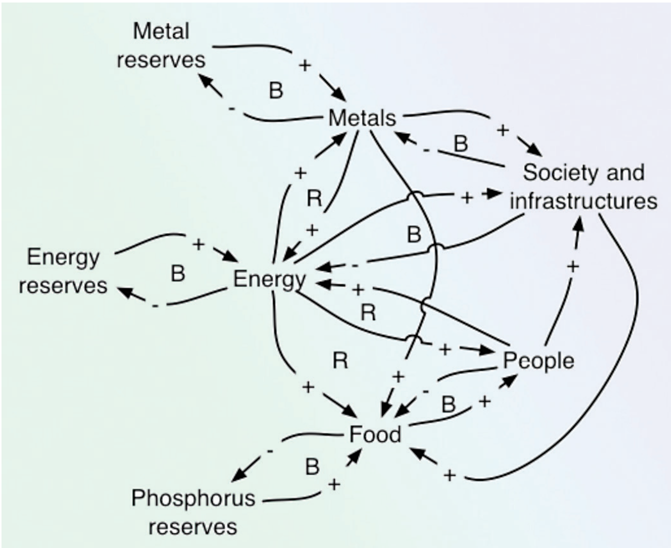


Figure 3.9 The basic feedback structure in metal, energy, food use and consumption.

Figure 3.9 shows the basic causal feedback structure for metal, energy, food use and consumption. The system has its own internal feedbacks, leading to population growth and increase in the use of metals.

4. THE GLOBAL CAPACITY FOR SUPPLY

The different metal and energy models exemplified here are all part of a larger programme, where we are building a global systems model called WORLD. The WORLD model attempts to model the world systems in a way similar to what the World3 model (Fig. 4.1) once did (Meadows *et al.*, 1972, 1992, 2004; Randers, 2012), however, with a more complete description of each individual and significant resource. Figure 4.2 shows an overview of the most important modules in the WORLD model. It takes several parts from World3, but has the resource part strongly expanded. The WORLD model does contain many other modules as well (Sverdrup *et al.*, 2013c), but these are outside the scope of this study and will not be further described no 2009 reference here. WORLD contains the submodels ALUMINIUM, STEEL, BRONZE, ENERGY and FoF that have been used for this work. The BRONZE model is a copper-zinc-lead model that also produces the dependent metals germanium, gallium, indium, selenium, antimony, bismuth and tellurium.

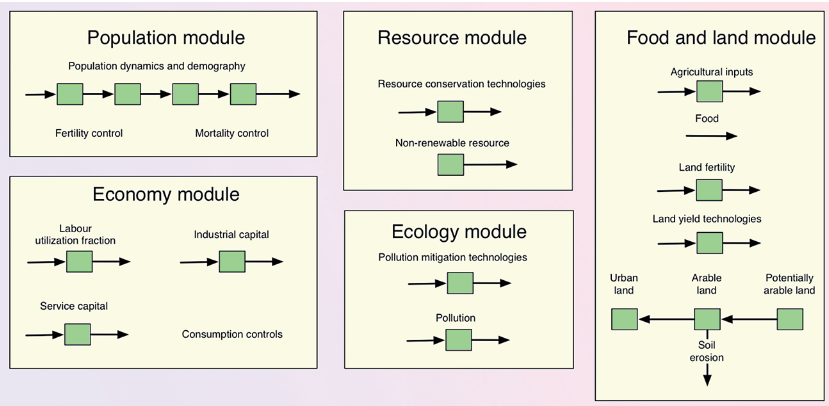


Figure 4.1 The World3 model by Meadows *et al.* (1972). The World3 model inspired the design of the WORLD model.

4.1 Metals

It is a fact that metals are limited on the Earth (Ragnarsdottir *et al.*, 2012). It is also generic wisdom that individual mines eventually go empty with time. *Harald* likes to use the analogy of drinking Soda Pop out of a bottle like he did at birthday parties when he was a kid. Once you start sucking on a straw, the bottle will empty, he remembers all too well. Thus, it is equally evident that all the mines will be empty one day, just like the soda pop bottle the kids drank from. And at the birthday party, some kid would always start screaming for more, but that did not refill the bottle.

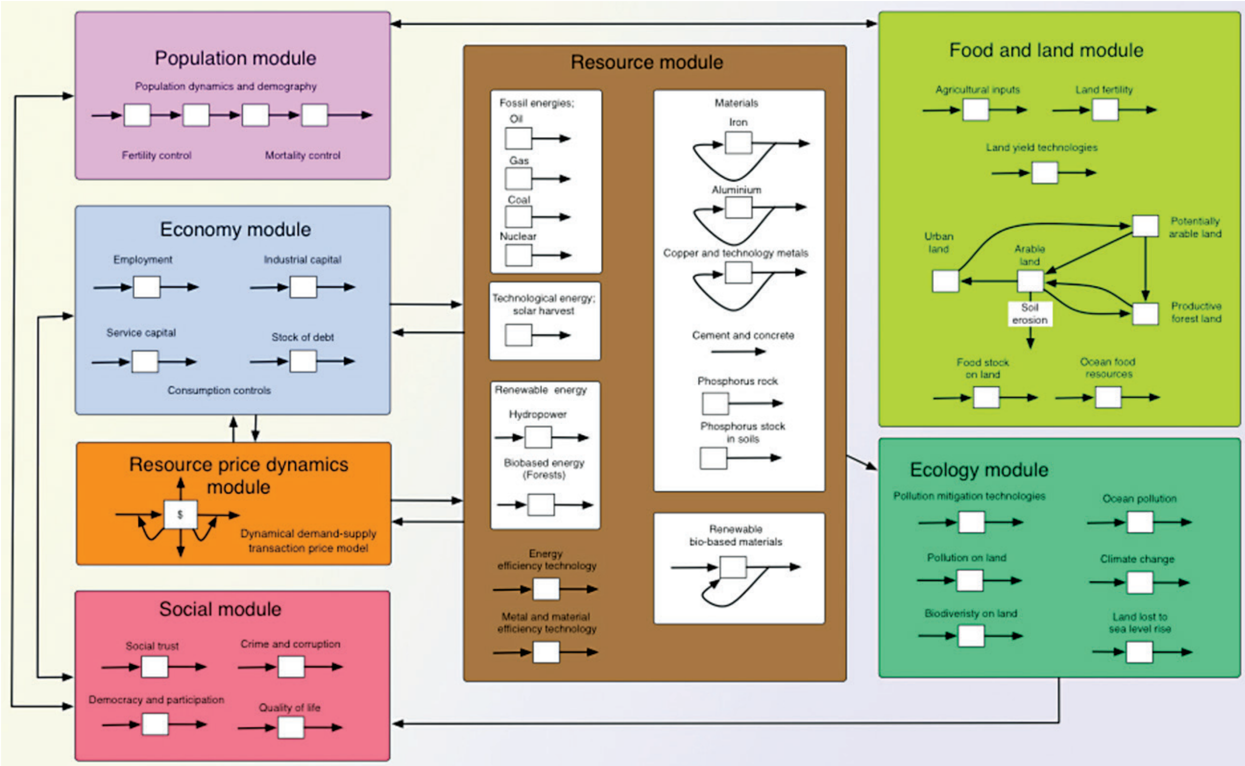


Figure 4.2 Overview of the most important modules in the WORLD model.

An integrated assessment of the security of long-term supply and the adequacy of the Earth's metal resources is therefore of strategic interest. Gordon *et al.* (2006), Rauch and Graedel (2007), Heinberg (2011), Radetzki (2012), Reck and Graedel (2012), Ragnarsdottir *et al.* (2012) and Sverdrup *et al.* (2013a) expressed concern about a potential future scarcity in resource production. The two single most important metals for society are iron and aluminium. Iron, nickel, manganese, chromium and cobalt are included in different types of steel and are very important for societal infrastructures. Zinc and copper are other major metals in infrastructures, and are of great economic importance. Copper, zinc, aluminium and silver are important for electrical infrastructures, and silver, copper and gold for electronics. Indium, platinum and rhenium are essential strategically for high technologies and as speciality catalysts. Gold and silver also have monetary value, and have a strategic position in the monetary system. The following metals will be discussed in some detail:

- Iron
- Aluminium
- Copper
- Silver
- Gold
- Platinum

For other metals, the authors have published a number of articles (Ragnarsdottir *et al.*, 2012; Sverdrup *et al.*, 2013a,b,c, 2014a,b) and more will follow soon. In these we explain the integrated assessment for over 40 different metals, materials and fossil energies. For more detail, please consult these papers. The metals listed above have been selected because they represents different needs of society.

Table 4.1 gives the relative amounts of 10 mined metals. Iron has the largest production of 1,350 million tonnes yr^{-1} whereas molybdenum and vanadium are mined at the rate of only 60,000 tonnes per year. You should keep these data in mind next time someone suggests the ease of metal substitution as a solution for resource exhaustion, because substitution can only be done upwards in volume (*i.e.* iron for aluminium – but not aluminium for iron).

Many metals have no mines of their own, they arise as by-products of mining of other metals (Fig. 4.3). This creates a very intricate network that is often referred to as the Reuter Wheel (Reuter *et al.*, 2005), and makes the supply dynamics quite complex as illustrated in Figure 4.3. There are groups of metals that are mined together. The production of copper, zinc and lead are often derived from what we could call polymetallic ores. The main income pillars of these mines will be for example copper, zinc and lead, with major income contributions from silver and gold. However, technologically important metals like germanium, gallium, tellurium, selenium and indium are produced as by-products and are also important contributors to income. Nickel and copper-nickel ores are other

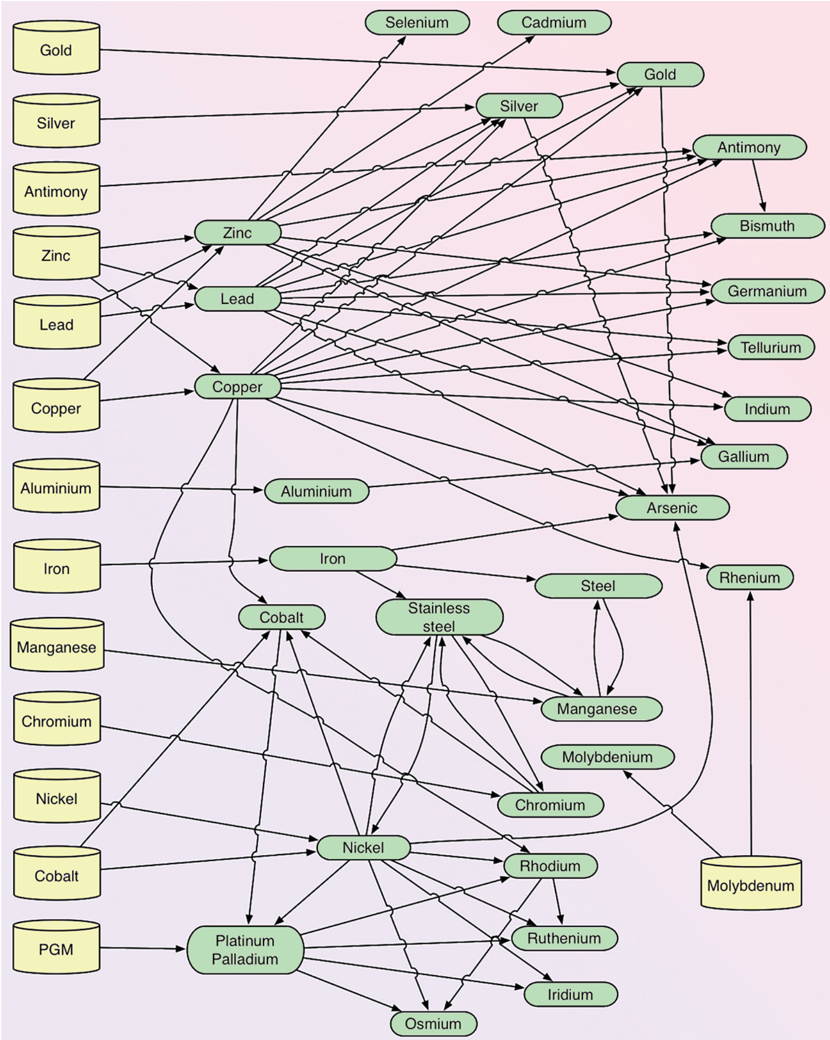


Figure 4.3 Connection between the production of many different metals and the parent metal ores. The figure shows that modelling the long-term supply of metals is a complex task, requiring computer simulation models. Cylinders stand for stocks, oval boxes for production rates.

important polymetallic ore types that yield significant amounts of silver, gold, platinum group metals and metals like cobalt and other speciality metals. Our team is developing the complex models required to deal with these systems, but the story is too long to tell here and we are also too early in the development process for these models to provide detail in this study. As the ore grade of the traditional mines dedicated to single metals decline, we can expect the exploitation of polymetallic ores to become more important in the future. This requires new technologies and has room for important technical advancements in the years to come.

Table 4.1 The relative amounts of different metals that are mined.

Group	Metal	Annual production, million tonnes per year		Fraction
Steel	Iron	1,350	1,390	93.5 %
	Manganese	18		
	Chromium	16		
	Nickel	2		
	Molybdenium	0.06		
	Vanadium	0.06		
Aluminium	Aluminium	50	50	3.4 %
Bronzes	Copper	16	34	2.3 %
	Zinc	14		
	Lead	4		
All other metals combined			12	0.8 %
Global metal production			1,486	100.0

Finding the input data. In our work we assess initially the Ultimately Recoverable Reserves (URR), for each metal resource from the literature, from scientific articles and from corporate information. The Hubbert's model is fitted to the production data, using the initial URR. The production rate and the shape of the curve helps set the Hubbert's curve fitting parameter b. Finally, the URR is adapted when required by production curves and estimates of how much is stored in high grade, low grade and ultra low grade ores. The recovery rate decreases with deceasing ore grade. Figure 4.4a shows an example of the required energy for uranium ore mining and milling. The Australian mine contains uranium, iron ore, mineral sands, silver–lead–zinc ores, and gold. This is polymetallic rock ore, and may be seen as a generic estimate for moving rock to retrieve ore. The implication of the diagram is that mining costs are strongly connected to energy prices.

Figure 4.4 (b) shows uranium recovery rate as a function of ore grade (in %U_3O_8). The lower the ore grade, the less is recoverable from the reserves. This puts an upper limit on the possible operational size of the URR, somewhat

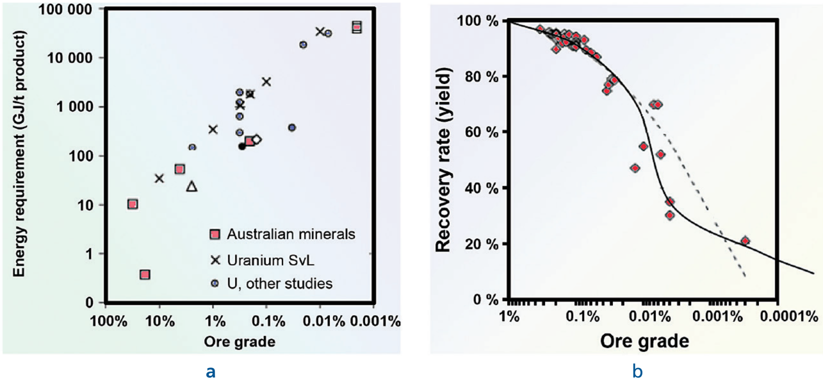


Figure 4.4 **(a)** Example of the energy used for metal ore mining and milling. Australian minerals are uranium, iron ore, mineral sands, silver–lead–zinc ores, and gold. Metal prices tend to go up because of increased production costs when the ore grades go down. **(b)** Uranium recovery rate as a function of uranium oxide ore grade (adapted data from Lenzen, 2008, and Prior *et al.*, 2013).

different depending on the regression line we choose. One regression suggests an ore grade limit of 0.0002 % or 2 g/tonne and possibly a lower estimate of this limit is about 0.00005 % or 0.5 g/tonne (Lenzen, 2008; Prior *et al.*, 2013). A reasonable limit seems to be at about 0.5-1 g/tonne, where gold production is now (2013), below that the production costs would be higher than the value of the ore. Our previous work for copper shows the URR for copper as a function of ore grade (Sverdrup *et al.*, 2013a, 2014b). The efficiency with declining ore grade goes down as shown in Figure 4.4b, so URR will converge on a final limit (Sverdrup *et al.*, 2013a). Recovery yield from ore is important as it puts a limit on the ultimately recoverable reserve estimates. The recovery yield decrease as the ore grade declines to lower grades.

Scarcity and metals prices. Figure 4.5 shows the dependence of recycling on metal prices. Note that the scale is logarithmic. As metal grades go down and energy prices rise, there will be a comparable rise in metal prices as the metal production rates decline while demand is still rising. However, recycling will be able to soften the blow to availability significantly if done properly, and is favoured by higher metal prices (see Fig. 4.5). For gold and platinum, recycling is very efficient, however, this has not prevented the price from rising over the last 25 years as ore grades and resources declined. Businesses should plan for a future with metal limitations and increasing demands for recycling services and technologies. This may be seen as a problem, but for entrepreneurs, it would be better to see them as challenges and as a way forward towards smart solutions. Thus, for many materials and metals, the burn-off time tends to be relatively constant over time, even when the burn-off times are short. Many estimates have remained around 40-60 years for nearly a century, resulting in caution in sounding an alarm that "the end is near." Lately, estimates of extractable amounts seem to have converged with time on final orders of magnitude. The Hubbert's estimate is more robust in this context as both the production history and estimates of extractable amounts are used for constructing the curves and both need to be internally consistent. Therefore, we present a detailed assessment of estimates of extractable amounts.

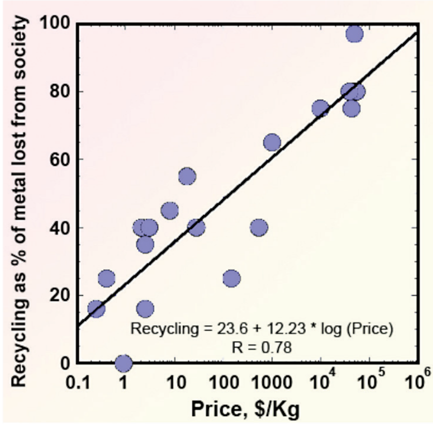


Figure 4.5 The general dependence of recycling rates on metal prices. The data comes from unpublished sources within the metals industry as well as from UNEP (2011b). The graph shows that the higher the price, the higher the recycling rate.

4.1.1 Iron

Iron, or rather steel is the most important metal for human society (Smith, 1776; Champion *et al.*, 1984; Rostoker *et al.*, 1984; Diamond 1997; World Steel Association, 2000, 2012, 2014a,b,c,d; Acemoglu and Robinson, 2013). We entered the iron age about 1,500 years ago, and have never left it. The amounts of iron moved around in the present world are truly enormous. Our estimate of the ultimately recoverable reserves (URR) for iron is 30 % larger than the USGS extractable amount estimate at 240 billion tonnes of iron. The iron metal yield from ore is at present 42 % iron (World Steel Association, 2014a,b,c). During the last 70 years, iron production has increased 5-10 % annually (Fig. 4.6). Table 4.2 shows the production of iron per country, the global production is 2,950 million tonne/year. The total production of steel is 1,350 million tonnes per year. Most of the world's production of manganese, chromium, and significant amounts of vanadium and molybdenum are alloyed into iron to make steel. Stainless steel needs a lot of these metals in the alloy; about 100 million tonnes are produced every year.

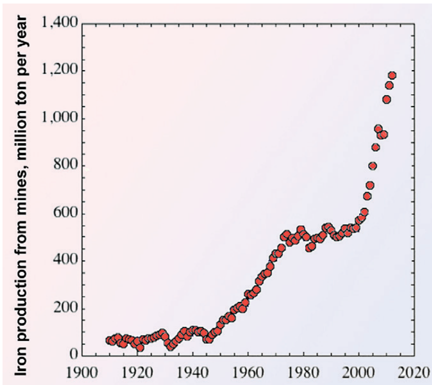


Figure 4.6 Annual global iron production since 1900 to the present.

Table 4.2 Production of iron ore per country, total iron ore concentrate production is 2,950,000,000 tonnes per year (metal plus rock). Amounts in tonnes per year.

Country	Tonnes	Year	Country	Tonnes	Year	Country	Tonnes	Year
China	1,320,000,000	2013	Chile	12,624,000	2011	Norway	700,000	2011
Australia	530,000,000	2013	Mauritania	12,000,000	2011	S. Korea	510,000	2011
Brazil	398,000,000	2013	Peru	10,459,000	2011	Germany	400,000	2011
India	150,000,000	2013	Malaysia	7,696,000	2011	Egypt	300,000	2011
Russia	102,000,000	2013	N. Korea	5,300,000	2011	Pakistan	300,000	2011
Ukraine	80,000,000	2013	Turkey	4,500,000	2011	Tunisia	175,000	2011
S. Africa	67,000,000	2013	Mongolia	3,000,000	2011	Colombia	174,000	2011
USA	52,000,000	2013	N Zealand	2,300,000	2011	Azerbaijan	60,000	2011
Canada	40,000,000	2013	Austria	2,050,000	2011	Indonesia	46,000	2011
Iran	37,000,000	2013	Bosnia	1,850,000	2011	Morocco	45,000	2011
Venzuela	30,000,000	2013	Algeria	1,500,000	2011	Portugal	14,000	2011
Sweden	26,000,000	2013	Greece	1,200,000	2011	Kenya	11,000	2011
Kazakstan	25,000,000	2013	Thailand	1,000,000	2011			
Mexico	14,482,000	2011	Vietnam	1,000,000	2011			

Development of the IRON and STEEL models

Data was gathered from a number of sources and earlier studies where it is readily available in open sources. Especially important were the following sources; Allen and Behamanesh (1994), Gordon (1996), World Steel Association (2000, 2012, 2014a,b,c,d), United Nations (2003), USGS (2005, 2007, 2008, 2013), Gordon *et al.* (2006), Johnson *et al.* (2007), Rauch and Graedel (2007), Wang *et al.* (2007), Radetzki (2008), Turner (2008, 2012, 2014), Rauch (2009), Rauch and Pacyna (2009), MinEx Consultants (2010), Crowson (2011a,b), UNEP (2011a,b, 2013), Chen and Graedel (2012), Cullen *et al.* (2012), International Stainless Steel Forum (2014), Nuss *et al.* (2014), Ramanaidou and Wells (2014), Stanway (2014), Wübbeke and Heroth (2014). Input for the global population for the demand calculation was derived using the FoF-model (Ragnarsdottir *et al.*, 2011; Sverdrup and Ragnarsdottir, 2011). The FoF-model uses a standard UN population model (United Nations, 2003), linked to a food production module that is limited by available phosphorus supply (see below). The available data were closely inspected for inconsistencies and averages and our expert adjustments were made when the available sources for input data were not internally consistent.

4.1.2 Theory and definitions

We apply the following fundamental assumptions:

1. We assume that the official statistics for iron resources in rock formations have the correct order of magnitude.
2. Iron is sold as the physical metal; we ignore the derivatives trade in our economics model and the price mechanism, as it is not a major part of the value flux.

We used data from earlier studies (Singer and Menzie, 2010; Ragnarsdottir *et al.*, 2012; Singer, 2011, 2013; Sverdrup and Ragnarsdottir, 2011; Sverdrup *et al.*, 2013a,b,c, 2014a,b) to estimate the extractable amounts of iron. We developed these kinds of sustainability assessment models earlier (Sverdrup and Ragnarsdottir, 2011; Kifle *et al.*, 2012; Sverdrup *et al.*, 2013a,b,c, 2014a,b). Exponential growth and market price mechanisms are incorporated in our process-oriented models. For all the metals, mass balance applies for society.

4.1.3 Iron extractable amounts, known and unknown

We assess the URR, equal to the sum of the presently extractable amounts and potential resources that may become reserves, which may be presently known or estimated as hidden, from the literature, from scientific articles and from corporate information (Heinberg, 2001; Müller *et al.*, 2006; Rauch, 2009; Rauch and Pacyna, 2009; Singer and Menzie, 2010; Crowson 2011a,b; Singer, 2011, 2013; World Steel Association, 2012, 2014a,b,c,d; Nuss *et al.*, 2014). Assessing the URR is difficult, as some resources have not been completely mapped. Testing shows that using Hubbert's model and linearisations of this approach may be the best estimates when compared to verifiable data (Bardi, 2013). Finally, the URR is distributed between the quality classifications high grade (60-40 % iron content), low grade (15-8 % iron content) and ultra low grade ores (3-1 % iron content and less). Tables 4.3 and 4.4 give an overview of estimates of iron ore extractable amounts in 2012, expressed as iron metal content, earlier extracted and ultimately recoverable reserves (URR), with the Hubbert's model fitted on data to measure URR and traditional estimates reported by the USGS.

Table 4.4 gives estimates of the global extractable amounts of iron by different authors at different times. The different estimates seem to be fairly consistent. A general tone in all published studies of estimates of extractable amounts of iron is that there are many iron deposits in the world, but many of these are probably not economic or technically viable, even at substantially higher prices. Figure 4.7 shows that iron mining leaves large holes in the ground, just like the diamond mine depicted on the cover of this *Perspective*.

Table 4.3 Distribution of iron ore expressed as iron metal content, distributed among known and hidden amounts in tonnes expressed as iron.

Country	Known		Hidden Million tonnes	Sum Million tonnes
	Million tonnes	Iron content, ore, %		
Brazil	16,000	52	51,000	67,000
Russia	14,000	45	45,000	59,000
Canada	2,300	38	42,000	46,300
Australia	17,000	48	24,000	41,000
United States	2,100	30	26,000	28,100
China	7,200	31	10,000	17,200
Zimbawe	400	44	15,000	15,400
India	5,200	64	8,000	13,200
Venezuela	2,400	60	8,000	10,400
Bolivia	2,200	44	6,600	8,800
Kazakstan	2,000	44	6,300	8,300
Sweden	2,200	63	5,600	7,800
Ukraine	2,300	35	5,000	7,300
Iran	1,400	56	4,000	5,400
Rest of world	4,300	49	3,400	7,700
Sum	81,000	50	259,000	340,000

Table 4.4 Different estimates of the total iron extractable amounts as a basis for potential mining of iron. The technical extractable amount (URR) is in the range 234-354 billion tonnes iron.

Source of Estimate	Presently known extractable amounts	Technically extractable amounts, known and hidden	Already mined	URR
	billion tonnes iron content in ore			
Verhulst's linearisation, Roper (2009)	50	300	54	354
USGS (2011) USGS (2014)	81	260 360	42	302
Hubbert's model, Sverdrup *et al.* (2013a,b,c, 2014a,b)	60	280	40	340
Geology based, Stockwell (1999)	50	270	31	301
Rauch and Pacyna (2009)	35	200	34	234
Averages	54	278	69	303

Figure 4.7 Iron mining makes large holes in the ground, removing whole mountains. Iron mining is one of the largest physical operations on Earth, only paralleled by mining of sand and gravel and the fossil carbon fuel extraction (coal and oil shale). The Mount Whaleback, Western Australia is an open-cast iron-ore mine that produced 35 millon tonnes iron ore in 2013.

4.1.4 Iron stocks in society and supply

A large amount of iron goes to society's infrastructure such as bridges, piping systems, railroads, ships, buildings, machinery, transportation vehicles etc. This puts iron out of circulation for a long time, because structures like buildings or railroads or hydropower installations typically are in use for 50-150 years before being torn down. Many household items also have a retention time of 20 to 60 years, such as cutlery. Most objects in steel are made to last, and they actually do so. Cars normally last 4-7 years; other every day items like tins and pots are turned over much faster. Figure 4.12 shows the production and stocks in society, matched to fit the global data. The population used to drive demand was derived from a FoF model run described later in this report (Ragnarsdottir *et al.*, 2011; Sverdrup and Ragnarsdottir, 2011). Global population, together with affluence are important drivers of iron demand in the model. Stainless steel has chromium, manganese, nickel, but at times also vanadium, niobium, molybdenium or tungsten added to it (International Stainless Steel Development Forum, 2014; EuroInox, 2014). Assuming, chromium is used on average at 15 % chromium content, the calculations associated with running the STEEL model shows that there is enough chromium for 4,370 million tonnes stainless steel. At 10 % added manganese, there is enough manganese for 14,400 million tonnes of steel. There is enough nickel for 2,200 million tonnes steel with 8 % nickel. The implication of these simple calculations is that we will run out of nickel, chromium or manganese long before we run out of iron. Mass balance was used to estimate recycling amounts. Total recycling as compared to net extraction is 23.5 %.

Table 4.5 Distribution of the world's recoverable iron in tonnes, the ore grades used in the IRON model simulations. Amounts are in million tonnes of iron. Note how the ore grades are related to extraction costs rather than actual content of iron.

Ore grade	Approximate order of magnitude in 2012 for the extraction costs	Known	Hidden	Sum	Existing but technically unavailable for mining
High	35 $/tonne	30,000	52,000	82,000	70,000
Low	130 $/tonne	12,000	80,000	92,000	150,000
Ultralow	400 $/tonne	8,000	158,000	166,000	400,000
Sum		60,000	280,000	340,000	620,000

4.1.5 The IRON model

The IRON and STEEL models are part of the WORLD model (Figs. 4.8, 4.10, 4.11). The WORLD model shows that phosphorus, iron, and energy resources are the most important resources determining the fate of our civilisation. They all depend on fossil deposits (phosphate rock, iron ore), hydrocarbons (oil, coal, gas) and soils for food production as a part of the Land and Food Module. All else can be said to being dependent on these. Under Business As Usual, iron has a significant (25 %), but insufficient recycling rate. For phosphorus present recycling is 16-20 % globally (Sverdrup and Ragnarsdottir, 2011); for fossil energy, long-term recycling is insignificant at present. If society fails on any of those issues, other shortages are redundant.

The IRON model simulations are used for quantification of flows, scenarios and future predictions. Besides being a submodel to the WORLD model, it is also a stand-alone model that can be used for simpler assessments such as those made in this study. The flow pathways and the causal chains and feedbacks loops in the system are mapped using systems analysis, and then the resulting coupled differential equations are transferred to computer codes for numerical solutions, using an environment such as STELLA® or Vensim®. The submodel IRON in the STEEL model is based on mass balance expressed differential equations, and solved numerically with a 4-step Runge-Kutta method, using a 0.2 year timestep in the integration.

The basic driving mechanism of mining operations comes from commercial profits and availability of a mineable resource. Mining is mainly profit driven, but affected by the mining cost, which is modified by oil price and ore grade. A lower ore grade implies that more rock must be moved to mine the iron. Consequently, a higher iron price is necessary to keep the iron production up. The price is set relative to how much iron or steel there is available in the market. Figure 4.8 shows the flow chart for the iron system. When assessing the steel stock in society we find market saturation at about 12-13 tonnes iron per person in the developed countries. The global average is about 2.5-3 tonnes per person (UNEP-IRP, 2013; World Steel Association, 2013a,b; International Stainless Steel Forum, 2014). China and India have 2.6 billion people and their population is still increasing. Stock-in-use in China is increasing; China is expected to reach the European level of stock-in-use per person in 2050, and India by 2060, under the assumption there is sufficient energy to support it. We will address that issue later in this paper. Table 4.3 shows the distribution of the world's recoverable amounts of iron ore in tonnes. We estimate that there are potentially 960 billion tonnes of iron contained in iron ores on Earth (Table 4.5). If all would be minable, the amount would be sufficient for all time. However, for different reasons such as iron ore being technically out of reach, too energy-intensive to extract because it is bound to silicates, or too heterogeneous for a mining operation or geologically blocked, only about 340 billion tonnes of iron are actually feasible to mine. These are the ore grades used in the IRON model simulations. Figures 4.9a,b show the ore quality

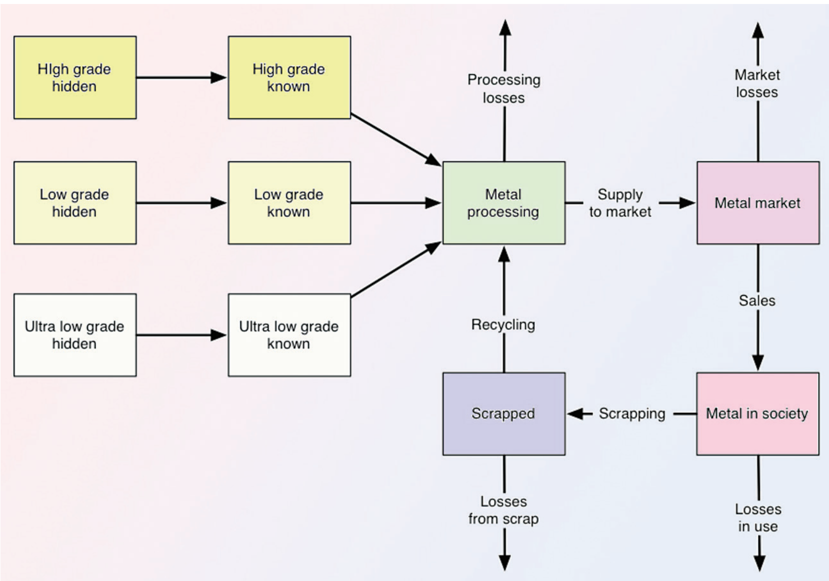
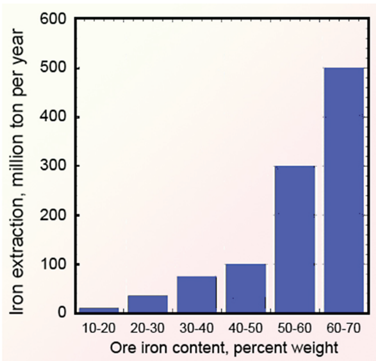


Figure 4.8 Basic flow chart for the IRON model.

being mined at present and distributed according to production rate. The iron weighted average ore grade in 2012 was 58.6 % (Polinares, 2012). In comparison, it also shows the distribution of the URR among different ore qualities. It is evident that we are at present mining the best ores, leaving poorer ores for the future.

Figure 4.10 shows the IRON model as a causal loop diagram for the whole world iron system. The causal loop diagram maps all causal connections in the system. It is important that the links are true causal links and not just correlations or modelled on chain of events. The causal loop diagram together with the flow chart, defines the model. The causal loop diagram shows us that the mining operation is driven by operations profit. This profit is driven by iron price and amount extracted, but balanced by the cost of operation. *Harald´s* experience from industry showed him that every aspect of the business is interconnected. The production operation cost is mainly determined by two important factors beside cost of investments – the energy price and the ore grade.



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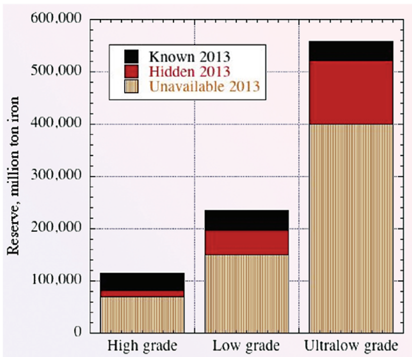


b

Figure 4.9 **(a)** Ore quality being mined at present distributed according to production rate per ore grade class. **(b)** Reserves and resources distributed by ore grade and classified as known or as a hidden in 2012 (adapted after Polinares, 2012).

The price of iron is determined by two factors: 1) it must stay above the production costs, and 2) by the amount in the market, which in turn depends on the balance between deliveries into the market from production and the shipments from the market in response to world market demand. Very importantly, price also drives the urge for urban mining and recovery of iron from society. The demand is driven mainly by population size and the gap between the target iron stock-in-use and the real stock in-use. At a stock-in-use level above 10-12 tonnes iron per person, the demand seems to stagnate towards the maintenance supply for infrastructure and short-term consumption. A higher price acts as a brake on demand. We finished such charts (Figs. 4.8 and 4.10) in detail before the actual code was built in the STELLA® system (Fig. 4.11). A further development was made, where the IRON model as shown in Figure 4.10 was combined with

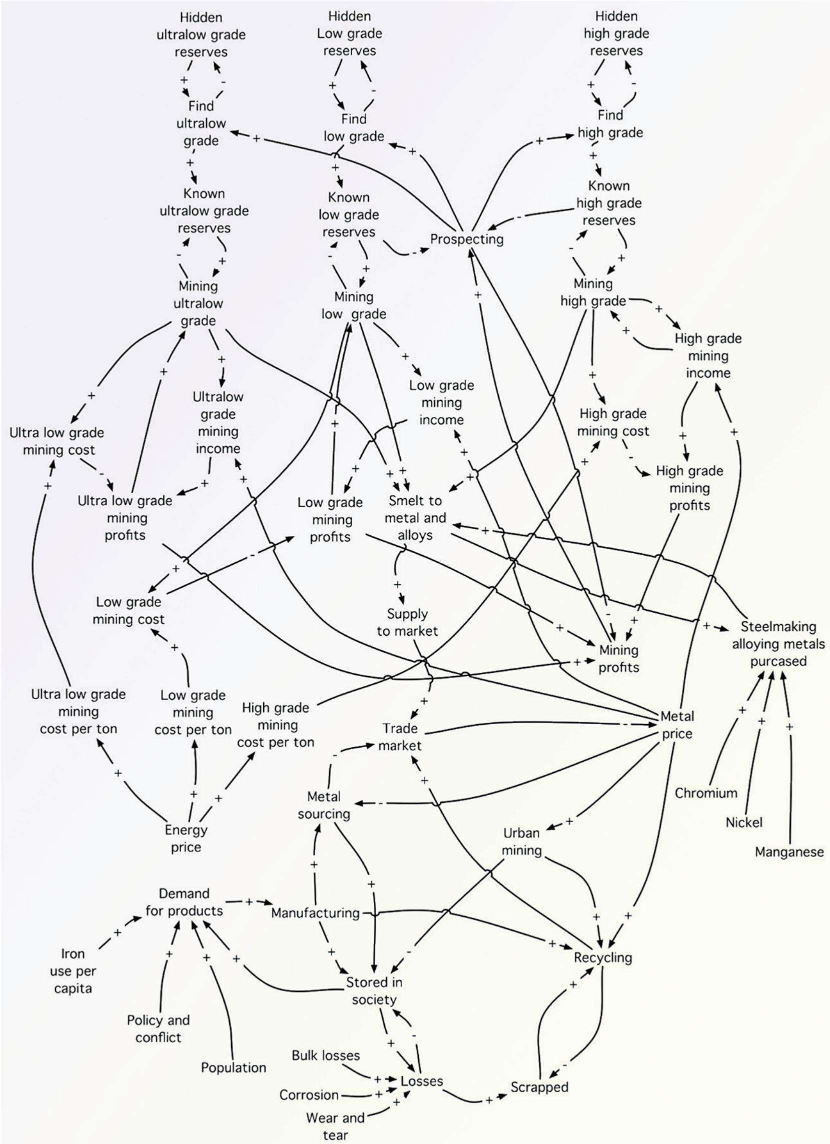


Figure 4.10 The IRON model shown as a causal loop diagram for the whole world iron system. This is exemplifies the other metal models used in our studies (GOLD, SILVER, ALUMINIUM, COPPER).

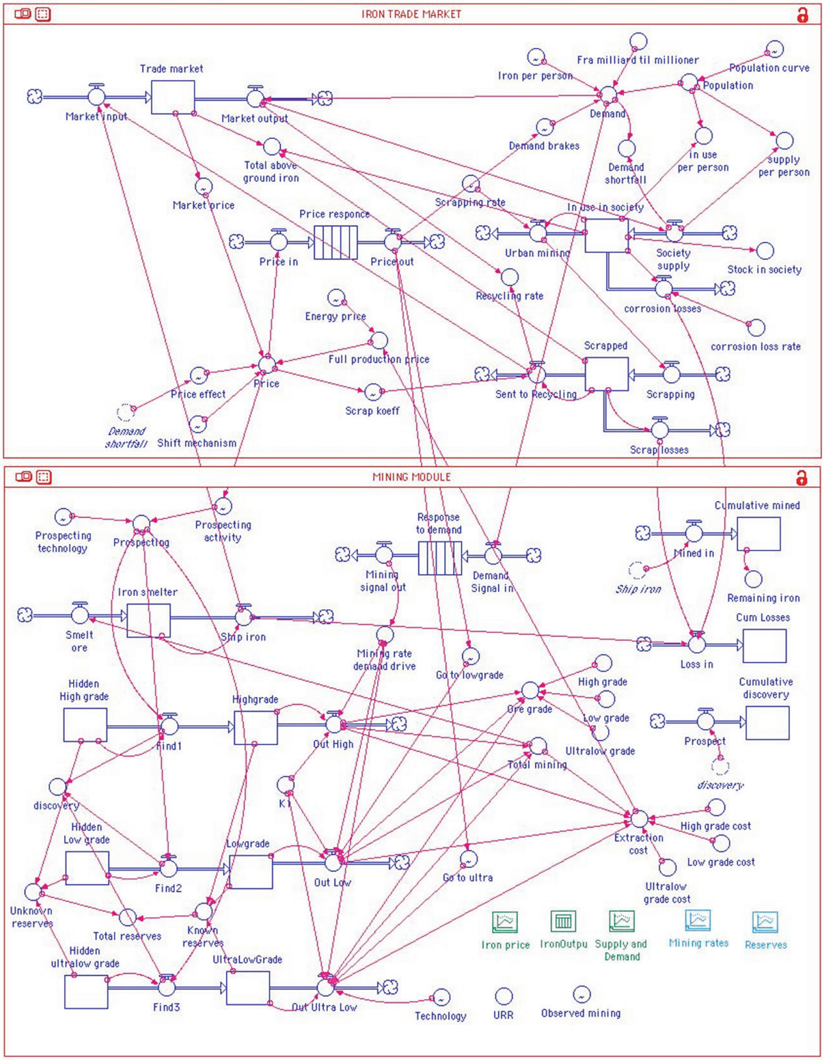


Figure 4.11 The STELLA® diagram for the IRON model.

a similar model for manganese, chromium and nickel into the STEEL model, simulating the production of stainless steel. The average global spot market price for iron ore in 2014 was about 60-65 $/tonne, the range is from 36 $/tonne at the low end to about 160 $/tonne at the highest end. The low range costs are not socially sustainable over the long run, and must be seen as a transient phenomenon. Specialty steel has a higher value, as it has been worked on to increase its properties, including strength and durability. Standard carbon steel prices in 2014 were from 300-400 $/tonne, depending on type and shape; this increased to 1,200 $/tonne during the 2005-2008 boom, but has fallen back during the economic crisis, due to temporarily less economic activity with a decrease in demand. As the global population is not decreasing, this can be considered to be a temporary slump in demand. Specialty alloys are traded at significantly higher prices, because of their significant contents of metals like chromium, molybdenum, vanadium, niobium, tungsten or nickel (Turner, 1900). Figure 4.12 shows a flow chart for iron for 2010 (modified and updated using data from Rauch and Pacyna, 2009). The amounts are in tonnes of iron. In society, the stock is estimated to be about 21 billion tonnes.

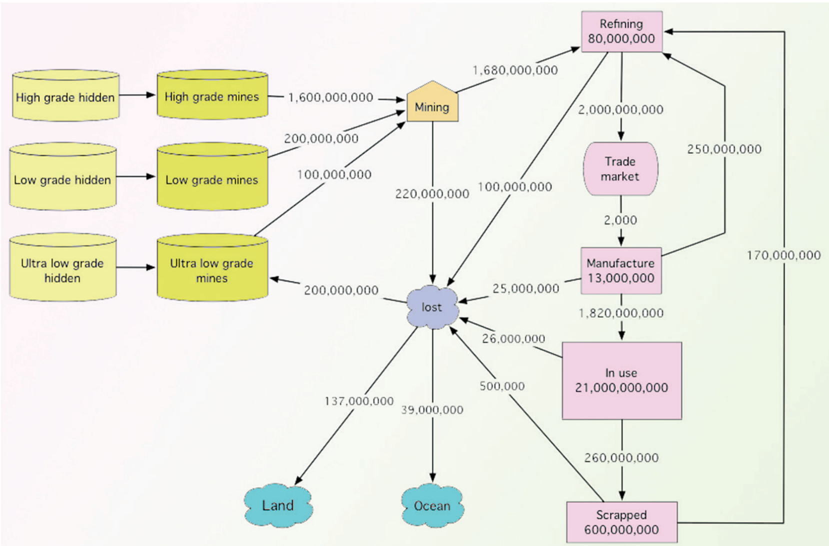


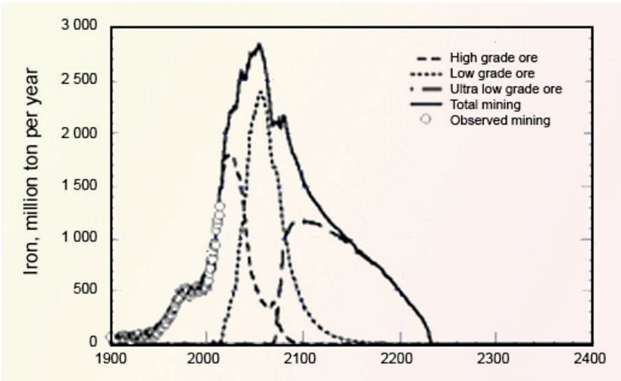
Figure 4.12 Flow chart for iron 2010. Amounts in million tonnes of iron. In society, the stock is estimated to about 21 billion tonnes (after Rauch and Pacyna, 2009).

The pricing mechanism in the IRON and the linked STEEL models has been adjusted to how the iron market has worked in the past and how it has recently changed. Principally, metal trading is supposed to operate as follows: the traders come to the trading floor with their lots to sell or to buy, and adjust their amounts as the price goes up and down. If demand is higher than production, the price goes up; in the opposite case the price is moved down. This is a self-adjusting mechanism that balances the trade by adjusting the prices until the demand to buy an amount at a price match the offers to sell an amount at a price. The sellers offer more at a lower price or less at a higher price, and the buyers do likewise. When there is a match, the price is set. This is based on *Harald´s* observation and experiences on the trading floors at the metal markets in New York and London from the time he worked in the precious metal company. Earlier, the steel industry was partly state controlled and considered to be a national asset with implications for military capacity. Thus, prices stayed under governmental influence. In the period of 1935-1956, most of the world's steel production was fully integrated with big power politics and subject to political controls.

A global free market for steel and iron ore did not really exist until the European Coal and Steel Union was created after World War II. That was the first attempt at creating a common market and the beginning of the European Union (EU). Over the last 40 years, iron ore prices have been decided amongst a small cartel of very large mining corporations and steelmakers, in a closed process. This implies that in the global arena, they eliminated the free market and established an oligopoly, where the supply and demand mechanisms were partly put out of function. The three largest iron ore producers are the Brazilian Vale, and the two Anglo-Australian mining corporations Rio Tinto and BHP Billiton (World Steel Association, 2012, 2014a,b,c,d; Mojarov, 2013). These very large actors dominate the markets. The deal reached between these has been focused on covering production costs and have set a benchmark that was followed by the rest of the industry. However, from 2010 and forward, the system has been loosened up slightly in response to demands for more dynamic short-term pricing. This has been paralleled by an increase in derivatives trade in iron ore. In the IRON model, we reflect this variation in price mechanisms from 1910 to 2010, and only after 2020 apply an open arbitration model for iron ore pricing. The relationship between the recycling rate and metal price is taken from Sverdrup *et al.* (2014a,b). The scrapping process for stock-in-use in society is not strongly driven by price.

4.1.6 Results for iron

Estimated flows and stocks from measurements in society. A very important confounding factor is the accumulation of metals in society, which still is substantial and prevents a steady-state situation. This introduces a delay in the system, and if we look at the data for copper and silver, the delay is 50-100 years in the system. Rauch (2009) mapped in-use stocks for aluminium, iron, copper and zinc and related this to gross domestic product (GDP) for some countries. He found that the stock in use was linearly proportional to the country's GDP. The model assessment shows that peak iron production will occur around 2030 (Fig. 4.13), implying a shortage in the market around 2080 (because of lower production capacity) and a financial and governance crisis following closely after that (because of lack of supply for societal infrastructure). This can be seen by studying Figures 4.13b and 4.14b. In Figure 4.14b we have plotted the demand before it is modified by price, and with the price modification. The demand shortfall has also been plotted in the same figure. This shortfall is a strong driver for the iron price. The causes for a peak are several: declining ore grades drive up the price, because of increased extraction costs. Increased prices will be able to affect demand negatively, thus starting a process where the money available for consumption will eventually be more limiting than physical amount of iron available. The variations in our URR estimate between that of the USGS estimate does not change the estimate for peak production significantly. After 2050 the iron supply flattens and we may expect the iron prices to go up significantly in the markets. Iron is the most important structural metal for modern society, and scarcity will have direct effect on our ability to maintain the infrastructure of our modern society. Greatly improved recycling is the one important answer to mitigate scarcity, and strongly reduced population numbers present another.



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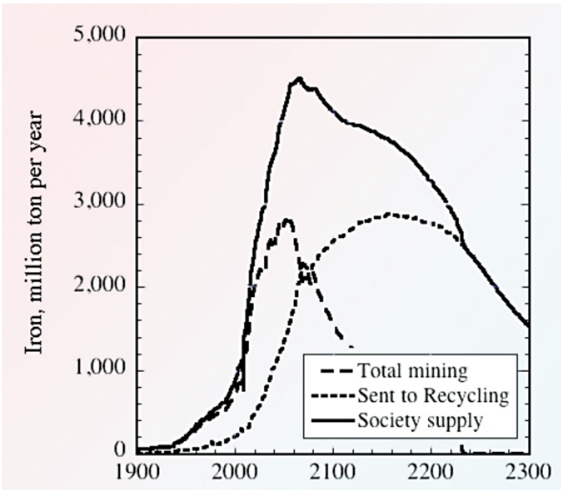

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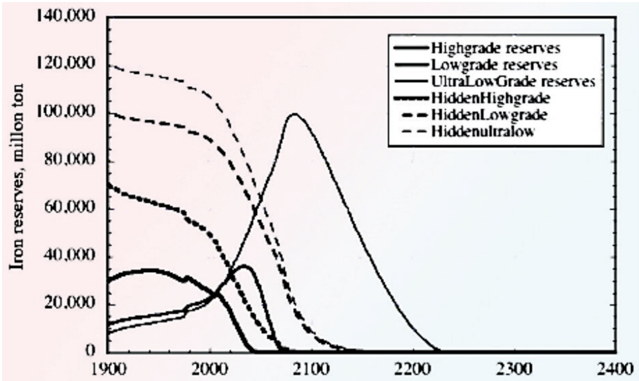
Figure 4.13 **(a)** Shows the mining rate as predicted by the IRON model. **(b)** Shows the supply rate to society, considering recycling (Sverdrup *et al.*, 2013a). URR = 340 billon tonnes iron for this simulation.



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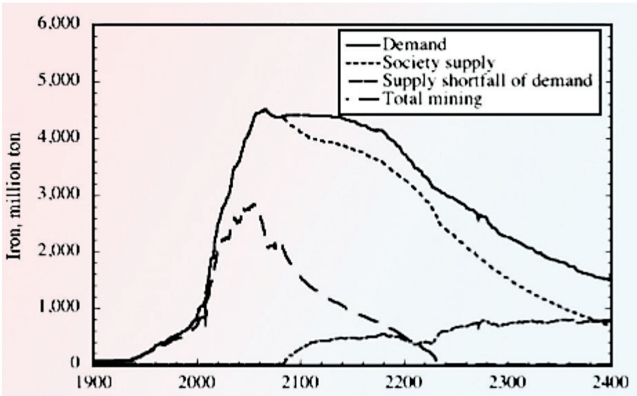

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Figure 4.14 **(a)** Shows known extractable amounts over time as predicted by the IRON model and the hidden extractable amounts over time. Y axis presents thousand tonnes produced per year and X axis time. **(b)** Shows the relationship between demand and supply. After 2080, demand can no longer be fully supplied or only at substantially higher price.

The model outputs from the IRON and STEEL models are summarised in Figures 4.13-4.15. Figure 4.13a shows the iron mining rate modelled in this study (Sverdrup *et al.*, 2013a). Figure 4.14 shows the development of the extractable amounts, known and hidden during the period 1900-2400 AD. Figure 4.15a shows the stocks in society and the known resources in comparison. This stock continues to rise for a long time, as the scrapping rate is quite low. We have set it at 2 % per year, implying that the average residence time is about 50 years. Figure 4.15b shows the IRON model output for ore grade. The diagram shows that even if no significant decrease in iron ore grade has yet been detected, this is predicted to occur soon (compare this to fish stock collapse in Meadows´ FishBanks® game, which occurs without any apparent warning). The ore grade decline in Figure 4.15b signals that the iron and steel prices will start to rise as costs of extraction rise. Figure 4.16a shows the simulated iron price and Figure 4.16b the fraction of supply to society expressed as % coming from recycling. The recycling fraction is driven by the price and the fact that mining declines with time after the production peak. When the STEEL model is used, it turns out that the first scarcity appears for stainless steel, because the alloying metals run out, the physical availability of the alloying metals becomes restricted (Fig. 4.21). First is nickel, and then later, scarcity of manganese and chromium appears. The scarcity is first manifested in rising manufacturing costs for stainless steel, later also by physical scarcity limiting the volumes of stainless steel that can actually be produced. When and how depend to a large degree on how efficiently the stainless steel can be recycled.

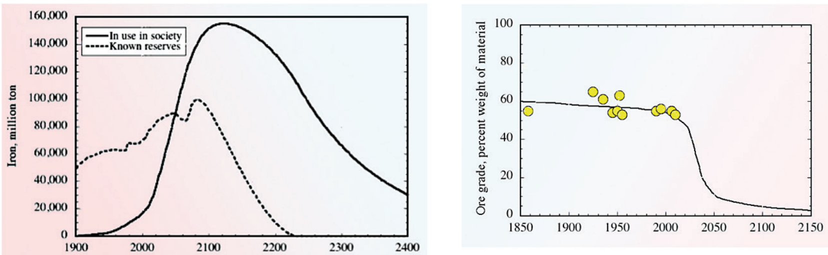

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Figure 4.15 **(a)** Stocks in society, and the amount scrapped in comparison as predicted by the IRON model. Y axis presents thousand tonnes produced per year and X axis time. The time after 2050 will be the era of urban mining, when more iron is in society that what is known for the mines. **(b)** The global ore grade (% weight) declined only very slightly from 1900 to 2000. It is expected to start decline at increased speed some time after 2025 and reach a stable low level by 2060.

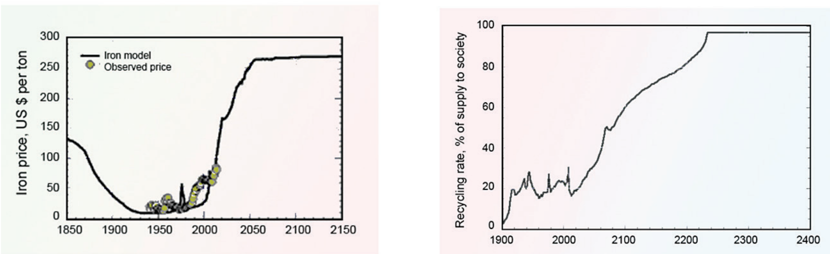

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Figure 4.16 **(a)** The IRON model output for the market price compared to the predicted by the IRON model. **(b)** The recycling rate. The recycling rate is the fraction in % of total supply to the market coming from recycling.

4.1.7 Field testing the IRON model

We tested the IRON model on data from the past, to assess its performance (Figs. 4.13-4.17). Only when a model reliably reconstructs the past, can it be used with confidence for future predictions, within the limits of its assumptions. We have tested the model on several aspects:

1. Mining rate
    a. With time as recorded 1910-2010
    b. With earlier Hubbert's model assessments
2. The estimated stock in society as reported by Rauch and Pacyna (2009) and UNEP (2011a)
3. The approximate ore grade (42 %)
4. The development of the iron ore price

Figure 4.17 shows the IRON model outputs tested against field data for mine production. The URR used was 340 billion tonnes. The correlation of observed to estimated mining rate is $r^2 = 0.97$, which is very good (Fig. 4.17). Figure 4.18a,b shows a comparison of mining rate using different values for URR. The production peak moves 10-20 years into the future with the larger extractable amounts. The shift is relatively small, as most of the increase in URR is allocated to the lower ore grades, those with the highest extraction costs, and thus those that will be extracted last. In the perspective of how serious iron scarcity is for modern society and standard of living, the change is insignificant with relationship to the fact that the iron resources and the scarcity risk must be handled and managed without much delay.

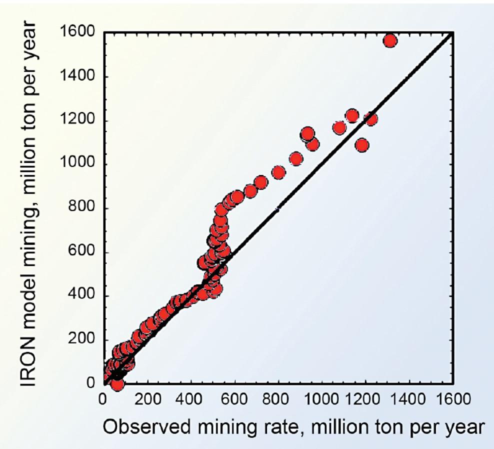


Figure 4.17 The IRON model output tested against field data for mine production. The correlation of observed to estimated is $r^2 = 0.97$.

In Figure 4.19 we compare data for ore grade to the ore grade outputs from the STEEL model for iron, manganese, chromium and nickel. In earlier years, siderites and other low grade ores were also mined. However, the volume of these early low-grade iron sources are too small to affect the overall balances, and they have been omitted. The trends seen in the observations and the simulations are the same, and represent an important warning message that scarcity risk is coming. The IRON and STEEL model simulations suggest that the ore grades may start to decline during the next decades if our iron ore estimates of the extractable amounts are right. When they do, the decline is indicated to be fast, and ore grade may fall from above 50 % to below 10 % in three decades. This fast decline in ore grade has been observed for other metals and materials (copper, zinc, uranium, coal, oil, gold, silver, palladium to mention some), and is an important diagnostic indicator of declining amounts of extractable material. An ore grade of 10 % instead of 50 % implies that we will need to excavate 5 times as much rock to obtain the same amount of iron ore.

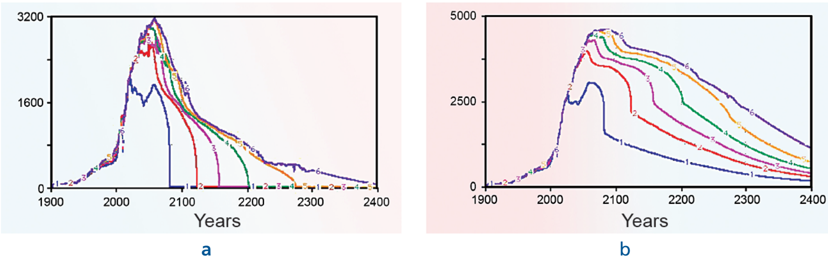


Figure 4.18 **(a)** Shows a comparison of mining rate varying URR from 150 billion tonnes iron and up in steps: 150, 250, 300, 350, 400, and 450 billion tonnes iron. **(b)** Shows the supply to society. Our estimate of URR is 340 billion tonnes and the USGS 2011 estimate is URR = 260 billion tonnes. Y axis presents mining production in million metric tonnes, X axis represents time.

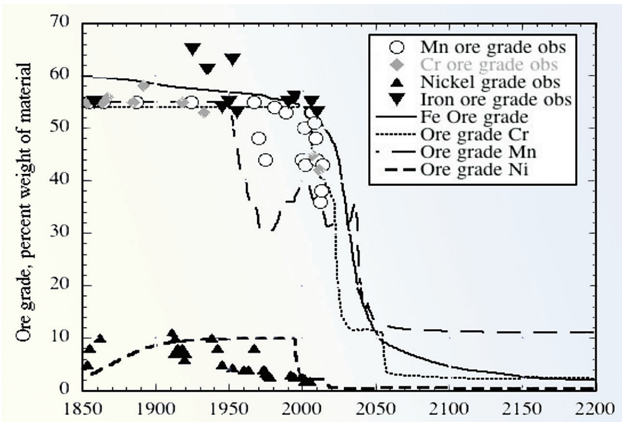


Figure 4.19 Data for the ore grade compared to the outputs from the STEEL model for iron, manganese, chromium and nickel. The dots are ore grade data (Mn, Cr, Ni, Fe) derived from the scientific literature.

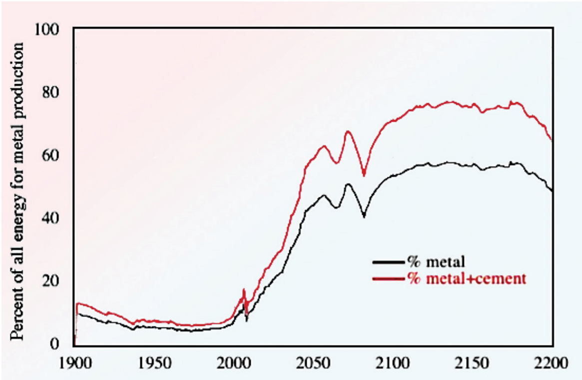


Figure 4.20 Assessment of the impact of steel production on the total energy available. The global energy production was estimated using the ENERGY module of the WORLD model.

4.1.8 Discussion

The IRON model yields several questions as well as some answers. One basic assumption behind these scenarios is that there will be a continued demand for iron, leading to a maximum feasible mining rate and corresponding consumption. The scarcity is mostly manifested as increased metal prices that impacts on demand. Thus, we may find ourselves running out of money before we run out of iron. Of note is that one important assumption we have made is that the global population will go down to around 2.5 billion by 2200 AD. Why will become clear in the section that follows on phosphorus. If the population is maintained at higher levels, such as 4-5 billion people, the iron deposits may run out twice as fast. Iron ore extraction and manufacturing of steel consumes today (2012) about 6-7 % of the global energy production. In a post peak oil time (starting now, see below), this share may increase as more effort is needed per tonne iron. Also to be considered is that the IRON model does not include the coal needed for metal reduction, hence a shortage in coal or carbon would further limit metal production. This is true also for other metals that require coal for reduction (*e.g.*, aluminium).

Over time, the share of the available energy used for iron production will go up. Eventually iron and steel production may take up more than 20 % of the global energy; this will put stress on the energy market, and may effect on the energy prices (see Fig. 4.20). And increased energy prices will in turn affect the iron and steel process, thus a lot of market dynamics will be set in motion. By 2200, fossil fuel production may have declined to about 20 % of what it is now, and fossil energy may be very expensive. Thus, after 2200, energy availability may pose a problem in addition to decline of both extractable amounts and ore quality. Table 4.6 shows the energy demand of different iron production pathways. It is evident that working from recycled material has huge energy advantages over production from iron ore. At present iron ore extraction and manufacture of steel consumes about 6-7 % of the world's energy production. Most of this is derived from fossil carbon, something like 12.5 billion tonnes of oil equivalents. This is when the iron ore grade is about 50 % as at present. Extracting and concentrating up the ore consumes about ¼ of the energy in steelmaking. When a majority of the steel comes from low-grade ore, at 12-8 % iron instead of 50-40 %, the energy demand will be significantly larger. Figure 4.20 shows an assessment of the impact of steel production on the total energy available, using the process step energy requirements taken from Table 4.6. To produce 1,350 million tonnes of steel, about 750,000 million tonnes of oil equivalents are used annually.

Table 4.6 Energy required to produce metals from different substrates, a comparison between different metals and pathways from raw material to finished metal.

Metal base	Source of product	Energy use MJ/kg	Relative ratio of the least energy demanding step compared to scrap iron	CO_2/kg
Iron	scrap iron	6-15	1	1
	iron ore	20-25	3	4
	bog ore	100-150	16	20
Stainless Steel	recycled steel scrap	6-15	1	1
	iron scrap	10-35	3	1
	high grade ore	40-75	7	7
	low grade ore	80-160	12	14
	ultralow ore	160-350	25	30

The energy estimates were derived by combining data from Hubbert (1956, 1962, 1966, 1972), Pogue and Hill (1956), Greene *et al.* (2003), Hirsch *et al.* (2005), Energy Information Administration (2007), Hall (2008), Holland (2006, 2009), Bassi *et al.* (2009), Hall *et al.* (2001, 2009), Nashawi *et al.* (2010), Patzek and Croft (2010). Most of this energy comes from coal. If we are to keep up steel production using fossil carbon, enormous amounts of coal must be mined and burned, creating huge emissions of CO_2, feeding into the problem of global climate change. Thus, not only ore exhaustion, but peak coal and climate change effects set limits to how much iron and steel we can allow ourselves to produce globally.

The concept of EROI (Energy Return on Energy Invested) is well known in the energy community. Here we introduce the "Iron Utility Return On Investment", or IUROI, a parallel EROI. When we need to invest more effort into getting iron and steel than the utility of having that iron and steel, then we need to stop and think. Because then it does not pay off anymore and we are indeed doing the "Red Queen's Dance" from the Red Queens' Kingdom (Carrol, 1871; Bardi, 2013). Everyone in the Red Queen's Kingdom had to run as fast as they could to stay in the same place. Bewildered, Alice observes that it is a lot of work to get nowhere. At low EROI or IUROI values, we are all in the Red Queen's dance.

The concept of overshooting the planetary boundaries as defined by Rockström *et al.* (2009) inevitably comes to mind. It appears from our work, as well as earlier work (Meadows *et al.,* 1972, 1992, 2004; Randers, 2012) that standard political and administrative planning horizons of 3, 5 or even 10 years are shortsighted. Plans must be for longer than the most significant delays in the system. For most natural systems this is normally more than decades and sometimes more than centuries (see above). This applies to resource dynamics, ecology, forestry, carbon cycles, climate change as well as human society. Regardless of how unpleasant or politically incorrect this may sound, failing to take in this message will inevitably lead to inadequate strategies, insufficient planning and the implementation of policies later regretted, even when the intentions are the very best.

Many of the conclusions we have drawn here, can be made based on the outcome of some simple calculations, some which have been published earlier (Hubbert, 1956; Daly and Ehrlich, 1992; Heinberg, 2001, 2005; Ragnarsdottir, 2008; Ragnarsdottir *et al.*, 2012), but somehow, that is not enough. Now we have gone all the way with complex modelling, and although the qualitative results are the same, we are now in a much better position to explain why. What we show is that we must expect and prepare for large paradigm changes in metal production and use. With proper preparation, many of these challenges may be handled and solutions may be found. However, not doing anything, making no preparations and relying on Business As Usual to continue will potentially lead to unpleasant surprises and problems for global society.

4.1.9 Conclusions for iron

The extractable amounts of iron are, at the present level of extraction, clearly exhaustible over the next centuries. It is to be expected that iron and steel will go up in price as ore grades decrease, increasing energy demands to keep the production up. The rate of extractable amounts depletion is dependent on population size and affluence in society. Whether scarcity will or will not occur, will depend on the availability of energy after 2050. The mining of the large stock-in-use in society can, under a scenario where the population size slowly decreases, and with increased recycling, largely compensate for the exhaustion of iron mines until about 2500 AD, or about 400 years into the future. That is about 10 generations from the present, which may be a reasonable sustainability horizon. We conclude the following:

1. Decrease in ore grade and dwindling extractable amounts of fossil fuels will make it difficult to uphold the present production volume for a very long time, despite large iron extractable amounts. After 2030 the best iron ores will have been used up.

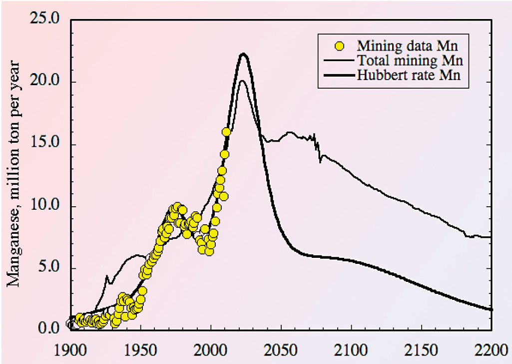
2. Iron and steel prices will depend on ore grade and energy prices. Availability (production volume and supply to society) and potential for future scarcity will depend on availability of large amounts of energy that we may not have at our disposal.
3. An effective recycling policy is crucial for iron and steel availability in the future. Recycling of iron is far more energy efficient than making it from ore, and thus as the cost of the mining effort goes up with decreasing ore grade, recycling as a source will increase its competitiveness. In the future, recycling from stock-in-use will be important.
4. Iron scarcity will not happen because of lack of available iron in extractable iron ores. But as it gets more and more difficult to extract, we will risk iron scarcity because we run out of cheap oil or energy or because we run out of money.

Several metals are important for making steel such as nickel, manganese, chromium, cobalt, vanadium, niobioum and molybdenum. The main use of these metals is in steel and we have therefore grouped them with iron. The future availability of these metals is considered briefly below.

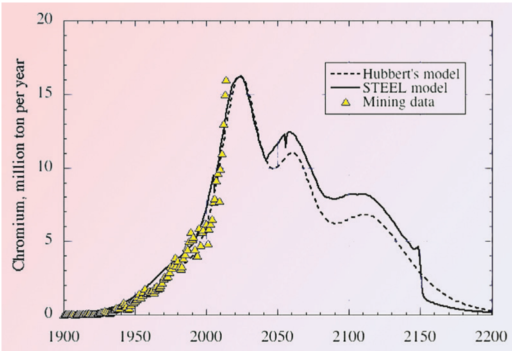
4.1.10 Nickel, Manganese, Chromium, Cobalt, Vanadium, Niobium and Molybdenum

The most important alloying metals for stainless steel are nickel, manganese and chromium. Without these, it becomes very difficult to make stainless steel. The global stainless steel production is at present about 45 million tonnes per year. These metals run the risk of becoming physically scarce long before iron.

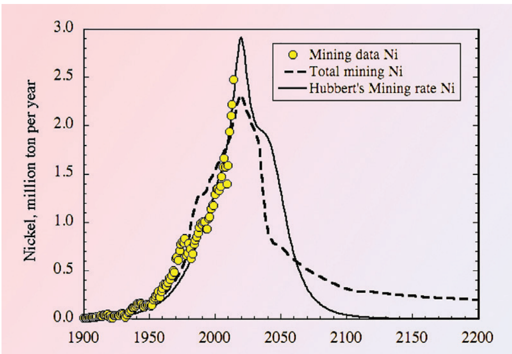
Nickel. Figure 4.23 maps the flows and stocks in society for nickel. We estimate the amount of nickel mined in the period 1850-2010 to be approximately 70 million tonnes. Of this we have preserved in society about 20 million tonnes according to Rauch and Pacyna (2009), or about 29 %. About 0.45 million tonnes is recycled every year. The net annual supply from refineries to the market is about 1.6 milion tonnes, thus we may say that 28 % of supply is from recycling. Of the stock in society of 20 million tonnes, about 2.7 % is recycled annually. Our extractable amounts estimates for nickel are substantially larger than the USGS estimate (by a factor of 2), but this is suggested by the fitting of the Hubbert's model to the most recent production data. Further assessment of reserves and resources for extractability, and grading them according to extraction costs, will give us an URR at any price of a maximum of 170 million tonnes. Our assessment points to a peak nickel production in 2025-2030, suggesting significant shortage in supply and significant price increases by 2030. The production curves are shown in Figure 4.21c, based on using Hubbert's model and our own STEEL model which is an enhancement of the IRON model.



a: manganese



b: chromium



c: nickel

Figure 4.21 Production curves for **(a)** manganese, **(b)** chromium and **(c)** nickel production assessment, using Hubbert's model and the systems dynamics model STEEL developed by the authors.

Manganese. For manganese, our URR estimate is larger than the USGS estimate, based on a Hubbert's model fit to the observed data (Fig. 4.21a). Manganese is a very important alloying metal for steel production. We estimate the URR to be about 4,900 million tonnes of manganese. Even if the URR is large, they are not inexhaustible. Peak production for manganese is predicted to occur in 2020, using the larger URR estimate.

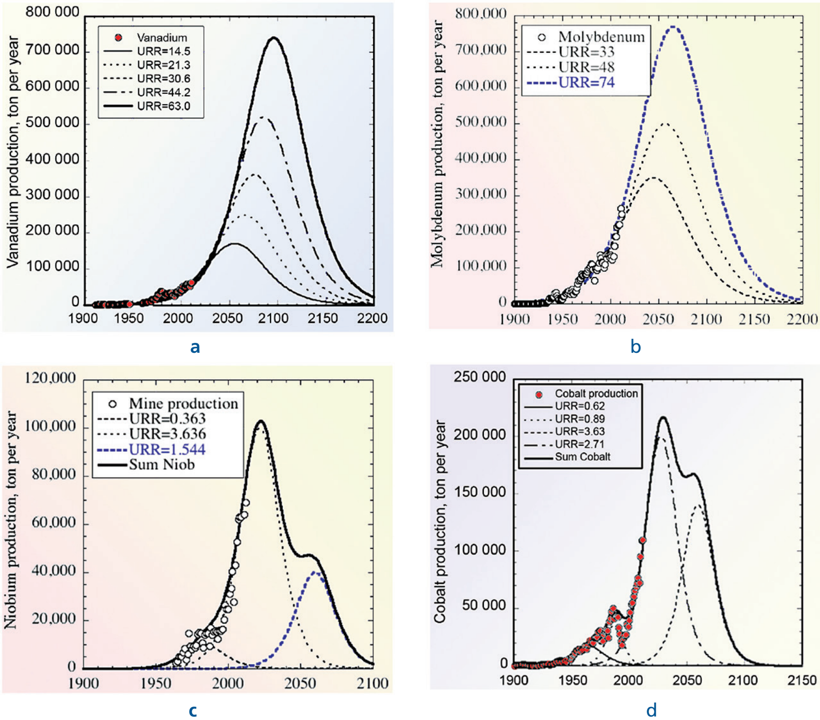


Figure 4.22 **(a)** Vanadium, **(b)** molybdenum, **(c)** niobium and **(d)** cobalt production curves made with Hubbert´s model. For vanadium the URR is not known, but fitting with the Hubbert's model suggests that the most likely URR is 21.5 million tonnes. For molybdenum URR is not known, but the Hubbert's model adaption suggests that an URR at 33 million tonnes is the most likely estimate at this time.

Chromium. For chromium, our estimate of ultimately recoverable reserves (URR = 2,744 million tonnes) is substantially larger than the USGS estimate of extractable amounts (URR >460 million tonnes). Our estimate is smaller than their estimated world reserve base (5,700 million tonnes), which includes unknown reserves and resources, and no assessment of extractability. Chromium has been reported by the industry to be sufficient in supply for a long time. However, working with the available data suggests that the Hubbert´s peak production will occur in 2020, taking account of the known extractable amounts estimates (Fig. 4.21b).

Cobalt. The USGS estimate for cobalt extractable amounts is in the same range as our ultimately recoverable reserve estimate from the fit to production data. Cobalt is a component of specialty alloys, but is also used as an important chemical catalyst. It may serve as a substitute for platinum group metals in certain catalysts, even if the efficiency is less. Cobalt ores contain small amounts of platinum metals. The Hubbert´s peak production is around 2025 (Fig. 4.22d).

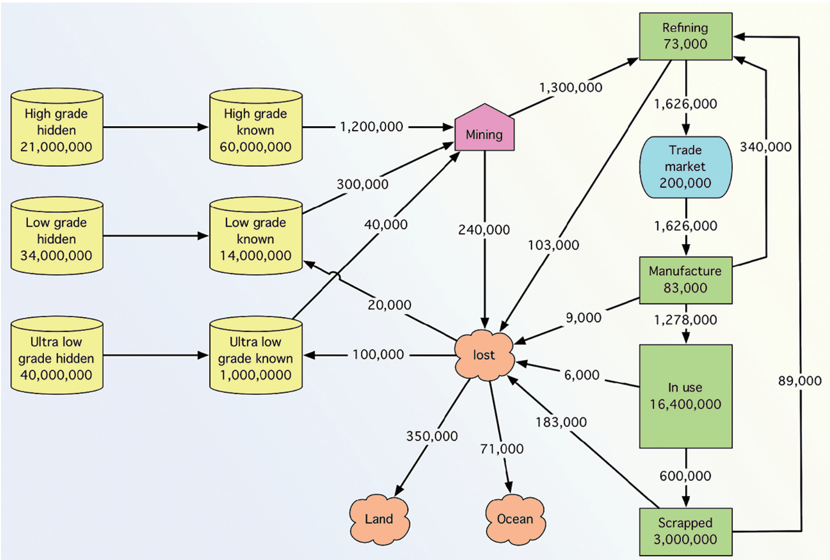


Figure 4.23 Flow chart for nickel 2010. 65 million tonnes have been mined so far, 16.4 million tonnes remain in society, so in total we have about 20 million tonnes as stock-in-use in society. Amounts in tonnes.

Vanadium. The USGS extractable amounts estimates for vanadium are uncertain and to a degree guesswork. One extractable amounts estimate (USGS) gives 15.6 million tonnes but another unpublished estimate from the mining industry suggests 63 million tonnes. This suggests that the resource estimates are very uncertain. We have made Hubbert's curves for different resource scenarios. Vanadium is a key metal in specialty steel production. We estimate the URR to be 21 million tonnes, based on the observed production data and the published literature, giving Hubbert´s peak production around 2070 (Fig. 4.22a).

Niobium is closely associated with tantalum and molybdenum in deposits. Its properties are very similar to those metals. Our assessment is that the URR for niobium is 5.45 million tonnes. The USGS suggests a URR of about 4 million tonnes for niobium. Niobium finds uses in high temperature-resistant steel alloys, such as for jet engines. The Hubbert´s production peak is expected around 2030 (Fig. 4.22c).

Molybdenum. Different URR scenarios were drawn up for molybdenum. USGS estimates the URR to be about 74 million tonnes. Molybdenum often occurs in association with niobium and tantalum and is used in high-performance steels and super-alloys. How much there really is in the total resource is unkown, thus we have made several URR scenarios with Hubbert's curves for molybdenum, giving peak production between 2050 and 2070 (Fig. 4.22b). For our estimate of 33 million tonnes, the peak production is predicted to be 2050.

4.2 Aluminium

Aluminium is the metal produced in the largest quantity, other than iron. Aluminium production is increasing and is expected to continue growing. There is no agreement in the literature on how much more aluminium is available. It is derived from bauxite and mined all over the world. Aluminium is widely used for construction, infrastructures, and consumables in all kinds of machinery. Any scarcity of aluminium will have huge implications for society, economics and politics.

It was long considered that aluminium was inexhaustible, however, the resources of bauxite are limited, and eventually, we may have to turn to other rock sources of aluminium, bringing the energy need and hence the price up very significantly. In Figure 4.24, we fit the production data to a reserve of 22,400 million tonnes of aluminium, not considering raw materials other than bauxite. Earlier we guessed this to be 25,000 million tonnes, based on a USGS estimate of ultimately extractable ores (Ragnarsdottir *et al.*, 2012). The USGS 2012 estimate suggests that there is 20,000 million tonnes aluminium held in bauxite, however, that estimate was made without considering any production limitations for bauxite. This is far more than earlier estimates, and not well documented. The Hubbert's model assessment indicates local production maximums in 2025, 2060 and 2108 (Fig. 4.24).

The Hubbert's production curve for aluminium is difficult to determine because of the large uncertainty in setting the URR. Most probably, aluminium production will be energy limited in the future. Aluminium has today a recycling degree of about 60 % world wide, and this will make aluminium globally available for the next centuries even when prices will go up. There is no immediate risk that aluminium will run out because of empty mines. In the longer run, energy demand for aluminium production will eventually set some limits when fossil fuels come to be scarce – which as for iron is important for both energy production and metal oxide reduction. Then aluminium pricing will change to fit production costs.

Hubbert's model parameters			
Reserve, million tonnes aluminium	b	P_{MAX}	T_{Peak}
680	0.100	17	1986
1,600	0.100	45	2025
2,670	0.060	40	2060
2,330	0.060	35	2108
4,000	0.015	15	2225
3,200	0.010	8	2450
14,480			

Hubbert's model diagram

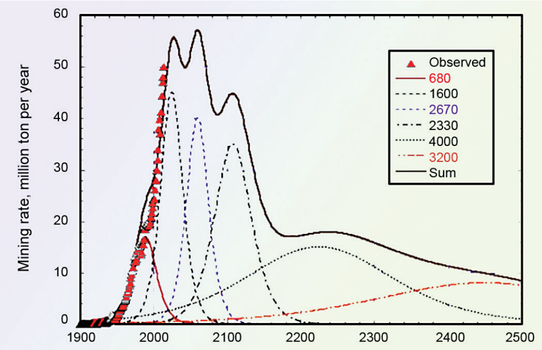


Figure 4.24 Hubbert's model assessment for aluminium extraction from bauxite.

Tables 4.7 and 4.8 show the distribution of the world's recoverable amounts of aluminium ore in tonnes, the ore grades used in the ALUMINIUM model simulations. These are the extractable amounts as estimated in 1930, before the large expansion in aluminium production began, and which are used as model input. The reserve qualities relate to cost of extraction, and thus the opportunity cost. In this way, the URR is not a fixed number before the simulation.

Table 4.7 Distribution of the world's recoverable amounts of aluminium ore in tonnes, the ore grades used in the ALUMINIUM model simulations. The numbers were derived after studying estimates like those listed in Table 4.8. Amounts are in tonnes of aluminium.

Type	Known Millon tonnes	Hidden Millon tonnes	URR Millon tonnes
High Quality	300	9,700	7,000
Low Quality	400	9,600	10,000
Other minerals	200	3,000	3,200
Sum	900	22,300	20,200

Table 4.8 Different estimates of the total aluminium extractable amounts.

Source	Million tonnes					
	Presently known extractable amounts bauxite	Aluminium content	Reserve base bauxite	Reserve base aluminium content	Aluminium content mined	URR
Roper (2009)	-	-	40,000	18,800	1,900	20,700
USGS (2011)	29,000	13,700	44,000	20,700	1,900	22,600
Rauch (2009)	-	16,000	34,040	-	1,900	17,900
Norsk Hydro	29,000	13,700	65,000	30,550	1,800	46,050
Averages	29,000	14,470	49,900	23,350	1,900	26,813

4.2.1 Energy use required for aluminium production

Energy plays an important role in aluminium production and for evaluating the extent to which aluminium production can be increased and whether aluminium can be substituted for other metals like iron, copper and zinc. The energy use for aluminium production is provided in Table 4.9 (Smirnov and Tikhonov, 1991; Smirnov, 1992, 1996; Norgate and Rankin, 2000a,b).

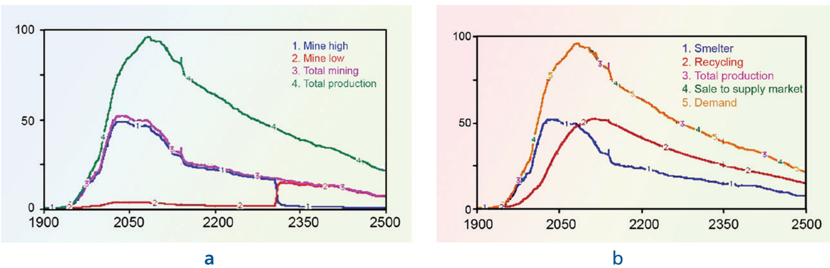
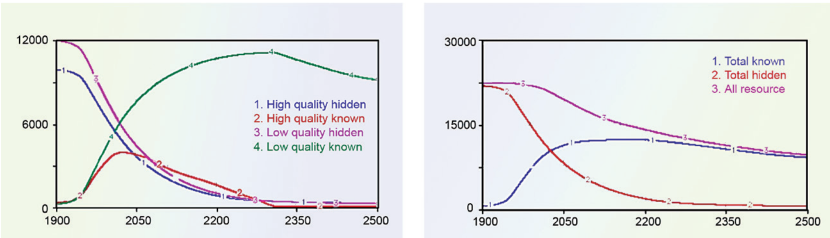


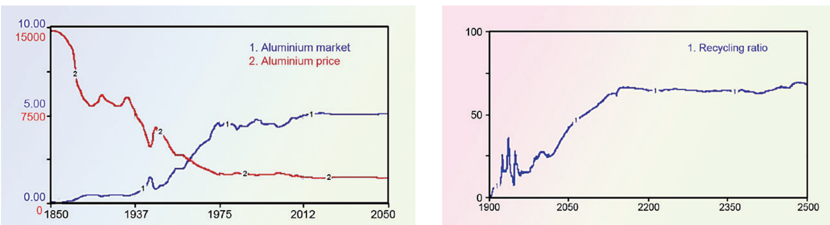
Figure 4.25 **(a)** Estimates of past and future aluminium mining rates, expressed as aluminium metal and delivery to the market. The mining from high quality resources is shown (line 1), from low quality, which is prioritised down as long as good quality ore is available (line 2). (Line 3) shows the total mining amount in million tonnes/year, (line 4) the total production into the market, and (line 5) the amount from the aluminium smelting. **(b)** One interpretation of recycling with (line 1) the amount from smelter production, (line 2) the amount being recycled from scrap, and (line 3) the total production into the market. Y axis gives production in million metric tonne per year, X axis date in years.

Table 4.9	Energy use in aluminium manufacturing.	
Pathway	**Energy need**	**Energy demand versus recycling**
Aluminum from recycled aluminum scrap	11-17 MJ/kg	1
Aluminum from high quality bauxite	227-300 MJ/kg	20
Aluminum from low quality bauxite	250-342 MJ/kg	25
Aluminum from nepheline	250-350 MJ/kg	30
Aluminum from muscovite or feldspar	500-1,400 MJ/kg	65



a b

Figure 4.26 Estimates of the evolution of bauxite deposits with time, expressed as million metric tonne of aluminium. **(a)** The resources in the ground, (line 1) high quality hidden, (line 2) high quality known, (line 3) low quality hidden, and (line 4) low quality known, and how they develop over time. **(b)** (Line 1) total known aluminium in bauxite deposits, (line 2) the amount hidden and (line 3) everything that is really there. Y axis gives production in million metric tonnes, X axis is the year.



a b

Figure 4.27 **(a)** Estimates of (line 1) the aluminium market stock in million metric tonne, and (line 2) the aluminium price in dollars per metric tonne. **(b)** The ratio of recycled material to the flux into the market. Y axis gives stock in million tonnes for the aluminium market, dollars per tonne for the price and % for the recycling rate, X axis is the year.

The numbers in Table 4.9 are for the Hall-Heroult process, that uses CaF_2 (cryolite) as a flux in the reduction process, which decreases the melting temperature of alumina (Al_2O_3) from 2200 °C to 980 °C. Aluminium is very tightly bound to oxygen in the ore and in the rocks where it frequently occurs. This determines which rocks containing aluminium constitute a realistic ore at present. Bauxite is the ore for which the extraction energy cost is the lowest. It is evident that recycled aluminium uses far less energy than making aluminium from ore (Table 4.9). The comparable values for iron are found in Table 4.6

The energy cost of making steel is only 7-12 % of that for making aluminium from bauxite ore and explains to a large degree why aluminium is more expensive than iron. Making steel from recycled material costs about 60-80 % of the cost per tonne for recycling aluminium. The energy cost of replacing iron with aluminium, when considering the difference in weight and strength, is about half by weight. Aluminium has a specific density of 2,700 kg m^{-3}, whereas for steel this is about 7,900 kg m^{-3}, which is 2.9 times higher. Because of strength differences, 1,000 kg of steel can be replaced by approximately 400-500 kg of aluminium. The metal production cost per use-unit would be equal for recycled iron or aluminium, but a huge difference exists for prime aluminium made from ore. Of importance also is that iron production is ten times higher than aluminium, and therefore aluminium is not a likely substitute for iron (see Table 4.22). Making aluminium from minerals other than bauxite is not economic at present, but may be in the distant future if bauxite reserves run out. Nepheline ($NaAlSiO_4$), a feltspatoid neosilicate, is the only other mineral also used for alumina production. $KAlSiO_4$ is the potassium end member of the continuous mineral solid solution of nepheline and could be an alternative mineral substrate. Nepheline is used in Russia today as a source of alumina for cement and aluminium production. Using other aluminiumsilicate minerals that are more tightly bound with oxygen would increase the energy costs significantly.

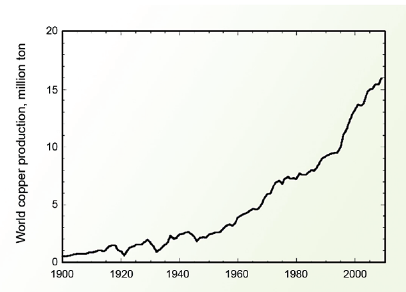
4.2.2 Remaining aluminium extractable amounts and scarcity mitigation

Figure 4.25a gives an overview of past and future aluminium mining rates, expressed as aluminium metal and delivery to the market. Figure 4.25b shows one interpretation of recycling. Figure 4.26a gives an overview of the development of the extractable amounts of bauxite, expressed as million of tonnes aluminium content. Figure 4.26b shows total known aluminium in bauxite deposits, the amount hidden and everything that exists. Figure 4.27a shows the aluminium market stock in million tonnes, and the aluminium price in dollars per tonne. Figure 4.27b gives the ratio of recycled material to the flux into the market. Recycling will be the most important source after 2060 (Fig. 4.25b).

4.3 Copper and Zinc

4.3.1 Copper

Copper is one of the bigger bulk metals in society, produced in amounts above 10 million tonnes per year. Copper is also a key element for many specialised technical applications, and especially for electronics. Several important key metals for technology are extracted from the anode sludges produced as a by-product of copper and zinc refining. Indium, germanium, gallium, bismuth, antimony, tellurium and selenium are examples of metals that have no individual mines, but are at times extracted with copper (Brewster, 2009; Statista, 2010; Graedel *et al.*, 2004; Geoscience Australia, 2009; Crowson, 2011a,b; Northey *et al.*, 2014). Figure 4.28a gives copper production from the year 1900 and 4.28b gives the copper market price. While the copper extraction has been rising exponentially, the price has fluctuated – showing a large jump since the year 1990. Figure 4.29 depicts the flow chart for copper (adapted after Sverdrup *et al.*, 2014b). The flow chart is substantially modified and updated based on Rauch and Pacyna (2009), using more recent industry data, and resolving internal conflicts in the literature data. 320 million tonnes, or about 50 % of what has been mined (about 500-600 million tonnes in total) is still in use in society. Copper is 100 % recyclable without any loss of quality, from any product. In volume, copper is the third most recycled metal after iron and aluminium (about 50-60 % is recycled). The average global per capita stock of copper in use in society is 35–55 kg. There is much more in stock in developed countries (140–300 kg per capita) than in developing countries (20–60 kg per capita).



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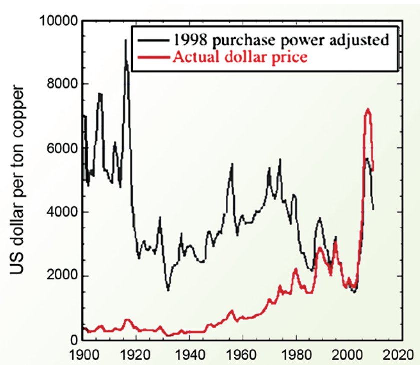

b

Figure 4.28 **(a)** The global copper production from mines, 1900-2010. Data adapted from the USGS (2012) database. **(b)** Running and value-adjusted copper market price 1900-2010.

Copper is the third most important metal for infrastructures in society, only after iron and aluminium. The Hubbert's estimates are confirmed by URR data, and the predictions are robust. We have constructed a full dynamic COPPER simulation model (Sverdrup *et al.*, 2014b), and the general market price can be predicted. Figure 4.30 gives data that assist in constraining the model: (a) URR vs ore grade, (b) price vs ore grade, and (c) URR as a function of time. The Hubbert's curve is shown in Figure 4.31a. For copper the curve marked URR = 3,500 million tonnes is the most relevant, suggesting a production peak in 2050. Of note is that in mining copper other metals are also mined as secondary products (see Fig. 4.3).

Table 4.10 Overview of mined amounts during certain periods and recoverable resources looking backwards and forwards in time, expressed in million tonnes of copper metal. Inherent in the table is a cut-off on extractable copper at 0.5 % ore grade.

	Million tonnes copper		
	Recovered	Losses	Cumulative
Mined before 1900	57	11	68
Mined 1990-2010	577	109	754
Remaining resources, extractable in part	467	83	1,304
Reserve base reported by USGS, extractable in part	369	65	1,738
Additional cumulative from all discoveries	1,240	186	3,164
Sums at the end of time	2,710	498	3,208

Table 4.11 Different estimates of globally extractable total copper extractable amounts, million tonnes.

Source of estimate	Extractable resources in 2010-2013	URR
Copper Development Association Inc. (2013)	2,185	2,938
United States Geological Survey, USGS (2013)	2,246	3,000
MinEx Consulting (2010); cumulative from prospecting	2,391	3,145
Laherrere (2010); Copper peak	1,600	2,354
Kesler and Wilkinson (2013)	2,246	3,000
Mohr *et al.* (2014)	1,950	2,700
Radetzki (2008)	1,400	2,200
Average URR		2,762

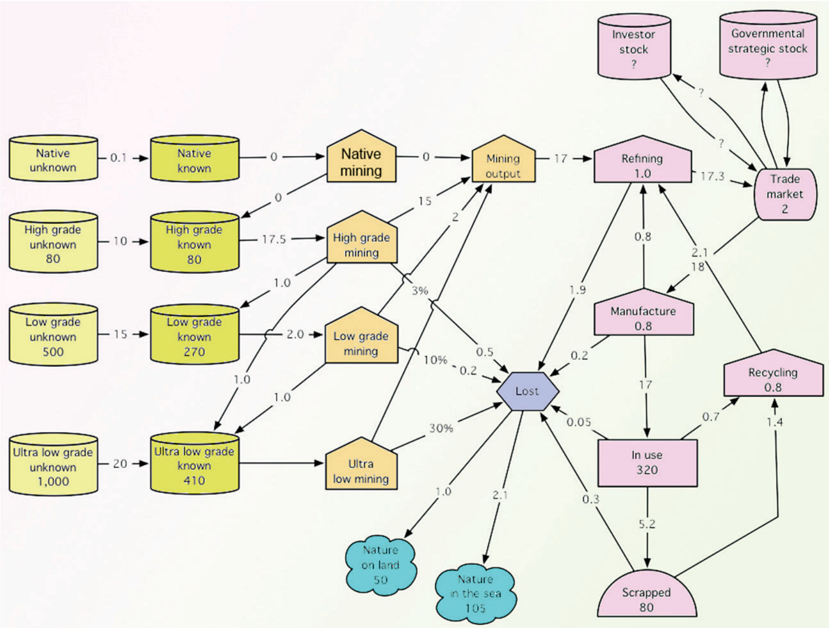

Figure 4.29 Flow chart for world copper material fluxes in 2005 in million tonnes as used in the COPPER model. Data from Gordon *et al.* (2006), Rauch and Graedel (2007), Radetzki (2008), Rauch and Pacyna (2009), Laherrere (2010), MinEx Consulting (2010), Crowson (2011a,b), Anglo-American Mining Corporation (2012, 2013), Kesler and Wilkinson (2013), USGS (2013).

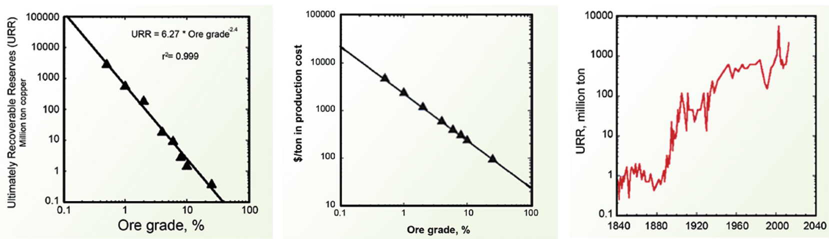

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Figure 4.30 Different diagrams made to assist the assessment with the COPPER model. **(a)** URR as a function of the lowest ore grade assumed to be extractable. **(b)** Production cost per tonne versus ore grade. **(c)** URR as a function of time for copper. As we go down in ore grade, it theoretically may look as if the reserve increases fast, but at the same time, the decreasing yield makes this irrelevant as we cannot extract it efficiently.

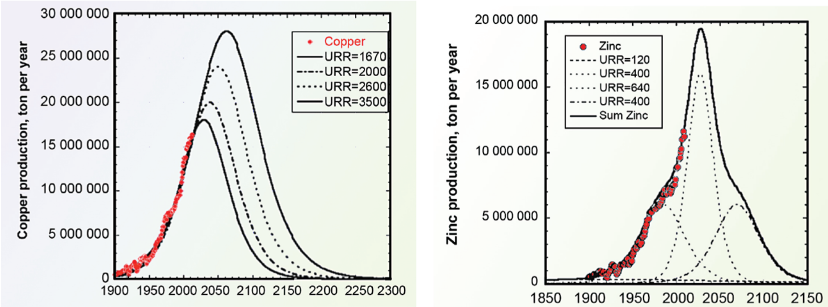

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Figure 4.31 The Hubbert's curves for copper, investigating different URR for copper (a) and Zinc (b). Open dots are observed mining quantities.

Table 4.10 gives an overview of mined copper over time and Table 4.11 gives different URR estimates. For copper, the size of the extractable amounts is controversial, as *Vala* witnessed by listening to several presentations at the International Geological Congress in Oslo in 2008. But when we look at the published literature, the values found for copper extractable amounts are those reflected in Table 4.11. Table 4.12 gives the input data for the COPPER model. The resources down to the extra ultralow grade were used as input to the COPPER model runs and the Hubbert's model in Figure 4.31. The numbers are updated with respect to our earlier publications (Sverdrup *et al.,* 2014b). Figure 4.31 shows the Hubbert's curves for copper and zinc, investigating different URR for copper. Figure 4.32a shows COPPER model simulations for copper production for the period 1800-2200. The model has recycling depending on the copper price built in, and after 2050 recycling of landfills and scavenging from the stocks in society become important means of supply. Figure 4.32b shows the change in time for different known oregrades in million tonnes. Figure 4.33 shows the COPPER model simulation of the supply of copper to society as compared to recycling and supply from mining.

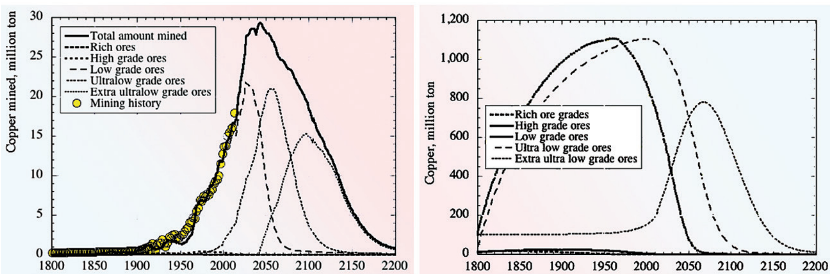

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Figure 4.32 **(a)** COPPER model simulation of the copper production during the period 1800-2200, re-run for this study. **(b)** Known copper reserves over time. Y axis gives million tonnes and X axis the date in years.

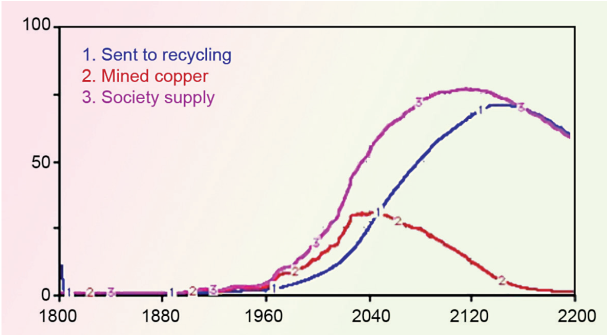

Figure 4.33 COPPER model simulation of the supply to society compared to supply from mining. The model run shows how supply becomes dominated by recycling and how the peak in mining comes in 2030-2050, but that the peak in supply to society comes 2100, or about 60 years later because of recycling.

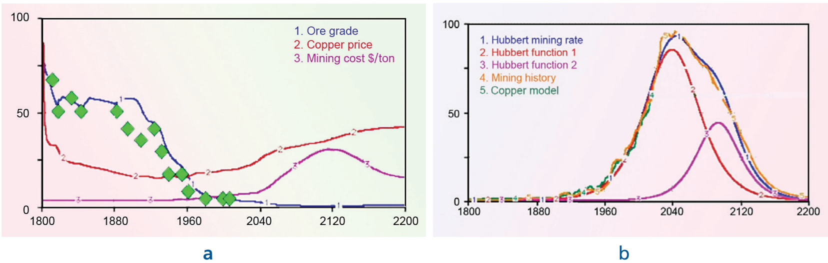

Figure 4.34 **(a)** Shows the COPPER model simulated ore grade (%) and copper price ($/kg) as compared to observations (diamonds); Y axis gives ore grade in % metal weight in the ore and X axis date in years. The price and mining costs are measured in $ per kg. **(b)** Shows the Hubbert's curve compared to the COPPER model using a two-component Hubbert's model. The same URR was used in both models. The increase in price matches the progression from high grade ore to lower grade ore. Y axis million tonnes per year and X axis date in years.

Figure 4.34a shows the COPPER model simulated ore grade (%) and copper price ($/kg) as compared to some observations. Figure 4.34b depicts a simulation showing how well the Hubbert's model compares with both the COPPER model and the actual observed history. The ore grade as well as the copper market price is somewhat over-predicted. We conclude that with the assumptions discussed above, maximum copper use in society will be available until around 2100 but due to recycling Cu is still available long after 2200.

Table 4.12 Input data to the COPPER model: the Ultimately Recoverable Reserves (URR). Y is the copper yield when extracting ore, R is the recycling % if it is driven by price alone. The minimum price is set as the production cost plus 20 %. Grading the extractable amounts like this is sometimes called "an opportunity cost based reserve estimate". This way the URR depends on how much the society will be able to pay for the metal.

Ore type	Cu content	Y %	Metal production cost, $/kg	R %	Minimum metal price, $/kg	Reserve, Million tonnes	
Rich grade, 400 kg/tonne	40	100	2	30	5	20	20
High grade, 50 kg/tonne	5	99	16	40	18	100	120
Low grade, 10 kg/tonne	1	98	80	48	76	1,300	1,420
Ultra low grade, 2 kg/tonne	0.2	91	400	54	334	1,215	2,635
Extra ultralow grade, 0.5 kg/tonne	0.05	80	1,600	60	1,200	1,200	3,835
Trace amounts, 0.1 kg/tonne	0.01	71	8,000	80	2,000	1,000	4,835
Precious metal, 0.01 kg/tonne	0.001	65	>40,000	90	40,000	300	5,135

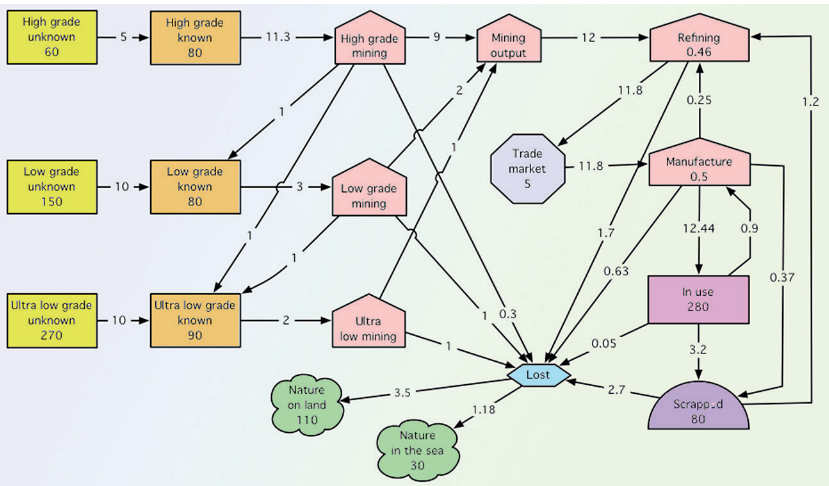

Figure 4.35 Flow chart for world zinc material fluxes in 2005. The diagram was based on Rauch and Pacyna (2009). Amounts in million tonnes, and fluxes in millions of tonnes per year.

4.3.2 Zinc

Zinc is one of the important bulk metals in society. Figure 4.35 shows the flow chart for zinc. The flowchart for zinc is substantially modified and updated by Sverdrup *et al.* (2013a), but original data is based on Rauch and Pacyna (2009). Zinc and copper mining are a major source of silver. The stock in society is 280 million tonnes, and a significant part has already been excavated (40 %). The USGS reserve estimate is 1,900 million tonnes, of the same order of magnitude as we get from the Hubbert's model assessment (Fig. 4.31b). The peak behaviour is easy to see from the production diagram and it is predicted to happen around 2030. The open dots in the Hubbert's diagram are observed mining data points (Fig. 4.31b).

4.4 Silver

The source of silver is increasingly becoming associated with mining of copper, zinc and to some extent lead. Like gold, silver has a tradition of being money or of value and has always been guarded and recycled; 74 % of the silver mined to date is still around in society. The silver ore grade has fallen from an average of 0.25 % to present 0.01 % (2,500 g/tonne to 100 g/tonne). This suggests that we are approaching the end of the reserve, and that production costs will continue to rise in the future. Mines supply 23,000 tonnes silver per year at present, but the market is supplied with an additional 17,700 tonnes per year from recycled silver, totalling about 40,000 tonnes silver coming to market every year (The Silver Institute, 2003; CPM Silver Yearbook, 2011). The available silver stock in society is still increasing by about 8,000 tonnes silver per year. The stock in society is about 1.1-1.3 million tonnes, including that held by banks, public, industry and strategic governmental reserves. We were able to reconstruct a large part of the silver mining history (Fig. 4.36), starting from 3000 BC. Note the logarithmic Y axis in the silver diagram. During history, silver also came from lead, gold, and later also from copper and zinc mining (Table 4.13). The total global URR is in the range 2.8-3.1 million tonnes of silver. We have built SILVER, a fully dynamic simulation model for silver (Sverdrup *et al.*, 2014a). Half the silver ever available has already been mined (approximately 1,465,000 tonnes; Sverdrup *et al.*, 2014a). About 50 % of all new silver now comes from secondary extraction from copper, zinc and lead. The mining for silver also supplies a significant amount of gold. Figure 4.36 depicts that silver production will peak in 2035 and sharply decline thereafter (Sverdrup *et al.*, 2014b).

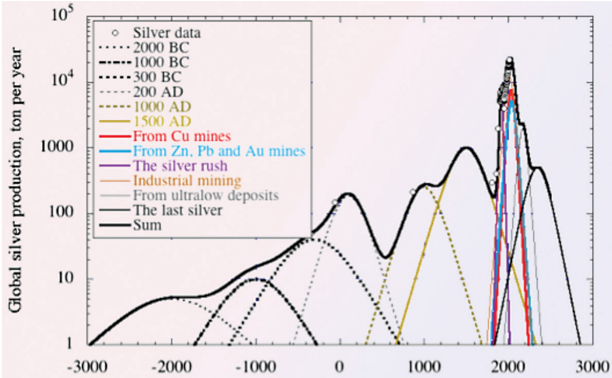

Figure 4.36 Individual and total sum of Hubbert's curves for silver production from 3000 BC to beyond 3000 AD. The parameters of the Hubbert's model used are listed in Table 4.12. The dots are observed production data.

Table 4.13 Overview of sources of silver in mining. The average reserve contents were adapted from unofficial information from Boliden AB, Rönnskärsverket, Sollefteå, Sweden and K. A Rasmussen A/S, Hamar, Norway as well as from scientific literature (Sverdrup *et al.*, 2014a).

Reserve type	Ultimately recoverable reserves (URR), tonnes parent metal	Silver content in the native metal	Silver content URR, tonnes	Range, tonnes	Fraction of total URR, %
Silver	1,078,100	100 %	1,078,000	916,000-1,240,000	39
Copper	2,700,000,000	0.032 %	805,000	684,000-925,000	30
Zinc	1,560,000,000	0.040 %	625,000	531,000-725,000	22
Lead	1,240,000,000	0.008 %	40,500	34,000-46,000	8
Gold	310,000	6 %	19,000	17,000-22,000	1
Sum			2,501,000	2,132,000-2,952,000	100

Figure 4.37a gives the simulated silver production through the years 1850-2200. Figure 4.37b shows the supply from mines according to the dynamic simulation with the SILVER model (solid line) and the observed production (open circles), $r^2 = 0.89$. We have included the observed mining rates to show that the rates fall on the predicted lines. Figure 4.37b also shows a comparison of the Hubbert's model and the SILVER model. When we test the Hubbert's model to data, we get $r^2 = 0.92$ (Fig. 4.37b). On the prediction of potential future silver

scarcity, then what possibilities are there for substitution? Gold may take the role silver does in some electronics applications, but gold is expensive and becomes scarce at the same time or earlier than silver (Ragnarsdottir *et al.*, 2012; Sverdrup *et al.*, 2013a,b,c). The global gold production is 2,900 tonnes/year in 2014 and the global silver production from mines is an order of magnitude higher at 23,000 tonnes/year. Therefore, gold can in no way substitute for the bulk of silver use. Copper may be used in some applications, but copper also becomes scarce when silver does (Ragnarsdottir *et al.*, 2012; Sverdrup *et al.*, 2013a,c, 2014b), but there is 10 times more copper than silver, so copper substitution for silver may work. Nickel may take over some of the roles of silver in some alloys, but nickel will become scarce about the time when copper and silver become scarce (Sverdrup *et al.*, 2014a,b). For some catalytic purposes, there may not be any attractive substitutes. In silver jewellery, massive silver is being substituted by silver-plated base metals. For many applications, silver is an important substitute for gold. The silver production is expected to go through a peak in the 2030s, and because of the rapid use and the very limited amount of silver available, future silver supply to industry is soon at risk. After 2100, most silver supply to society will have to come from recycling and urban mining of the in-use stock in society.

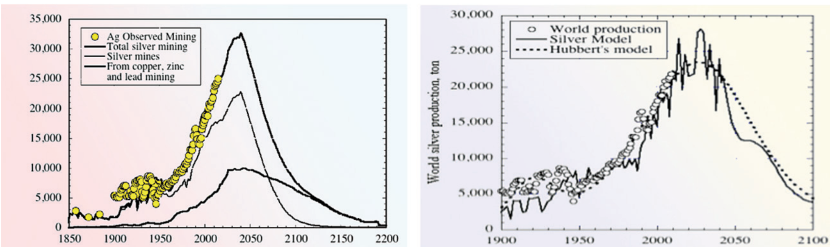

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Figure 4.37 **(a)** The SILVER model outputs 1850-2200. **(b)** Simulated silver production through the years 1900-2100 using the SILVER model output in tonnes silver and the comparison between silver mined according to Hubbert's empirical model (dotted line), the dynamic simulation model SILVER (solid line) and observed production data (open circles). Y axis gives amounts in tonnes silver and X axis date in years.

Figure 4.38 The first coins were made in the Kingdom of Lydia, about 650 BC in silver and gold (modern day Western Turkey). It was a great success. Trade and commerce flourished when payments were standardised (Sear, 1978).

4.5 The Story of Gold

Gold is an interesting element, because it is important for society, but also in how it interacts powerfully with our concept of money, finance and greed. Gold is a metal that is scarce, as it has always been, and if we want to know what happens when we have metal scarcity, gold is an excellent example to study. Gold may seem unimportant for technology, but that is not the case. There is gold in every cellphone (1.5 billion cellphones are made per year) and in every computer motherboard. It is a good example of a minor metal with large importance for new technologies. It is also the only metal that can be said to be sufficiently well recycled. It is one of the oldest monetary bearers of value in existence; it has been used since the beginning of agricultural society. The grandfather of *King Kroisus* (550 BC) of Lydia, *King Sadyattes* (about 650 BC), was the first to issue governmental money in gold and silver as coins (see Fig. 4.38 for the first coin made, and also Sear, 1978; Kock Johansen, 2001; Butt and Hough, 2009). At several times in history man has experimented with paper money – in China during the Han dynasty 200-400 AD, during the Yüeh dynasty 1340-1450 AD, and originally in Sweden and afterwards in European states from 1700-present. All governments are tempted to overprint paper money to pay bills when the till is empty. Many governments have succumbed to that temptation and have subsequently ruined their economies.

Gold is a limited resource, and the gold market is affected by the fact that it is a free market within set physical limits. Gold is the third most traded resource in the world in value after fossil hydrocarbons and iron. Gold has been traded in many ways, and the following illustrates how the story of a resource is also the story of money in modern times:

- The gold market over the past two hundred years has been complex:
  - From about 1812 to 1925, many currencies were pegged to gold and silver in a dual metals system.
  - Before 1932 there was a free, relatively unregulated gold market, for traders outside the state, gold was the same as money, gold was the ultimate currency.
  - 1932-1971 the market was a state-run command and control system. Gold possession was prohibited for private persons in many countries.
  - After 1971 gold is for most practical purposes a free market, and movement of gold has been relatively unrestricted.
- Paper gold, existed through the bank notes being gold certificates from 1830 to 1935 and after 1973 as a separate market for gold certificates. Forwards are promise notes, however, with no required physical backing. These are not available to the public, but to companies and financial institutions.
- There is not full substitutability in the gold market:
  - There is a limited substitute in silver and in modern times by platinum and palladium as bearers of monetary value.

- Palladium and platinum are substitutes in a number of technical applications.
- The total physical amounts of all gold, silver and platinum are limited.

- Gold is sold as physical metal as well as paper gold. Ownership of gold is shown on a metal bank account and in different types of speculative constructions resembling gambling. The amount on the account has a corresponding amount of physical metal somewhere if the trader is genuine. Gold is traded in several different variants:

  1. Physical sales
     a. Gold is traded as physical commodity. The money and physical metal change hands simultaneously at the trading moment.
     b. The ownership of physical gold deposited at a safe storage is traded. The gold is allocated and physically verifiable.
  2. Gold banking
     a. Gold is sold or bought from a metal account in a bullion bank or a gold refinery. The gold is not allocated, but assumed to exist in reasonable quantity to back up the accounts. Most of the time the gold is all there or at least a substantial part of it.
     b. Metal is deposited to a metal account with a bullion bank or a gold refinery. The physically stored amount has ownership allocated and physical metal is handled.
     c. In earlier times, the central banks issued bank notes that could be used as paper money or exchanged for physical gold at the central bank. The system was largely abandoned in 1925-1932.
  3. Derivatives
     a. Forward: gold can be traded forward, that is sold or bought now for physical supply later.
     b. Hedge: gold is sold now for re-purchase at a later date at the same price. This is used to "secure" the price and eliminate price risks on stock for trading companies and refineries.
     c. Short: gold is sold without having possession at a point in the future, the seller gambles on being able to buy it at a later date. Normally the seller must be able to show a guarantee for 10 % of the amount.
     d. Naked short: gold is sold without having possession at a point in the future, the seller gambles on being able to buy it at a later date. The seller is not able to show a guarantee for 10 % of the amount, and makes a monetary guarantee for 10 % instead.
     e. Blank: the seller borrows gold and sells it, gambling on being able to buy it back when it is needed to repay the metal loan to the owner. The owner may need to consent or not, depending on country legislation.

f. Futures: a collection of different instruments, including forwards, hedges, short, naked short and/blank.

Bankers will have us believe that gold is not money, however, the large banks treat it behind closed doors as the ultimate money regardless. *Harald* has witnessed this many times.

4.5.1 The physical gold resource situation

Gold comes ultimately from mines, and approximately 187,000 tonnes have been mined so far (2012). It is estimated that approximately 80,000-100,000 tonnes remain to be mined (USGS, 2011; Ragnarsdottir *et al.*, 2012, see Tables 4.13 and 4.14). Of the existing amounts extracted, we have lost about 6,000 tonnes, or about 4 % of all the gold excavated. One may ask how this much gold can be really lost, and there are several types of losses that can be identified: losses in the deep ocean when ships at sea are lost (several hundred tonnes); gold plating that was worn off and irreversibly lost (about a thousand tonnes); gold that went into graveyards through history as jewellery, dental materials and ornaments (about a thousand tonnes); and into modern garbage landfills as municipal technology waste, with electronics, machinery, ornaments etc (several thousand tonnes). In absolute terms, very little has been lost (Tables 4.14-4.15).

Table 4.14 Gold estimates of historical production to 2012. Compiled by the authors from literature sources of various kinds. All amounts are in tonnes of gold.

Time Period	Amount mined, tonnes	Tonnes per yr	Cumulated stock, tonnes Au	People billion	g gold per person
4,000-500 BC	600	0.13	420	0.1	3.0
500-1 BC	2,200	4.4	2,312	0.4	5.5
1-400 AD	4,400	11	6,272	0.5	12.6
401-1491	8,100	8.1	13,643	0.6	22.7
1492-1600	6,500	60	19,623	0.7	27.8
1601-1800	12,310	62	31,071	0.9	34.0
1801-1900	11,500	115	41,881	1.5	27.2
1901-2000	116,000	1,160	152,081	3.0	48.4
2001-2012	25,400	2,310	176,465	7.0	24.0
Sum	187,010		176,465		

There are three ways to own gold physically and several through proxies:

1. Physical possession of coin, minted ingots, in the shape of jewellery or just metal, most commonly to the layman as ownership of gold

ornaments and jewellery. You own it and you have it. It's real. Coins and ingots trade like money, the others require refining as part of selling.

2. As dental gold and medical implants as a part of your body. You have it and own it.
3. Gold on a metal account with a bullion bank or refinery or as a certificate at a bank, financial house, trader or metal processing firm. You hold an account, thus a claim against the institution. The gold is not physically identifiable, and you have it only when you demand delivery and they deliver physical gold. Unless the bank gives you physical gold, you do not have any.
4. Gold on a forward or a hedge contract with a trader. Then you own a contract and not the gold. You have physical gold only after delivery.

Table 4.15 Location of gold resources between gold mines and other types of metal mines. All amounts are in metric tonne gold.

Primary metal reserve	URR, host metal, tonne	Gold content, %	URR Gold, tonne	Mined to 2012	Remaining reserve in 2012, tonne
Gold	237,000	92	237,000	151,472	85,528
Silver	2,512,000	0.008	21,740	15,590	6,140
Copper	2,700 mill	0.002	54,000	15,938	38,062
Poly-metallic ores			20,260	4,000	16,260
Sum	-	-	333,000	187,000	146,000

When we look at the market, we need to add up the amounts in all these categories and then set that against what gold is physically available; this sets an absolute limit for how many contracts can be honoured. Gold mining companies, processing companies, recycling companies and refining companies, normally have metal accounts backed up by their own metal stock. They are usually very well covered and able to deliver promptly. It is also useful to remember that mining and recycling are for many practical purposes almost the same in the refining stage.

Figure 4.39 shows a flowchart for world gold material fluxes. Most trades occur through the retail market, trades are geographically dispersed, but linked through the price systems at the London and New York Metal exchanges. Trading houses and banks have their own metal stocks that they declare openly, although some do not. Here transparency is small and the risks are as with other bank certificates. Several banks and trading houses back up their contracts with forward contracts and metal accounts with others, and the whole system becomes much less transparent. In 1925, the first breakdown in the gold-silver currency came with the abandonment of the right to exchange paper money to gold at will, first in many European countries, and in 1932 the United States, followed with prohibition of private possession of gold and a forced state exchange of gold at a fixed price. In 1973, the American *President Nixon* removed gold backing from the dollar totally when the French government attempted to exchange their dollars for gold. After that, there is no real precious metal standard for the public for any currency. In case something drastic happens, several Central Banks still keep substantial amounts of gold and silver metal as a last safety resort. From the moment the currencies of the world became based on social trust alone, many fell an easy prey to inflation.

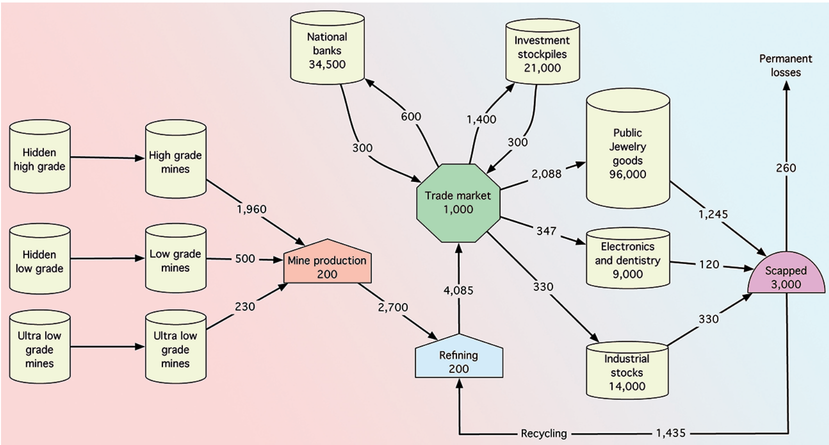


Figure 4.39 Flow chart for world gold material stocks and fluxes in tonnes or tonnes / year (after Sverdrup *et al.*, 2013a).

Figure 4.40 is a causal loop diagram for the price mechanism working in the gold market. It shows that there is a physical gold system and a paper gold system, with no or little physical backing. The upper part shows the causal links in a physical market system. Gold is mined because it gives profit. Profit comes from income, but is decreased by costs. More mining gives smaller reserves, but gives more gold to the market. More gold in the market lowers the price. The amount supplied times the price gives the income.

It needs to be remembered that about 60 % of the world's population live in countries with a low degree of state financial accountability (Democracy Web, 2013; Freedom House, 2013). For all people living under these conditions, commodities, gold and silver are the only real money existing that will persist through crises. Paper money is called a "fiat" currency, the Latin word for "trust". If a majority of the population has little or no trust in their government, then the paper bills presented as money will have no value. If we look at Europe, only

Norway, Sweden, Denmark, Great Britain, the Netherlands and Switzerland have managed their national finances in such a way that they have avoided crashing their currency in recent history and in modern times.

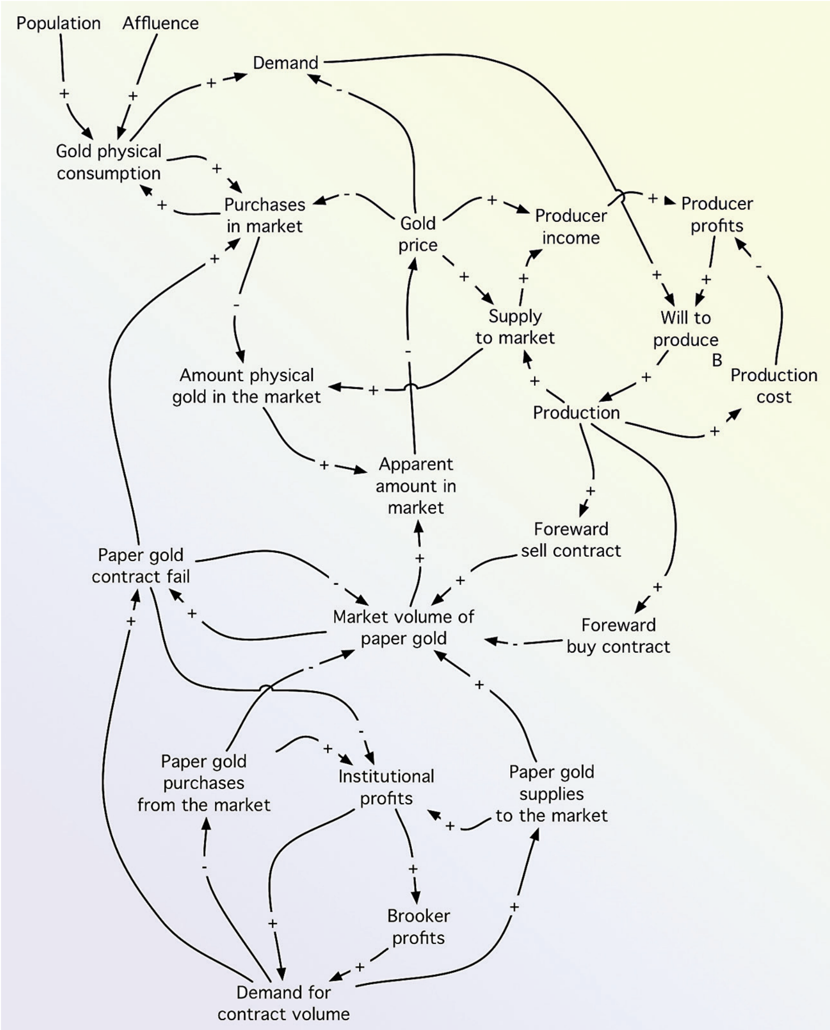


Figure 4.40 The price mechanism working in the gold market. Note that there is a physical market and an imaginary market with "paper gold".

Table 4.16 shows our estimate of location of gold reserves between gold mines and other types of mines for other metals. We have assumed that some of the reserve base to be included as contents in silver, lead and copper ores. The production of individual metals is to a degree interdependent. 20 % of gold comes from silver and copper mining. Tables 4.15 and 4.16 show an overview of where the gold in the world comes from, where it is and who owns it now. The numbers were collected from unofficial sources by the authors. There is no way to officially verify these numbers, except that they must add up to the appropriate sums that make sense.

Table 4.16 Gold; an overview of where it is and who owns it at the end of 2013. The numbers have been collected largely from unofficial sources and unpublished industrial statistics by the authors. It has been back-checked against publications by the World Gold Council (2013). Units in metric tonne.

Land	Central Bank stock	People's stock	Total stock
Europe	13,162	37,387	50,549
Asia	8,553	51,575	60,128
Americas	9,337	13,400	22,737
Africa and Middle East	3,650	11,450	15,100
Global amounts	34,702	113,812	148,514
Refineries	-	4,000	4,000
Electronics	-	4,000	4,000
Dental gold	-	3,000	3,000
Industrial uses	-	12,000	12,000
Investment	-	21,000	21,000
Sum	33,933	157,812	192,514
Losses as the missing term	-	-	3,486
Total mined	-	-	196,000

4.5.2 Gold methods and definitions

The flow chart for gold is shown in Figure 4.39. The flow chart is quite robust, because the material is so valuable that humans keep good track of it (Tables 4.16-4.17). This makes it the world's best recycled material (93 %). Gold is currently at the global peak production (Figs. 4.41-4.42) and we have mapped historical data for over 8,000 years. The numbers indicate approximate amounts of gold in tonnes held at each station in early 2009. The flux into the investment pool is what appears as visible to banks and large western metal trades. There is probably a flux caused by the unofficial trade of gold at open-air markets and in bazaars (after Sverdrup *et al.*, 2013b). Total ultimately recoverable gold reserves

(URR) are estimated at about 333,000 tonnes (Table 4.15) if all potential extractable amounts are included. We include gold that comes as secondary product from the mining of other metals (see Fig. 4.3).

Table 4.17 Physical and virtual precious metal amounts and associated paper metal estimates in 2008. The table is updated from an earlier published version (data from Sverdrup *et al.*, 2013b, 2014a, and USGS, 2013).

Metal	World above-ground content	Market stocks estimate	Paper metal estimate	Bedrock reserve estimate	Mining rate	Value of paper market	Value of physical above ground[1]	Fraction paper gold to actual metal
	Tonnes				Tonnes/ year	Billion $		
Gold	196,000	12,000	96,000	146,000	2,800	3,800	7,700	48 %
Silver	1,300,000	250,000	400,000	1,200,000	23,000	400	650	54 %
Platinum	4,400[2]	1,500	3,000	49,000	190	60	176	68 %
Palladium	5,000	1,500	3,000	20,000	210	30	100	60 %
Sums						4,290	8,626	50 %
Sum						12,916		

1. 1 tonne gold or platinum= $40 million, 1 tonne silver = $0.5 milion, 1 tonne palladium = $20 million.
2. The above ground amount of platinum group metals is very difficult to assess. No proper surveys are available, and the estimate comes from ball-parking up from what would be possible.

The ore grades have steadily degraded from mines with 20-30 gram per tonne rock about 150 years ago to 1-3 gram per tonne today. This suggests we are coming towards the end of the gold extractable amounts and that most of the rich gold ore on the planet has been exhausted. The majority of the world's gold is available and in the hands of the global population as jewellery (people´s stock; see Table 4.16). For the gold market, this acts as a large buffer, softening price responses and being an available reserve. Gold is at peak production now; a broad peak running 2010-2015 (Sverdrup *et al.*, 2013b). The Hubbert's curve for gold production is shown in Figure 4.41, showing gold production assessment in a historical perspective over 8,000 years of the past and looking into the future. The data come partly from modern statistics (Ragnarsdottir *et al.*, 2012; Sverdrup *et al.*, 2013b; USGS, 2013), partly from working with the archaeological and historical literature and ancient historical accounts, using both direct data and relationships to silver production (Sverdrup *et al.*, 2014a).

In 1973, the gold market was liberalised, and a system with paper gold was initiated by the central banks and large private banks, which lent out the ownership of 23,000 tonnes of gold, creating a total metal loan market of approximately 32,000 tonnes. In the years after that, metal traders and innovative bankers added another 50,000-60,000 tonnes of paper gold that probably never had any physical backing.

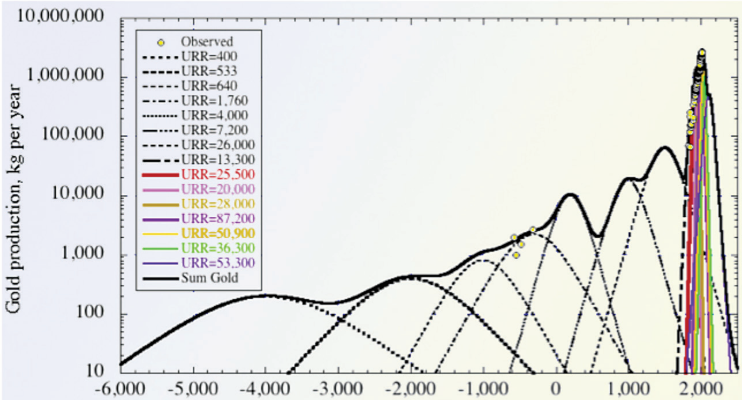
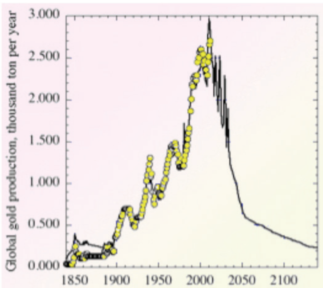


Figure 4.41 Hubbert's model assessment for gold production from mines from year 6,000 BC to 2,500 AD. The data come partly from modern statistics (USGS, 2013; Sverdrup *et al.*, 2013b) and partly from working with the archaeological and historical literature and ancient historical accounts, using both direct data and relationships to silver production (Sverdrup *et al.*, 2013b). Note the logarithmic Y axis scale. The scale of the Y axis is kg fine gold, the X axis is calendar years.



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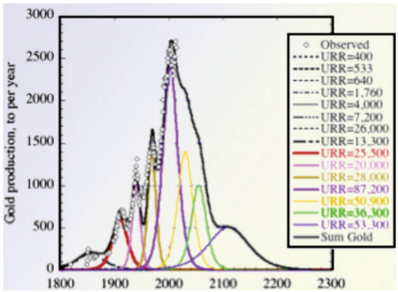

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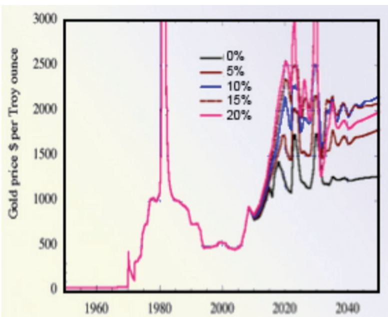


c

Figure 4.42 Outputs of the **(a)** GOLD and **(b)** Hubbert´s models. **(c)** GOLD model simulation of past and future gold price in $ per troy ounce, adjusted for inflation with anchor point 2008, for the period 1950-2050. The strong ups and downs reflect different assumptions concerning derivatives and unwinding of paper gold.

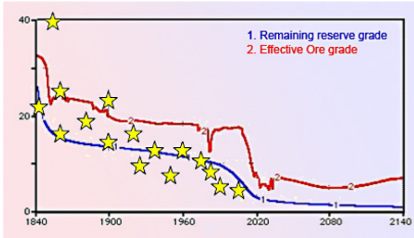


Figure 4.43 **(a)** The gold supply to the market as compared to gold from mining. Mining only supplies a minor part of the gold used every year by society. The amount supplied includes physical transactions also in investment, but excludes paper gold which has no substance on its own, it is a claim and not physical metal. **(b)** Observed and simulated ore grade. The ore grade on the Y axis is gram gold per tonne rock extracted, the X axis are the years. The red line is the GOLD model simulated, the stars represents observations on ore grades after Mudd (2007).

4.5.3 Gold results and assessments

Hubbert's model was used to create a simulation of production and reserve depletion. Figure 4.41 shows gold production assessment in a historical perspective. Table 4.15 shows a summary of the assessment and the ultimately recoverable reserves (URR) used. The Hubbert´s diagram takes neither recycling nor trade into account, only the supply from mines. The results show a production peak 2010-2015, with a sharp decline in output from mines after that. A full dynamic simulation model is available for gold as the GOLD model (Sverdrup *et al.*, 2013b). When paper gold is added to the model, the whole system becomes much more complex and unstable, as there are now two interconnected systems. The GOLD model simulations were done for the time period from 1840 to 2150, to be able to assess the past performance, as well as predict for the future. Figures 4.42-4.43 show GOLD model simulation results. Prominent in the simulations is that present mines are exhausted after 2030, when the supply from low-grade mines become quite restricted. Figure 4.43a shows that a very substantial part of the gold used comes from recycled metal from society. Figure 4.42b compares the GOLD model and Hubbert´s assessment. Figure 4.42c shows GOLD model simulation of past and future gold price in $ per troy ounce. Figure 4.43a shows the gold supply to the market as compared to gold from mining. Figure 4.43b shows observed and simulated ore grade. The red line is the GOLD model simulation, the stars represents observations on ore grades after Mudd (2007). The pattern is reproduced reasonably well, suggesting that the physical part of the model is acceptable.

4.5.4 Discussions about gold

Paper gold, how real is it? In international trade, metals and commodities are traded as physical entities with actual physical delivery of the commodity. Estimates for the categories of current stockpiles of gold in society are made in Table 4.16. Roughly, we estimate that readily available tradable gold is about 10,000 tonnes in the markets (jewellery, industrial materials, coins, privately held ingots). In addition, approximately 30,000 tonnes are held by central banks worldwide. Gold held by central banks is not readily physically tradable, and requires political action for sale or purchase. The privately held gold mostly goes through recycling before being available to investors. The model predictions have to get the fluxes and amounts to obey mass balance. From those calculations we get the following picture (adapted from information given by *Professor Yu Yongding,* LBMA conference talk in 2012):

Central bank backed metal loans and contracts:	32,000 tonnes
Market backed metal loans and contracts:	14,000 tonnes
Contracts with no physical backing:	50,000 tonnes
Total derivatives and paper gold markets:	96,000 tonnes

The annual global gold production in 2013 was 2,900 tonnes, and thus the outstanding amount is at least 38 years of today's production. All in all, the global physical gold trade, including trade of ownership but no physical movement, as well as forwards, shorts, blanks, fractional banking metal loans and hedges that are virtual with no physical metal involved, brings the turnover number to 1,012,510 tonnes of physical and virtual gold per year. Some of that is the same gold that returns to be sold again (Chapman, 2000; Ash, 2002, 2009; Mylchreest, 2009, 2011, 2012a,b). This much is never physically moved, but is a transfer of ownership only. Many other metals are also traded with derivatives, and much of that trade probably would not look good if it were to be properly inspected (OCC, 2009, 2013; CME, 2013). Resources are important for the survival of societies, the livelihood of people and our security, and thus should not be the subject of risky financial games without our knowledge and consent.

4.5.5 Conclusions for gold

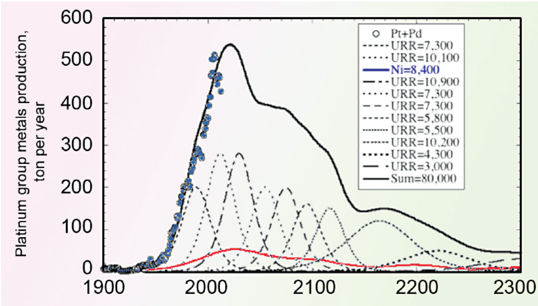
The gold price in the market can be explained using the available estimates of metal supply to the market and the free market mechanisms. However, the occurrence of gold in the world is physically limited, and this puts a strong limit on the market behaviour. Gold has the highest recycling rate of all non-radioactive metals, and as such is as sustainable as it can be within our technical means. The effect of the large amount of uncovered paper metal contracts remains to be fully exposed before we can make more firm statements of its effect on the trade and the supply situation. By using the known history, we can reconstruct the past price development, suggesting that the model has captured the most important causalities of the gold market. Uncertainties arise from what we think will happen to paper gold trading and the stock of uncovered gold futures. The percentages reflect how much of these would be unwound every year. After the financial crash in 2008, one would think that the commodity derivatives would have been unwound and reduced, leading to a high gold price. However, this has not been the case, and the derivatives trade continues.

4.6 Platinum Group Metals

The **Platinum Group Metals** (PGM) have always been rare and scarce. They all have a high market price, and have on many occasions had physical scarcity in the market because they have been difficult to extract. For the platinum group metals, the main reason for scarcity is the high price that limits the ability to create a large demand. The PGM reserve estimate is of the same order of magnitude as the USGS estimate, however we have revised it somewhat after a critical review of the scientific and industrial literature. The commercial term platinum group metals include **platinum**, **palladium** and **rhodium**, but **iridium**, **ruthenium** and **osmium** are also a part of this group. Platinum (180 tonnes/year), palladium (200 tonnes/year) and rhodium (27 tonnes/year) are used industrially and regularly traded on the metal exchanges. Iridium (3.5-4 tonnes/year comes primarily from platinum mining and nickel refinery sludge) finds limited use in specialty alloys, and osmium (1.2 tonnes/year mostly from nickel and copper anode sludge) and ruthenium (22 tonnes/year) are little used because of the great difficulty and dangers in refining them. Ruthenium and osmium form very toxic tetraoxides. Iridium is nearly insoluble in any chemical solution up to 1600 °C; it is the most inert metal known. The Hubbert's curve for PGM is shown in Figure 4.44. The USGS 2013 reserve estimate of 65,000-68,000 tonnes is a bit below our estimate from the Hubbert's diagrams and mining corporation reports, but consistent with the mining data. We estimate the URR to be 85,000-95,000 tonnes, however there are some uncertainties in these estimates. The platinum metals are always found together in ores and significant amounts originate from nickel mining. Of this, 63,000 tonnes of platinum group metals are estimated to be located in the Bushweld Igneous Complex in South Africa. How much of this is realistically recoverable is far from certain, and remains to be determined. The total mined until 2013 was approximately 13,000-15,000 tonnes; we estimate that 11,000 tonnes are still in stock in society (73-85 %).

South Africa is a fragile democracy today with the risk that it may one day fail, which may jeopardise the platinum metal production needed by the global community. There is no significant buffer stock in the global society, and platinum pricing tends to move sharply with respect to market demand and supply changes. Platinum production from mines is peaking at present (2010-2020), and the South African mines are near the end of their lifetime. The mines there are very deep (down to 4 km depth), the extraction is very difficult and the ore grade is declining, especially for platinum (Mudd, 2007). The ore grades have been steadily deteriorating for the last 15 years, signalling that the mines are slowly approaching exhaustion. Discoveries from prospecting peaked in the late 1970s and the extraction should be about to reach the peak shortly (Sverdrup *et al.*, 2013b), or 40 years after the discovery peak (see above). The new platinum fields found are significantly smaller than earlier. Figure 4.44a shows a detailed Hubbert's model assessment of production of the platinum group metals platinum, palladium and rhodium. The last platinum metal resources will be the supply from nickel production. Figure 4.44b shows the comparable systems dynamics model simulation to the Hubbert´s estimates in Figure 4.44b. After 2350, we see no realistic significant source of platinum metals available outside of recycling. Serious scarcity can be expected after 2040 for all of these metals.

Platinum has three different, but very important uses in society, where there is in principle no substitute; as a catalyst in the Ostwald-reaction, essential for making the world's industrial fertilisers and explosives, for car catalysts to keep exhausts clean, and as a chemical catalyst for hydrogenation reactions in organic chemistry, essential in the manufacturing of modern pharmaceutical medicines. The thought of not having platinum group metals available is an industrial nightmare. Wasteful uses like car catalysts that are not properly recycled, as well as high load, high pressure nitric acid factories should be prohibited and strictly regulated to minimise platinum metals losses. The extraction is distributed as platinum 44 %, palladium 48 %, and rhodium 5 % of the total PGM flow. The effect of scarcity on the price can be expected after 2040.



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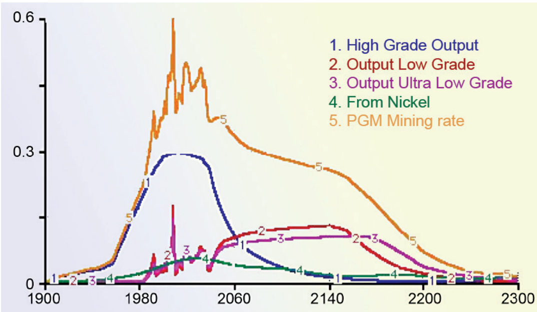


b

Figure 4.44 Details of the production predictions for the platinum group metals platinum, palladium and rhodium using **(a)** Hubbert's model and **(b)** the systems dynamics model for PGM. Platinum production appears to be peaking now (2010-2020). The different curves represent different platinum lodes mined. Y axis in diagram (b) is thousand metric tonne per year produced, X axis date in year.

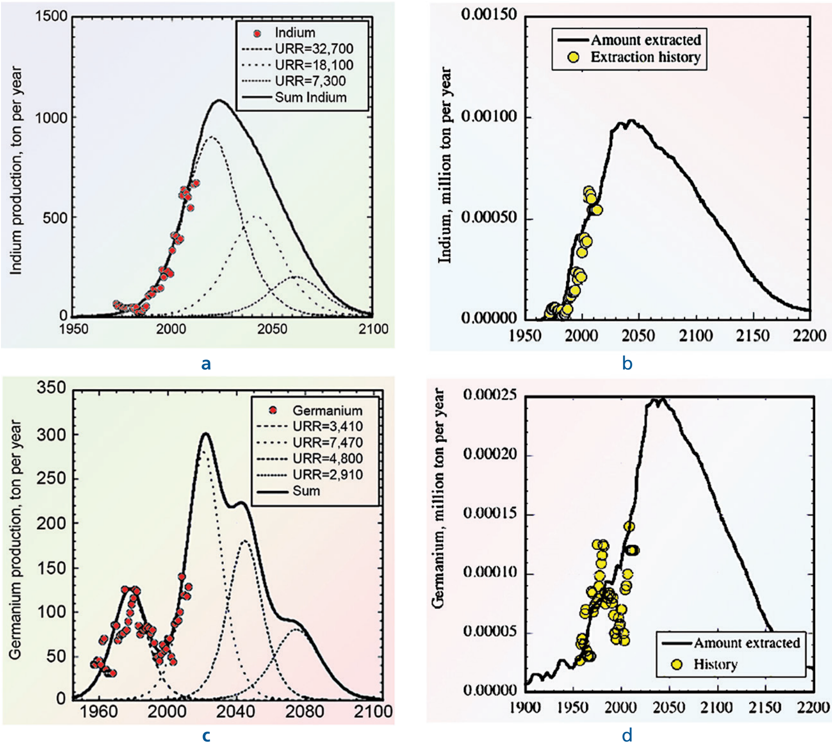


Figure 4.45 **(a,b)** Indium and **(c,d)** germanium production. Diagrams a and c are Hubbert's curves, b and d are outputs from the BRONZE model. The coloured dots are observed production data points; data are from USGS (2014). The dotted lines are sub-functions of the Hubbert's model, representing different mined deposits. Both metals are totally dependent on copper for their extraction. A systems dynamics model for these metals was used (BRONZE). X axis date in year.

4.7 Indium, Germanium, Tantalum, Tungsten, Lead and Tin

A full integrated global supply systems dynamics model (BRONZE) is under development. It is an extension of the COPPER model to include zinc and lead and the secondary extraction of metals used in specialist technology like indium, germanium, gallium and a number of other metals.

4.7.1 Indium

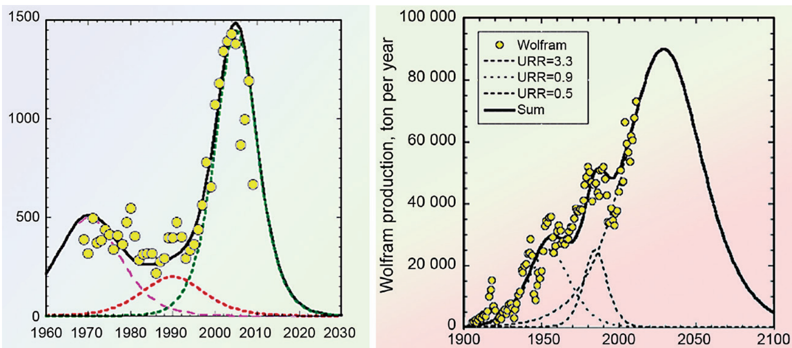
Indium is important for electronics and light sources. There is no USGS resource estimate available for indium. Our estimate, URR = 58,100 tonnes comes from Hubbert's curve fit to the production data (Fig. 4.45a). The resource is very small and the indium production 900 tonnes per year in 2012 is dependent on copper and zinc anode slimes and expensive extraction. This implies a total burn-off time of 60 years since indium was taken into use in 1970, suggesting a shortage after 2035. The Hubbert's model assessment suggests a production peak by 2020, the BRONZE model suggests 2020-2045 (see Figs. 4.45a and b). Since production depends on copper and zinc, the production peak for indium is set by the peak for copper and zinc.

4.7.2 Germanium

Germanium is important for electronics components, superconductors and for computer core chips. Germanium is a metal with properties similar to carbon and silicon. The germanium supply is associated with certain zinc ores and is recovered during the zinc refining process from anode sludge. A Hubbert´s curve for germanium is given in Figure 4.45b, showing peak production in 2020. The output from the BRONZE model is shown in Figure 4.45d. The peak production is suggested to occur in 2020-2040.

4.7.3 Tantalum

Tantalum is one of the rarest elements in the universe, even if the Earth has a significant stock of it. Tantalum production peaked in 2005 (Fig. 4.46a) and the extractable amounts are probably going to run low soon. Tantalum is a dense and very corrosion-resistant metal at room temperature, and it has among the highest known melting points. In ores, tantalum and niobium sometimes occur together (this is the coltan mining referred to in news paper articles about the People's Republic of Congo conflict; see above).

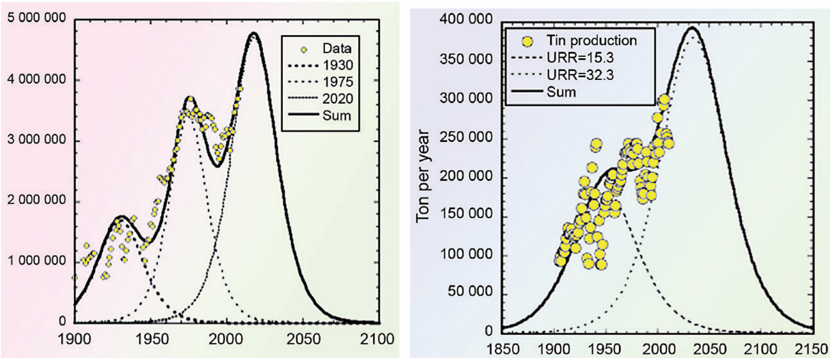


a b

Figure 4.46 Hubbert's model for (a) tantalum and (b) tungsten production. Wolfram is the central European name for tungsten. The Y axis in (a) is tons of tantalum extracted annually, the X axis is calendar year.

4.7.4 Tungsten

Tungsten (also known as wolfram) is known as the metal with the highest melting point. It is a hard and brittle metal. It has some special properties, a very low thermal expansion, and high density. Its main source is currently in China, where it is mined in association with manganese and iron deposits. The URR is estimated to 4,7 million tonnes based on the Hubbert's diagram (Fig. 4.46b). The USGS suggests that the URR is about 3,7 million tonnes, which is of the same order of magnitude. Tungsten production is estimated to peak at around 2035.



a b

Figure 4.47 Hubbert´s curves for (a) lead and (b) tin production. The Y axis in (a) is tons of lead extracted annually, the X axis is calendar year.

4.7.5 Lead

Lead has been mined since antiquity, when it was used in construction, roofing, containers, plumbing, insulation, and as projectiles. USGS estimates URR, including mined, known and unknown are at least 2,000 million tonnes. Our reserve estimate that fits the production data, gives URR = 1,36 billion tonnes, but this may be a significant underestimate, the correct number is more likely 3.5-4.5 billion tonnes. Peak production is now as shown on the Hubbert´s diagram (Fig. 4.47a). Lead was earlier used as a petrol anti-knocking agent, however this is no longer so because of its toxicity and linked environmental regulations, and the metal is less in demand than in previous years. 447 million tonnes have been produced so far according to our Hubbert's reconstruction of the mining history. Mining is slowly declining because of a lack of market, rather than deposit decline. Large amounts of lead are still used in batteries, cable insulations, roofing and as a solder in electronics. It is also an important metal for handgun bullets. Because of toxicity to humans and environmental concerns, efforts are under way to reduce or phase out lead use. The global stock in society is 52 million tonnes (UNEP, 2011b).

4.7.6 Tin

Tin has been mined since 2,500 BC; its main use was in bronze alloy and as a component in low-melting solder with antimony and lead. Tin tableware (plates and cups) was also once popular, mostly because of its ease of production, but now that market has declined to a low level. The estimated URR is the sum of several terms; what was mined in antiquity (1500 BC-500 AD) is estimated at 4 million tonnes (4,000 tonnes/year), mined during medieval times (500-1900) is 47 million tonnes (33,000 tonnes/year), and we estimate that mining during the period of 1850-2013 produced 23 million tonnes (141,000 tonnes/year). To this we need to add what the USGS suggests is left; 5-7 million tonnes and all of this makes up the URR = 76 million tonnes. The Hubbert estimate from available data gives URR = 96 million tonne (Fig. 4.47b). The peak production will be in 2035, but the curve is assymetrical; much was mined in antiquity, and more than 90 % of the URR had been mined by 2014. The stock in society we estimate to be 2.4 million tonnes in 2010.

Our analysis shows that the Hubbert's curve is less suitable for dependent metals like germanium or indium, unless the Hubbert's function used is a combination of the Hubbert's curves for the mother metals.

4.8 Decoupling, Efficiency and Material Flow Volume Reduction

Decoupling between development and resource use is a proposed solution to resource scarcity but it has limitations. Rauch (2009) mapped in-use stocks for aluminium, iron, copper and zinc and related this to the GDP (Gross Domestic Product) for some countries. He found that the use of these metals was linearly proportional to the country's GDP. The following relationships were found (Rauch, 2009):

$$S_{Fe} = 397.00 \times 10^6 \times GDP, \quad r^2 = 0.85 \tag{4.1}$$

$$S_{Al} = 13.50 \times 10^6 \times GDP, \quad r^2 = 0.99 \tag{4.2}$$

$$S_{Cu} = 8.33 \times 10^6 \times GDP, \quad r^2 = 0\text{-}94 \tag{4.3}$$

$$S_{Zn} = 5.49 \times 10^6 \times GDP, \quad r^2 = 0.81 \tag{4.4}$$

where S is the stock used by society in tonnes and GDP is expressed in billions of dollars. For zinc, the stock-in-use in society (S) is 280 million tonnes, for copper 320 million tonnes, for aluminium 611 million tonnes, for iron 21 billion tonnes (2012). There are a few take home messages from this. Metals are in principle indefinitely recyclable, but never with 100 % yield. However, proper recycling may cause a significant reduction in the required mine supply rates to society. What is observed as decoupling arises from two factors:

1. The use of less metal through increased efficiency, less waste material in manufacture, better recycling, shorter delay in society.

2. Shifting the manufacture or part of the resource use to another country. This does not increase efficiency in metal use, but rather shifts the use (and the problem associated with production) to another country. When inspected critically, this may appear as decoupling when seen on a national level, however, it normally cancels out on the global level. Moving engine manufacture from Great Britain to China will decrease resource and energy use in Britain (and hence CO_2 emissions), but increase it in China, plus further increase in CO_2 output because of the extra transportation.

A key solution for increasing efficiencies in the future is organised large scale recycling. For metals, recycling can be a very important tool where a steady state situation exists, only the losses from the system need to be replaced (Fischer-Kowalski *et al.*, 2011). Thus, 90 % recycling will cut down the required input from mining by a factor of 10. We can increase efficiencies and recycling to a certain degree, but driving systems without material and energy is not possible. Metals can to a large degree be recycled, however, 100 % efficiency does not exist (see Table 4.18).

Table 4.18 The estimation of efficiencies in any supply chain. Relevant to most metals but also phosphorus. To have 95% overall efficiency, we need 99 % efficiency in every step.

Process step	Efficiency of conversion down through a chain of steps %					
1. Step efficiency	70	80	90	95	97	99
2. Step efficiency	49	64	81	90	94	98
3. Step efficiency	34	51	73	86	91	97
4. Step efficiency	24	41	66	81	89	96
5. Step efficiency	17	33	59	77	86	95

Some processes have absolute requirements, some materials are not substitutable and there decoupling is not meaningful. The ultimate test might be to decouple oneself from food. Numerous experiences show that previous gains in efficiencies have been used to expand the total consumption, and not to do the same with less. A part of the solution is to make equipment small, durable, fixable and ultimately recyclable. Also, equipment sharing is a part of the solution.

In *Vala*´s sustainability cafés held for the people of Bristol a decade ago, one sustainability solution that was proposed was that every street or neighbourhood had a shed with tools and equipment that people could share, which would be a viable solution to reduce demand on resources. During the second world war in Norway, all imports and exports were cut off and then this kind of sharing became necessary. When items with significant amounts of metal were needed, *Harald*´s grandparents told him that people would sometimes be asked to bring scrap metal to match the amount in the item you would buy. No metal was lost, and people became really good recyclers, out of necessity. In 1945, when the war had been won, it was all quickly forgotten. But *Harald* remembers that his grandmother (*Thora Sverdrup*, 1891-1990) would collect metal scrap *e.g.*, bent nails, hammer iron tins flat and stack them in the basement) out of old habit from those times. When the incentives are big enough, recycling can become efficient.

Table 4.19 Comparison of intrinsic society loss rates with metal price suggesting that an expensive metal is less likely to be lost than a cheap one.

Metal	Mined metal cumulatively supplied to society from mining to 2012, in tonnes	Stock in society, tonnes	Stock in society in % of total extracted	Duration of mining, years	% loss per year	Price, $/kg
Iron	40,000,000,000	21,000,000,000	51 %	400	0.200	0.2
Lead	447,000,000	52,000,000	12 %	3,000	0.001	2.0
Zinc	520,000,000	280,000,000	54 %	3,000	0.015	2.0
Aluminium	1,700,000,000	711,000,000	42 %	100	0.700	2.1
Manganese	410,000,000	21,000,000	5 %	80	0.064	2.4
Cadmium	740,000	248,000	34 %	200	0.003	2.5
Chromium	470,000,000	41,000,000	9 %	80	0.110	2.5
Copper	702,000,000	320,000,000	42 %	5,000	0.012	8.0
Tin	24,400,000	2,385,000	10 %	200	0.050	24
Nickel	74,000,000	20,000,000	29 %	160	0.440	18.0
Cobalt	2,100,000	775,000	37 %	80	0.470	27.0
Silver	1,465,000	1,110,000	76 %	5,000	0.004	1,000.0
Platinum	15,000	11,000	67%	100	0.330	50,000
Gold	190,000	183,000	96%	6,000	0.001	52,000

Table 4.18 gives step efficiency in any supply chain. Industrial knowledge tells us that a recycling rate in excess of 60 % may be hard to achieve unless the metal in question is very valuable and corrosion resistant (like gold or platinum). It is interesting to compare the % loss of several metals per year with their market price (Table 4.19), and it becomes evident that the higher the price the lower the loss. This gives us an indication that most natural resources are priced too cheaply in the market. Table 4.20 indicates which resources will be scarce in the

years of 2050, 2100, 2200. Table 4.21 shows the URR, resource already exploited and how much metal is left. The analysis of natural resources presented in this volume allows us to calculate sustainable metal consumption (Table 4.22) for different time horizons (2,500, 5,000 and 10,000 years). It becomes evident that most natural resources are currently being consumed at rates exceeding sustainable consumption, and therefore we are in overshoot and outside the planetary boundary for all of those resources. Table 4.23 gives a corresponding sustainable metal extraction for the same time horizons. Table 4.24 summarises natural resource production rates, recoverable reserves, recycling rate, reserve/production ratio (time to scarcity) and peak production year.

Table 4.20 Estimated risk of scarcity, using burn-off, Hubbert's estimate and results from dynamic modelling.

Element	Burn-off, years	Hubbert, years	Dynamic model, years	Scarcity		
				2050	2100	2200
Iron	214	176	200	no	no	yes
Aluminium	478	286	300	no	no	no
Copper	31	71	120	yes	yes	yes
Lithium	25	75	330	yes	yes	yes
Rare earths	660	600	1,090	no	yes	yes
Gold	37	37	75	no	yes	yes
Silver	14	44	30	yes	yes	yes
Platinum	73	163	50	yes	yes	yes
Palladium	61	134	Not yet done	no	yes	yes
Oil	44	100	99	yes	yes	yes
Coal	78	174	220	no	yes	yes
Natural gas	64	143	100	no	yes	yes
Uranium	144	140	Not yet done	no	no	yes
Thorium	187	140-470	330	no	no	yes
Phosphorus	161	190	230	no	yes	yes

Table 4.21 Estimates of available extractable amounts for metal extraction. The table should be interpreted as being our best estimate. Magnesium and titanium are mainly used for other purposes (chemicals, pigment) than producing metal.

Metal	URR, tonnes	Amount mined before 2010, tonnes	Remaining recoverable amounts, tonnes
Iron	340,000,000,000	40,000,000,000	300,000,000,000
Magnesium	200,000,000,000	4,000,000	200,000,000,000
Aluminium	20,700,000,000	1,700,000,000	22,400,000,000
Titanium	3,600,000,000	1,500,000	3,600,000,000
Manganese	1,440,000,000	410,000,000	1,030,000,000
Zinc	1,560,000,000	450,000,000	1,110,000,000
Copper	1,260,000,000	702,000,000	558,000,000
Lead	1,283,000,000	590,000,000	693,000,000
Chromium	904,000,000	470,000,000	437,000,000
Rare Earths	220,000,000	4,000,000	216,000,000
Nickel	170,000,000	74,000,000	96,000,000
Molybdenum	33,000,000	10,500,000	22,500,000
Tin	96,600,000	20,400,000	76,200,000
Lithium	39,000,000	1,000,000	40,000,000
Vanadium	21,000,000	1,600,000	19,400,000
Thorium	23,000,000	1,000,000	22,000,000
Uranium	16,000,000	2,000,000	14,000,000
Cobalt	13,700,000	2,100,000	11,600,000
Antimony	12,700,000	6,700,000	7,000,000
Niobium	5,452,000	1,470,000	3,972,000
Silver	3,200,000	1,892,000	1,308,000
Bismuth	541,000	181,000	360,000
Gold	330,000	190,000	140,000
Selenium	280,000	102,000	171,000
Tantalum	159,500	109,000	58,500
Indium	58,100	11,000	47,100
Platinum	50,600	6,500	44,100
Palladium	44,500	8,500	36,000
Tellurium	19,520	7,600	11,080
Germanium	18,600	6,100	12,500
Gallium	8,990	2,700	5,200
Rhenium	5,990	1,800	4,190

Table 4.22 Living within the planetary boundaries requires an assessment of sustainable metal extraction rates. This is an estimation of global sustainable consumption of different metals and the present overshoot. The table shows an assessment of the effect of choosing different time horizons.

Metal	Production now, tonnes/year	Time horizon applied, years from now Sustainable metal consumption, tonnes/year		
		10,000 years	5,000 years	2,500 years
Iron	1,400,000,000	57,500,000	114,500,000	229,000,000
Aluminium	44,000,000	8,100,000	19,200,000	38,400,000
Manganese	18,000,000	257,500	515,000	1,030,000
Chromium	16,000,000	218,500	437,000	874,000
Copper	16,000,000	279,000	558,000	1,116,000
Zinc	13,000,000	277,500	555,000	1,110,000
Magnesium	750,000	10,000,000	20,000,000	40,000,000
Lead	4,600,000	643,000	1,286,000	2,572,000
Nickel	1,700,000	24,000	48,000	96,000
Titanium	283,000	360,000	720,000	1,480,000
Molybdenum	280,000	11,250	22,500	45,000
Tin	354,000	38,100	76,200	152,400
Titan	283,000	360,000	760,000	1,520,000
Antimony	180,000	1,750	3,500	7,000
Cobalt	110,000	5,800	11,600	23,200
Vanadium	70,000	9,700	19,400	38,800
Niobium	68,000	1,986	3,972	7,994
Silver	23,000	653	1,308	2,616
Bismuth	7,000	90	180	360
Selenium	2,200	43	85	170
Gold	2,700	34	67	134
Indium	670	12	24	48
Tantalum	790	30	59	118
Gallium	280	2.6	5.2	10.4
Palladium	220	45	90	180
Platinum	180	44	88	176
Germanium	150	6.2	12.5	25
Tellurium	120	2.5	5	10
Rhenium	50	4	8	16

Table 4.23 Living within the planetary boundaries requires an assessment of sustainable metal extraction rates. This is an estimation of global overshoot in excess of the sustainable consumption of different metals. The table shows an assessment of the effect of choosing different time horizons.

Metal	Production now, tonnes/year	Time horizon applied, years from now Metal use exceeding the sustainable use level, tonnes/year		
		10,000	5,000	2,500
Iron	1,400,000,000	1,342,000,000	1,285,500,000	1,171,000,000
Aluminium	44,000,000	35,900,000	24,800,000	5,600,000
Manganese	18,000,000	17,743,000	17,485,000	16,970,000
Chromium	16,000,000	15,782,000	15,563,000	15,126,000
Copper	16,000,000	15,721,000	15,342,000	14,884,000
Zinc	13,000,000	10,723,000	10,455,000	9,890,000
Magnesium	750,000	none	none	None
Lead	4,600,000	3,357,000	2,714,000	1,286,000
Nickel	1,700,000	1,676,000	1,652,000	1,601,000
Titanium	283,000	none	none	None
Molybdenum	280,000	268,750	257,500	235,000
Tin	354,000	261,900	223,800	147,600
Antimony	180,000	178,750	176,500	173,000
Cobalt	110,000	104,200	99,400	86,800
Vanadium	70,000	70,300	50,600	31,200
Niobium	68,000	66,014	64,028	60,006
Silver	23,000	22,347	21,692	20,384
Bismuth	7,000	6,910	6,870	6,640
Selenium	2,200	2,157	2,115	2,030
Gold	2,700	2,566	2,533	2,466
Indium	670	658	644	622
Tantalum	790	570	541	482
Gallium	280	277	275	270
Palladium	220	175	130	40
Platinum	180	136	92	4
Germanium	150	143.8	137.5	125
Tellurium	120	118	115	110
Rhenium	50	46	42	34

Table 4.24 Present global production rates, present recoverable amounts, estimated recycling rates and the fraction of total metal extracted still remaining in the society and available.

Metal	Production 2012, tonnes/year	Presently recoverable amounts, tonnes	Recycling %	Present known amounts to production ratio, years	Estimated peak production year
Iron	1,400,000,000	340,000,000,000	60	242	2032
Aluminium	44,000,000	22,400,000,000	75	436	2080
Manganese	18,000,000	1,030,000,000	45	57	2020
Chromium	16,000,000	437,000,000	22	27	2026
Copper	16,000,000	558,000,000	60	35	2034
Zinc	11,000,000	1,110,000,000	20	101	2030
Lead	4,000,000	693,000,000	65	173	2018
Nickel	1,700,000	96,000,000	60	56	2025
Titanium	1,500,000	600,000,000	20	400	n. d.
Zirconium	900,000	60,000,000	10	67	n. d.
Magnesium	750,000	200,000,000,000	40	260,000	n. d.
Strontium	400,000	1,000,000,000	0	2,500	n. d.
Tin	300,000	76,200,000	20	254	2036
Molybdenum	280,000	22,500,000	40	80	2045
Vanadium	260,000	19,400,000	40	75	2076
Lithium	200,000	40,000,000	10	200	2025.
Antimony	180,000	7,000,000	15	39	2018
Rare Earths	130,000	100,000,000	15	770	2060
Cobalt	110,000	11,600,000	40	105	2026
Tungsten	90,000	2,900,000	40	32	2029
Niobium	68,000	3,972,000	60	58	2025
Silver	23,000	1,308,000	80	57	2034
Yttrium	8,900	540,000	10	61	n. d.
Bismuth	7,000	360,000	15	51	2011

Metal	Production 2012, tonnes/year	Presently recoverable amounts, tonnes	Recycling %	Present known amounts to production ratio, years	Estimated peak production year
Gold	2,600	135,000	95	52	2012
Selenium	2,200	171,000	N5	78	2022
Caesium	900	200,000,000	0	220,000	n. d.
Indium	670	47,100	40	70	2022
Tantalum	600	58,500	25	97	2005
Gallium	280	5,200	15	19	2026
Beryllium	250	80,000	20	320	n. d.
Palladium	200	36,000	60	180	2020
Platinum	180	44,100	70	245	2020
Germanium	150	12,500	30	83	2022
Tellurium	120	11,080	0	92	1984
Rhenium	50	4,190	85	84	2038
Rubidium	22	5,000,000	0	227,000	n. d.
Thallium	10	380,000	0	38,000	1995.

Table 4.25 Summary of peak estimates, and range of the estimate, considering the lowest and highest possible reserve estimates still permitted within the data.

Metal	Pessimistic	Average	Optimistic	Comments
All ready peaked (The problem is here and now)				
Mercury		1962		Phased out by political action, target is 2010.
Tellurium		1984		Dependent on copper and zinc mining.
Zirconium		1994		No good production data is available.
Cadmium	1900	1998	2010	Phase out by political action, target is 2010. Dependent on zinc.
Thallium		1995		Reserve and production data unavailable. Dependent on copper.
Tantalum		1995		Partly dependent on mining in Congo.
Platinum	2010	2015	2025	Partly dependent on nickel. Serious challenge. Scarcity prevailing.

Metal	Pessimistic	Average	Optimistic	Comments
All ready peaked (The problem is here and now)				
Palladium	2010	2015	2025	Partly dependent on nickel. Serious challenge. Scarcity prevailing.
Rhodium	2010	2015	2025	Partly dependent on nickel and platinum mining. Serious challenge. Scarcity prevailing.
Gold	2012	2013	2017	The only real money, well conserved. Partly dependent on silver, copper and platinum.
Coming within the next 10 years (we own the problem, no escapes).				
Lead	2013	2018	2023	Limited by political action, target is 2010.
Niobium	2014	2018	2023	
Indium	2018	2020	2025	Dependent on copper-zinc mining.
Gallium	2018	2020	2022	Dependent on copper-zinc mining.
Manganese	2018	2021	2025	
From 10 to 20 years from now (we own the problem).				
Selenium	2022	2025	2035	Dependent on zinc.
Chromium	2022	2025	2035	
Zinc	2018	2025	2028	This is a serious challenge!
Cobalt	2020	2025	2030	Dependent on copper, nickel and platinum mining.
Nickel	2022	2026	2028	This is a serious challenge!
Iron	2025	2040	2080	This is a serious challenge!
From 20 to 30 years from now (escape possible; next generation gets the problem)				
Silver	2028	2034	2040	Partly dependent on copper and zinc.
Rhenium	2030	2035	2040	Dependent on molybdenum.
Copper	2032	2038	2042	This is a serious challenge!
Phosphorus	2025	2040	2100	This is a very serious challenge! Size of URR is disputed (16-60 billion tonnes) but it only shifts the peale by some centuries.
From 30 to 50 years from now (escape possible; next generation gets the problem).				
Molybdenum	2048	2057	2065	
More than 50 years from now (escape possible; our grandchildren get the problem).				
Vanadium	2055	2076	2096	Dependent on iron.
Aluminium	2030	2130	2230	This is a challenge!

Table 4.25 summarises which metals have already peaked in production, which will peak in the next 10 years, which will peak 10-20 years, 20-30 years and 30-50 years from now. The practical implication of a metal passing the peak is that the price likely will shoot up. For some metals, the decline coincides with a loss of demand for the metal; this is particularly true for mercury and cadmium, both being very toxic and outlawed in most countries by 2010. Lead is also in decreasing demand and will eventually be phased out from many uses. This summary is sobering, and shows that our behaviour today does not take account of the well-being of future generations. As parents and grandparents we are appalled and wonder why policy makers do not have their fingers on the pulse. One explanation might be that scientists are not good at communicating their findings. Others are afraid that if they speak out, then that will affect the market prices. Here we have attempted to close these gaps. They could all learn from *Peter Seeger,* the late American folk singer and activist who stated: *"If it can't be reduced, reused, repaired, rebuilt, refurbished, refinished, resold, recycled or composted, then it should be restricted, redesigned, or removed."*

4.9 Conclusions for All Metals

It is evident that many of the most important metals for human society may run into scarcity within the next decades, unless substantial adjustments to their management in society are achieved. One key root cause for consumption beyond the planetary limits is a too large a global population (Meadows *et al.*, 1972, 1992, 2004; Ehrlich, 1968; Sverdrup and Ragnarsdottir, 2011). All the big infrastructural metals iron (peak year 2030), zinc (peak year 2025), copper (peak year 2040) threaten to run into scarcity in our time – or a decade or so after the peak production years, aluminium production follows a century later (peak year 2135). Without iron and oil (peak years 2012-2018; Hubbert, 1972; Hirsch *et al.*, 2005; Aleklett, 2007; Bardi, 2008, 2013; Aleklett *et al.*, 2012; Sverdrup *et al.*, 2013a), we would have very limited access to machinery, and beside renewable energy, human labour and animal traction may again become important sources of manufacturing energy. Recycling will be able to extend the lifecycle time of most metals until global population numbers have declined to sustainable levels, hopefully not too long after 2100 (Meadows *et al.*, 1972, 1992, 2004; Sverdrup and Ragnarsdottir, 2011).

5. PHOSPHORUS: THE STORY OF HOW ROCKS, SOIL AND OIL CREATE PEOPLE

5.1 Introduction

Several studies of the phosphorus cycle and the sustainability of phosphorus have been published (Malthus, 1798, von Liebig, 1843; Osborn, 1948; Vogt, 1948; Meadows *et al.*, 1972, 1992, 2004; Daily and Ehrlich, 1992; Ehrlich *et al.*, 1992; Daily *et al.*, 1994; Evans, 1998; Sverdrup *et al.*, 2006; Modin *et al.*, 2007; Filippelli, 2008; Oelkers and Valsami-Jones, 2008; Turner, 2008; Cordell *et al.*, 2009, 2011a,b; Hodson, 2010, Ehrlich and Ehrlich, 2013). The problem of phosphorus is analogous to that of oil (Meadows *et al.*, 2004; Aleklett, 2003, 2007; Greene *et al.*, 2003; Hirsch *et al.*, 2005; Gordon *et al.*, 2006; Oelkers and Valsami-Jones, 2008; Brown, 2009a,b; Cordell *et al.*, 2009, 2011a,b; Rosemarin *et al.*, 2009; Ragnarsdottir *et al.*, 2011; Sverdrup and Ragnarsdottir, 2011; Mohr and Evans, 2013; Cordell *et al.*, 2011a,b). All these studies agree that phosphorus is a limited resource and the resource may run out if the present consumption rate continues, and recycling is not improved. Importantly no substitute of any kind is available because phosphorus is an important building block of DNA and thus protein and all life on Earth.

Phosphorus is critical to food production and thus the human population. Not all studies, however, agree; there are a number of studies that give estimates of the carrying capacity of the Earth (*e.g.,* the number of people that can be sustained) from different perspectives. These estimates range from optimistic population estimates of hundreds of billions of people to significantly less than a billion people (Fig. 3.2 summarises many carrying capacity assessments). They all have in common that they have a short time perspective, focus on technical solutions to short-term problems, and often seem to forget or not comprehend the limitations of the resource. In 2011 we explored what the long-term time perspectives are (Ragnarsdottir *et al.*, 2011; Sverdrup and Ragnarsdottir, 2011). Burn-off time estimates assume no feedbacks from prices and market dynamics, cannot readily account for dynamic effects of recycling and therefore wrongly estimate the time to scarcity. A limited resource does not end abruptly; as it gets scarcer, prices tend to go up and bring demand down. Depending on how insistent the demand is, how strong or weak regulatory feedbacks are, the end of the resource may come quickly or slowly (Smith, 1776; Klein, 2007; Lövin, 2007).

Researchers have estimated the carrying capacity of the world, expressed as a maximum global population (Cohen, 1995 made a compilation we have expanded on, see Fig. 3.2). These estimates vary wildly, because of very different assumptions. Many of these are not what we would call sustainability estimates if we inspect them more closely, and many have unclear or unstated underlying assumptions. Many of these assumptions do not comply with sustainability as we understand the concept today. We therefore explore this concept futher in this volume. There is however a trend towards lower estimates for sustainable population.

5.2 Scope and Intent for the Analysis of Phosphorus

In earlier studies, resource burn-off rates were investigated (Ragnarsdottir, 2008; Ragnarsdottir *et al.*, 2011). These studies are based on quantifying the resource over quantity used per year (with some indications of recycling). Even though this is rather simplistic, it can serve as a useful indicator of how far resources can last into the future. We then analysed the world resource system and focused the study on phosphorus, people and society based on system dynamics (Sverdrup and Ragnarsdottir, 2011). Hubbert's curves for phosphorus and systems analysis outputs are given in Figures 5.2-5.3 and outputs from the system dynamics model FoF in Figure 5.5. The figures show that peak phosphorus is upon us and we need to bear this in mind when thinking about food security and population, because the mined phosphorus is largely turned into fertiliser for food production. Our aim was to understand sustainability constraints to help decision-makers plan for a future. We addressed the following research questions:

1. How long will the world's phosphorus supply last under the present rate of use and recycling paradigm?
2. How much can the supply be extended in terms of time and population size by enhanced recycling of all kinds?
3. How large a population can we supply with food for 10,000 years with the available phosphorus resources?

In our previous study we adopted a long-term perspective, where the short-term perspective is the time period of 1900-3600 AD (1,700 years), and the long-term perspective is the time until the next glaciation, approximately 10,000 years from now. We illustrate our case with the phosphorus cycle and the human population, modelled on a global scale with a simple model.

We did not address the following issues in this work in any detail:

- The availability of agricultural soils, loss of arable land due to soil erosion, loss of agricultural land to encroachment, soil salinisation etc. It is known that soil erosion is much faster than soil formation (Brantley *et al.,* 2007).
- The effect of climate change on agricultural soils, effects of drought, increased temperatures on growth of crops, water shortages and new soils becoming available further north.
- Future technical miracles that would save us from all problems.
- Pollution, pesticide soil damage or chemical spill damage to soils.
- Effects of limitation in energy in the future on food production.
- Effect of soil sealing due to city and road construction.

Despite these clear limitations, we made estimates and subsequently discuss them in the light of these assumptions.

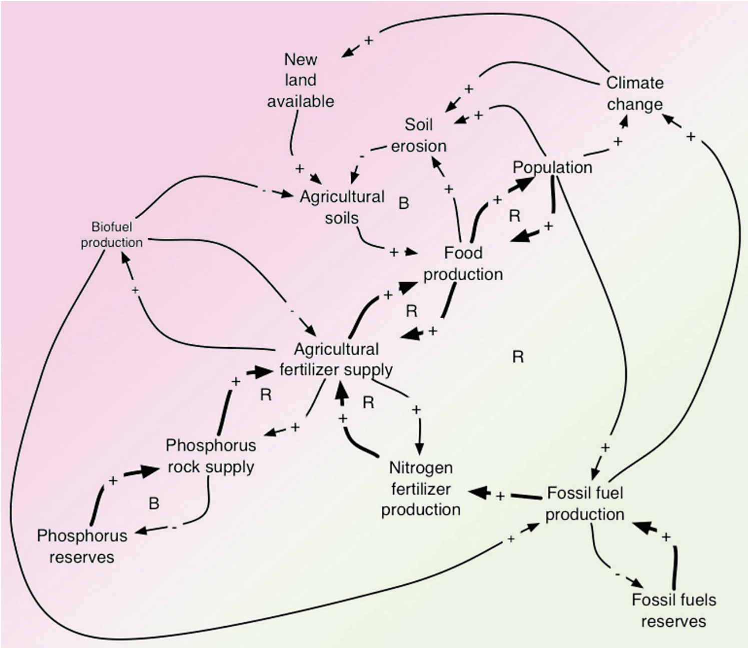


Figure 5.1 The food system is linked to resources through phosphorus extractable amounts and fossil fuels, as well as metals. Soils are also a very important, non-renewable resource. R is reinforcing loop, B is a balancing loop.

Figures 5.2-5.3 show that not only are we at peak phosphorus, but we are also at a time of peak tilled soils according to our Hubbert´s analysis of soil data from FAO (2010, 2011) (Fig. 2.1). It is therefore imperative not only to study the peak production behaviour of phosphorus for food security in the future, but also to link that to the population carrying capacity of the Earth. Applying the Hubbert's model to soil data, assumes that we are mining a resource where the mining rate exceeds the regeneration rate. The Hubbert's model fits the data well, suggesting that we may view our soil resource to be undergoing mining through erosion. As is apparent from the curve (the peak soil figure shown in Fig. 2.1), the soil resource peaked in 2005. We should interpret this as a diagnostic indicator; that there is something very unsustainable in how we are at present managing soils as a resource. This could potentially be the single largest identified threat to the general survival of civilisation on the planet because soils form very slowly (of the order of 10 mm per 100 years; Brantley *et al.*, 2007). Without soils there will be no way to feed the population. This augments the gravity of the situation created by peak phosphorus.

5.3 Methods

The main resource prerequisites for food production aside from land and water are phosphorus and nitrogen as is illustrated in Figure 5.1. These two rely heavily on fossil deposits of phosphorus rock and oil (for hydrogen to capture nitrogen from the atmosphere). Animals play an important role in providing phosphorus and nitrogen to the nutrient chain. It is evident that with increased population, the consumption of phosphate rock increases, which in turn increases production. Increasing consumption and population are the two major factors for an increasing demand for phosphorus in the world. Recycling represents a way to increase phosphorus in the cycle without depleting resources. Thus in the world of limited resources this becomes a strategic management tool. Environmental degradation and declining resources have an effect on political and public awareness. Penck (1925), based on the work of von Liebig *et al.* (1841) and von Liebig (1843), defined the basic equation for the number of people that can be fed, the maximum population, called "Liebig's law":

$$\text{Sustainable population} = \text{Total resource available annually}/\text{Individual annual consumption} \tag{5.1}$$

The equation is applied if the resource is renewable. If it is neither renewable nor substitutable, but constitutes a one-time heritage, then the annual sustainability estimate is:

$$\text{Total resource available annually} = \text{Total resource volume}/\text{Time to doomsday} \tag{5.2}$$

The time to doomsday is estimated as the time to the end of our consideration, potentially the time of eclipse of human civilisation (Bech Nielsen, 1989; Gott III, 1994; Leslie, 1998, Sowers, 2002; Sober, 2003; and the other alternatives of Hubbert 1956, 1982). We have to remember that the individual consumption is not the individual physiological requirement, and it includes all the efficiencies from the first extraction from the deposit, until it reaches the individual consumer.

$$\text{Supply} = \text{Extracted amount} * \text{Product of all efficiencies in the supply chain} \tag{5.3}$$

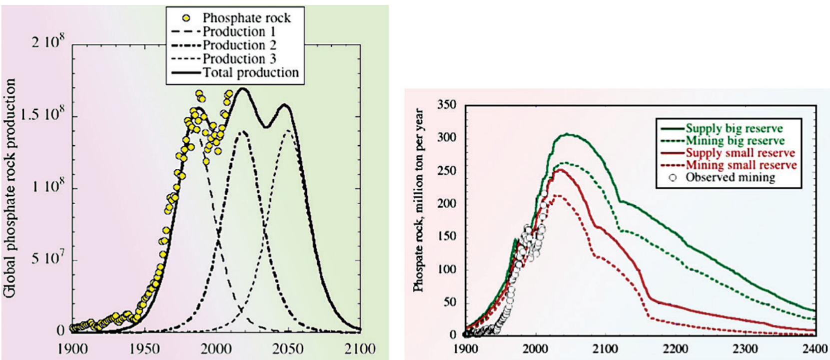
The extraction steps may be many and the inefficiencies may add up. The carrying capacity of the Earth under total sustainability will be a sustainable population number:

$$\text{Sustainable population} = \min_i \{\text{SustPop}_i\} \tag{5.4}$$

Where SustPop_i is the sustainable population estimate for limiting factor $_i$. $_i$ may be based on phosphorus, nitrogen, water, soil, oil etc. Figure 5.3 depicts the supply of phosphorus over demand for a best-case scenario (a) and worst case scenario from a model study reported by Mohr and Evans (2013). The model projections were created by running a flow sheet model of supply against demand. Of note is that their shape is similar to our Hubbert's curves for phosphorus production (Fig.5.2) from 2011, indicating that both methods are pointing towards scarcity in the not so distant future. Note the consistency between Figures 5.2 and 5.3, deriving from two independent assessments, suggesting that we identified a significant issue. Where estimates represent the different aspects that can limit growth (nitrogen, phosphorus, water, light, essential elements, soil substrate availability). Many studies have considered these one by one, a few have done several, but none have done them all.

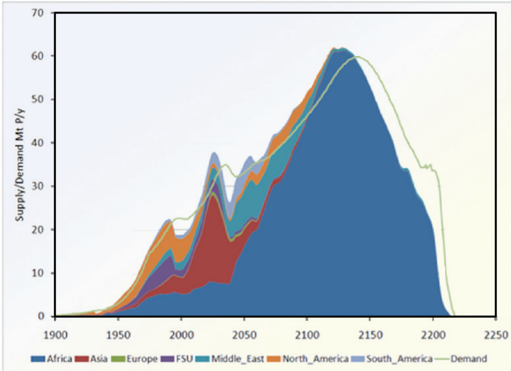
Table 5.1 Input data for URR to the integrated phosphorus supply model assessment. Major global phosphate extractable amounts (adapted from Ehrlich *et al.*, 1992; Smil, 2001; Filippelli, 2008; USGS 2008), and scaled for use in the model.

Deposit type	Phosphate rock, tonnes	Availability
High grade deposits	16,000 million	High grade
Low grade deposits	25,000 million	Low grade
Ultra low grade deposits	50,000 million	Ultra low grade
Sum known amounts (1800)	**93,000** million	
Hidden high grade 1800	4,000 million	High grade
Hidden low grade 1800	20,000 million	Low grade
Hidden ultralow grade 1800	50,000 million	Ultra low grade
Sum unknown amounts (1800)	**74,000** million	
Stored in soils of all kinds	200,000 million	Available for plants only

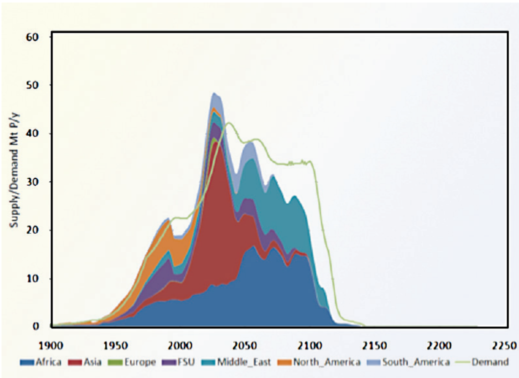


a b

Figure 5.2 Hubbert's curves, using our 2011 available reserve estimates **(a)**, but eliminating resources that are contaminated or technically out of reach (URR = 19 billion tonne phosphate rock). The different curves reflect different types of deposits, in broad terms as high grade, low grade and ultralow grade amounts. The Y axis has tonne per year phosphate rock in (a). **(b)** Shows the output from the WORLD model, using estimates of URR of 31 billion tonne phosphate rock (small reserve) and 62 billion tonne phosphate rock (big reserve). Soil resources as 200 billion tonne phosphate rock equivalent comes in addition. The X axis in both plots are calendar year.



a



b

Figure 5.3 Two phosphorus supply projections created by running a flow sheet model of supply against demand. **(a)** The best case and **(b)** The low demand case. In either case the phosphorus supply is limited (Jasinski, 2006; Mohr and Evans, 2013). Each plot shows in million metric tonne phosphorus per year. Our study falls in between these predictions.

5.4 Model Description

The phosphorus model (FoF) is constructed into several modules (Sverdrup and Ragnarsdottir, 2011):

1. The population and consumption module
2. The mining and market module
3. The social stress module

The model is formulated as a series of differential equations, derived from mass balances for phosphorus:

$$dP/dt = \text{inputs} + \text{produced} - \text{outflows} - \text{accumulation in the system} \quad (5.5)$$

The following 13 different coupled reservoirs are considered in the model through coupled differential equations based on mass balance. We have exhaustible resources:

- Known and hidden high grade deposits
- Known and hidden low grade deposits
- Known and hidden ultra low grade deposits
- Soil contents

Population is divided into:

- Young persons (0-20 yr)
- Fertile middle age persons (21-44 yr)
- Infertile middle age persons (45-65 yr)
- Old persons (65+ yr)

Society has two places where phosphorus may stay:

- Market stock
- Waste stock

Important independent phosphorus flows are: mining of phosphorus from three reserve qualities; 1) Chemical weathering of phosphorus from soils that can be harvested; 2) Consumption of phosphorus by the population; 3) Recycled phosphorus waste. We also consider phosphorus lost beyond recapture to the ocean and as dissipative losses. The phosphorus flow chart as we have modelled it is shown in Figure 5.4. We considered the bedrock substrate for soil genesis to be inexhaustible. We have considered ocean sediments as being out of reach. Marl is considered to be in ultra-low grade extractable amounts. The transient reserve in the animal stock has been ignored. All stocks and flows are measured by their phosphorus content. The mass balances are made for each reservoir. Phosphorus flows from hidden deposits, after being discovered by prospecting, to known extractable amount from where it is mined, and converted to fertiliser and taken to the market. Phosphorus also enters the markets embedded in food after being harvested from soils through crops, or as manure taken from animals and sold directly. From the fertiliser market, phosphorus flows into crops and enters the cycle. From each step there is waste that is partly recycled. Recycling is especially important for capturing the soil phosphorus as this mainly enters the market as animals, crops and manure. The following assumptions were made in the construction of the model: demand and thus consumption is dependent on human population size, but with elasticity based on phosphate cost. The phosphate rock extractable amounts are brought in from mining, depending on phosphate market price. Mining of low-grade phosphate rock starts when the price reaches the $800-1,000 per tonne, and ultralow grade phosphate rock are mined when the price reaches $1,800-2,000 per tonne. These break-off points are based on earlier modelling and experiences from metal markets (Ragnarsdottir *et al.*, 2011, 2012; Sverdrup and Ragnarsdottir, 2011). When 90 % of a phosphate rock resource has been removed, then the mining efficiency drops drastically.

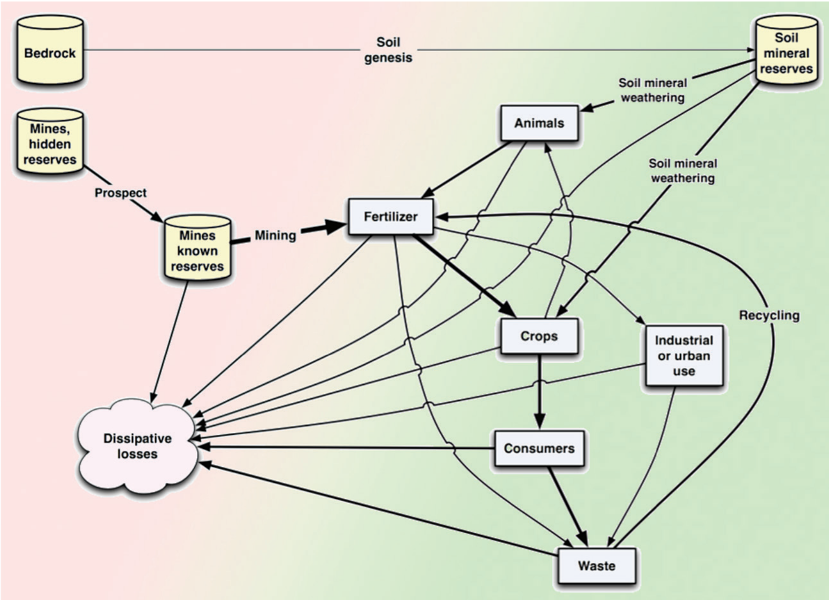


Figure 5.4 Flow chart of the phosphorus cycle. Flow charts are used together with the causal loop diagrams to define the simulation model used here (after Sverdrup and Ragnarsdottir, 2011).

Starting values for phosphate rock extractable amounts are shown in Tables 5.1-5.3. They show population sizes, estimated average phosphate consumption and phosphate rock flux available from natural sources through animal husbandry and agricultural activities. As phosphorus becomes scarce, price is augmented and recycling increases. In the model, we assume recycling to be dynamic and depending on price, with 25 % at $100 per tonne up to 90 % at $1,000 per tonne. We have made certain assumptions on generalising the Earth's soil resources and using established weathering rate estimates – at present 30 million tonnes per year – are brought in from agricultural fields and pasture-land, based on unpublished regional assessments of continental European soil weathering rates using the PROFILE model (Sverdrup and Warfvinge, 1988a,b). We assumed that in this model, neither energy supply nor any trace elements will cause population size limitation. We have also assumed that water is not limiting.

We deliberately chose to have a dynamic world population model, rather than using input curves, as we want to have the feedback from phosphorus rock availability on population dynamics. We have chosen to model the phosphorus rock supply and relate that to the size of the global population. In the market, more purchase will reduce market availability, whereas supply from phosphate rock mining or recycling increases availability. Increase in the availability of phosphorus reduces the price. Increase in the price decreases consumption (food gets expensive) and increases recycling and may increase mining up to the maximum capacity. More consumption leads to waste, but more waste permits more recycling. Mining reduces the phosphate rock reserves, and as the phosphate rock extractable amounts get exhausted, that in itself may reduce mining. Tables 5.2-5.3 give phosphorus consumption rate and intensities used to start the model run. The population model used is based on four age ranges; children, adults working and fertile, adults working and infertile, and elderly. More birth rate increases the population, which in turn generates more births, which is a reinforcing loop. The level of education reduces birth rates, and is an effective way of birth control. More population generates more deaths, reducing population, which is a balancing loop. Mortality is also affected by available consumption, a proxy for food. Less consumption below a certain threshold will increase mortality, and take its toll on the population. The population model has two special features. The availability of phosphate rock controls extra mortality when it becomes scarce. Secondly, the rate of education will reduce birth rates. It is well documented that the best birth control measure of all is achieved by emancipation and giving women good and lasting education (Shorter, 1973). World average mortality rates were used. In the model the phosphate consumption serves as a proxy for food. The simple phosphate consumption and market model used was validated against population development from 1850 to now.

Table 5.2 Data on consumption rates and population. Stocks and fluxes all converted to phosphate rock.

Parameter	Source	Estimate
World population 2014	IIASA / UN	7,300 million
Annual mining 2015, phosphate rock	USGS	200 million tonnes/year
Supply from natural sources (soil mineral weathering) through agricultural harvesting and animal husbandry	Estimate from authors based on European critical loads programme (UN-ECE LRTAP).	20 million tonnes/year
Recycling of used phosphorus (16 %)		40 million tonnes/year
Phosphorus from fish, using an annual global catch of 93 million tonnes fish and average P content of 0.5 %	Calculated from content and fish catch size	0.5 million tonnes/year
World annual supply	USGS, Filippelli (2008)	260 million tonnes/year

Table 5.3 Intensities of phosphate consumption.

Average consumption, phosphate rock 2014		26.0 kg/person year
Average consumption, phosphate rock 2008		25.6 kg/person year
Average consumption, phosphate rock, 2000	USGS (2008)	29 kg/person year
Average consumption, phosphate rock, 1840	Authors estimate	20 kg/person year
Agricultural use of phosphate rock, 2000	Official statistics at FAO	20 kg/person year
Non-food use of phosphate rock, 2000	Filippelli (2008)	7 kg/person year
From natural sources, equivalents of phosphate rock, 2000	Filippelli (2008)	6.3 kg/person year
Minimum dietary requirement in phosphate rock equivalents, assuming 100,% uptake efficiency	Filippelli (2008)	7.3 kg/person year

5.5 Recycling of Phosphorus

We may turn the question around; how large a population may we have, given certain bridging times required to get population numbers down in a civilized manner, recycling rates and assumed future phosphate use per person? The available amount of phosphate rock per person per year as a function of total available extractable amounts (annual mine extractable amounts, annual soil resources (flux from fishing is ignored as it is insignificant as a phosphorus source on the global level), time to be bridged and recycling fraction were calculated using:

$$\text{Phosphate per person} = \frac{\text{URR} + \text{Soil content}}{(1 - \text{R}) \bullet t_{\text{DOOM}} \bullet \text{P}} \quad (5.6)$$

Where P is the population number, R is the fraction of supply being recycled and t_{DOOM} is the time perspective (2,500, 5,000 or 10,000 years).

Recycling is a way to keep more phosphorus in the system, equivalent to feeding more people on the same net supply. The amount of phosphate rock we can keep flowing in the system is given by:

$$\text{System flux available} = \text{Supply into system} / (1 - \text{R}) \quad (5.7)$$

Figure 5.5 shows the population that can be sustained if the bridging time is 10,000 years and the recycling rate varies from 0 %, 40 %, 75 % to 90 %.

5.6 Input Data to the Systems Dynamics Model

The data (Tables 5.1-5.3) were adapted from published literature (Sherman, 1920; Daily and Ehrlich, 1992; Ehrlich *et al.*, 1992; Meadows *et al.*, 1972, 1992; Daily *et al.*, 1994; van Andel 1994; Beder, 2000; Smil, 2001; Ehrlich and Goulder, 2007; Filippelli, 2008; Turner, 2008; USGS, 2008; Al-Rawashdeh and Maxwell, 2011; Ragnarsdottir *et al.*, 2011; Sverdrup and Ragnarsdottir, 2011) and the official website of the USGS with updated statistics. Table 5.1 shows major global phosphate extractable amounts (adapted from Ehrlich *et al.*, 1992; Smil, 2001; Filippelli, 2008; USGS, 2008), scaled for use in the model. In our modelling all the resources are converted into phosphate rock equivalents. Tables 5.2 and 5.3 show data on production rates, consumption rates and population. Stocks and fluxes are all converted to phosphate rock (apatite equivalents). Human phosphate rock consumption is dominated by agricultural use as fertiliser for crops. Other uses include detergents, soap, additives to food, food supplements for animals as well as technical use in industry. In total 80 % of the total global phosphate flux is associated with production or processing of food. The direct phosphorus dietary requirement in the food we eat is about 1 g day^{-1} $person^{-1}$; in phosphate rock equivalents it corresponds to approximately 20 g day^{-1} $person^{-1}$ or 7.3 kg $person^{-1}$ yr^{-1} of phosphate rock. By simple comparison, in 1750, before the production of artificial fertiliser, the world's population was about 500-700 million and the phosphate was derived from biological sources exclusively. This population corresponds to the population number that would be possible from the harvest of weathering alone (without artificial fertlisers), and that the average use per person was just above the necessary requirement. We assume that the potential amount of phosphorus that can be harvested from soils by agricultural means is 50-60 million tonnes of phosphate rock equivalents per year. All living organisms need phosphorus in fixed minimum amounts to sustain protein metabolism and life and there is no substitute for it (Ehrlich, 1968; Brown, 2009a,b). Phosphorus rock is a fossil resource, forming very slowly and requiring geological times for regeneration. Therefore it is a non-renewable resource.

A roughly estimated burn-off time of phosphorus has been estimated to be of the same order of magnitude as for oil (50-100 years; Evans, 1998; Meadows *et al.*, 1972, 1992; Daily and Ehrlich, 1994; Sverdrup and Ragnarsdottir, 2011). At present, with a world population of over 7 billion, we are using phosphate rock globally at a rate of 29 kg $person^{-1}$ yr^{-1} of phosphate rock. We estimate that the minimum requirement for sustaining a population is approximately 7.3 kg $person^{-1}$ yr^{-1} of phosphate rock, in diet, with 50 % efficiency, we need to harvest phosphorus equivalent to approximately 14 kg $person^{-1}$ yr^{-1} of phosphate rock as a minimum. Modern consumption is thus 4 times the minimum requirement. We harvest approximately 30 million tonnes yr^{-1} of phosphate rock equivalents through agriculture and we extract 147-157 million tonnes yr^{-1} of phosphate rock from mines, for a total consumption of 177 million tonnes yr^{-1} in 2010. The ratio of mined to natural supply is thus 17 %. If the full potential of harvested phosphorus is used, this may perhaps be raised to 50 million tonnes yr^{-1} (28 %) if animal use is optimised for phosphate harvesting. Using a back-of-an-envelope calculation, this points to a long-term sustainable population of a maximum of 2 billion people, which agrees with many other studies (Fig. 3.2). This is valid if we assume the soil phosphate supply from weathering to stay constant, which in reality may be an unrealistic assumption, as the content of minerals subject to chemical weathering changes with time (Sverdrup and Warfvinge, 1988a, 1995b; Warfvinge *et al.*, 1992) and soils are degrading at an alarming rate – suggesting that only 60 years of soils are left[14].

14. http://www.scientificamerican.com/article/only-60-years-of-farming-left-if-soil-degradation-continues/

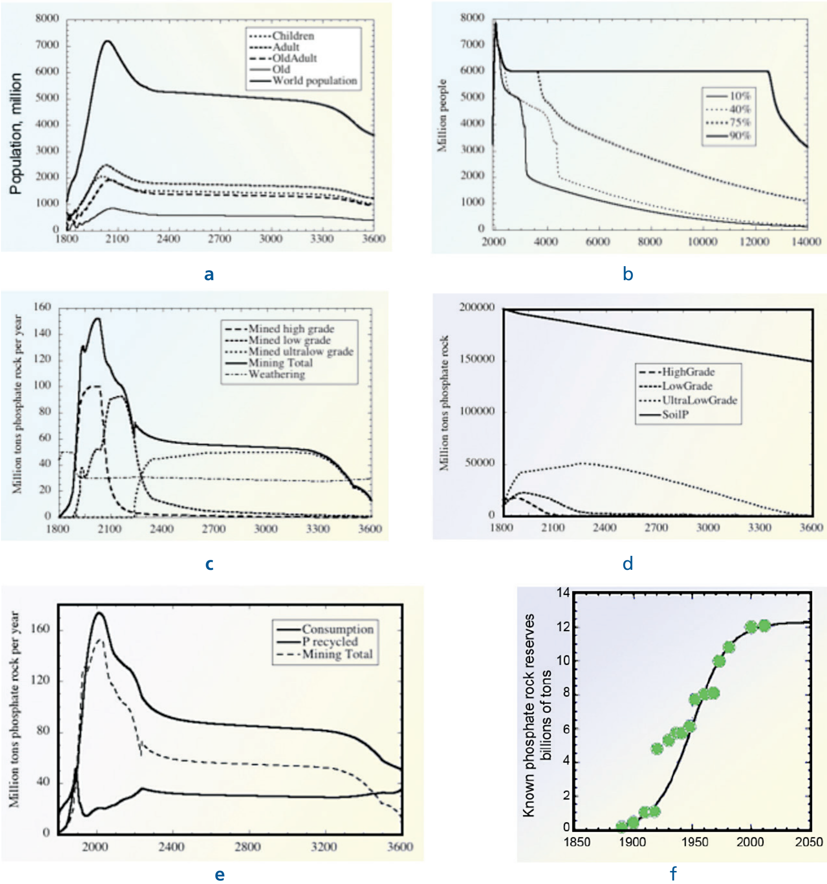


Figure 5.5 **(a)** Estimated population over time, using a standard population dynamics model, modified for phosphorus availablity limiting population growth. **(b)** Sensitivity analysis of the model with respect to the degree of recycling of phosphorus and population size. **(c)** The mining rates from different sources in the longer term, showing the peak behaviour, how the production from high grade, then low grade and lastly ultra low grade peaks. **(d)** The soil and rock extractable amounts in the longer term, showing the peak behaviour, how the production from high grade, then low grade and last ultra low grade peaks. **(e)** The total use of phosphate rock divided between recycling and sources from newly mined material. **(f)** Cumulative prospecting of phosphorus. The curve shows that suddenly upgrading total extractable amounts to 64 billion tonnes is inconsistent with all earlier prospecting and evaluation of what constitutes an extractable amount.

5.7 Results for Phosphorus

5.7.1 *The standardised basic run*

More comprehensive estimates can be made using the FoF phosphorus model. In the first series of phosphorus model runs, the model was set to run from 1800 to 3600 AD, to see when the reserves run out. Other runs were made covering the period from 1800 AD to 15,000 AD, when soil phosphorus is almost exhausted. During the runs, recycling is dependent on phosphorus rock market price, and has a maximum recycling rate of 50 % (recycling is currently about 16 %). As recycling we count any recapture of phosphorus-containing waste, such as animal manure, human excrements, residuals from food production, from technical uses, waste from crop processing etc. This is far higher than at present and represents an ambitious goal compared to the present practice.

Figure 5.5 shows the outputs from the FoF-model on the global level. Figure 5.5a shows the predicted global population passing through 7 billion in 2010 and peaking shortly after at 7.3-8 billion. The main reason for the downturn of the population curve after 2050 is the availability of phosphorus. It also shows the development of global phosphorus extractable amounts over time. We can see that the high-grade ore amounts run out after 2100, the low grade after 2200 (Fig. 5.5c). After that time only ultralow grade extractable amounts are available to mankind. It can be seen that the phosphorus rock production from high-grade ore is at the peak at present and will start declining around 2030-2040. After 3600 AD, harvesting via weathering will be the main source of phosphorus to society. The degree of mining was set to depend on the price and the market perception of immediate scarcity. The output illustrates that the market alone cannot efficiently regulate the use of a finite essential commodity.

The model assessment shows that the price increase only comes when the resource has already become scarce, when too much of the resource has already been wasted, before more efficient practices can come into use. Relying on the market alone will not allow for the long-term sustainability with a resource we know soon will be scarce. The market price mechanism only measures the instant, and thus takes no account for any future. This suggests that market solutions do not provide the solution to the resource sustainability, unless backed up with governmental policies, legislation and different types of incentives. The production of phosphate from low grade ore will steadily rise to compensate, but resulting in a higher price. The difference between mining and consumption is filled by the phosphorus originating from weathering harvested by plants and by animals. We have made assumptions for fertility rate developments based on the IIASA (International Institute of Applied Systems Analysis) scenarios. It can be seen that after the peak, the population will sink to 4-5.5 billion people for as long as the low grade (1800-2250) and ultra low-grade (1800-3300) deposits can be mined (Fig. 5.5c). When all of mineable extractable amounts are exhausted 3100-3300 AD, another food-based reduction will follow, settling on 2-1.5 billion people that can be sustained by harvesting by soil weathering alone (Fig. 5.5d-e). During 1800-3600 AD, about 25 % of the soil phosphorus that can be harvested would be depleted. High-grade reserves run out in 2140, low grade reserves run out around 2340 and the ultra low grades around 3100 AD (Fig. 5.5c). Changing the URR upward only shifts these dates by some decades, the basic underlying problem remains. After that humanity must rely on collection of soil phosphorus originating from soil mineral weathering. After 3100, the only market available phosphorus will be that recycled from waste. Soil weathering will be near exhaustion after 9000 AD (Fig. 5.5d). Unless something drastic occurs with phosphate rock supply, a world population above 7.5 billion appears problematic.

5.7.2 Investigating scenarios

To assess the validity and address alternative futures, we undertake a series of sensitivity runs. These are: setting the recycling rate at politically determined rates instead of relying on market price mechanisms alone after 2010: 10 %, 42 %, 74 %, 90 % (Fig. 5.3b). The results were created with the dynamic model in the STELLA-system in sensitivity-mode.

Figure 5.5 shows the population output for the different recycling scenarios for the time period of 2000 to 14,000 AD, a very long time perspective (Fig. 5.5b). The present rate of recycling (16 %) corresponds to something between scenario 10 % and 40 %. These scenarios imply that we run out of phosphorus after 3300 AD and eventually will experience large population decrease by famine if we have not brought down the population numbers by other means before that. As recycling increases, the population tipping point resulting from phosphorus is moved forward in time, for 74-80 % recycling the time to scarcity has moved up to 3800 AD, for 90 % recycling, the time limit to scarcity reaches 12,500 AD before the tipping point occurs. All scenarios except the 75 % and 90 % recycling imply that we will sooner or later run into large social stresses caused by food shortages. What will follow from the high stresses we can only speculate. Zhang *et al.* (2007) made a study of resource limitations in China and the occurrence of warfare in China during the last two millennia that could serve as food for thought.

If we can globally harvest 30 million tonnes yr^{-1} of phosphate rock from the natural soil phosphate supply through plants and animals and maintain a per person net use of 10 kg $person^{-1}$ yr^{-1} after recycling has been accounted for, we may maintain a world population of 3 billion people. Animal husbandry will be important in the future as they can harvest phosphorus from plants over large areas, and can bring the phosphorus home as manure for collection. This will be needed for maintaining agricultural fields at efficient yields. If the fundamental problem is the total volume of consumption, then the problem will persist until we can reduce total overall consumption significantly. It is well known that unlimited growth in populations may lead to ecosystems collapse (Malthus, 1798; Hardin, 1968; Robèrt *et al.,* 2002) and the human population is not excluded from this. Overpopulation of any species of animals normally represents a significant ecosystem problem.

5.7.3 Recycling and population

If we assume that the minimum personal allotment is 14 kg person^{-1} yr^{-1} of phosphate rock, we get a sustained population of 3 billion people for no recycling, 4.8 billion people for 50 % recycling, and we could maintain almost 7 billion people at 29 kg person^{-1} yr^{-1} with 80 % recycling, assuming the time to bridge is 10,000 years (Fig. 5.5). If the bridging time is 100,000 yrs (a full glaciation cycle) and the recycling rate varied from 0 %, 50 %, 80 % to 90 %, and if we assume that the minimum personal allotment is 15 kg person^{-1} yr^{-1} of phosphate rock, we get a sustained population of 35 million people for no recycling, 70 million people for 50 % recycling, 1.7 billion people with 80 % recycling and 3.5 billion people at 90 % recycling. At present, the overall efficiency is in the range of 12-18 %, which is grossly inadequate. Increasing recycling and increasing the efficiency of transfer from fertiliser to finished food from present 60 % to 80 %, would still only yield 55 % overall efficiency. Raising all step efficiencies to between 95 % and 98 % would be required to reach 90 % overall systems efficiency.

Table 5.4 Back of the envelope calculation of necessary recycling to keep the present phosphorus flux in the loop using data for 2015. To maintain the same flux in society, but have nothing from mining, we would have to recycle 85 % of the flux. This is possible, necessary but not easy. Compare with Table 4.18.

Parameter	Estimate
Annual mining 2100, phosphate rock	0 million tonne/year
Supply from natural sources through agricultural harvesting and animal husbandry with additional supply by optimisation	40 million tonnes/year
Recycling of used phosphorus	220 million tonnes/year
World annual supply	260 million tonnes/year

Table 5.4 shows a back of-the-envelope calculation of necessary recycling to keep the present phosphorus flux in the loop. If we look at the table, we have at present 260 million tonnes/year flowing through the global system. If the annual mining rate is reduced to near zero because of reserve exhaustion or extraction difficulties, we would have to recycle at least 220 million tonnes or 85 % of the present flux. This is about the same order of magnitude as we obtained with the systems dynamics model FoF discussed above. It will be a very tough challenge to organise, but not really impossible. Especially if we have no choice, then degree of difficulty becomes irrelevant.

5.7.4 Discussion

Today's use of mined phosphorus rock is without doubt unsustainable. Present governmental policies have not sufficiently recognised this problem and the policies are at present inadequate as the world's phosphate rock extractable amounts can only sustain humanity at levels of use and recycling rates similar to today's for a maximum of 200-300 years. Several possible future scenarios exhaust all available mineable extractable amounts within the next 1,600 to 3,200 years, leaving future generations in a very difficult situation. Only a fraction of the present world population can be sustained under any phosphate management regime of wasteful nature for any significant amount of time. The different scenarios seem to converge on a world population of 1,200-1,600 million people, unless the issue of significantly improved recycling can be resolved.

Market mechanisms act on the instant, without foresight, and thus are unfit for solving the scarcity problem of a limited finite resource in time. The market mechanism only starts to have an effect when scarcity is established, and thus, if the resource is unique, this is far too late. By then too much phosphorus will have been wasted. Rationing phosphorus consumption, implying also restricted food supply, will cause social stresses, with a potential for loss of civic control, potential for violent conflict, potential loss of democracy and resort to oppression, and is possibly not long-term socially sustainable as a policy. Our conclusions for phosphorus are:

1. The world is on trajectory towards phosphorus scarcity appearing during the next 100 years. Scarcity of phosphorus becomes noticeable as increased prices for fertilisers and following that price increases for food, increasing the risk for associated social problems and issues of unrest and conflict.
2. There is no substitution option available for phosphorus in food, and it is beyond any discussion.
3. The world cannot support a population at the present order of magnitude without closing the phosphorus cycle. Today, it is open.
4. Closing the phosphorus cycle requires very high recycling efficiencies in every single transaction step, and can only be achieved if given proper attention (check the challenges of multi-step recycling in Table 4.18). Our estimate is that we need better than 80 % recycling rate if we want to have a chance of supporting 5 billion people into the distant future (Fig. 5.5).
5. Simple steps, such as setting up dry toilets globally with mandatory composting is one solution. Another includes keeping water toilets but refining all sewage in cities around the world and capturing the phosphorus as well as the nitrogen for fertiliser production.

Phosphorus limits point to the fact that the population issue must be addressed, regardless of whether it is popular or not. Lack of phosphorus will affect food production and there is no substitute for phosphorus. If the situation is allowed to reach phosphorus scarcity, that may bring about a forced population decline and all the problems that comes with that. Experience shows that with proper care for the elderly, low child mortality and full human rights for women, including giving them higher education, is the most effective way of making population growth stop or decline. But that appears to be incredibly difficult in certain parts of the world.

6. ENERGY

6.1 Fossil Fuels

It is now well documented that fossil fuels are experiencing peak production now. This is shown in Figure 6.1 from the Association for the Study of Peak Oil (Aleklett, 2007; Aleklett *et al.*, 2012). It appears to be a consensus among petroleum geologists that conventional oil went through maximum production around 2005-2010 and that the continued increase in production comes from unconventional sources like tar sands, shale oil and deep ocean extraction (Bartlett, 1999; Campbell, 2013). Figure 6.2 shows another figure published by Association for the Study of Peak Oil in 2007. It is evident that non-fossil energy sources are going to be limited, and we will be faced with the prospect of having to run society with 20-30 % of the energy we have available now by the end of the century.

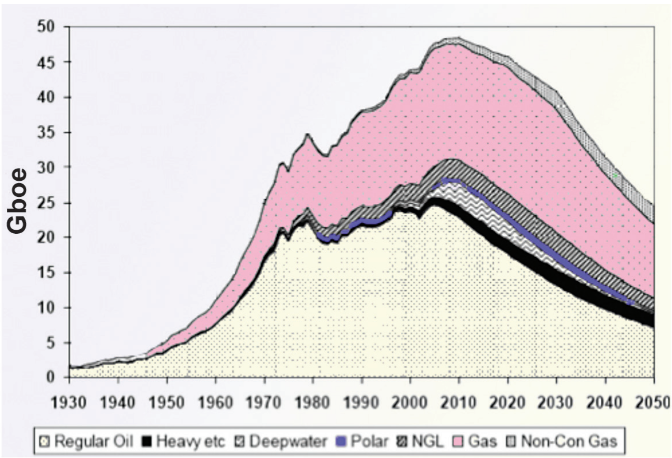


Figure 6.1 A figure published by ASPO (Association for the Study of Peak Oil) in 2007 for fossil fuels. Since then they have repeatedly published updates and the world is largely following this path. This pattern is reproduced by the ENERGY submodule within our WORLD model and used for this study. Gboe stands for Giga barrels of oil equivalents.

Since we come from Norway and Iceland it is interesting to analyse the future oil prospects in our countries. Figure 6.3a gives the production history for oil in Norway, showing that the peak oil production was in the year 2000. The figure was made using publicly available governmental data. Norway is the only country that has good transparency in its extractable amounts and production

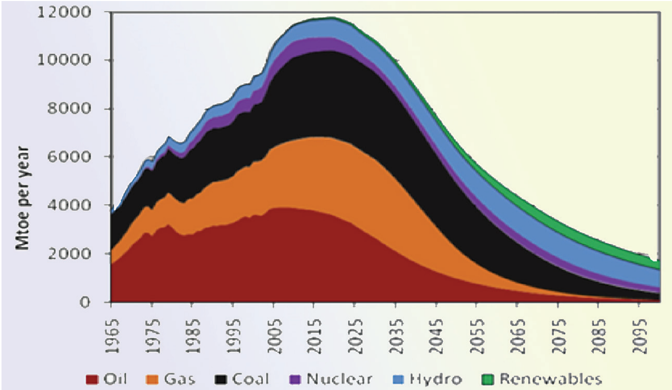


Figure 6.2 All energy in millions of tonnes per year. The figure shows that nuclear energy from uranium will not increase, that hydropower can only increase slightly and that all renewable energy can only be a fraction of fossil energy (figure published by ASPO, Association for the Study of Peak Oil in 2007; see Aleklett, 2007, and Aleklett *et al*., 2012). Mtoe is million tonne oil equivalents.

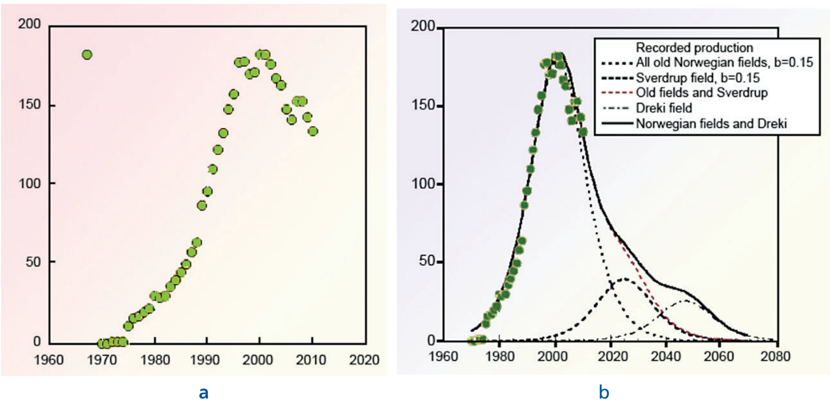


Figure 6.3 **(a)** Norwegian oil production to date. **(b)** Summary of Norwegian oil production assessment. The Sverdrup field is newly discovered in the North Sea. The Dreki field is between Iceland and Norway. Iceland has a 60 % claim to the field, Norway 40 %. The Dreki field is not yet fully explored and the oil quantities are therefore estimates. The Y axis in both plots are energy production millions of tonnes of oil equivalent per year.

data and have them readily available on the web. Figure 6.3b gives Hubbert´s estimates of future oil production in Norway, including the recent finds in the Sverdrup field (named after the prime minister *Johan Sverdrup* – a relative of

Harald's) off shore in the Western North Sea and the Dreki field between Jan Mayen island, a Norwegian island and Iceland – where Norway owns 40 % of the expected extractable amounts, and Iceland owns 60 %. The figure shows that the oil age in Norway will end around 2060 – and Iceland´s dream of becoming an oil nation will be short lived and peak in 2050 (marked Dreki field on Fig. 6.3b). Of note is that the oil in the Dreki field (if it is indeed there) is at an ocean depth of more than 1,000 m and geological formation depth of around 3 km. As stated previously, Energy Return On Energy Investment (EROI) expresses whether the resource extracted really has more value for us than what we have to put in in terms of cost and effort to get it. This is normally used for fossil fuels, but we may actually extend this to any resource by simply saying Resource Utility Return On Investment (RUROI). The first oil discovered was easy to extract and had an EROI of over 100, now it is more like 40. The deep ocean oil described in the North Atlantic will be costly to extract and technically challenging, as it is in a stormy and icy sea and will thus have low EROI (much less than 10).

Figure 6.4 shows the discovery of oil over time. It is now established that there is a 40 year lag time from peak discovery (about 1965) and peak production (see the compilation in Table 6.3), putting conventional oil peak production in 2005-2010. Conventional oil production appears to have reached a plateau during 2008-2014 (Campbell, 2013; IEA, 2014). There are several sources of fossil energies. The total oil production is slightly increasing; the increase is caused by production from unconventional sources like shale oil, fracking, heavy tar sands extraction, oil extraction at extreme ocean depths etc. The main fossil sources available for energy production are:

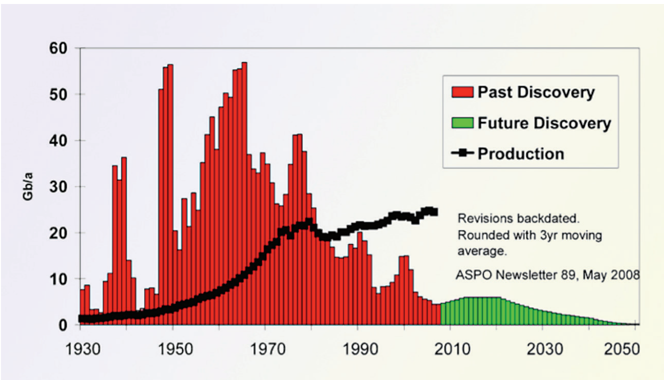


Figure 6.4 Evidence suggests that production peaks about 40 years after the peak in discoveries (see Table 6.3). For oil, global discoveries peaked in 1965, the inflection point of the cumulative curve is about 1973. Despite finds of reportedly "gigantic fields," this trend has not changed and we should expect peak oil to occur in 2012 plus or minus 3 years. Diagram from the ASPO website (2014). Gb/a stands for Gigabarrels per year.

1. Hydrocarbons — conventional oil, tar sands, bitumen, natural gas, tight gas, shale gas, oil shale, tight oil and gas and oil retorted from carbon shales;
2. Carbon fuels — coal, brown coal, peat, and carbon-rich shale;
3. Conventional nuclear power generation based on uranium and thorium;
4. Fossil geothermal heat;
5. Nuclear reactors, using uranium 235 and old nuclear weapons plutonium as fuel.

Table 6.1 shows a summary of total hydrocarbon extractable amounts (oil, gas, coal). The numbers were derived from Campbell (2004, 2013), Campbell and Laherrere (1998, low estimate), Al-Husseini (2009 high estimate) as well as our own ongoing assessments. "Oil" includes all kinds of oil, conventional, shale, tar sands, tight oil or oil retorted from rock. The same applies to natural gas and coal. There is not full agreement of how much will be extractable, but we propose that the reality is somewhere between the high and the low estimates given in Table 6.2.

Table 6.1 Total hydrocarbon extractable amounts, million tonnes oil equivalents (Aleklett *et al.*, 2012; Campbell, 2013).

	Low estimate	Average estimate	High estimate	World extraction rate in 2012
	Million metric tonne oil equivalents			Million metric tonne oil equivalents per year
Oil	660,000	870,000	1,000,000	3,700
Natural gas	450,000	700,000	900,000	2,600
Coal	1,823,000	2,227,000	3,000,000	7,400
Sum	2,873,000	3,797,000	4,900,000	13,700

These resources all have in common that they are mined, and once they are gone, then they are lost forever from a human civilisations perspective. Breeder reactors are not yet ready technologically, but may extend the lifetime of thorium-based reactors to 30,000-50,000 years with some additional development. Research for fusion reactors for power generation are on-going at present, but nowhere near anything useful for energy production for the foreseeable future.

Figure 6.5 shows the world fossil fuel production, distributed among different fossil fuel types, including some new fuels claimed "to remove the problem of peak oil." The estimates of extraction rates show this to be a very naïve opinion, as all fossil energy use must obey mass balance. Conventional nuclear energy is also a limited resource and with present use it will not last any longer than oil. The curves are based on observed production data from the open literature and the oil and coal corporation production estimates for the next decades. The data used is given in Table 6.1. The global conventional oil production peaked around 2008-2014, total oil production including unconventional sources will peak around 2014-2022. The global coal production will peak soon (possibly around 2015-2020). The range arises from the issue of how much of the remaining coal can actually be extracted. Coal is more abundant than oil but also a finite resource, and the regeneration rate is insignificant. The global oil production and the resulting global wealth production follow closely the shape of a Hubbert's curve. Once oil is completely consumed, then there will be no extra global oil resources left. At that point the situation could become difficult to steer away from a grand scale systemic collapse, which would potentially cause many problems. This is because the whole world economy is fuelled by fossil fuels (Meadows *et al.*, 1972; Heinberg, 2005, 2011; Bleischwitz *et al.*, 2012 and many others).

The renewable natural energy sources at large scale are mainly hydropower, but wood and small amounts from wind and direct capture of sun as heat or electricity contribute locally to energy pools. Figures 6.1-6.2 and 6.5-6.7 show the different energy types used to supply the world. They suggest that renewable energy will never replace the current "cheap" fossil energy at the rate that is currently being used without apparent consideration for future generations. Without a paradigm shift by 2200, we will have to adjust to about 20 % of the energy supply we have now. Not easy, but not impossible. Figure 6.5 shows past global energy production and a future projection.

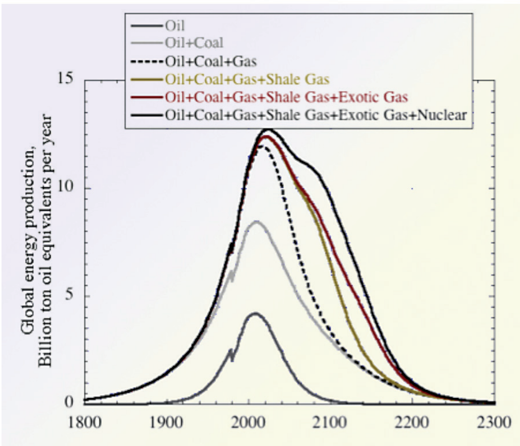


Figure 6.5 Hubbert´s production curves for many different types of fossil fuels. Hubbert's curves were estimated by the authors using published reserve estimates (Al-Husseini 2009; Campbell, 2013).

Table 6.2 Remaining recoverable reserves of fossil fuels with estimates of peak production.

Fossil energy source	Remaining recoverable extractable amounts in 2010	Initial extractable amounts in 1840 (URR)	Estimated production peak time (this study)
	Billion tonnes oil equivalents		
Oil	320-380	650-700	2009-2015
Coal	750-1,400	1,600-3,000	2020-2055
Natural gas	310-330	690	2015
Shale gas	320-450	300-700	2040-2080
Exotic fuels	100-210	100-210	2130
All energy	1,795-2,745	3,540-5,250	2015-2020

Table 6.3 Delay between peak in reserve discovery and peak production. The data suggest an average delay of 40 ± 4 years (after Sverdrup *et al.*, 2013a).

Substance	Discovery peak	Production peak	Delay (years)
Gold	1968	2008	40
Oil, global	1965	2008	42
Oil, Norway	1978	2002	30
Oil, United States	1938	1971	33
Oil, Russia	1961	1989/1998	37
Oil, Saudi Arabia	1958	2002	44
Coal, United States	1950	1992	42
Coal, Russia	2030	2070	40
Phosphorus, global	1955	2000	45
Coal, Great Britain	1880	1922	42
Iron, global	1978	2025	45
Global copper	1996	2036	39
Global silver	1995	2030	35
Average			40

Figures 6.1-6.3 are based on historical data and the predictions are assembled from published projections of the major energy companies (Höök *et al.*, 2008). The net current geologic production of new fossil oil can be estimated from a simple calculation to be a maximum of 100,000 tonnes per year. The formation of coal from peat and organic sediments may be 100,000 tonnes per year. At present (2012) consumption rates, this corresponds to 15 minutes world use for oil and 9 minutes of world use for coal (Strahan, 2007, 2008; Zittel and Schindler, 2007).

Figure 6.6 shows an energy supply simulation output from the ENERGY sub-module in the WORLD model. It shows how fossil fuels dominate, and how large the challenge of energy supply after 2150 will be if the global population has not gone down significantly by then. Figure 6.7 shows the energy return on investment (EROI) for various ways we produce energy. The figure shows that currently average world oil EROI is around 60-80 but will soon plummet down to 10 and even less in 2050. This is the maximum EROI estimated for deep oil, such as the oil in the Dreki area in the Arctic Sea, northeast of Iceland, now being considered for development by Iceland and Norway. Renewable energy now has an EROI of 3-50, depending on type of source and will decrease to about 25 around 2100 with an increased hydropower fraction. The size of the hydrocarbon reservoirs of OPEC states have been somewhat inflated in the statistics, because, in the past, larger reported national extractable amounts gave larger national production quotas.

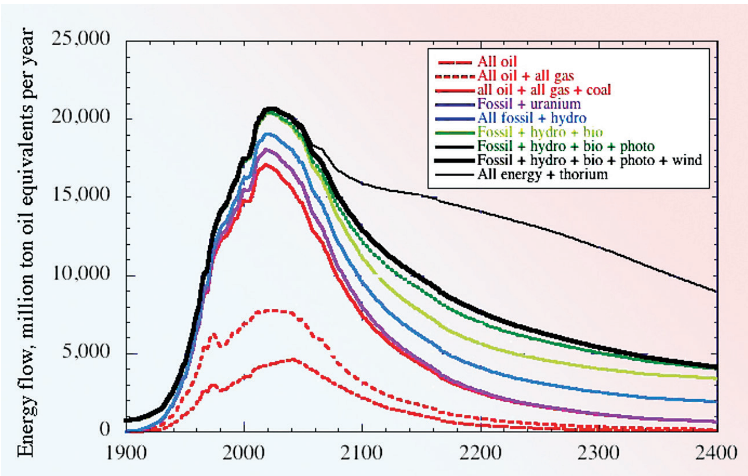


Figure 6.6 Different long-term energy sources and what they can yield in the next 300 years. The fossil fuels have all been added up (oil, shale oil, tar sands, gas, tight gas, shale gas, coal, brown coal and carbon shales and nuclear energy using conventional technology). After the peak we assume renewable energy potential to be used, yielding about 50 % of the 2010 global energy production. In this we have also assumed the use of the potential in nuclear power based on thorium. This can be compared to Figure 6.5.

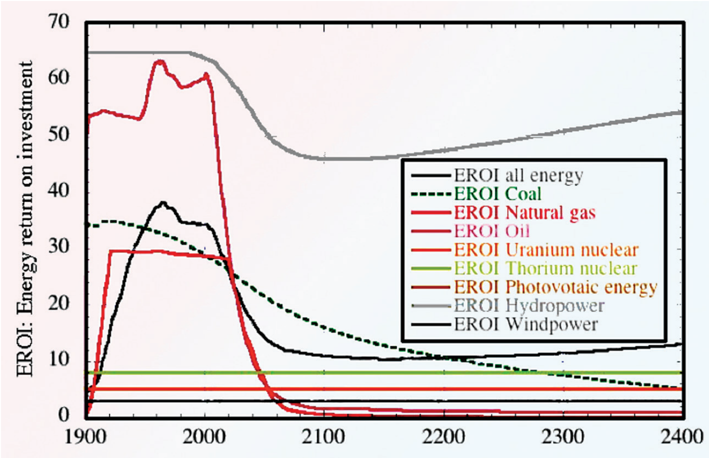


Figure 6.7 Changes in the EROI, the "Energy Return On Investment" with time. When the EROI fall below 1.5, the energy source does not produce any significant benefit. Data for the runs behind the diagrams was taken from diverse sources and graphs assembled by the authors, the curves are outputs from the ENERGY submodule within the WORLD model being developed.

It needs to be kept in mind, however, that we can only burn less than 25 % of the fossil fuels left in the ground (Meinshausen *et al.*, 2009) if we aspire to keep below the 2 °C average global warming figure agreed by nations of the UN. Therefore if a climate agreement is reached in Paris in December 2015 a large part of the fossil fuels shown in Figure 6.5 will not burnt for energy, unless CO_2 capture technology is at hand.

6.2 Alternative Energy Sources

Figures 6.6-6.7 show a future possible scenarios where alternative technologies and renewable energies are used to replace fossil fuels. There are four main types of alternative energy sources:

1. **Renewable energy sources**:
   a. Hydropower is by far the largest sustainable source of long-term renewable energy, Central Asia and the mountains of both Americas still have areas with significant un-harvested hydropower available.
   b. Geothermal energy is available in many areas.
      i. Renewable geothermal energy. Those that are located in volcanically active regions have a renewable capacity, as long as heat extraction does not exceed heat influx. But the technical

capacity limitations for extraction widely exceed the renewability capacity. If exploited to the full technical capacity, the geothermal resource will be extracted like a fossil resource subject to mining and will be damaged or destroyed.

ii. Fossil geothermal heat is available in many parts of the world. This is old volcanic heat or old radioactive heat, and is not renewed after extraction (when comparing with human lifetime). It is a fossil reserve that will potentially be exhausted by mining.

c. Biomass may provide both a large amount of fuel, building materials, polymers and a substrate for synthetic oils. Much of the biomass potential is already taken up by production of food and materials for structural wood and paper, and the room for extra production is possibly there but needs careful planning and testing to determine that it is really sustainable. It is important that we harvest sustainably, avoiding mining out forests and causing land and soil degradation. The technical capacity for extraction widely exceeds the renewability capacity for biomass production. Hydro- and bio-energy types can support approximately 20 % of the present global energy supply when fully developed, however, there are some significant challenges to be tackled.

2. **Technology assisted sources of energy** such as the technology-based direct and indirect solar energy harvesting strategies (photovoltaic, wind energy harvesting, active or passive heat harvesting, wave power harvesting) all have significant technological and social challenges and require rare materials that may become scarce or volume-limiting and thus require very strict recycling. These are often presented as renewable, but they are arguably not as the technology and installations are not renewable. The equipment requires exotic metals (indium, europium, neodymium, silver, germanium, gallium, selenium, gold, platinum, energy for manufacture) and materials and thus has significant finite resource constraint.

3. **Nuclear energy:**

a. *Breeder technologies for fission.* Large amounts of long-term energy can be added by introducing thorium breeder nuclear reactors based on thorium as fuel (Jayaram, 1985; Kasten, 1998; Francois *et al.*, 2004) with nuclear fuel recycling, a system that would be able to yield about 40-50 % of the global energy production that was produced in the year 2010. Thorium in such use may be estimated to last at least 4,000 years, possibly more. The weapons proliferation issue is limited for a thorium energy technology solution. Another major advantage is that it generates limited nuclear waste (3-10 % the volume of uranium waste for the same energy production, and much of the waste can readily be reprocessed to reusable reactor fuel). There are, however, serious safety and radiation challenges that will require a huge effort to make thorium installations safe and reliable. The recycling technologies required are in general available, but still require more development to be safe and to improve efficiencies.

b. *Uranium breeder technologies* have potential to deliver a maximum of half the energy as can a thorium solution. Uranium breeder technologies present severe and profound problems with nuclear weapons proliferation and highly radioactive waste produced in large amounts. No good solution exists for the nuclear arms risk, and this technology has therefore been abandoned. The waste amount is large and the cooling/decay time is very long (more than 100,000 years, leaving the problems to future generations), which constitutes a significant cost as well as a security problem. Reactor engineering has also proven very difficult to make operable and robust because of the high radiation loads from the high velocity flux of neutrons.

c. *Fusion technologies* have to be classified as a large disappointment so far. Research and development has been going on continuously since 1955, with no viable technology available to this day, despite enormous investment in prestige, hardware and manpower. There is no operational powerplant solution in sight for the foreseeable future, while research costs are escalating exponentially, and the engineering problems accumulate instead of decrease (Hamacher and Bradshaw, 2001). No reasonable solutions appear to be feasible for the forseeable future if some honesty is applied. This technology is likely to be abandoned in a resource-restricted post-oil era. It needs to be mentioned that Lockheed in the USA has recently made positive statements about fusion advancements, but technical economic feasibilities are still unclear.

4. **Exotic sources of fossil hydrocarbons** like deep ocean clathrate, tundra soil methane, pyrolysis of low carbon rocks, fossilised biomass mining are not renewable, but rather disruptive as they mine huge swaths of land or ocean areas. They generally generate huge amounts of CH_4, CO_2 and chemical pollution and are known to upset ecology, geology and disturb public comfort. They are in short summary:

   a. Peat and soil carbon mining. Strip mining of landscapes to burn it up in huge furnaces. The mining disrupts the hydrological cycle of the landscape and implies total annihilation of the *in situ* ecosystem.

   b. Shale carbon and oil taken out by strip mining across landscapes, such as in densely inhabited Central Europe. Popular support is quickly dwindling, huge waste piles are produced and pollution is difficult to avoid. These operations have high risk for contaminant leakage despite efforts in reconstructing landscapes.

c. Tight oil and natural gas taken out with fracking. Fracking has significant detrimental effects on groundwater and ground stability issues are occurring, with frequent earthquakes in many areas.
d. Tar sand and solid bitumen mining tear up landscapes and whole regions. This implies total annihilation of the *in situ* ecosystem, as in Alberta, Canada.
e. Clathrates and methane hydrates from the sea floor. The technology is unknown, and there are big risks in deep ocean operations with high risk of environmental damage.

Potentially, all these alternative energy production methods may be able to sustain the present energy production level (but not increase it) until 2080, after which a convergence and contraction to about 50 % of 2010 production levels will have to occur regardless of what we do. This is a best-case scenario that requires a substantial effort in research and societal preparation, however, the advantage with thorium-based nuclear power is that it produces no material useful in nuclear arms and thus prevents nuclear arms proliferation. In the best case we will end up with 50 % of 2010 energy production level, but more likely something like 18-25 % of 2010 energy production level. For the best case (-50 %), it will be possible to adapt to it with serious and determined efforts, but the more likely scenario (-75 % to -82 %) is a tough challenge that will require a huge efforts, including major political and cultural adaptations and changes.

Table 6.4 shows assumptions underlying our energy production assessment. These are basic numbers behind the simulated curves with estimates from energy reserves in 2010. The numbers for coal and shale gas vary widely, depending on at which quality the cut-off is made. Much of the higher estimates include extractable amounts of very low quality where it is highly questionable if they will ever be or can be extracted. The different national energy agencies in many countries have systematically down-adjusted their estimates of extractable coal reserves. Possibly much of the known or probable coal resources will never become extractable because of a too low or negative energy return on investment of extraction. That implies that we will run out of coal because of lack of extractability and lack of money when extraction becomes significantly more expensive. Exotic fuels include deep sea clathrates, sea floor coal beds and other reserves presently out of technical reach. Data were assembled to a database and analysed by the authors using Hubbert's model and dynamic modelling (WORLD model early versions). Table 6.2 shows data for shale gas and oil; included are hydrocarbons released through the controversial shale fracking.

To combat climate change there is a need to reinvent today's existing energy systems. Even though there is a clear trend towards renewables, only a small part of the world's primary energy is supplied from renewable energy sources. A change in nuclear energy technology to thorium technology will probably be considered. Table 6.4 gives a conservative estimate based on the present paradigm and technology for using nuclear power. The time limits are 60 years to burn-off for uranium and 380 years for thorium (Hoisington, 1959). This leaves us with traditional nuclear energy technologies in the same "peak uranium" – type of paradigm as with hydrocarbon-based fossil fuels.

Table 6.4 Estimates of energy resources and rates of depletion as well as burn-off times and time limit to scarcity using Hubbert curves (Hubbert, 1982). The new type of uranium and thorium-based energy production can yield long-term solutions for energy supply in industrially significant amounts. The thorium estimate is valid if a closed recycling thorium technology as adapted.

Element	Mining rate % per year	Burn-off time years	Year of peak production	Hubbert-curve decline to 10 % of reserves, years	Estimated total world deposits 2012 million tonnes	World mining rate 2012 million tonnes/yr
Oil	2.3	45	2012-2020	100	164,000	3,700
Coal	1.6	80	2018-2025	175	470,000	6,000
Gas	1.6	65	2018-2025	145	164,000	2,600
U-235	1.6	60	2026-2030	140	4	0.050
Thorium	0.16	380	2034-2100	4,400	22	0.005
Biofuels	6	35	n.a.	n.a.	15,000	900

6.3 New Potentials for Energy Production

The nuclear fuel reserves are with conventional technologies have the same time-horizon as the fossil fuels. However, with new technologies the time horizons would increase an order of magnitude to 25,000 years if thorium is used and 8,000 years if uranium is used, as long as the thorium, uranium and waste including redundant plutonium are combined (Etherington, 1958; Hoisington, 1959; Francois *et al.*, 2004; Sverdrup *et al.*, 2013c). The technology implies recycling all nuclear waste, combined with steps to separate radioactive isotopes from stable isotopes, and to burn all radioactive residuals into stable isotopes in the reactor core, generating electricity in the process, eliminating the existing and newly generating nuclear waste in a repeated series of cycles. The technology has the potential to increase thorium fuel yield to more than 90 % (Etherington, 1958; Francois *et al.*, 2004; www.scatec.com). In Figure 6.8, we illustrate an energy system with a closed thorium cycle. The uranium cycle is very inefficient, 0.7 % of the uranium metal is used for energy, and it generates waste that remains for almost eternity (from human perspective as it needs to be kept safely for at least 100,000 years). With an integrated closed thorium cycle, all waste can be reprocessed and all thorium and uranium be burned to energy, generating little or no residual waste. The strength of the closed cycle thorium-based system is that a counterforce to nuclear arms proliferation is introduced into the international nuclear energy system, because thorium-based nuclear power plants do not produce feasible weapons grade material. With the reprocessing technology comes also the possibility to convert vast stockpiles of old waste as well as weapons stockpiles to energy. The same type of technology would also be feasible with uranium as the power source, however, the nuclear arms and plutonium issue would then remain a significant problem.

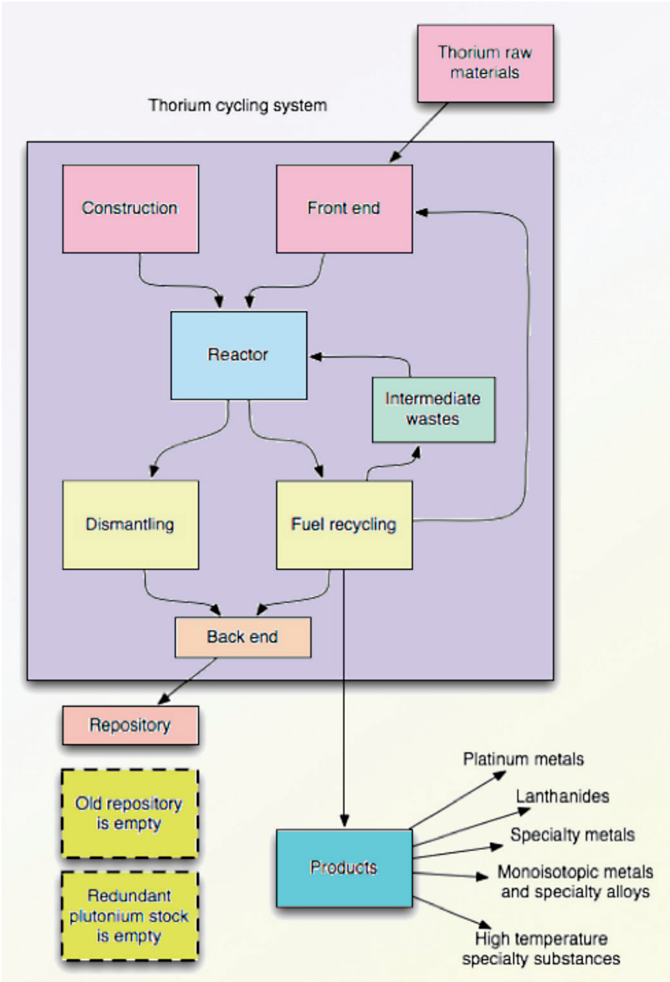


Figure 6.8 Outline of an integrated nuclear thorium system such as those that have been proposed in India and Norway. None have been fully developed and built yet, but research and development work is ongoing.

The thorium-based nuclear energy system cannot self-accelerate; it will always remain subcritical. It is kept in operation by a neutron spallation source, normally a proton accelerator hitting a tungsten or tantalum target for continuous neutron generation. If the electricity to the accelerator is broken, the nuclear reaction automatically dies out instantly. In a thorium-based system, the reactor core and surrounding materials will still be radioactive and will eventually have to be processed. By adopting a system that decomposes and transmutes the nuclear waste to stable isotopes, smaller amounts of life-threatening waste will be left for future generations than with the present uranium-based technology.

Figure 6.8 shows an outline of an integrated nuclear thorium system such as those that have been proposed for India and Norway. Here even uranium-based nuclear waste could be reprocessed.

Estimates for fossil energy resources are shown in Tables 6.2-6.4. There it can be seen that the time limit for scarcity of fossil fuels is approximately 45 years; this could be extended by dynamic price-consumption-demand mechanisms, but not enough to really make a significant difference. For coal the time horizon is longer, but burning all coal deposits would possibly destabilise the Earth's climate to a degree that human society would be at significant risk of severe problems with sufficient food production. Scientists have estimated that only about 25 % of the remaining fossil fuels can be burned in order to keep the average temperature rise since pre-industrial era under 2 °C (Meinshausen *et al.*, 2009).

The estimate of thorium recoverable amounts is connected to the extractable amounts of rare earth metals, with which thorium regularly occurs. Large resources are found in India, Australia, Norway, USA, China, and Africa.

7. LINKING RESOURCES AND WEALTH

7.1 Historical Perspectives – the Roman Empire as an Example

Harald is an avid reader of ancient and modern history. There is a clear link between resources and the viability and stability of civilisations (Zang *et al.*, 2007). Tainter (1988) analysed the stability of nations, defining collapse as when an empire, nation, chiefdom or tribe experiences a "significant loss of an established level of socio-political complexity." It manifests itself in decreases in vertical stratification, less occupational specialisation, centralisation and information as well as simpler trade flows, poorer literacy, decreased artistic achievement, shrinking territorial extent and less investment in the "epiphenomena of civilisation" (palaces, granaries, temples, etc.). Tainter summarises a large number of historic civilisation collapses. Figure 7.1 shows the example "rise and fall of the Roman Empire" drawn by the authors using data taken from Kennedy (1987), Tainter (1988, 1995, 1996), Bardi and Pagani (2008), Bardi and Lavacci (2009), Fleming (2011), Fukuyama (2011, 2014) and Bardi (2013). The content of silver in the Roman coinage went down steadily from the time of Augustus until the end of the empire. By 300 AD, the power of the Roman Empire was largely over in the western part of Europe. Resources dried up for the Romans as old resources became exhausted and the new territories could not deliver more; this seems from visual inspection to follow the shape of a Hubbert's curve reasonably well (Fig. 7.1). The extent of human activity in the Roman Empire, in today's Italy, as reflected by abundance of archaeological artefacts is also shown in Figure 7.1. The manpower of the Roman army is shown in the figure to illustrate how much surplus they could divert to defence and expansion. Resources lead to wealth, which leads to more people and leads to larger military might (Fig. 7.2). That leads to larger territory and more resources in the resource base. By steadily acquiring more new territories, the army must hold more land, thus it becomes weaker and more stretched, unless it is correspondingly increased, thus increasing running costs.

Peak resource for the Roman Empire came in the years of Emperor Augustus, in 14 AD (Fig. 7.1); imperial peak wealth seems to have occurred about 120 AD; the imperial expenses peaked in 270 AD; the Western Roman Empire perished as a state a century after. In 410 AD Roman rule was rejected by the Visigoths, and then a real Roman Empire no longer existed. For the Western Roman Empire, the delay between resource peak and wealth peak seems to be about 100 years, and the delay between the wealth peak and the cost peak appears to be 100-200 years. We assume the time of maximum cost to be the time of maximum army size (280 AD).

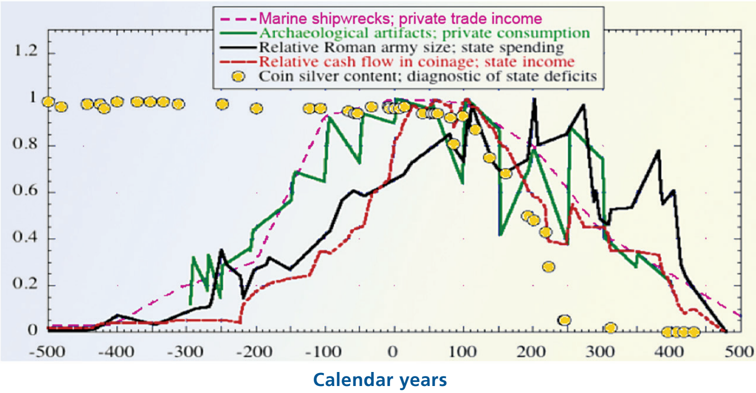


Figure 7.1 The rise and fall of the Roman Empire in observed numbers. The depletion of silver in Roman coins 0-270 AD (yellow dots) shows the inflation as the coin silver content was reduced. The archaeological artefacts reflect household income and the manpower of the Imperial Roman Army reflect Roman state costs. All parameters shown have been rescaled to the same unitless scale, with 1 being the maximum value (after Sverdrup *et al.*, 2013a).

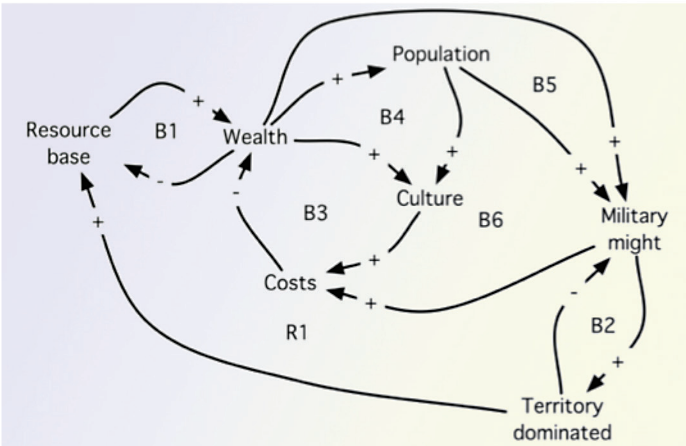


Figure 7.2 A simple causal loop diagram, to illustrate why the Roman Empire disappeared. The causal loop diagram is a logical variant of Tainter's principle as shown in Figure 7.3 and discussed in the text (Tainter, 1988). In short, surplus wealth drives up consumption into overshoot, where the income no longer can support the activity, whereupon a contraction (in a peaceful environment) or in the worst case a collapse (as in a conflict environment) follows. R is a reinforcing loop driving the system forward. B1-B6 are balancing loops that slow the system down. As the Romans ran out of territory to dominate and exploit, the steam went out of their economic system with only limiting loops left.

The collapse of the Roman Empire began 170 years after the resource peak (about 270 AD). It never revived properly after that, as the resource base for a recovery was no longer present. The reasons for the fall of the Roman Empire have been much debated. *Gibbon*'s "*Rise and fall of the Roman Empire*" suggests that it came from a progressing moral inadequacy caused by the introduction of Christianity and the rise of decadence and corruption. Later it was suggested that it was a resource collapse (Diamond, 1997, 2005), or a systemic collapse of a complex organisation (Tainter, 1988, 1996, 1997). In Figure 7.2, a causal loop diagram is shown where we depict some of the reasons for the fall of the Roman Empire. To us it appears that decadence and corruption ("culture") are partial causes that are involved as components of a larger systemic collapse. There are several balancing loops in the causal loop diagram but only one reinforcing loop based on resources. This illustrates why an empire with a good resource base can achieve great might, but that it inevitably also must decline as it runs out of resources.

When complex systems fall out of their stable envelope of operation, the structural collapse of the complex organisation may be catastrophic with respect to the power elite, the imperial structure and complexity. As the Roman Empire evolved and grew in size, it also developed a state and societal organisation with increasing complexity. More and more complex structures were built, such as sewer systems, water supply systems, including complex piping in the cities, aqueducts, storage dams and cisterns, roads, road construction organisations, materials sub-suppliers, maintenance organisations, state agencies, bureaucracies and offices for various operations. But also complex structures like roads, canal and communications inside a larger Empire need a coordinating organisation with complex tasks. This would imply physical infrastructures, organisational structures for trade, security, finance and education, and personal networks between organisations and between people. All require maintenance including the replacement of key people at regular intervals, providing them with adequate training and education. The maintenance backlog builds up because of delays in decay in the system, as well as a delay in the detection of increased maintenance demand. Depending on the structures, the delays may vary from a few years to 100 years. The backlog in terms of maintenance costs will eventually catch up with the stock of infrastructures, and become large enough to exceed the available income for maintenance and thus undermine the economy. If the overshoot is too large, it may lead to maintenance shortage and the collapse of structures. For the Roman Empire, we can see how it evolved through four different stages:

1. Expansion of the area of dominance with a very simple and low-cost organisation, efficient for the task. As new territories were acquired, they were harvested for resources, energy, labour and skilled people at a high profit return on monetary investment, and the energy and material return on investment values are high.
2. The increased land area with military dominance, augmented the running costs of military operations in consolidating gains, the

increased access to low cost short-term wealth that leads to specialisations and increased complexity of the organisation of society gaining that extra wealth.

3. The continued expansion of the Empire created a backlog of cost that slowly built up in the system. The further expansion of the domain, after the acquisition of the best areas for resources, then ran into diminishing returns on further effort. The exploitation of internal domestic resources stagnated and declined as they approached exhaustion, compensated by unsustainable taxation to fill the gap. For the Roman Empire, this implied that local mines (*e.g.*, silver) became depleted, the landscape was deforested (and fuel was depleted) and the agricultural soils eroded away (as still evident on the Adriadic coast and North Africa). This reduced and depleted the domestic resource base, and increased reliance on resources harvested far away and new conquests they could no longer afford.
4. The maintenance cost backlog catches up, income declines and as a result, huge budget deficits developed throughout the whole structure. As the reserves inside the imperial system structure ran out, the system experiences systemic decline that may under stress accelerate to *collapse*.

The Roman Golden Age as defined by classical authors actually occurred during the period right after the resource peak, illustrating how peak wealth comes some decades (30-100 years) after peak resource outputs. This kind of collapse is not unique to the Roman Empire, but generic of many complex societies. This phenomenon is described by Tainter (Tainter, 1988, 1996 and is often referred to as “Tainter´s principle” and describes the rise and fall of complex organisations). As shown on the causal loop diagram (Fig. 7.3) resource extraction leads to wealth and consumption. With wealth we tend to build physical and social infrastructures. The costs of maintaining these are significant, and thus if the growth slows down, stops or declines, such systems very often experience overshot and subsequent contraction. This is what happened to the Roman Empire, British Empire, the PanAmerican Airlines (PANAM) or other large empires. Figure 7.4 describes the consequence of Tainter´s principle. In times of growth infrastructures are built with a delay, financed with debts. This results in interest payments, morgage payments and the structures themselves have maintenance costs. When the growth slows and turns down, we cannot re-mortgage loans, start having problems with interest payments, and finally fail on maintenance. The system fails, and the system simplifies or disintegrates into smaller units. The Empire “falls.” *Tainter* himself refers to this as simplication from complex systems to more simple systems. *Vala* was relieved when reading *Tainter,* because then she saw in her mind a better and simpler world coming forth this century, after the vastly complex globalised system we have today will have crumbled. It would appear that the global financial, resource and ecological difficulties we are experiencing now may be indicating the initiation of the simplification process.

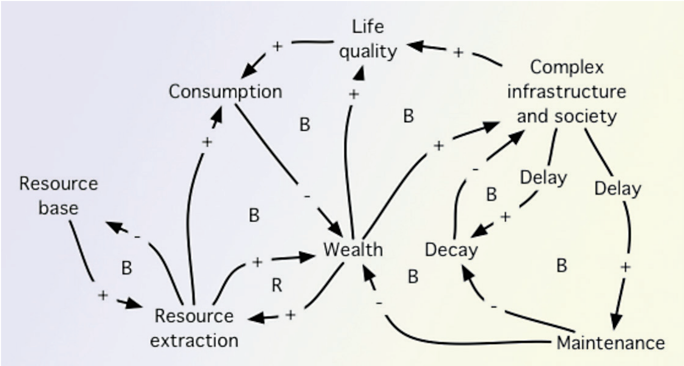


Figure 7.3 Tainter's principle or model (Tainter, 1988) for rise and fall of complex organisations. Resource extraction leads to wealth and consumption. With wealth we tend to build physical and social infrastructures. The costs of maintaining these have significant costs, and thus if the growth slows down, stops or declines, such systems very often experience overshoot and subsequent contraction. This is what happened to the Roman Empire, British Empire or other large empires. R are reinforcing loops, keeping the system going. When we run out of resources, the reinforcing loop is weakened and the balancing loops (B) will eventually stop the system.

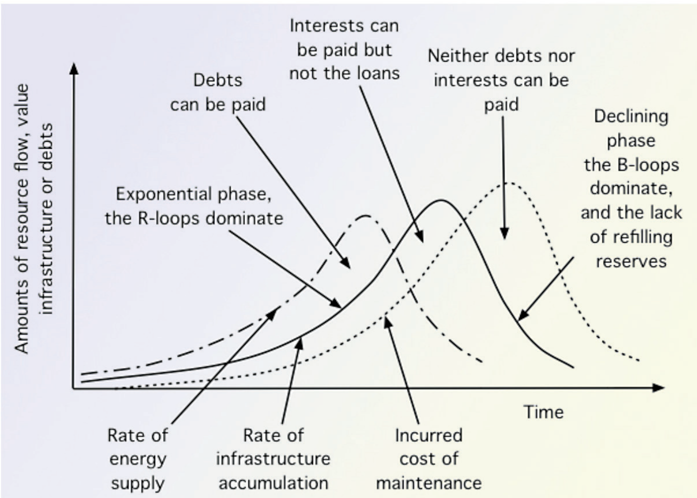


Figure 7.4 Tainters model (Tainter, 1988) has the consequences illustrated above. In times of growth we build infrastructure with a delay, financed with debts, resulting in interest and mortgage payments and the structures themselves have maintenance costs. When the growth slows and turns down, we cannot pay mortgage loans, start having problems with interest payments, and finally fail on maintenance. The system fails, and the system simplifies or disintegrates into smaller units. The Empire "falls."

7.2 The World Model

The WORLD model is in development and is an integrated model for the world economic system, based on biological and physical realities of the world. Figures 7.3 and 7.4 show how the model is constructed. The components of the WORLD model were outlined earlier (Fig. 4.2). In Figure 7.5 the integration of the WORLD model with the German econometric GINFORS model is shown to combine into a new SIMRESS model. This modelling was commissioned by the German government which has put a serious focus on Germany having a resource based, zero carbon economy by 2030. To our knowledge no other government in the world has such advanced thinking. The German government commissioned *Harald* to lead the modelling, just like he had done for the critical load work earlier (see above).

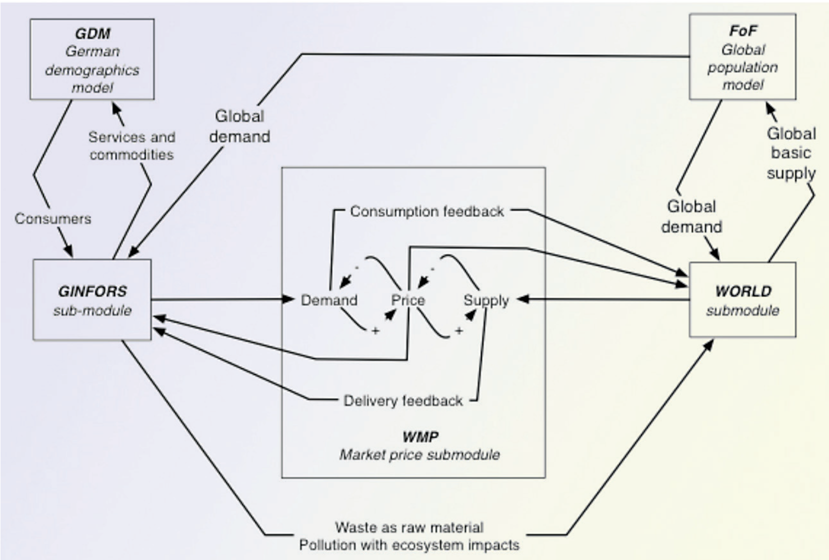


Figure 7.5 The chart shows how the WORLD model interacts with GINFORS in the SIMRESS model system.

The WORLD model was used in this study to estimate the rise, peak and decline of some empires and check this against available data to assess the accuracy of our predictions. Table 7.1 shows data on rates of resource discovery, resource extraction and wealth creation over time, cost over wealth overshoots and predicted civilisation declines, and an attempt at a preliminary prognosis. Resource peaks are for land, coal, oil and metals. The decline dates assume that governance and society continues along the practice of Business As Usual, without any consideration of effective measures to attain sustainability. Bold numbers in italics in Table 7.1 are model predictions – very approximate years, normal font dates are the observed dates based on historical data. There is a 40-year delay between discovery peak and resource peak. The wealth peak is about 10 years after the resource peak. Costs start to become larger than wealth about 15 years after the wealth peak. Collapse occurs around 20 years after costs are larger than wealth. Possibly, modern society has more sophisticated means of postponing the ramifications of long-term sustainability (Roberts, 2013). Through derivatives, market distortions, corruption and money creation, extisting value can be better and more completely siphoned off to cover up for deficits, making the crash all the more disastrous and complete (Roberts, 2013).

The tentative WORLD model outputs in Table 7.1 show possible futures resulting from a Business As Usual assumption. The purpose of such scenarios is to create the understanding that Business As Usual may not be the best planning for the future, and to avoid unpleasant potential future situations like those suggested by Table 7.1, some fundamental and real changes would be required (Roberts, 2013). When reading the numbers, remember that model outputs give possible scenarios, and no guarantee that the predicted date events really will happen.

Table 7.1 Known resource discovery, resource extraction and wealth creation peaks, cost over wealth overshoots and civilisation collapses, assessed with early prototypes of the WORLD model. *Italics* are model predictions very approximate years, black dates are the observed dates based on historical data. Resource peaks are for land, coal, oil and metals. The potential collapse dates assume that governance and society continues along the practice of Business As Usual, without any consideration of effective measures to attain sustainability (adapted after Sverdrup *et al.*, 2013c).

Empire	Predicted with meta-model based on the WORLD5-model, calendar year					
	Discovery peak	Resource peak	Wealth peak	Cost larger than wealth	Predicted collapse	Observed collapse
Roman	14 AD	80-120	120-160	180-220	240-280	First 287 Final 400
Norwegian	1066-1100	1220-1280	1292	1330	1340	1349-1450
Swedish	1520	1632	1688	1712	1732-1750	1788-1809
British	1888	1928	1938-1943	1958-1963	Dismantled 1947-1965	
Spanish	1520	1550	1565	1580-1600	1620-1660	1700-1750
Great Britain	1965	1988	2000	2010-***2020***	***2025-2040***	?
Soviet	1932	1948	1960	1985-1990	1995-2005	1990-1993
Russian	1932	1993	2005	***2020-2025***	***2035-2045***	?
American	1955	1971	1983-1986	1998-2006	2015-***2025***	?
Chinese	2000	***2020-2025***	***2035-2040***	***2050-2060***	***2060-2080***	?
Indian	1990	***2040-2048***	***2052-2065***	***2068-2080***	***2077-2090***	?
Global	1975	2007	***2017-2022***	***2040-2060***	***2060-2080***	?

7.2.1 Peak world and the end of the golden age

Oil is peaking now, and coal will peak in the near future; peak oil production was passed in the period 2008-2010, the coal peak comes in the period 2015-2020, peak energy will occur in 2015-2020 and thus may anticipate that wealth peak will arrive around 2017-2022. From then on global growth of GDP will be impossible without increased efficiencies, and a new economic paradigm for supply of life quality to the citizens must be in place (Costanza *et al.*, 2014). There is a delay of 50 years between initial investment, and the cost of maintenance for infrastructural renewal was assumed to increase by 1.5 % per year. The WORLD model, used to produce the model runs presented in this study is similar to the approach taken by Meadows *et al.* (1972, 1992, 2004) in their World3 model, presented in the *Limits to Growth* study. However, they considered energy and material resources all together, so missing the dynamics when they are coupled but separate, as shown here. Materials can be recycled very well, whereas much of energy use in its fundamental function is non-recyclable.

There are convincing examples where resource exhaustion is the cause for social crisis and potentially also war. For documented past examples, see for China: Zhang *et al.* (2007), for Easter Island: Bahn and Flenley (1992), but also more general considerations: Ehrlich (1968), Hardin (1968), Meadows *et al.* (1972, 1992, 2004), Tainter (1988, 1995, 1996), Ehrlich and Ehrlich (2013), Diamond (1997, 2005), Leslie (1998), Ash (2002, 2009), Haraldsson and Sverdrup (2004), Tilly (2003, 2007), Klein (2007), Lövin (2007), Greer (2008), Sachs (2008), Brown (2009b), Rockström *et al.* (2009), Fukuyama (2011). We conclude that lack of resources is a potentially dangerous situation globally. The solutions to our sustainability problems are as much in the social domain as any other domain, and engineering and economics interact with the social machinery. However, people and social processes control and shape behaviour. The sustainability challenge is thus a social challenge and the willingness to change people´s and society´s behaviour. The use of all resources available to us at maximum rate as we do now, creates a significant limitation for future generations, and such behaviour carries ethical consequences (Costanza and Daly, 1992; Holmberg *et al.*, 1996; Beder, 2000; Holmberg and Robèrt, 2000; MacIntosh and Edward-Jones, 2000; Heinberg, 2001, 2005; Lietaer, 2001, 2003; Ainsworth and Sumaila, 2003; Lietaer *et al.*, 2010).

In 1973, when the United States went through local peak oil, and started importing large amounts of oil from the Middle East, the world had a warning of what happens when global peak oil is passed. The world went through an oil crisis at the same time. The assessment made by the Club of Rome, the *Limits to Growth* report that was published in 1972 (Meadows *et al.*, 1972, 1992, 2004), predicted the coming of resource and energy scarcity for the beginning of this millenium and the ramifications afterwards. The lessons were heeded by a few and then quickly forgotten by both the public and politicians (Nørgård *et al.*, 2010; Kanninen, 2013; Turner, 2014). At that point politicians failed in their statesmanship and their strategic planning. Economic science failed in not applying systems thinking, not understanding the basics of exponential economic growth, not understanding that the Earth is limited by mass balance, and not learning from past historical experiences with collapses and declines (Tainter, 1988, 1996; Greer, 2008; Heinberg, 2001, 2005, 2011; Fukuyama, 2011).

The world is fast moving towards its limits. As presented in this *Perspective*, we see peak behaviour in most of the strategically important metals, materials and fossil fuels that are fundamental to running of our societies. The crisis we experienced in 2007-2009 in the western world was not only a financial crisis, but also a crisis that showed the first symptoms of resource-backed economic growth that cannot be sustained because of the physical limits of the world (Meadows *et al.*, 1972; Tainter, 1988, 1996, 1997; Greer, 2008; Jackson, 2009; Heinberg, 2011; Arnarson *et al.*, 2011; Bardi, 2013; Sverdrup *et al.*, 2013a,b; Ragnarsdottir *et al.*, 2014a). In a world of limits, planning for further growth is a fool's policy that will fail. There are still influential people stuck in denial of the finite nature of resources. A too large global population in a world of physical limits for resource extraction will most likely be a world of great poverty. When the resources continue to decline at the same time as the population rises, the situation will get worse. This is one of the largest challenges ever faced by mankind.

Every problem is a challenge, every challenge is an opportunity, and every opportunity turned into a solution is a success. Solutions must be found. All of us, including geochemists, need to rise to the occasion to find the solutions. Business As Usual is the worst case. There are many possible ways forward, there are many solutions to develop, and there is much change needed to make it all work. For example new development indicators are needed, that go beyond GDP (*e.g.*, Kubiszewski *et al.*, 2013; Costanza *et al.*, 2014; Ragnarsdottir *et al.*, 2014a). Solutions thinking is very much at the core of sustainability science. This is the reason why *Vala* was happy to take on the responsibility as an associate editor of the fusion magazine/academic journal *Solutions*, which publishes articles focusing on solutions for a sustainable and desirable future.

7.3 Food for Thought – The Story of Helium

In this volume we have gone through many of the most important materials and metals used in society. We did, however, not yet mention helium. This rare gas is primarily produced as a by-product of oil extraction. As outlined by Ragnarsdottir *et al.* (2012) the Business As Usual world scenario gives a burnoff rate of a decade and this has caught the eye of *Vala*´s concerned students in Iceland. Yet, we are wasting it in helium balloons for children. How are we going to run our sophisticated accelerators and medical equipment in the future when no further helium is available in the market for cooling, if we use it up on party implements and entertainment follies? This is left here as food for throught on human ability for foresight and for reflection on our own behaviour.

We are teetering at the edge of exhaustion of all the resources, within the same era, but our governmental policies are still modelled on economic growth as if all resources were endless on a finite planet. We know it is wrong, but seem unable to admit it and to make the changes we need to do. Is humanity really destined for inevitable collapse, or does it have the mental capacity to rethink and change course? We have tried to have a perspective to the future; to outline the challenges we have to overcome. There is no holistic plan yet, but many researchers are beginning to think about these issues. As the former research director of the Swedish Environmental Agency, *Dr. Jan Nilsson*, said at the Skokloster 1988 workshop: "We need a future vision of a goal, a strategy and a plan, and then we must act!". *Vala*´s friend *Harold Helgeson* at Berkeley used to sing at various geochemical gatherings "There´s no tomorrow…". But we would like to state: we must act now or never, and this is our final *Perspectives* message!

REFERENCES

Acemoglu, D., Robinson, J.A. (2013) Why nations fail. The origins of power, prosperity and poverty. Profile Books Ltd, London, 529 pp.

Ainsworth, C., Sumaila, U. (2003) Intergenerational discounting and the conservation of fisheries resources: A case study in Canadian Atlantic cod. In: Sumaila, U. (Ed.) *Three essays on the economics of fishing*. Fisheries Centre Research Reports, Vancouver, 26-33.

Al-Hassani, S. (2008) 1000 Years of Missing Industrial History. In: Calvo Labarta, E., Mercè Maymo, C., Puig Aguilar, R., Rius Pinies, M. (Eds.) *A shared legacy: Islamic science East and West*. Edicions Universitat Barcelona, Barcelona, 57–82 [63].

Al-Husseini, M. (2009) World production of conventional petroleum liquids to 2030: A comparative overview. *GeoArabia* 14, 215-267.

Al-Rawashdeh, R., Maxwell, P. (2011) The evolution and prospects of the phosphate industry. *Mineral Economics* 24, 15-27.

Aleklett, K. (2003) The Peak and Decline of World Oil and Gas Production. *Journal of Minerals and Energy* 18, 15-20.

Aleklett, K. (2007) Peak oil and the evolving strategies of oil importing and exporting countries. *Discussion paper 17*. Joint Transport Research Centre, OECD, International Transport Forum.

Aleklett, K., Lardelli, M., Qvennerstedt, K. (2012) Peeking at peak oil. Springer, Heidelberg, 335 pp.

Allen, D.T., Behamanesh, N. (1994) Wastes as Raw Materials. In: Allenby, B.R., Richards, D.J. (Eds.) *The Greening of Industrial Ecosystems*. National Academy Press, Washington, D.C., 68-96.

van Andel, T.H. (1994) New views on an old planet: A History of Global Change. Second Edition, Cambridge University Press, Cambridge, 458 pp.

Anderson, S., Blum, J., Brantley, S.L., Chadwick, O., Chorover, J., Derry, L.A., Drever, J.I., Hering, J.G., Kirchner, J.W., Kump, L.R., Richter, D., White, A.F. (2004) Proposed initiative would study Earth´s weathering engine. *EOS* 85, 265-272.

Anglo-American Mining Corporation (2012) Fact Book 2011/12. Platinum. Johannesburg, South Africa, 19 pp.

Anglo-American Mining Corporation (2013) Ore reserves and mineral resources report 2013.

Arnarson, M., Kristjánsson, Þ, Bjarnason, A., Sverdrup, H., Ragnarsdottir K.V. (2011) The Icelandic Economic Collapse, A Systems Analysis Perspective on financial, social and world system links. University of Iceland, Reykjavik, 74 pp.

Arndt, N.T., Lesher, C.M., Czamanske, G.K. (2005) Mantle-derived magmas and magmatic Ni-Cu-(PGE) deposits. In: Hendenquist, J.W., Thompson, J.F.K., Goldfarb, R.J., Richards, J.P. (Eds.) *Economic Geology One Hundredth Anniversary Volume*, Society of Economic Geologists, Littleton, 5-24.

Ash, A. (2002) Gold derivatives growth unsustainable. New study from the world gold Council. The BullionVault Website 2009.

Ash, A. (2009) Still paying and missing out on gold's $60bn-per-day whole sale deals. The BullionVault Website 2009.

AtKinson, A. (2008) The ISIS Agreement. Earthscan from Routledge, London, 336 pp.

Bahn, P., Flenley, J. (1992) Easter Island, Earth Island. Thames and Hudson Ltd, London, 240 pp.

Bardi, U. (2005) The Mineral Economy: A Model for the Shape of Oil Production Curves. *Energy Policy* 33, 53-61.

Bardi, U. (2007) Peak oil's ancestor: the peak of British coal production in the 1920s. *Newsletter 73*. The Association for Study of Peak Oil (ASPO), Uppsala, Sweden.

Bardi, U. (2008) Peak oil and The Limits to Growth: two parallel stories. The Oil Drum, Europe, http://www.theoildrum.com/node/3550.

Bardi, U. (2009a) Peak Civilization: The Fall of the Roman Empire. The Oil Drum, Europe, http://www.theoildrum.com/node/5528.

Bardi, U. (2009b) The fifth problem: peak capital. The Oil Drum, Europe, http://www.theoildrum.com/node/5434.

Bardi, U. (2011) The Limits to growth revisited. Springer Briefs in Energy, Springer, New York, 136 pp.

Bardi, U. (2013) Extracted. How the quest for mineral wealth is plundering the planet. The past, present and future of global mineral depletion. A report to the Club of Rome. Chelsea Green Publishing, Vermont, 299 pp.

Bardi, U., Yaxley, L. (2005) How General is the Hubbert Curve? The Case of Fisheries. In: Aleklett, K. (Ed.) Proceedings of the 4th International ASPO Conference. ASPO, Lisbon, online: http://europe.theoildrum.com/files/bardiyaxleyaspo2005.pdf.

Bardi, U., Pagani, M. (2008) Peak Minerals. The Oil Drum, Europe, http://www.theoildrum.com/node/3086.

Bardi, U., Lavacchi, A. (2009) A Simple Interpretation of Hubbert's Model of Resource Exploitation. *Energies* 2, 646-661.

Barnes, H. (Ed.) (1996) Geochemistry of Hydrothermal Ore Deposits. Third Edition, Wiley, New York, 992 pp.

Barrie, C.T., Hannington, M.D. (Eds.) (1999) Volcanic-Associated Massive Sulfide Deposts: Processes and Example in Modern and Ancient Settings. *Reviews in Economic Geology* V8, Society of Economic Geologists, Denver, 408 pp.

Bartlett, A.A. (1999) An Analysis of U.S. and World Oil Production Patterns Using Hubbert-Style Curves. *Mathematical Geology* 31, 1-17.

Bassi, A.M., Powers, R., Schoenberg, W. (2009) An Integrated Approach to Energy Prospects for North America and the Rest of the World. *Energy Economics* 32, 30-42.

Bech Nielsen, H. (1989) Random dynamics and relations between the number of fermion generations and the finite structure constants. *Acta Physica Polonica* B20, 427-468.

Beder, S. (2000) Costing the earth: Equity, sustainable development and environmental economics. *Journal of Environmental Law* 4, 227-243.

Bellamy, P.H., Loveland, P.H., Bradley, R.I., Lark, R.M., Kirk, G.J.D. (2005) Carbon losses from all soils across England and Wales 1978-2003. *Nature*, 437, 245-248.

BEKKER, A., SLACK, J.F., PLANAVSKY, N., KRAPEZ, B., HOFMANN, A., KONHAUSER, K.O., ROUXEL, O.J. (2010) Iron formation: The sedimentary product of a complex interplay among mantle, tectonic, oceanic and biosphere processes. *Economic Geology* 105, 467-508.

BENNING, L., SEWARD, T. (1996) Hydrosulphide complexing of Au(I) in hydrothermal solutions from 150-400 ºC and 500-1500 bar. *Geochimica et Cosmochimica Acta* 60, 1849-1871.

BLEISCHWITZ, R., MEYER, B., GILJUM, S., ACOSTA, J., DISTELKAMP, M., MEYER, M., PIRGMAIER, E., SCHÜTZ, H., RITSCHE, D. (2012) Wirtschaftliches Wachstum mit weniger Ressourcennutzung-Die absolute Entkopplung ist möglich. Ökologisches Wirtschaften 2/2012, 30-33.

BINDRABAN, P.S., VAN DER VELDE, M., YE, L., VAN DEN BERG, M., MATERECHERA, S., KIBA, D.I., TAMENE, L., RAGNARSDOTTIR, K.V., JONGSCHAAP, R., HOOGMOED, M., HOOGMOED, M., VAN BEEK, C., VAN LYNDEN, G. (2012) Assessing the impact of soil degradation on food production. *Current Opinion in Environmental Sustainability* 4, 478-488.

BODDE, D. (1991) Chinese Thought, Society, and Science: The Intellectual and Social Background of Science and Technology in Pre-modern China. University of Hawaii Press, Honolulu, 441 pp.

BOETTEKE, P.J. (1997) Where did economics go wrong? Modern economics as a flight from reality. *Critical Review* 11, 11-64.

BRANTLEY, S.A., GOLDHABER, M., RAGNARSDOTTIR, K.V. (2007) Crossing disciplines and scales to understand the critical zone. *Elements* 3, 307-314.

BREWSTER, N. (2009) Outlook for commodity markets. Rio Tinto Inc. MF Global Seminar 2009.

BROWN, L.B. (2009a) Plan B 4.0. Mobilizing to save civilization. Earth Policy Institute, Norton and Company, London, 199 pp.

BROWN, L.B. (2009b) Could food shortages bring down civilization? *Scientific American* 301, 38-45.

BRUHNS, K.O. (1994) Ancient South America. Cambridge University Press, Cambridge, 448 pp.

BUTT, C.R.M., HOUGH, R.M. (2009) Why gold is valuable. *Elements* 5, 277-280.

CAMPBELL, C. (2004) The Coming Oil Crisis. Independent Publishers Group, Chicago, 210 pp.

CAMPBELL, C. (2013) Campbell's Atlas of Oil and Gas Depletion. Springer Verlag, Berlin, 788 pp.

CAMPBELL, C., LAHERRERE, J.H. (1998) The end of cheap oil. *Scientific American*, 78-83.

CANFIELD, D.E. (2005) The early history of atmospheric oxygen: homage to Robert M. Garrels. *Annual Review of Earth and Planetary Science* 33, 1-36.

CARROL, L. (1871) Through the looking glass. Pseudonym for Charles Ludtwige Dodgson. Sequel.

CARTER, B., MCCREA, W.H. (1983) The anthropic principle and its implications for biological evolution. *Philosophical Transactions of the Royal Society of London* A310 (1512), 347–363.

CATLING, D.C., CLAIRE, M.W. (2005) How Earth´s atmosphere evolved to an oxic state: A status report. *Earth and Planetary Science Letters* 237, 1-20.

CHAKHMOURADIAN, A.R., ZAITSEV, A.N. (2012) Rare earth mineralization in igneous rocks: Sources and processes. *Elements* 8, 347-353.

CHAMPION, T., GAMBLE, C., SHENNAN, S., WHITTLE, A. (1984) Prehistoric Europe. Academic Press, London, 365 pp.

CHAPMAN, D. (2000) The $24 trillion monster. http://www.gold-eagle.com/article/24-trillion-derivatives-monster.

CHEN, W.Q., GRAEDEL, T.E. (2012) Anthropogenic Cycles of the Elements: A Critical Review. *Environmental Science & Technology* 46, 8574-8586.

CME (2013) A global highlights summary of metals markets; Highlights, Futures and options. *Monthly Metals Review*, CME Group, Chicago, 17 pp.

COHEN, C. (2007) Earth's natural wealth, an audit. *New Scientist* 2605, 34.

COHEN, J.E. (1995) Population Growth and Earth's Human Carrying Capacity. *Science* 269, 341-346.

CORDELL, D., DRANGERT, J.-O., WHITE, S. (2009) The story of phosphorus: Global food security and food for thought. *Global Environmental Change* 19, 292-305.

CORDELL, D., WHITE, S., LINDSTRÖM, T. (2011a) Peak phosphorus: the crunch time for humanity? http://www.thesustainabilityreview.org/2011/04/peak-phosphorus-the-crunch-time-for-humanity/.

Cordell, D., Rosemarin, A., Schroder, J.J., Smit, A.L. (2011b) Towards global phosphorus security: A systems framework for phosphorus recovery and reuse options. *Chemosphere* 84, 747-758.

Copper Develoment Association Inc. (2013) Copper in the USA: Bright Future Glorious Past. http://www.copper.org/education/history/g_fact_future.html

Costanza, R., Daly, H.E. (1992) Natural capital and sustainable development. *Conservation Biology* 6, 1-10.

Costanza, R., Graulich, L.J., Steffen, W. (Eds.) (2005) Sustainability or collapse? An integrated history and future of the people on Earth. The MIT Press, Cambridge Massachusetts.

Costanza, R., McGlade, J., de Bonvoisin, S., Farley, J., Giovannini, E., Kibizewski, I., Moore Lappe, F., Lovins, H., Pickett, K., Norris, G., Prugh, T., Ragnarsdottir, K.V., Roberts, D., Wilkinson, R. (2013) The Future we Really Want. *Solutions* 4, 37-43.

Costanza, R., Kubiszewski, I., Giovannini, E., Lovins, H., McGlade, J., Pickett, K.W., Ragnarsdottir, K.V., Roberts, D., de Vogli, R. Wilkinson, R. (2014) Development: Time to Dethrone GDP. *Nature* 505, 282-285.

Cox, D.P., Lindsey, D.A., Singer, D.A., Moring, B.C., Diggles, M.F. (2007) Sediment-hosted copper deposits of the world: Deposit models and database. *USGS Open-File Report* 03-107 Version 1.3.

CPM Silver Yearbook (2011) Euromoney Books. CPM Group, New York.

Crowson, P.C.F. (2011a) Mineral reserves and future minerals availability. *Mineral Economics* 24, 1-6.

Crowson, P.C.F. (2011b) Some observations on copper yields and ore grades. *Resources Policy* 37, 59–72.

Cullen, J.M., Allwood, J.M., Bambach, M.D. (2012) Mapping the Global Flow of Steel: From Steel-making to End-Use Goods. *Environmental Science & Technology* 46, 13048-13055.

Daily, G.C., Ehrlich, P. (1992) Population, sustainability and the earth's carrying capacity. A framework for estimating population sizes and lifestyles that could be sustained without undermining future generations. *Journal of Bioscience* 42, 761-771.

Daily, G.C., Ehrlich, A.H., Ehrlich, P.R. (1994) Optimum Human Population Size. *Population and Environment* 15, 469-475.

Davidson, C.F. (1965) A possible mode of origin of strata-bound copper ores. *Economic Geology* 60, 942-954.

Democracy Web (2013) http://www.democracyweb.org/.

De Vogli, R. (2013) Progress or Collapse: The Crises of Market Greed. Abingdon, Routledge.

Diamond, J. (1997) Guns, Germs, and Steel: The Fates of Human Societies. W.W. Norton and Co., New York, 528 pp.

Diamond, J. (2005) Collapse. How societies choose to fail or survive. Penguin Books, New York, 590 pp.

Edwards, R., Atkinson, K. (1986) Ore Deposit Geology. Chapman Hall, London, 466 pp.

Ehrlich, P. (1968) The population bomb. Ballantine books, New York, 201 pp.

Ehrlich, P.R., Goulder, L.H. (2007) Is current consumption excessive? A general framework and some indications for the United States. *Conservation Biology* 21, 1145-1154.

Ehrlich, P.R., Ehrlich, A. (2013) Can a collapse of global civilisation be avoided? *Proceedings of The Royal Society* B, 280, 20122845.

Ehrlich, P., Daily, G., Goulder, L. (1992) Population growth, economic growth and market economics. *Contention* 2, 17-35.

Energy Information Administration (2007). U.S. Crude Oil, Natural Gas, and Natural Gas Liquids Reserves, 2006. *Annual Report*. DOE/EIA-0216.

Etherington, H. (1958) Nuclear Engineering Handbook, McGraw Hill, New York, 1876 pp.

EuroInox (2014) International Stainless Steel Forum Austenitic chromium-manganese stainless steels, A European approach. The European Stainless steel development Association, *Materials and application Series* 12, 2-20.

Evans, L.T. (1998) Feeding the Ten Billion - Plants and Population Growth. Cambridge University Press, Cambridge, 264 pp.

EYLES, N. (2008) Glacio-epochs and the supercontinent cycle after ~2.0 Ga: Tectonic boundary conditions for glaciation. *Palaeogeography, Palaeoclimatology, Palaeoecology* 258, 89-129.

FAGAN, B. (2008) The great warming. The rise and fall of great civilizations. S. Martin Pr., London, 282 pp.

FAO (2010) The State of Food Insecurity in the World – Addressing Food Insecurity in Protracted Crisis. Food and Agricultural Organization of the United Nations, Rome, 62 pp.

FAO (2011) Review of the State of World Marine Fishery Resources. United Nations Food and Agriculture Organisation, Rome, 354 pp.

FEYNMAN, R.P. (1999) The pleasure of finding things out. Helix Boox, Perseus Publishing, Cambridge, Massachusetts, 300 pp.

FILIPPELLI, G.M. (2008) The global phosphorus cycle: Past, present and future. *Elements* 4, 89-95.

FISCHER-KOWALSKI, M., SWILLING, M., VON WEIZSÄCKER, E.U., REN, Y., MORIGICHI, Y., CRANE, W., KRAUSMANN, F., EISENMENGER, N., GILJUM, S., HEINDRICKE, P., ROMERO LANKAO, P., SINBAN MANALANG, A. (2011) United Nations Environment Programme. Decoupling natural resources use and environmental impacts from economic growth. A report of the working group on decoupling to the international resource panel. UNEP, 150pp.

FLEMING, R. (2011) Britain after Rome. The fall and rise 400 to 700. Penguin books, London, 456 pp.

FORRESTER, J. (1971) World dynamics. Pegasus Communications, Waltham Massachusetts.

FRANKLIN J.M., GIBSON H.L., GALLEY A.G. AND JONASSON I.R. (2005) Volcanogenic massive sulfide deposits. In: Skinner, B.J. (Ed.) *Economic Geology 75th Anniversary Volume*, Society of Economic Geologists, 485-627.

FRANCOIS, J-L., NUNEZ-CARRERA, A., ESPINOSA-PAREDES, G., MARTIN-DEL-CAMPO, C. (2004) Design of a boiling water reactor equilibrium core using thorium-uranium fuel. American Nuclear Energy Symposium 2004, Miami Beach.

FREEDOM HOUSE (2013) http://www.freedomhouse.org/.

FUKUYAMA, F. (2011) The origins of political order. From pre-human times to the French revolution. Farrar, Straus and Giroux. New York, 550 pp.

FUKUYAMA, F. (2014) Political Order and Political Decay: From the Industrial Revolution to the Globalization of Democracy. Farrar, Straus and Giroux, New York, 672 pp.

GEOSCIENCE AUSTRALIA (2009) Australia's identified mineral resources in 2009. Geoscience Australia, Canberra, 111 pp.

GIBBARD, P., VAN KOLFSCHOTEN, T. (2004) The Pleistocene and Holocene Epochs. In: Gradstein, F. M., Ogg, J.G., Smith, A.G. (Eds.) *A Geologic Time Scale*. Cambridge University Press, Cambridge, 610 pp.

GIBERT, F., PASCAL, M.L., PICHAVANT, M. (1998) Gold solubility and speciation in hydrothermal solutions: Experimental study of the stability of hydrosulphide complex of gold ($AuHS^o$) at 350-450 ^oC and 500 bars. *Geochimica et Cosmochimica Acta* 62, 2931-2947.

GLIESSMAN, S.R. (2006) Agroecology: The Ecology of Sustainable Food Systems. Second edition, CRC Press, London, 408 pp.

GOKLANY, I. (2009) Has increases in population, affluence and technology worsened human and environmental well being? *The electronic Journal of Sustainable Development* 1, 3-28.

GOLDFARB, R.J., BAKER, T., DUBÉ, B., GROVES, D.I., HART, C.J.R., GOSSELIN, P. (Eds.) (2005) Economic Geology. *100th Anniversary Volume*. Society of Economic Geologists, Littleton, Colorado, 407-450.

GORDON, R.B. (1996) American Iron 1607-1900. The Johns Hopkins University Press, Baltimore, 344 pp.

GORDON, R., BERTRAM, B., GRAEDEL, T.E. (2006) Metal Stocks and Sustainability. *Proceedings of the National Academy of Science* 103, 1209-1214.

GOTT III, J.R. (1993) Implications of the Copernican principle for our future prospects. *Nature* 363, 315–319.

GOTT III, J.R. (1994) Future Prospects Discussed. *Nature* 368, 108.

GRAEDEL, T.E., ERDMANN, L. (2012) Will metal scarcity impede industrial use? *Metals Research Society Bulletin* 37, 325-333.

GRAEDEL, T.E., VAN BEERS, D., BERTRAM, M., FUSE, K., GORDON, R., GRITSININ, A. (2004) Multi-level Cycle of Anthropogenic Copper. *Environmental Science & Technology* 38, 1242-1252.

GRAEDEL, T.E, BUCKERT, M., RECK, B.K. (2011) Assessing mineral resources in society. Metal stocks and recycling rates. UNEP, Paris, 32 pp.

GREENE, D.L., HOPSON, J.L., LI, J. (2003) Running Out of and Into Oil: Analyzing Global Depletion and Transition through 2050. *ORNL/TM-2003/259*. Oak Ridge National Laboratory, Oak Ridge, Tennessee, 124 pp.

GREER, J.M. (2008) The long descent. A user's guide to the end of the industrial age. New Society Publishers, Gabriola Island, Canada, 288 pp.

GUILBERT, J.M., PARK, C.F. (1986) The Geology of Ore Deposits. W.H. Freeman, New York.

HAGEMANN, S., ROSIÈRE, C., GUTZMER, J., BEUKES, N.J. (Eds.) (2008) Banded iron formation-related high-grade iron ore. *Reviews in Economic Geology* 15, Society of Economic Geologists, 414 pp.

HALL, C. (2008) Energy return on investment and our economic future. *Proceedings of the 33rd International Geological Congress*, Oslo, Norway.

HALL, C., LINDENBERGER, D., KUMMEL, R., KROEGER, T., EICHHORN, W. (2001) The need to reintegrate the natural sciences with economics. *BioScience* 51, 663-667.

HALL, C.A.S., BALOGH, S., MURPHY, D.J.R. (2009) What is the Minimum EROI That a Sustainable Society Must Have? *Energies* 2, 25-47.

HAMACHER, T., BRADSHAW, A.M. (2001) Fusion as a Future Power Source: Recent Achievements and Prospects. *Proceedings of the 18th World Energy Congress*. World Energy Council, 19 pp.

HARALDSSON, H.V., SVERDRUP, H.U. (2004) Finding Simplicity in complexity in biogeochemical modelling. In: Wainwright, J., Mulligan, M. (Eds.) Environmental Modelling. Wiley, New York, 494 pp.

HARDIN, G. (1968) The Tragedy of the Commons. *Science* 162, 1243-1248.

HEINBERG, R. (2001) Peak Everything: Waking Up to the Century of Decline in Earth's Resources. Clairview Books, Forest Row, 224 pp.

HEINBERG, R. (2005) The party's over. Oil, war and the fate of industrial societies. New Society Publishers, Gabriola Island, Canada, 288 pp.

HEINBERG, R. (2011) The end of growth. Adapting to our new economic reality. New Society Publishers, Gabriola Island, Canada, 288 pp.

HEMLEY, J.J., HUNG, J.P. (1992) Hydrothermal ore-forming processes in the light of studies in rock-buffered systems: II. Some general geologic applications. *Economic Geology* 87, 23-42.

HESSLER, A.M., LOWE, D.R., JONES, R.I., BIRD, D.K. (2004) A lower limit for atmospheric carbon dioxide levels 3.2 billion years ago. *Nature* 428, 736-738.

HIRSCH, R.L., BEZDEK, R., WENDING, R. (2005) Peaking of world oil production: Impacts, mitigation and risk management. "*The Hirsch report*". US Department of Energy, 91 pp.

HODSON, M.E. (2010) The need for sustainable soil remediation. *Elements* 6, 363-368.

HOFMANN, P.F., SCHRAG, D.P. (2002) The snowball Earth hypothesis: Testing the limits of global change. *Terra Nova* 14, 129-155.

HOISINGTON, D.B. (1959) Nucleonic fundamentals. McGraw-Hill Publishers, New York, 410 pp.

HOLLAND, H.D. (2006) Oxygenation of the atmosphere and oceans. *Philosophical Transactions of the Royal Society of London B* 361, 903-9015.

HOLLAND, H.D. (2009) Why the atmosphere became oxygenated: a proposal. *Geochimica et Cosmochimica Acta* 73, 5241-5255.

HOLLAND, S.P. (2008) Modelling peak oil. *The Energy Journal* 29, 61-80.

HOLLEMAN, A.F., WIBERG, E., WIBERG, G. (2007) Cobalt. *Lehrbuch der Anorganischen Chemie*. 102nd Edition, De Gruyter, Berlin, 2033 pp.

HOLMBERG, J., ROBÈRT, K.H. (2000) Backcasting - a framework for strategic planning. *International Journal of Sustainable Development and World Ecology* 7, 291-308.

HOLMBERG, J., ROBÈRT, K.H., ERIKSSON, K.E. (1996) Socio-ecological principles for sustainability. In: Costanza, R., Olman, S., Martinez-Alier, J. (Eds.) *Getting Down to Earth – Practical Applications of Ecological Economics*. International Society of Ecological Economics, Island Press, Washington, 494 pp.

HOOKE, R. (2000) On the history of humans as geomorphic agents. *Geology* 28, 843-846.

HÖÖK, M., ZITTEL, W., SCHINDLER, J., ALEKLETT, K. (2008) A supply-driven forecast for the future global coal production. Contribution to ASPO 2008. Uppsala University, Uppsala, 48 pp.

HORZ, G. (2000) The treasure of gold and silver artifacts from the Royal Tombs of Sipan, Peru, a study on the Moche metalworking techniques. *Materials Characterization* 45, 391–420.

HOSLER, D. (1999) Recent insights into the metallurgical technologies of ancient mesoamerica. *JOM Journal of the Minerals* 51, 11–14.

HUBBERT, M.K. (1956) Nuclear energy and the fossil fuels. Presented to the spring meeting of the southern district, Division of production. American Petroleum Institute. Publication no. 95. Shell Development Company, Houston, 57 pp.

HUBBERT, M.K. (1962) Energy Resources. A Report to the Committee on Natural Resources. National Academy of Sciences, National Research Council, Washington, DC, 54 pp.

HUBBERT, M. K. (1966) History of Petroleum Geology and Its Bearing Upon Present and Future Exploration. *AAPG Bulletin* 50, 2504-2518.

HUBBERT, M.K. (1972) Estimation of Oil and Gas Resources. Workshop on Techniques of Mineral Resource Appraisal. U.S. Geological Survey, Denver, 16-50.

HUBBERT, M.K. (1976) Exponential growth as a transient phenomenon in human history. Paper presented to World Wildlife Fund, Fourth International Congress, The Fragile Earth, Towards strategies for survival. *Other issues*. World Wildlife Fund, San Francisco, 75-84.

HUBBERT, M.K. (1982) Techniques of Prediction as Applied to Production of Oil and Gas. NBS Special Publication 631, US Department of Commerce, 737 pp.

HUGH, R.M., BUTT, C.R., FISCHER-BÜHNER, J. (2009) The crystallography, metallography and composition of gold. *Elements* 5, 297-302.

HUH, C.A., KU, T.L. (1984) Radiochemical observations on manganese nodules from three sedimentary environments in the north Pacific. *Geochimica et Cosmochimica Acta* 48, 951-964.

INTERNATIONAL ENERGY AGENCY (IEA) (2014) Key world energy statistics. Energy data centre of the IEA, Paris, 82 pp.

INTERNATIONAL STAINLESS STEEL FORUM (2014) The stainless steel family. International Stainless Steel Forum, Brussels, 5 pp.

JACKSON, T. (2009) Prosperity without Growth. Economics for a Finite Planet. Earthscan, London, 288 pp.

JASINSKI, S.M. (2006) Phosphate Rock. Statistics and Information US Geological Survey. USGS Mineral Resources Program, 2 pp.

JAYARAM, K.V.M. (1985) An overview of world thorium resources, incentives for further exploration and forecast for thorium requirements in the near future. In: Proceedings of a Technical Committee Meeting on Utilization of Thorium-Based Nuclear Fuel: Current Status and Perspectives. International Atomic Energy Agency (IAEA), Vienna, Austria, 158 pp.

JEVREJEVA, S., GRINSTED, A., MOORE, J.C. (2014) Upper level for sea level projections by 2100. *Environmental Research Letters* 9, 10.

JOHNSON, J., HARPER, E. M., LIFSET, R., GRAEDEL, T. E. (2007) Dining at the Periodic Table: Metals Concentrations as They Relate to Recycling. *Environmental Science & Technology* 41, 1759-1765.

KAMIENSKI, C.W., MCDONALD, D.P., STARK, M.W., PAPCUN, J.R., CONRAD, W. (2004) Lithium and lithium compounds. *Kirk-Othmer Encyclopedia of Chemical Technology*. John Wiley & Sons.

KANNINEN, T. (2013) Crisis of Global Sustainability. Global Institutions Series. Routledge, Agingdon, 208 pp.

KASTEN, P.R. (1998) Review of the Radkowsky thorium reactor concept. *Science and Global Security* 7, 237-269.

Kasting, J.F., Ono, S. (2006) Palaeoclimates: the first two billion years. *Philosophical Transactions of the Royal Society of London* B 361, 917-929.

Keatinge, R.W. (1988) Peruvian Prehistory: An Overview of Pre-Inca and Inca Society. Cambridge University Press, Cambridge, 384 pp.

Kemper, W.D., Rosenau, R.C. (1986) Aggregate stability and size distribution. In: Klute, A. (Ed.) *Methods of Soil Analysis Part 1. Physical and Mineralogical Methods.* American Society of Agronomy-Soil Science Society of America, Madison WI, 1358 pp.

Kennedy, P. (1987) The Rise and Fall of the Great Powers: Economic Change and Military Conflict From 1500 to 2000. Random House, London, 677 pp.

Kesler, S.E., Wilkinson, B.H. (2013) Earth's copper resources estimated from tectonic diffusion of porphyry copper deposits. *Geology* 41, 255-258.

Kifle, D., Sverdrup, H., Koca, D., Wibetoe, G. (2012) A Simple Assessment of the Global Long Term Supply of the Rare Earth Elements by Using a System Dynamics Model. *Environment and Natural Resources Research* 3, 1-15.

Klein, C. (2005) Some Precambrian banded iron-formations (BIFs) from around the world: Their age, geologic setting, mineralogy, metamorphism, geochemistry, and origins. *American Mineralogist* 90, 1473-1499.

Klein, N. (2007) The Shock Doctrine: The Rise of Disaster Capitalism. Penguin Books, London, 576 pp.

Kock Johansen, Ö. (2001) Fra stenpenger til Euro. Betalingsmiddlenes forunderlige verden. DnB, Oslo.

Kubiszewski, I., Costanza, R., Franco, C., Lawn, P., Talberth, J., Jackson, T., Aylmer, C. (2013) Beyond GDO: Measuring and achieving global genuine progress. *Ecological Economics* 93, 57-68.

Kukla, G. (2005) Saalian supercycle, Mindel/Riss interglacial and Milankovitch's dating. *Quaternary Science Reviews* 24, 1573-1583.

Kump, L.R., Kasting, J.F., Barley, M.E. (2001) Rise of atmospheric oxygen and the "upside down" Archean mantle. *Geochemistry Geophysics Geosystems* 2, 1.

Kynicky, J., Smith, M.P., Xu, C. (2012) Diversity of rear earth deposits: The key example of China. *Elements* 8, 361-367.

Laherrere, J. (2010) Copper peak. *The oildrum Europe* 6307, 1-27.

Leach, D.L., Sangster, D.F. (1993) Mississippi Valley-type lead-zinc deposits. In: Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., Duke, J.M. (Eds.) *Mineral Deposits Modeling*. Geological Association of Canada Special Paper 40, 289-314.

Leach, D.L., Bradley, D.C., Huston, D., Pisarevsky, S.A., Taylor, R.D., Gardoll, S.J. (2010) Sediment-hosted lead-zinc deposits in Earth History. *Economic Geology* 105, 593-625.

Lenzen, M. (2008) Life cycle energy and greenhouse gas emissions of nuclear energy: A review. *Energy Conversion and Management* 49, 2178–2199.

Lehtinen, T., Lairg, G.J., Mentler, A., Gisladóttir, G., Ranarsdóttir, K.V., Blum, W.E.H. (2014a) Soil Aggregate quantification using low dispersive ultrasonic energy levels. *Soil Science Society of America Journal* 78, 3, 713-723.

Lehtinen, T., Schlatter, N., Baumgarten, A., Bechini, L., Krüger, J., Grignani, C., Zavattaro, L., Costamagna, C., Spiegel, H. (2014b) Effect of crop residue incorporation on soil organic carbon and greenhouse gas emission in European agricultural soils. *Soil Use and Management* 30, 4, 524–538.

Leslie, J. (1998) The End of the World: The Science and Ethics of Human Extinction, Routledge, London, 320 pp.

von Liebig, J. (1843) Familiar letters of chemistry and its relation to commerce, physiology and agriculture. J. Gardener, London.

von Liebig, J., Playfair, L, Webster, J.W. (1841) Organic chemistry and its applications to agriculture and physiology. J. Owen Publishing house, Cambridge.

Lietaer, B. (2001) The Future of Money: Creating New Wealth, Work and a Wiser World. Century, London, 384 pp.

Lietaer, B. (2003) A World in Balance? *Reflections*, the journal of the Society for Organizational Learning (SOL), Special issue on "The feminine approach to leadership", 15 pp.

Lietaer, B., Ulanowicz, R.E., Goerner, S., McLaren, N. (2010) Is Our Monetary Structure a Systemic Cause for Financial Instability? Evidence and Remedies from Nature. *Journal of Futures Studies*, Special Issue on the Financial Crisis 4, 3, 89-108.

Lövin, I. (2007) Tyst Hav. Ordfront Förlag AB, Stockholm, 237 pp.

Long, D.G.F., Ulrich, T., Kamber, B.S. (2011) Laterally extensive modified placer gold deposits in the Paleoproterozoic Mississagi Formation, Clement and Pardo Townships, Ontario. *Canadian Journal of Earth Sciences* 48, 779-792.

Lumpkin, G.R., Ewing, R.C. (1985) Geochemical alteration of pyrochlore group minerals: pyrochlore subgroup. *American Mineralogist* 80, 732-743.

Lütken, O.D. (1761) Undersøgning om Hindringer for Folkemængden. Sorø, Denmark, 118 pp.

MacIntosh, A., Edwards-Jones, G. (2000) Discounting the children's future? *Geophilos* 1, 122-133.

Macdougall, D. (2004) Frozen Earth: The Once and Future Story of Ice Ages. University of California Press, Oakland, 267 pp.

Malthus, T.R. (1798) An essay on the principle of population as it affects the future improvement of society, reprinted as "The mathematics of food and population". In: Newman, J. (Ed.) *The world of mathematics*. Simon and Schuster, New York, 1956, 1192-1199.

Marchak, P. (1995) Logging the globe. McGill Queen's University Press, Montreal, 440 pp.

Mayer, A. (2000) Contraction and Convergence. Schumacher Briefing 5. Totnes: Green Books.

McDonnell, T.C., Belyazid, S., Sullivan, T.J., Sverdrup, H., Bowman, W.D., Porter, E.M. (2014) Modeled subalpine plant community response to climate change and atmospheric nitrogen deposition in Rocky Mountain National Park, USA. *Environmental Pollution* 187, 55-64.

Meadows, D.L., Wright, D. (2008) Thinking in Systems. A Primer. Chelsea Green Publishing, White River Junction, VT, 240 pp.

Meadows, D.H., Meadows, D.L., Randers, J., Behrens, W. (1972) Limits to growth. Universe Books, New York, 205 pp.

Meadows, D.L., Behrens III, W.W., Meadows, D.H., Naill, R.F., Randers, J., Zahn, E.K.O. (1974) Dynamics of Growth in a Finite World. Wright-Allen Press, Cambridge, Massachusetts, 637 pp.

Meadows, D.H., Meadows, D.L., Randers, J. (1992) Beyond the limits: confronting global collapse, envisioning a sustainable future. Chelsea Green Publishing Company, White River Junction, VT, 320 pp.

Meadows, D.H., Randers, J., Meadows, D.L. (2004) Limits to growth. The 30 year update Universe Press, New York, 368 pp.

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S.C.B., Frieler, K., Knutti, R., Frame, D.J., Allen, M.R. (2009) Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature* 458, 1158-1163.

Melezhik, V.A. (2006) Multiple causes of Earth´s earliest global glaciation. *Terra Nova* 18, 130-137.

Meyer, A. (2000) Contraction and Convergence. Schumacher Briefing 5. Green Books, Totnes, 96 pp.

Meyer, B., Meyer, M., Distelkamp, M. (2012) Modeling green growth and resource efficiency: new results. *Mineral Economics* 24, 145-154.

MinEx Consulting (2010) www.minexconsulting.com/publications.html.

Modin-Edman, A.K., Öborn, I., Sverdrup, H. (2007) FARMFLOW–A Dynamic Model for Phosphorus Mass Flow, Simulating Conventional and Organic Management of a Swedish Dairy Farm. *Agricultural Systems Agricultural systems* 94, 431-444.

Mojarov, A. (2013) The Iron Ore Market Situation – views of UNCTAD. Powerpoint presentation shown at the 74th session of the OECD Steel Committee 1-2 July 2013, Paris, France. UNCTAD Trust Fund on Iron Ore Information.

Mohr, S., Evans, G. (2013) Projections of future phosphorus production. *PHILICACOM* 2013, article number 380.

Mohr, S., Mudd, G.M., Weng, Z., Giurco, D. (2014) Modelling future copper ore grade decline based on a detailed assessment of copper resources and mining. *Resources, Conservation and Recycling* 83, 190-201.

Morrigan, T. (2010) Peak energy, climate change and the collapse of global civilization. The current peak oil crisis. 2nd edition, University of California, Santa Barbara, 270 pp.

Mountain, B.W., Seward, T.M. (1999) The hydrosulphide/sulphide complexes of copper (I): Experimental determination of stoichiometry and stability at 22 ºC and reassessment of high temperature data. *Geochimica et Cosmochimica Acta* 63, 11-29.

Mudd, G.M. (2007) Gold mining in Australia: linking historical trends and environmental and resource sustainability. *Environmental Science & Policy* 10, 629-644.

Mudd, G.M. (2009) Historical Trends in Base Metal Mining: Backcasting to Understand the Sustainability of Mining. *Procedures of the "48th Annual Conference of Metallurgists"*. Canadian Metallurgical Society, Sudbury, Ontario.

Mudd, G.M. (2010) The environmental sustainability of mining in Australia: Key mega-trends and looming constraints. *Resources Policy* 35, 98-115.

Mungall, J.E., Naldrett, A.J. (2008) Ore deposits of the platinum-group elements. *Elements* 4, 253-258.

Murck, B.W., Skinner, B.J., Porter, S.C. (1996) Environmental Geology. Wiley, New York, 560 pp.

Murr, L.E. (2014) A brief history of metals. *Handbook of Materials Structures, Properties, Processing and Performance*, 1-7.

Müller, D.B., Wang, T., Duval, B., Graedel, T.E. (2006) Exploring the engine of anthropogenic iron cycles. *Proceedings of the National Academy of Sciences of the United States of America* 103, 44, 16111–16116.

Mylchreest, P. (2009) Gold market – accident waiting to happen or crime scene? Don't shoot the messenger. Thunder Road Report, 30 pp.

Mylchreest, P. (2011) Gresham's law squared–gearing up for game over. Thunder Road Report, 25 pp.

Mylchreest, P. (2012a) *Caught Red Handed:* massive manipulation of the Gold Market since America lost its "AAA" credit rating – implications for bullion & gold equities (and the monetary system). Thunder Road Report, 57 pp.

Mylchreest, P. (2012b) Inflationary deflation: Creating a new bubble in money. Banks versus the Long Wave. Thunder Road Report, 75 pp.

Nashawi, I.S., Malallah, A., Al-Bisharah, M. (2010) Forecasting world crude oil production using multicyclic Hubbert model. *Energy Fuels* 24, 1788-1800.

Nest, M. (2011) Coltan. Polity Publishers, Whiley, Cambridge, 200 pp.

NDP Steering Committee and Secretariat (2013) Happiness: Towards a New Development Paradigm. Report of the Kingdom of Bhutan, Thumphu, 20 pp.

Nilsson, J. (Ed) (1988) Critical loads for sulphur and nitrogen. Miljörapport 1988, 15, 380 pp.

Nørgård, J.S., Peet, J., Ragnarsdottir, K.V. (2010) The history of limits to growth. *Solutions* 1, 59-63.

Norgate, T.E., Rankin, W.J. (2000a) Greenhouse gas emissions from aluminium production – a life cycle approach. Proceedings of the International Symposium on Greenhouse Gases in the Metallurgical Industries: Policies, Abatement and Treatment, August 26-29, Toronto, Ontario, Canada. Metallurgical Society of the Canadian Institute of Mining Metallurgy and Petroleum, 275-290.

Norgate, T.E., Rankin, W.J. (2000b) Life Cycle Assessment of Copper and Nickel Production. Proceedings, Minprex, International Conference on Minerals Processing and Extractive Metallurgy, 133-138.

Northey, S., Mohr, S., Mudd, G.M., Weng, Z., Giurco, D. (2014) Modelling future copper ore grade decline based on a detailed assessment of copper resources and mining. *Resources, Conservation and Recycling* 83, 190-201.

Nuss, P., Harper, E.M., Nassar, N.T., Reck, B.K., Graedel, T.E. (2014) Criticality of Iron and Its Principal Alloying Elements. *Environmental Science & Technology* 48, 4171-4177.

OCC (2009) Controller of the Currency Administrator of National Banks. OCC's Quarterly Report on Bank Trading and Derivatives Activities. Fourth Quarter 2009. Washington, DC, 53 pp.

OCC (2013) Controller of the Currency Administrator of National Banks. OCC's Quarterly Report on Bank Trading and Derivatives Activities. First Quarter 2012. Washington, DC, 51 pp.

O´Day, P.A., Vlassopoulos, D. (2010) Mineral-based amendments for remediation. *Elements* 6, 375-381.

Oelkers, E.H., Valsami-Jones, E. (2008) Phosphate mineral reactivity and global sustainability. *Elements* 4, 83-87.

Osborn, F.L. (1948) Our Plundered Planet. Little, Brown and Company, London, 217 pp.

Oxfam (2014) Working for the Few. Political Capture of Economic Inequality. Oxfam, London, 32 pp.

Pardis, S., Hannigan, P., Dewing, K. (2007) Mississippi Valley-type lead-zinc deposits. In: Goodfellow, W.D. (Ed.) *Mineral deposits of Canada: a synthesis of major deposit-types, district metallogeny, the evolution of geological provinces, and exploration methods.* Geological Association of Canada, Mineral Deposits Division, Special Publication 5, 185-203.

Patzek, T.W., Croft, G. (2010) A global coal production forecast with multi-Hubbert cycle analysis. Energy 35, 3109-3122.

Penck, A. (1925) Das Hauptproblem der Physischen Anthropogeographie. Zeitschrift für Geopolitik, Vol. 2, 330-348.

Phelan, J., Belyazid, S., Kurz, D., Guthrie, S., Cajka, J., Sverdrup, H., Waite, R. (2014) Estimation of soil base cation weathering rates with the PROFILE model to determine critical loads of acidity for forested ecosystems in Pennsylvania, USA; Pilot application of a potential National methodology. *Water, Air and Soil Pollution* 225, 2109-2128.

Piketty, T. (2014) Capital in the Twenty-First Century. Harvard University Press, 667pp.

Pimentel, D, Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S, Shpritz, L., Fitton, L., Saffouri, R., Blair, R. (1995) Environmental and economic costs of soil erosion and conservation benefits. *Science* New Series 267, 1117-1123.

Pipkin, B., Trent, D.D., Hazlett, R., Bierman, P. (2013) Geology and the Environment. Seventh Edition, Cengage Learning, Boston, 656 pp.

Pogue, J.E., Hill, K.E. (1956) Future Growth and Financial Requirements of the World Petroleum Industry. Presented at the annual meeting of the American Institute of Mining, Metallurgical, and Petroleum Engineers, Petroleum Branch, New York, February 1956.

Pohl, W.L. (2005) Economic Geology. Principles and Practice. Wiley-Blackwell, Chichester, 678 pp.

Polinares (2012) POLINARES working paper n. 41. Fact Sheet: Iron Ore. http://www.polinares.eu/.

da Pisa, R.. (around 1300) The Travels of Marco Polo. Reprinted by Penguin Book 1958, London, 550 pp.

Prior, T., Daly, J., Mason, L., Giurco, D. (2013) Resourcing the future: Using foresight in resource governance. *Geoforum* 44, 316-328.

Radetzki, M. (2008) A Handbook of Primary Commodities in the Global Economy. Cambridge University Press, Cambridge, 244 pp.

Radetzki, M. (2012) The perseverance of the on-going metal and mineral boom. *Mineral Economics* 25, 2-3, 83-88.

Reardon, A.C. (2011) Discovering metals – a historical overview. *Metallurgy for the non-metallurgist* Second Edition, 73-84.

Ragnarsdottir, K.V. (2008) Rare metals getting rarer. *Nature Geoscience* 1, 720-721.

Ragnarsdottir, K.V., Walther, J.V. (1983) Pressure sensitive "silica geothermometer" determined from quartz solubility experiments at 250 °C. *Geochimica et Cosmochimica Acta* 47, 941-946.

Ragnarsdottir, K.V., Walther, J.V. (1985) Experimental determination of corundum solubilities in pure water between 400-700 °C and 1- 3 kbar. *Geochimica et Cosmochimica Acta* 49, 2109-2115.

Ragnarsdottir, K.V., Walther, J.V., Arnorsson, S. (1984) Description and interpretation of the composition of fluid and alteration mineralogy in the Svartsengi geothermal system, Iceland. *Geochimica et Cosmochimica Acta* 48, 1535-1553.

Ragnarsdottir, K.V., Sverdrup, H.U., Koca, D. (2011) Challenging the planetary boundaries I: Basic principles of an integrated model for phosphorous supply dynamics and global population size. *Applied Geochemistry* 26, 303-304.

Ragnarsdottir, K.V., Sverdrup, H.U., Koca, D. (2012) Assessing Long Term Sustainability of Global Supply of Natural Resources and Materials. In: Ghenai, C. (Ed.) *Sustainable Development. Energy, Engineering and Technologies - Manufacturing and Environment* 5, 83-116.

Ragnarsdottir, K.V., Costanza, R., Giovannini, E., Kubiszewski, I., Lovins, H., McGlade, J., Pickitt, K.E., Roberts, D., de Vogli, R., Wilkinson R. (2014a) Beyond GDP. Exploring the hidden links between geology, economics and well-being. *Geoscientist* 24, 12-17.

Ragnarsdottir, K.V., Haider, J., Apetrei, C., Czunyi, S., Lovins, H., Pinter, L., Greenfield, O. (2014b) The SDGs and Framing a New Narrative: About the 2014 Balaton Group Meeting. www.balatongroup.org/blog.

Ramanaidou, E.R., Wells, M.A. (2014) Sedimentary Hosted Iron Ores. In: Holland, H.D., Turekian, K.K. (Eds.) *Treatise on Geochemistry*, 313-355.

Randers, J. (2012) 2052, a global forecast for the next 40 years. A report to the club of Rome. Chelsea Green Publishing, Vermont, 416 pp.

Rauch, J.N. (2009) Global mapping of Al, Cu, Fe, and Zn in-use stocks and in-ground resources. *Proceedings of the National Academy of Sciences* 106, 1-6.

Rauch, J.N., Graedel T.E. (2007) Earth's anthrobiogeochemical copper cycle. *Global Biogeochemical Cycles* 21, 1-13.

Rauch, J.N., Pacyna, J.M. (2009) Earth's global Ag, Al, Cr, Cu, Fe, Ni, Pb, and Zn cycles. *Global Biogeochemical Cycles* 23, 1-16.

Raynaud, D., Barnola, J-M., Souchez, R., Lorrain, R., Petit, J.-R., Duval, P., Lipenkov, V.Y. (2005) Palaeoclimatology: The record for marine isotopic stage 11. *Nature* 436, 39–40.

Reck, B., Graedel, T.E. (2012) Challenges in Metal Recycling. *Science* 337, 690, 6095, 690-695.

Renfrew, C. (1989) Archaeology and language - The puzzle of Indo-European origins. Penguin Books, London, 368 pp.

Renfrew, C. (1994) Before Babel, Speculations on the origins of linguistic diversity. *Cambridge Archaeological Journal* 1, 3-23.

Reuter, M.A., Boin, U.M.J., van Schaik, A., Verhoef, E., Heiskanen, K., Yang, Y., Georgalli, G. (2005) The Metrics of Material and Metal Ecology, Harmonizing the Resource, Technology and Environmental Cycles. Elsevier, Amsterdam, 720 pp.

Ridley, J. (2013) Ore Deposit Geology. Cambridge University Press, Cambridge, 409 pp.

Robb, L. (2005) Introduction to Ore forming processes. Blackwell, Oxford, 386 pp.

Robb, L., Hayward, C. (2014) Geochemistry of placer gold – a case study of the Witwatersrand Deposits. *Treatise in Geochemistry*, 13, 433-461.

Robèrt, K.-H., Schmidt-Bleek, B., Aloisi de Larderel, J., Basile, G., Jansen, J.L., Kuehr, R., Price Thomas, P., Suzuki, M., Hawken, P., Wackernagel, M. (2002) Strategic sustainable development – selection, design and synergies of applied tools. *Journal of Cleaner Production* 10, 197-214.

Roberts, P.C. (2013) The failure of laissez faire capitalism. The economic dissolution of the west. Towards a new economics for a full world. Clarity Press Inc., Atlanta, 190pp.

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, III, F.S., Lambin, E., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, M., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B.H., Liverman, D., Richardson, K., Crutzen, C., Foley, J. (2009) A safe operating space for humanity. *Nature* 461, 472-475.

Rodale Institute (2012) The Farming Systems Trial. Celebrating 30 years. Rodale Institute, Pennsylvania, 13 pp.

Roper, L.D. (2009) World mineral reserves. http://www.roperld.com/science/minerals/Reserves.htm

Rose, A.W. (1976) The effect of cuprous chloride complexes in the origin of red-bed copper and related deposits. *Economic Geology* 71, 1036-1048.

Rosemarin, A., de Bruijne, G., Caldwell, I. (2009) Peak phosphorus: The next inconvenient truth. http://www.thebrokeronline.eu/en/Articles/Peak-phosphorus.

Ross, J.V., Bustin, R.M. (1990) The role of strain energy in creep graphitization of anthracite. *Nature* 343, 58-60.

Rostoker, W., Bronson, B. (1990) Pre-Industrial Iron: Its Technology and Ethnology. *Archeomaterials Monograph* 1.

Rostoker, W., Bronson, B., Dvorak, J. (1984) The Cast-Iron Bells of China, Technology and Culture. *The Society for the History of Technology* 25, 750-767.

Sachs, J. (2008) Common Wealth: Economics for a Crowded Planet. Penguin Press, London, 400 pp.

Schumacher, E.F. (1973) Small is Beautiful. Penguin Books, London, 288 pp.

de Schutter, O., Vanloqueren, G. (2011) The new green revolutions: How twenty-first-century science can feed the world. *Solutions* 2, 4, 33-44.

Science (2004) Soil: The Last Frontier. *Science* Special Issue on Soil June 2004.

Sear, D. (1978) Greek coins and their values; Europe. Seaby Publishers, New York.

Seedorff, E., Dilles, J.H., Proffett, J.M., Einaudi, M.T., Zurcher, L., Stavast, W.J.A., Barton, M.D., Johnson, D.A. (2005) Porphyry-related deposits: Characteristics and origin of hypogene features. *Economic Geology* 100th Anniversary Volume, 251-298.

Senge, P. (1990) The fifth discipline. The art and practice of the learning organisation. Century Business, New York, 464 pp.

Senge, P.M., Smith, B., Schley, S., Laur, J., Kruschwitz, N. (2008) The Necessary Revolution: How Individuals and Organisations Are Working Together to Create a Sustainable World. Doubleday Currency, London, 460 pp.

Seward, T.M. (1976) The stability of chloride complexes of silver in hydrothermal solutions up to 350 °C. *Geochimica et Cosmochimica Acta* 40, 1329-1341.

The Silver Institute (2003) International Association of silver miners, silver refiners, silver fabricators and silver wholesalers. A comprehensive website with statistics on silver, literature references and market news. www.silverinstitute.org

Simonson, B.M. (2011) Iron ore deposits associated with Precambrian iron formations. *Elements* 7, 119-120.

Singer, D.A. (2011) A lognormal distribution of metal resources. *Journal of China University of Geosciences* 36, 2, 1–8.

Singer, D. (2013) The lognormal distribution of metal resources in mineral deposits. *Ore Geology Reviews* 55, 80-86.

Singer, D.A., Menzie, W.D. (2010) Quantitative Mineral Resource Assessments - An Integrated Approach. Oxford University Press, New York, 219 pp.

Shen, K. (1088) Dream pool essay. Mengxi Garden Estate, Zhenjiang, China.

Sherman, H.C. (1920) Phosphorus requirement of maintenance in Man. *Journal of Biological Chemistry* 41, 173-179.

Shorter, E. (1973) Female emancipation, birth-control and fertility in European history. *American Historical Review* 78, 605-640.

Smil, V. (2001) Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production. MIT Press, Cambridge, 360 pp.

Smirnov, V.S. (1992) Raw Materials of Russian Aluminium Industry - New Investment Projects. Paper presented at the international conference Russian Aluminium Industry -Strategy of Development and New Investment Projects, St. Petersburg, 15-18 September, 1992.

Smirnov, V.S. (1996) Alumina production in Russia, part 1, Historical background. *JOM* 48, 24-26.

Smirnov, V.S., Tikhonov, N.N. (1991) Main Trends of Alumina Industry Development in USSR. Paper presented at the international conference Scientific and Technical Progress in Non-Ferrous Metallurgy, St. Petersburg, 17 September 1991.

SMITH, A. (1776) An Inquiry into the Nature and Causes of the Wealth of Nations. Reprint by the University Of Chicago Press, Chicago, 550 pp.

SOBER, E. (2003) An Empirical Critique of Two Versions of the Doomsday Argument - Gott's Line and Leslie's Wedge. *Synthese* 135-133, 415-430.

SOWERS, G.F. (2002) The Demise of the Doomsday Argument. *Mind* 111, 37-45.

STANWAY, D. (2014) China steel output near peak, say executives, in bad news for miners. http://www.reuters.com/article/2014/03/06/china-parliament-steel-idUSL3N0LT13W20140306.

STATISTA (2010) Global zinc reserves by country. http://www.statista.com/statistics/194101/global-zinc-reserves-by-country/.

STEFANSSON, A., SEWARD, T.M. (2003a) Stability of chlorigold(I) complexes in aqueous solutions from 300 to 600° C and from 500 to 1800 bar. *Geochimica et Cosmochimica Acta* 67, 4559-4576.

STEFANSSON, A., SEWARD, T.M. (2003b) Experimental determination of the stability and stoichiometry of sulphide complexes of silver(I) in hydrothermal solutions. *Geochimica et Cosmochimica Acta* 67, 1395-1413.

STEFANSSON, A., SEWARD, T.M. (2004) Gold(I) complexing in aqueous sulphide solutions to 500° C and 500 bar. *Geochimica et Cosmochimica Acta* 68, 4121-4143.

STERMAN, J.D. (2000) Business Dynamics, System Thinking and Modelling for a Complex World. Irwin McGraw-Hill, New York, 768 pp.

STOCKWELL, L.E. (1999) World Mineral Statistics 1993-97: Production, Exports, Imports. British Geological Survey, Keyworth, 268 pp.

STRAHAN, D. (2007) The Last Oil Shock: A survival guide to the imminent extinction of petroleum man. John Murray Books, New York, 304 pp.

STRAHAN, D. (2008) Coal: Bleak outlook for the black stuff. *New Scientist* 2639, 38-41.

SVERDRUP, H. (1990) The Kinetics of Chemical Weathering. Lund University Press, Lund, 245pp.

SVERDRUP, H. (1999) Calculating language relationships and paths of dispersal in Eurasia during the last 100,000 years using the LANGUAGE model. In: Shevoroshkin, V., Sidwell, P. (Eds.) *Historical linguistics and lexicostatistics. Association for the History of Language Monographs and Serials* 3, 169-200.

SVERDRUP, H. (2002) Exploring the properties of the Rätian language. In: Shevoroshkin, V., Sidwell, P. (Eds.) *Languages and their speakers in ancient Eurasia: Studies in linguistics and culture.* Association for the History of Language Monographs and Serials 4, 85-114.

SVERDRUP, H., WARFVINGE, P. (1988a) Weathering of primary silicate minerals in the natural soil environment in relation to a chemical weathering model. *Water, Air and Soil Pollution* 38, 387-408.

SVERDRUP, H., WARFVINGE, P. (1988b) Assessment of critical loads of acid deposition on forest soils, In: Nilsson, J. (Ed) *Critical loads for sulphur and nitrogen*. *Miljörapport* 1988, 15, 81-130.

SVERDRUP, H., WARFVINGE, P. (1995a) Critical loads of acidity for Swedish forest ecosystems. *Ecological Bulletins* 44, 75–89.

SVERDRUP, H., WARFVINGE, P. (1995b) Estimating field weathering rates using laboratory kinetics. In: White, A.F, Brantley, S.L. (Eds.) *Chemical weathering rates of silicate minerals. Reviews in Mineralogy* 31, 485–541.

SVERDRUP, H., STJERNQUIST, I. (2002) Developing principles and model for sustainable forestry in Sweden. Kluwer Academic Publishers, Dordrecht, 480 pp.

SVERDRUP, H., SVENSSON, M. (2002) Defining sustainability. In: Sverdrup, H., Stjernquist, I., (Eds.) *Developing principles for sustainable forestry, Results from a research program in southern Sweden. Managing Forest Ecosystems* 5, 21-32. Kluwer Academic Publishers, Amsterdam.

SVERDRUP, H., SVENSSON, M. (2004) Defining the concept of sustainability, a matter of systems analysis. In: Olsson, M., Sjöstedt, G. (Eds.) *Revealing complex structures - Challenges for Swedish systems analysis*, 122-142. Kluwer Academic Publishers, Amsterdam.

SVERDRUP, H., GUARDANS, R. (2008) A study of the ancient Iberian language. In: Shevoroshkin, V., Sverdrup, H. (Eds.) *Bygone Languages Reconstructed–On Language Origins and their Relationships.* Underskoven Forlag 2, 30-95.

SVERDRUP, H., RAGNARSDOTTIR, K.V. (2011) Challenging the planetary boundaries II; Assessing the sustainable global population and phosphate supply, using a systems dynamics assessment model. *Applied Geochemistry* 26, 307-310.

SVERDRUP, H., WARFVINGE, P., JANICKI, A., MORGAN, R., RABENHORST, M., BOWMAN, M. (1992) Mapping critical loads and steady state stream chemistry in the state of Maryland. *Environmental Pollution* 77, 195–203.

SVERDRUP, H., WARFVINGE, P., BRITT, D. (1996) Assessing the potential for forest effects due to soil acidification in Maryland. *Water, Air and Soil Pollution* 87, 245-265.

SVERDRUP, H., WARFVINGE, P., WICKMAN, T. (1998) Estimating the weathering rate at Gårdsjön using different methods. In: Hultberg, H., Skeffington, R. (Eds.) *Experimental Reversal of Acid Rain Effects; The Gårdsjön Roof Project*: John Wiley Science, Oxford, 488 pp.

SVERDRUP, H., STJERNQUIST, I., THELIN, G., HOLMQVIST, J., WALLMAN, P., SVENSSON, M. (2005) Application of Natural, Social, and Economical Sustainability Limitations to Forest Management, Based on Swedish Experiences. *Journal of Sustainable Forestry* 21, 147-176.

SVERDRUP, H., ALVETEG, M., WESTLING, O., AKSELSSON, C. (2006) Critical loads for acidity to ecosystems - How environmental limits came to set the policy. In: Haines-Young, R., Potschin, M., Chesire, D. (Eds.) *Defining and Identifying Environmental Limits for Sustainable Development. A Scoping Study*, 159-168.

SVERDRUP, H., BELYAZID, S., KURZ, D., BRAUN, S. (2008) A proposed method for estimating critical loads for nitrogen based on biodiversity using a fully integrated dynamic model, with testing in Switzerland and Sweden. In: Sverdrup, H. (Ed.) *Towards critical loads for nitrogen based on biodiversity*. Swiss Federal Office of the Environment (FOEN), Bern, 3-37.

SVERDRUP, H., KOCA, D., RAGNARSDOTTIR, K.V. (2013a) Peak metals, minerals, energy, wealth, food and population; urgent policy considerations for a sustainable society. *Journal of Environmental Science and Engineering* B 1, 189-222.

SVERDRUP, H., KOCA, D., GRANATH C. (2013b) Modeling the gold market, explaining the past and assessing the physical and economical sustainability of future scenarios. In: Schwanninger, M., Husemann, E., Lane, D. (Eds.) *Proceedings of the 30th International Conference of the System Dynamics Society*. University of St. Gallen, Switzerland, 5, 4002-4023.

SVERDRUP, H., KOCA, D., RAGNARSDOTTIR, K.V. (2013c) The World 5 model; Peak metals, minerals, energy, wealth, food and population; urgent policy considerations for a sustainable society. In: Schwanninger, M., Husemann, E., Lane, D. (Eds.) *Proceedings of the 30th International Conference of the System Dynamics Society*. University of St. Gallen, Switzerland, 5, 3975-4001.

SVERDRUP, H., KOCA, D., RAGNARSDOTTIR, K.V. (2014a) Investigating the sustainability of the global silver supply, reserves, stocks in society and market price using different approaches. *Resources, Conservation and Recycling* 83, 121-140.

SVERDRUP, H., RAGNARSDOTTIR, K.V., KOCA, D. (2014b) On modelling the global copper mining rates, market supply, copper price and the end of copper reserves. *Resources, Conservation and Recycling* 87, 158-174.

SVERJENSKY, D.A., LEE, N. (2010) The great oxidation event and mineral diversification. *Elements* 6, 31-36.

SWEENEY, M.A., BINDA, P.L. (1989) The role of diagenesis in the formation of the Konkola Cu-Co orebody of the Zambian Copperbelt. In: Boyle, R.W., Brown, A.C., Jefferson, C.W., Jowett, E.C., Kirkham, R.V. (Eds.) *Sediment-hosted stratiform copper deposits*. *Geological Association of Canada Special Paper* 36, 499-518.

TAINTER, J.A. (1988) The Collapse of Complex Societies. Cambridge University Press, Cambridge, 177 pp.

TAINTER, J.A. (1995) Sustainability of complex societies. *Futures* 27, 397-407.

TAINTER, J.A. (1996) Complexity, problem solving and sustainable societies. In: *Getting down to Earth: Practical Applications of Ecological Economics*. Island Press, Washington DC, 494 pp.

TAYLOR, K.G., KONHAUSER, K.O. (2011) Iron in Earth surface systems: A major player in chemical and biological processes. *Elements* 7, 83-88.

TILLY, C. (2003) Trust and Rule. Cambridge University Press, Cambridge, 280 pp.

Tilly, C. (2007) Democracy. Cambridge University Press, Cambridge, 320 pp.

Tilton, J.E., Lagos, G. (2007) Assessing the long-run availability of copper. *Resources Policy* 32, 19-23.

Tosdal, R.M., Butt, C.R.M., Fischer-Bühner, J. (2009) From source to sinks in auriferous magmatic-hydrothermal porphyri and epithermal deposits. *Elements* 5, 289-295.

Trendall, A.F., Blockley, J.G. (1970) The iron formations of the Precambrian hemersley Group Western Australia, with special reference to the associated crocidolite. *Geological Survey of Western Australia Bulletin* 119, 366 pp.

Turner, G.M. (2008) A comparison of the limits to growth with thirty years of reality. Socio-economics and the environment in discussion. *CSIRO Working papers*, 2008-2009.

Turner, G. (2012) On the Cusp of Global Collapse? Updated comparison of the limits to growth with historical data. *GAIA Ecological Perspectives for Science and Society* 21, 2, 116-124.

Turner, G. (2014) Is global collapse imminent? An updated comparison of the Limits to Growth with historical data. *MSSI Research paper* 4, 21 pp.

Turner, T. (1900) The Metallurgy of Iron. Second Edition, Charles Griffin & Company, London, 403 pp.

United Nations (1987) (The Brundtland Commission) Report of the World Commission on Environment and Development: Our Common Future. Transmitted to the General Assembly as an Annex to document A/42/427 - Development and International Co-operation: Environment.

United Nations (2003) World Population Prospects: The 2002 Revision. United Nations publication, Sales No. E.03.XIII.6, I, 36 pp.

United Nations (2014) United Nations Open Working Group for Sustainable Development Goals. United Nations Sustainable Development Knowledge Platform.

UNEP (2011a) The UNEP yearbook 2011. UNEP division of early warning and assessment, Nairobi, Kenya, 92 pp.

UNEP (2011b) Recycling Rates of Metals - A Status Report. In: Graedel, T.E., Allwood, J., Birat, J.-P., Reck, B.K., Sibley, S.F., Sonnemann, G., Buchert, M., Hagelüken, C.A (Eds.) *Report of the Working Group on the Global Metal Flows to the International Resource Panel*. 48 pp.

UNEP-IRP (2013) The International Resource Panel. In: Reuter, M., Hudson, C., Schalk, A., Heiskanen, K., Meskers, C., Hagelüken, C. (Eds.) *UNEP Metal recycling; Opportunities, Limits, Infrastructure*. 317 pp.

USGS (2005) Commodity Statistics for a Number of Metals. United States Geological Survey http://minerals.usgs.gov/ minerals/pubs/commodity/.

USGS (2007) Commodity Statistics for a Number of Metals. United States Geological Survey http://minerals.usgs.gov/ minerals/pubs/commodity/.

USGS (2008) Commodity Statistics for a Number of Metals. United States Geological Survey http://minerals.usgs.gov/ minerals/pubs/commodity/.

USGS (2011) Commodity Statistics for a Number of Metals. United States Geological Survey http://minerals.usgs.gov/ minerals/pubs/commodity/.

USGS (2012) Commodity Statistics for a Number of Metals. United States Geological Survey http://minerals.usgs.gov/ minerals/pubs/commodity/.

USGS (2013) Commodity Statistics for a Number of Metals. United States Geological Survey http://minerals.usgs.gov/ minerals/pubs/commodity/.

USGS (2014) Commodity Statistics for a Number of Metals. United States Geological Survey http://minerals.usgs.gov/ minerals/pubs/commodity/.

Valsami-Jones, E., Ragnarsdottir, K.V., Putnis, A., Bosbach, D., Kemp, A.J., Cressey, G. (1998) The dissolution of apatite in the presence of metal cations in acidic solutions. *Chemical Geology* 151, 215-234.

Vargas, M., Kashefi, K., Blunt-Harris, E.I., Lovley, D.R. (1998) Microbial evidence for Fe(III) reduction on early Earth. *Nature* 395, 65-67.

Vogt, W. (1948) Road to survival. William Sloane Associates Inc, New York, 335 pp.

de Vries, B.J.M. (2013) Sustainability Science. Cambridge University Press, Cambridge, 550 pp.

de Vries, W., Kros, H., Reinds, G.J., Wamelink, W., van Dobben, H., Bobbink, R., Smart, S., Evans, C., Schlutow, A., Kraft, P., Belyazid, S., Sverdrup, H., van Hinsberg, A., Posch, M., Hettelingh J-P. (2006) Developments in modelling critical nitrogen loads for terrestrial ecosystems in Europe. Developments in Deriving Critical Limits and Modeling Critical Loads of Nitrogen for Terrestrial Ecosystems in Europe. Alterra, Wageningen, 230 pp.

Vronsky, I.M. (1997) The story of gold. Gold Eagle Website. http://www.gold-eagle.com/article/history-gold

Wackernagel, M., Rees, W. (1996) *Our Ecological Footprint.* New Society Publishers, Gabriola Island, BC, 176 pp.

Walshe, J.L., Cleverley, J.S. (2009) Gold deposits: Where, when and why. *Elements* 5, 289-295.

Walther, J.V. (2013) Earth´s Natural Resources. Jones & Bartlett Learning, Burlington, 434 pp.

Wang, T., Müller, D.B., Graedel, T.E. (2007) Forging the Anthropogenic Iron Cycle. *Environmental Science & Technology* 41, 5120-5129.

Wang, X., Schröder, H.C., Wiens, M., Schlossmacher, U., Müller, W.E.G. (2009) Manganese/polymetallic nodules: micro-structural characterization of exolithobiontic- and endolithiobiontic microbial biofilms by scanni electron microscopy. *Micron* 40, 350-358.

Warfvinge, P., Sverdrup, H., Ågren, G., Rosen, K. (1992) Effekter av luftföroreningar på framtida skogstillväxt. In: Svensson, L. (Ed.) *Skogspolitiken inför 2000-talet-1990 års skogspolitiska kommitte*. Statens Offentliga Utredningar, SOU, 76, 377–412.

Wellmer, F.-W. (2008) Reserves and resources of the geosphere, terms so often misunderstood. Is the life index of reserves of natural resources a guide to the future? *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften* 159/4, 575-590.

Wilkinson, B.H. (2005) Humans as geologic agents: A deep-time perspective. *Geology* 33, 161-164.

Wilkinson, R., Pickett, K. (2011) The Spirit Level: Why Greater Equality Makes Societies Stronger. Bloomsbury Press, London.

Williams-Jones, A., Heinrich, C.A. (2005) Vapour transport of metals and the formation of magmatic-hydrothermal ore deposits. *Economic Geology* 100, 1287-1312.

Williams-Jones A., Bowell, R.J., Migdisov, A.A. (2009) Gold in solution. *Elements* 5, 281-287.

Williams-Jones, A.E., Migdisov, A.A., Samson, I.M. (2012) Hydrothermal mobilization of the rare earth elements – at tale of “ceria” and “yttria.” *Elements* 8, 355-360.

White, W.E. (2013) Geochemistry. Wiley-Blackwell, Chichester, 668 pp.

World Gold Council (2013) Gold Demand Trends, First Quarter 2013. Based on statistics collected by Thompson Reuters GFMS. World Gold Council, London, United Kingdom.

World Steel Association (2000) Steel statistical yearbook 1999. International Iron and Steel Institute, Brussels, 248pp.

World Steel Association (2012) The white book of steel. World Steel Association, Brussels, 49 pp.

World Steel Association (2013a) World steel in figures 2013. World Steel Association, Brussels, 17 pp.

World Steel Association (2013b) Economic Sustainability, Policy and Indicators Association 2013. World Steel Association, Brussels, 12 pp.

World Steel Association (2014a) Crude steel production 1980-2012. World Steel Association, Brussels.

World Steel Association (2014b) Blast furnace iron production 1980-2012. World Steel Association, Brussels.

World Steel Association (2014c) Direct reduced iron production 1980-2012. World Steel Association, Brussels.

World Steel Association (2014d) A handbook of world steel statistics. World Steel Association, Brussels, 69 pp.

Wübbeke, J., Heroth, T. (2014) Challenges and political solutions for steel recycling in China. *Resources, Conservation and Recycling* 87, 1-7.

Yongding, Y. (2012) LBMA Gold Conference talk, Hong Kong 2012. Institute of World Economics and Politics, former member of the Monetary Policy Committee of the PBOC, China.

WWF (2014) Living Planet Report 2014. Species and Spaces, People and Places. WWF, Gland, Switzerland.

Zhang, D.D., Zhang, J., Lee, H.F., He, Y. (2007) Climate change and war frequency in Eastern China over the last millennium. *Human Ecology* 35, 403-414.

Zittel, W., Schindler, J. (2007) Coal: Resources and future production. A background paper produced by the Energy Watch Group. Ludwig Bolkow Foundation, Ottobrunn, 47 pp.

Zolotov, M.Y., Shock, E.L. (2000) A thermodynamic assessment of the potential synthesis of condensed hydrocarbons during cooling and dilution of volcanic gases. *Journal of Geophysical Research* 105(b), 539-559.

Zotov, A., Baranova, N.N. (1989) The solubility of Au_2S and AuAgS in near-neutral sulphide solutions at temperatures of 25 and 80^o C and pressures of 1 and 500 bars. In: Kjarka, Y.K., Chudaev, O.V. (Eds.) *Water-Rock Interaction-8*. Balkema Press, 113-115.

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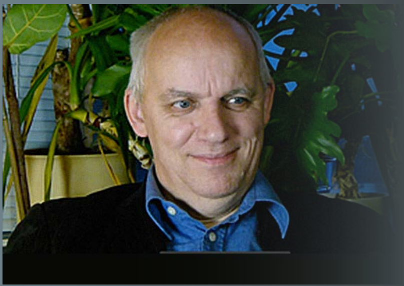

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