Peak metals, minerals, energy, wealth, food and people towards the end of the golden age; considerations for a sustainable society

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Abstract

In this paper we show that several metals, elements and energy resources are about to run into scarcity within the next decades, most elements within some centuries. A new global systemic model was assembled to analyse this scarcity as a continuation of the model used in the Limits-to-Growth model. The authors show that this scarcity will lead to "peak wealth", "peak population", "peak costs", "peak junk", "peak problems" and possibly "peak civilization", unless some urgent measures are systematically taken throughout the world. Scarcity implies that materials that underpin modern society will largely be unavailable for global mass production of goods. The material volumes that can be supplied from fossil reserves will be reduced with respect to today and all materials will go up sharply in price. The future resource supply situation is thus unsustainable as long as resource use continues the way it does today. The creation of money from work, conversion of resources and the extensive borrowing from the future, cause concerns that peak oil and peak materials may lead to "peak wealth" and the end of the golden age we live in the developed nations. Our policy recommendations are that governments must take the issue seriously and immediately start preparing for legislations that can close material cycles, optimize energy use and minimize all types of irreversible losses as soon as possible. Forceful programs promoting extensive recycling are needed as well as special care in closing loops and reducing irreversible losses. Research efforts in this field needs to be based on systems thinking and a concerted effort is needed globally. Three things stand out as imperative for reaching a sustainable society:

1. Close all material cycles and keep extraction of renewable resources below the critical extraction rate by a good margin.
2. Base all energy production on a multitude of methods for harnessing the power from the sun directly (heat collection, photovoltaic) or indirectly (wave, wind, waterpower, photosynthetic bioenergy) with a positive EROI and MROI larger than 2. Limit the use of all fossil fuels to a time-to-doomsday perspective of at least 5,000 years (uranium, thorium, oil, gas, coal, geothermal energy).
3. Reduce to insignificance corruption and abuse of power in government, society in general, and promote the liberal form of democracy with adequate balancing of influences, demanding accountability of all offices of power. Marginalize all non-democratic modes of governance and create open information governance and a liberal and secular society.

Convergence and contraction is the concept used to attempt to develop a sustainable society where we have local growth and global contraction under the same roof.

Key words: *sustainability, metals scarcity, Hubbert's curve, systems dynamics, modelling, burn-off time, natural resource, peak oil, peal metals, peak phosphorus, planetary boundaries, convergence, contraction, global population policy, EROI, MROI, peak wealth, golden age, future studies.*

1. Introduction

The "peak" phenomena (mostly known is "peak oil") has been shown to be applicable to natural resources such as phosphorus, minerals or metals but also to other aspects of society as well as national economies (Bardi and Yaxley 2005, Bardi 2007a,b, 2008a,b,c, 2009a,b, 2010, Bardi and Lavacci 2009, Laherrere 2009a,b). Peak resource x implies that resource x production goes through a maximum and then declines to insignificanceover time. These findings become a practical tool for evaluation of finite resources that are being exploited. We have come to a period in human history where we may catch glimpses of what may constitute the sunset of modern technological civilization as we know it, unless significant changes to the present course of events is made within the next four decades (Heinberg 2001, 2005, 2011, Greer 2005, Ragnarsdottir et al. 2011a,b, Sverdrup and Ragnarsdottir 2011). There has never been a lack of prophets predicting doomsday, however, the gloomy estimates presented here of resource depletion are based on scientific calculations that are based on on a robust field data foundation. There have been several early warnings about doomsday over the years (Malthus 1798, Ehrlich 1968, Forester 1971, Meadows et al. 1972, 1992, 2005, Ehrlich et al. 1992, Brown 2005), however, these have so far gone unheeded with respect to taking actions on the ground. This paper presents several serious challenges in terms of scientific research that must be undertaken. We need to transform scientific results into sustainability policies and to convince society to understand the reasons and necessity in implementing those measures consistently. This is because national success and prosperity and wealth generation is closely linked to resource conversion and the work associated with it. We base this work on our own earlier studies (sustainability assessments based on mass balances for ecosystems; Sverdrup and Warfvinge 1988, 1992, Sverdrup et al., 1996a,b, 2002, 2006, 2007, 2010, 2011, for resources; Sverdrup et al. 2011a,b,c, general systemic studies; Forrester 1971, Meadows et al. 1972, 1992, 2005, Ragnarsdottir et al., 2011a,b, Sverdrup and Ragnarsdottir, 2011, Sverdrup et al., 2011) as well as the studies of others pioneers in this field (Malthus 1798, Pearson and Harper 1945, Osborn 1948, Hubbert 1956, Pogue and Hill, 1956, Meadows et al. 1972, 1992, 2005, Bahn and Flenley, 1992, Daily and Ehrlich 1992, Ehrlich et al. 1992, Ehrlich et al., 1992, Brown and Kane 1994, Daily et al. 1994, Campbell and Laherrere 1998, Evans, 1998, Smil, 2001, 2002, Greene et al. 2003, Heinberg, 2001, 2005, 2011, Aleklett 2003, 2005, Hirsch et al.

2005, Greer 2005, Gordon et al., 2006, Fillipelli, 2008, Brown, 2009a,b Ehrlich and Ehrlich, 2009, and many more).

2. Objective and scope

The objective of this study is to build on our earlier work (Ragnarsdottir 2008, Ragnarsdottir et al. 2011a,b, Sverdrup and Ragnarsdottir 2011, Sverdrup et al. 2011a,b), and assess the degree of sustainability of the present economic paradigm and its potential for surviving in the future. We present the follow-on causal chain valid after peak fossil fuels, peak phosphorus and peak metals in this study, investigating the connection between resource extraction and wealth generation in society. The results are used to initiate a process to develop policy advice and developing future scenarios for sustainable societies across the globe.

3. Methods of assessment

In this chapter we use several methods:

1. The standard methods of systems analysis and design engineering: Systems analysis to map the essential causal chains, find root causes and qualitatively explore the basic dynamics of the problem and identify the key components of what constitutes the real problem.
2. Simple back-of-the-envelope type of calculations to estimate the order of magnitude of important aspects, such as burn-off times and Hubbert's curve responses
3. Integrated systems dynamics modelling based on causal loops and chains derived by systems analysis for scenario analysis and iterative mode for back-casting from goals to find the limits of global sustainability. The models are for securing model output quality, verified against the ability to predict the events of the past.

This study uses generic systems thinking, systems analysis and systems dynamics procedures found in the literature (Forrester 1971, Meadows et al. 1972, Senge 1990, Sterman, 2000, Sverdrup and Svensson 2002, Haraldsson et al. 2002, 2004, 2007, Haraldsson and Sverdrup 2004, Haraldsson, 2007). The method used for constructing the model followed a strict scheme, as well as deriving links by empirical, experimental and Delphi methods (Adler and Ziglio 1996). The model systems were programmed in the STELLA® computer modelling environment.

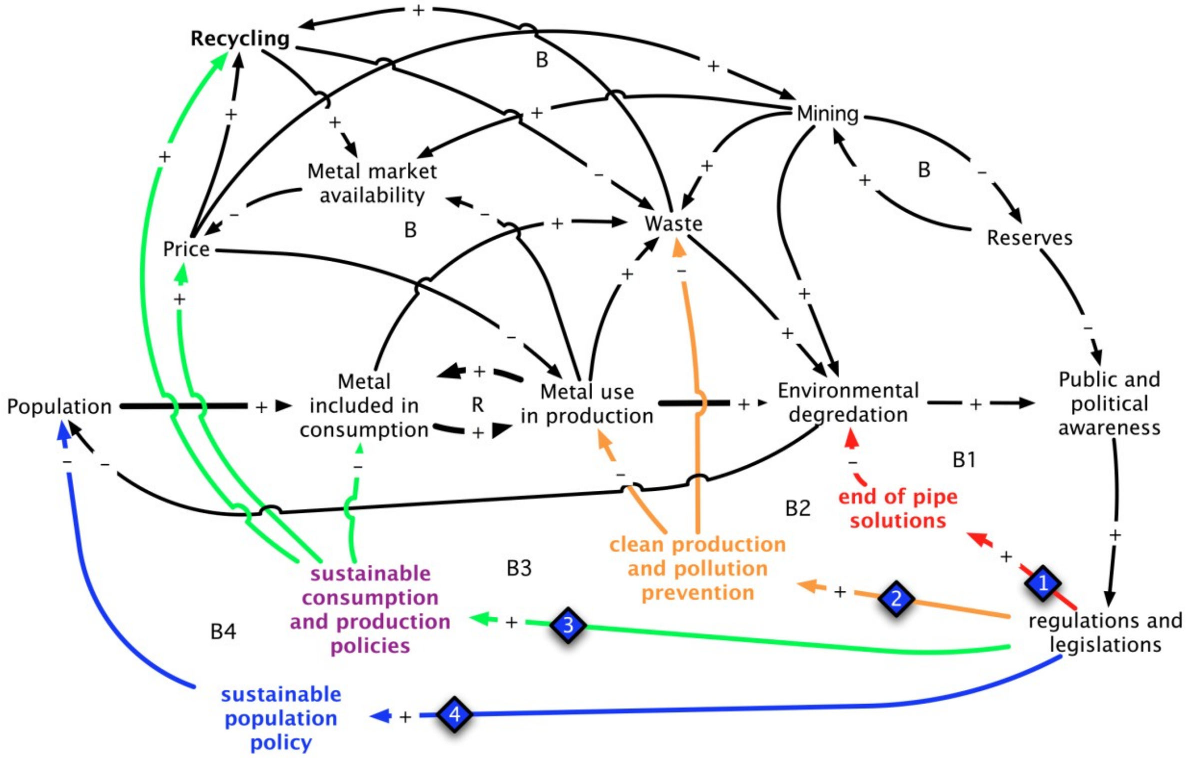


Figure 1. *Sustainability of resource use has moved over many system levels from end-of-pipe (fighting pollution) to the root cause (overpopulation). Attention has over time moved from end-of-pipe to more focus on recycling, slimmer consumption patterns and sustainable production. Ultimately the world must also address the consumption volume as a function or per capita use as well as the number of consumers, directly proportional to the size of the global population. Adapted from Ragnarsdottir et al. (2011). B1-B4 are different balancing loops that can be put into the system by governance.*

4. Theory

4.1. Overall general world analysis

The basic analysis of our Earth systems supply of resources is described in the causal loop diagram in Figure 1. Here we see that with increased population, the consumption of resources increases, which in turn increases the production. Emissions and waste generated from both the production and consumption lead to environmental degradation. Increased environmental degradation increases concerns and forces society to take necessary policy actions. Increasing consumption and population are the two major factors for an increasing demand in the world. An increase in the population drives consumption, depleting markets, increasing prices and increasing supply from production to market. This allows for continued consumption increase as well as increased resource use. Increased resource use rate and associated waste generation leads to environmental degeneration. Recycling represents a way to increase material in the cycle without depleting resources. End of pipe solutions during the early 1950's were used as a first response to increased concerns over environmental degradation. Instead of draining out wastewater from industrial process to rivers, wastewater treatment plants were built; or instead of emitting hazardous waste gasses into the atmosphere, treatment units were constructed. During the early 1990's, the economic value of natural resources and waste was realized, and cleaner production and pollution prevention practices were introduced to increase the efficiency in the production processes, and thus decrease the use of natural resources, the waste generated and gasses emitted to the atmosphere. In the last decade, focus has been on the sustainable consumption and production behaviour.

We now need to ask how changes in our life style can be made in order to decrease the demand for goods, and how to consume less. This may eventually decrease the global resource overconsumption, reduce resulting environmental degradation and put us on a path towards sustainability. It can be seen from the causal loop diagram in Figure 1 that we can trace back the main root cause for today's increasing environmental degradation and impending resource exhaustion to the increase in the world's population. We can also see from the diagram that there is a need to introduce sustainable population policies, together with sustainable consumption and production policies in order to decrease the global population in the future and reduce demand on resources. A sustainability policy for resource consumption, including aspects of the world population size will thus be needed, as a part of avoiding that the total flux of resources will be outrunning planetary capacities. It would appear that a global population contraction during this century must be planned as suggested by several people as early as the 18th century (Malthus 1798, Ehrlich 1968, Meadows et al. 1972, 1992, 2005, Bahn and Flenley 1992, Daily and Ehrlich 1992, Ehrlich et al. 1992, Daily et al., 1994, Evans, 1998, Brown 2009a,b, Ehrlich and Ehrlich 2009). Lack of sustainability in this context arises from:

1. End of pipe pollution output from the system;
2. Unsustainable production or resource use in products;
3. Excessive volume consumption of resources;
4. The number of consumers in excess of the carrying capacity of the Earth.

The carrying capacity of the world for population has been estimated many times, but with different results because of differences in fundamental assumptions (e.g. Cohen 1995, Sverdrup et al. 2011). We propose that the concept of convergence and contraction may be an important part of the answer to the global sustainability issue. To minimize impact on the Earth, we need to convert from linear flow through of resources to circular use through recycling.

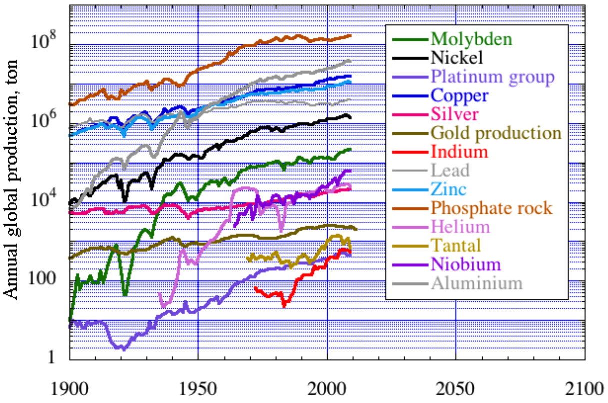


Figure 2. *During the period 1900-2010, metal and element output from the world's mines increased enormously. The Y-axis in logarithmic, and a straight line implies that the growth in volume is exponential.*

This is an aspect of the concept of convergence. Contraction is to minimize per capita use, as well as the number of capita using resources, assuming equitable access to resources of the world population. In Figure 2, we show how during the period 1900-2010, metal and element output from the world's mines increased enormously. The Y-axis in Figure 2 is logarithmic, and a straight line demonstrates that the growth in volume is exponential. In a finite world, exponential growth forever is impossible (e.g. Boulding 1956).

General definitions

In this essay, we use some terms we need to define at the beginning:

- **Collapse**: A society collapses when it displays a rapid, significant loss of an established level of socio-political complexity (be it empire or chiefdom). Diagnostic signs of ongoing collapse is systematically increasing social stratification, less interconnectedness in the governmental organizations, less global networking in society, less occupational specialization, deterioration in education sophistication and starting signs of local separatism (Tainter 1988, Greer 2008, Diamond 2005, Tilly 2007). Special cases are failed states like Somalia, Pakistan or Congo; total failure of the society with loss of all coordinated organized activity towards common services, loss of all accountancy, no justice apparatus, no rule of law, no organized commodity flows and corruption everywhere.

- **Convergence and contraction** The term was originally created to deal with the contraction in fossil fuel use that would be necessary for mitigating climate change (Meyer 2002, Pontin and Rodrick 2007). However, it has become something more in a European research network context for developing sustainable communities called (www.convergeproject.org), and has been extended to include all widths of sustainability: nature, economy, society, well-being of humans (AtKisson 2008). It involves issues such as ecological footprint, the natural step system conditions, critical loads, sustainable population levels, a contraction of everything human society needs of resources in order to stay within the planetary boundaries, and contracting towards low resource intensity solutions and converging on a high degree of circular resource use. Originally, the idea was about the developing world converging and the developed world contracting. For many resources, it is possible that all must contract and significantly increase recycling, some must contract more, others less.

- **Systems thinking**, systems analysis, and systems dynamics, is the art of seeing the whole system as framed by the issue or the problem, disregarding artificial disciplinary boundaries created by humans for their creation of academic hierarchies and territories of dominance and social recognition (Senge 1990). Emphasis is on mapping causal links and causal chains, and detect when these are circular, creating feedback loops. These two types of diagrams are called causal loop diagrams and flow charts. They follow strict logical rules, and map the system to reveal its dynamic properties. System thinking is closely linked with adaptive management and with adaptive learning networks, conducted using group work as an important feature to create a shared insight and shared systems view of ownership.

- **Carrying capacity** is the maximum activity or population a certain defined area can support on an eternity basis (Sverdrup and Rosen 1996). That implies that the society in the area has an energy and resource consumption that is within the limits of the regeneration capacity of the system. A special case of carrying capacity with respect to pollution is the critical load (Sverdrup and Warfvinge 1988, 1992, Sverdrup et al. 1990).

- **Sustainability** and a **society within the sustainability constraints**. This is about making society or an activity take such a shape that it can go on virtually for ever, without ruining its own conditions. This is fundamentally different from sustainable development (which need a careful definition of what development really is) and sustainable growth (which does not exist as a reasonable concept in the long term). Hard thermodynamic limits are set by mass balances for use resources in finite supply (energy, metals, structural materials, fibre, and food through phosphorus and nitrogen). Only resources that have inbuilt regeneration function may be made to last for ever. Limits are also set by social systems in terms of personal integrity and security, interpersonal trust, transparency and degree of democracy. These are different from sustainable development which sometimes include perpetual economic or mass volume growth, which is not possible on a limited Earth and therefore greatly unsustainable.

- **Steady state** is a system state that a dynamic system may stabilize itself in the vicinity of. The system has a stability envelope, where disturbances will change the state a bit but it will converge back on the steady state level. A collapse or a system state change implies that the system has been hit by such a large push that it falls out of the stability envelope. It is feared that the Earth's climate has such meta-stable system properties, and there are indications that there are two stable climatic states, one "warm-moist" and one "cold-dry". We are in the "cold-dry" steady state now, which alternate between ice-ages and relatively mild interglacial periods. The dinosaurs lived in a "warm" period with no glaciations about 60 million years ago.

- **Long term.** In the language of sustainability and times involved in natural systems, short term is everything less than 200-300 years. The intermediate term is in the range 200-1,000 years, and long term is more than 1,000 years. Sustainability time is 5,000-10,000 years (Sverdrup et al. 2002, 2012, Ragnarsdottir et al. 2011).

- **Time to scarcity** is the time required to arrive at a level where the supply has sunk down to 10% of the peak production is used in this study.

- **The Golden Age**, the era we lived in for the last 5 decades in the developed nations, where resource limitation never really was an issue. Within the next 5 decades it may largely disappear and become **A world of limits**.

- **Exponential growth,** implies that something will grow as a proportion of what is already there every time step. At proportional growth at constant rate, any growth would eventually explode whatever contained it, including the World. Exponential systems double in size with increasing speed.

- **EROI** is "energy return on investment". How much energy must be put in to get one unit of energy out. If energy obtained is less that what we need to spend to get it, we should stop extraction. **MROI** is "material return on investment". How much material must be put in to get one unit of material out. If material obtained is less that what we need to spend to get it, we should stop extraction. EMROI is the combination of EROI and MROI in the same activity

Convergence and contraction for materials

To keep a society healthy and with ability to change, growth is needed on the small scale. Small businesses need to grow to replace those that fail, large or small, but the sum of the total activity needs to stay within the sustainability constraints. To make room for the new that bring innovation and change, older, petrified or too large companies must split up, contract or fail. Thus, there will be growth and succession going on at the same time. The long-term growth rates of small businesses, need to be matched by an equal failure rate of dysfunctional, petrified or too large companies. At present, we know how to promote growth through increase in resource flow-through, however, for creating sustainable economic or population contraction, we are less able. Some researchers and leaders in society like to consider energy and material resources to be endless and unlimited in supply, and deny the prospect of future limitations, openly declaring that they are hoping for some yet undiscovered technological miracle to solve all problems of shortages. This is a dangerous and passive attitude to future planning of sustainability; there are many examples of where such approaches failed in the past, some of them with ugly outcomes (e.g. Keynes et al., 1932, Sabloff, 1990, Bahn and Flenley, 1992; Diamond, 2003). An integrated assessment over all essential components is needed in the long run, and the study of Forrester (1971) and Meadows et al., (1972, 1992, 2005) are the pioneering studies that came the closest to achieve this. In a future society, local economic growth will be both present and necessary. Trade and taxation systems are the normal systems for redistribution in society, apart from the distributions that are through work and personal performance. The normal societal model is one of solidarity, where those with means help share the burden of those with less means. Among nations, that becomes more problematic, as the systems are more intricate and intertwined, and because social norms and standards are different. In the principles of contraction and convergence, systemic corruption represents an especially difficult problem that will be able to derail the redistribution process as well as sidestepping democratically made decisions.

Resource use and wealth, an analysis

The basic principle behind the need for convergence and contraction is illustrated in Figure 3. This figure shows the basic engine of societal economic growth as a causal loop diagram. The R's represents reinforcing loops, the B's represents balancing loops. In the causal loop diagram, prosperity and wealth will be driven by resource availability, but growth will consume resources. Waste and pollution tend to reduce the regenerative capacity. For many metals and elements dug from the Earths crust and surface, the regenerative capacity is nearly insignificant for most practical purposes. The regenerative feature is important and represents a reinforcing loop in the system (R4). A sustainably managed fishery or sustainably managed forestry works in this way, and principally may give a supply forever. Growth is normally defined as increase in total transaction volume (GDP) and is normally not well connected to the quality of life. Prosperity and wealth is better correlated, and is used here. Resource-use causes waste and pollution, which in turn may damage regenerative functions when they are in operation. Natural systems normally have regenerative functions, such as forests or fish stocks. Wealth is created from resources and work, and enhanced by education and quality convergence. R1-R5 are reinforcing loops, B1-4 are balancing loops. Early in the exploitation of the resource, the loops R1, R2, R3 dominate and we have exponential growth. It will be limited by B1, B2 and B3 if the rate of R4 is not exceeded. If R4 is exceeded significantly, the system will be reduced to a finite reserve mining system. This is the case with ocean fisheries and tropical forest logging at present. The causal loop diagram for non-renewable fossil resources is shown in Figure 4. Here we have further elaborated on the diagram in Figure 3, by removing the regenerative capacity, which is insignificant for fossil resources such as metals and minerals except some carbonates. Instead, we have introduced recycling as a partial regenerative feature. This introduces another reinforcing loop that can partly replace the effect of the regenerative capacity. In nature, only systems with regenerative features survive as part of being sustainable in the ecosystem. Early in the exploitation of the resource, the loops R1, R2, R3 dominate and we have exponential growth. Later as the reserves get depleted, R1 will dominate and become limited by B1, B2, but supported by R3 if recycling is kept on a significant level. There is no new resource generation from recycling, but the recycling may reduce irreversible losses significantly and considerably extend the lifetime of the available reserves.

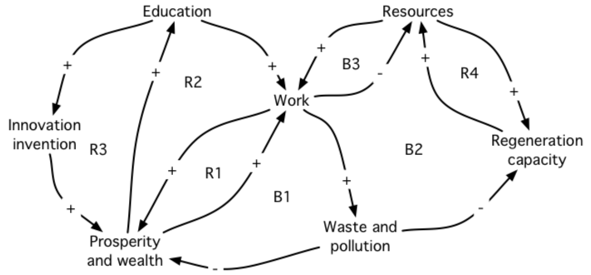


Figure 3. *Economic growth is largely driven by resources when transformed by work, as illustrated in the causal loop diagram. Early in the exploitation of the resource, the loops R1, R2, R3 dominate and we have exponential growth. It will be limited by B1, B2 and B3 if the rate of R4 is not exceeded. If R4 is exceeded significantly, the system will be reduced to a finite reserve mining system.*

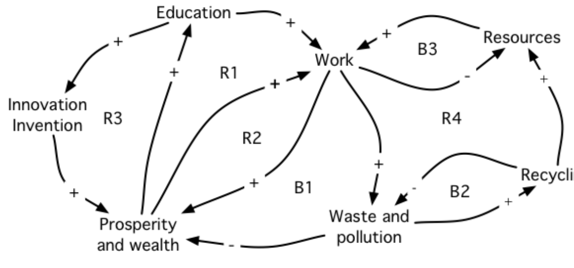


Figure 4. *For fossil resources the regenerating capacity is generally insignificant. All material that is lost is to be considered as lost forever for society. Early in the exploitation of the resource, the loops R1, R2, R3 dominate and we have exponential growth. Later as the reserves get depleted, R1 will dominate and become limited by B1, B2, but supported by R3 if recycling is kept on a significant level.*

Material growth in itself as a foundation for society is something that cannot be sustained forever, a fact based in thermodynamics and mathematics. Resources can be obtained from finite resources, but as we have seen earlier, also by recycling what resources we already have on the way through our systems. Recycling is at present much too dependent on the price of the commodity in the market and thus will increase only when the resource becomes scarce. Exploitation through mining fills the market as long as the resource lasts. Use of resources depletes the market, and when resupply of virgin material dwindles, recycling of waste is the only other process that will resupply material from society. At the same time, this must be done as efficiently as possible, in order to keep permanent losses low. Scarcity in the market drives prices up, which stimulates recycling, which in turn reduce waste. But as the supply of recycled material reaches the market that may cause prices to fall.

Figure 5 shows the qualitative development that can be read out of the causal loop diagram shown in Figure 4, assuming the recycling to be insignificant. Initially the process is driven by maximizing resource extraction that leads to exponential behaviour. As the resource goes empty, the exponential growth can no longer be sustained and we get "peak" behaviour. Eventually as the resource base is depleted the system declines. "R" means that reinforcing loops in the causal loops in the production system shown in Figure 2 dominate, "B" means that balancing or retarding loops in the causal loops of the production system shown in Figure 4 dominate. Initially the process is driven by maximizing resource extraction that leads to exponential behaviour. As the resource goes empty, the exponential growth can no longer be sustained, we get "peak" behaviour and eventually as the resource base is depleted the system declines.

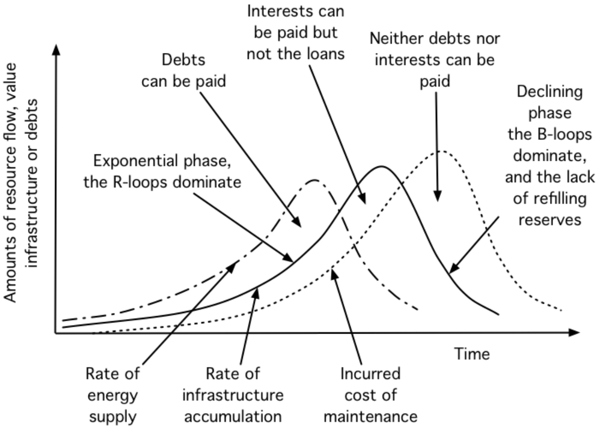


Figure 5. *The system output that can be read out of the causal loop diagram given in Figure 2. Initially, the process is driven by maximizing resource extraction, which leads to exponential growth. As the resource is depleted, the exponential growth can no longer be sustained, we get "peak" behaviour, then the system declines with depletion. "R" means a reinforcing loop in the causal loop system, "B" means a balancing loop in the causal loop system. When the EROI becomes too low, then the investment cannot be paid back. Value and infrastructure accumulation are produced as a result of work derived from the energy. The infrastructure stock grows to a level that requires a large input of resources. As reserves are depleted, more and more capital must be used for obtaining resources, leaving less to be invested for future maintenance and development.*

Energy is a prerequisite for both phosphorus and material extraction. The fundamentals of wealth creation in a society, is arising from extraction of oil-phosphorus-, and metal reserves and the input of productive work. Oil, coal, metals, material- and phosphate reserves are all finite resources and subject to a final date of extraction. In the long perspective, only renewable resources may last forever. This postulates that there is a "peak" component to wealth production. Prosperity and welfare for the individual and the family is what the people want to get from the economic growth driven resource use, but resource extraction volume growth is not necessarily a prerequisite for prosperity. True wealth can only created in three ways:

1. Converting natural resources to benefits;
2. Converting social resources to benefits;
3. Work, innovation and intellectual achievement.

Wealth can also be brought in by taking loans from the future. This does, however, not create it, but rather bets on the possibility that wealth will be made in the future in time to cover the loans made. There are two other sources of apparent wealth when wealth does not yet exist:

1. Taking loans,
    a. By appropriating with acceptance from the owners, present wealth for later repayment;
    b. By appropriating wealth believed to exit in the future, committing the future generations to pay it without seeking their consent. These are generally referred to as derivatives or futures.
2. By calling into existence money that does not exist, except in the minds of those that created the deception.

This is a sustainable loan if it obeys the sustainability limits and if the wealth materializes and the future generation stays with the obligation. It constitutes loans from somewhere in terms of resources to be exploited in the future or by laying claims to work to be performed in the future. In a sustainable society, wealth and its creation is important and monetization must be compatible with the wealth created. Today, monetization is subject to manipulations causing inflation and imaginary wealth. In a future society, economic growth will be both present and necessary. The same thing applies to other imbalances in society, where a fair share implies a redistribution of wealth. Trade and taxation systems are the normal systems for redistribution in society, apart from the distribution of wealth that is created through work and personal performance. The normal social model is one of rights, solidarity and duties, where those with means help share the burden of those with less means, respecting the integrity of the individual. Among nations, that becomes more problematic, as the systems are more intricate and intertwined, and because social norms, standards and culture are different. In the principles of contraction and convergence, systemic corruption represents an especially difficult problem that will be able to derail the redistribution process through graft, lack of transparency and well as sidestepping democratically made decisions. Local growth is needed in a societal economy to ensure the creation of new businesses to secure the necessary business structures, innovations, products and services evolution. There cannot be any net long-term growth of the whole system beyond the resource limitations, as that would in the long term violate mass-balance-based sustainability constraints. We will need to grow small businesses, but kill off on contract those that are petrified or too large.

Calculation methods

We use three different types of methods in order to estimate the time horizon of a raw material or metal resource (Ragnarsdottir et al. 2011):

1. **Burn-off time** (BOT) we define as known mineable reserves divided by the estimated average annual mining rate, the formula is given as Equation (1):

   Burn-off time = reserves / mining rate [yrs] (1)

   The Burn-off time is a worst-case scenario, and give a worst case estimate. It does not consider exponential growth nor market price mechanisms

2. **Hubbert's-curve estimates** of **peak production** (t_{max}) and **time to scarcity** (t_S): Hubbert's time to scarcity is named after a geologist at Shell Oil that discovered that all extraction follow the same type of curve-shape (Hubbert 1956, 1966, 1972, 1982). It can be used to predict the life-time of oil wells and oil fields. The Hubbert's curve is defined by the simple equation for cumulative production is Equation (2):

   $$M = M_{max} / (1 + e^{-b*(t-tmax)}) \quad [ton] \qquad (2)$$

   where M is the sum of all resource produced to time t, t_{max} is the time of the peak, M_{max} is the size of the whole resource, and a and b are constants. The annual production is given by Equation (3):

   $$P = 2* P_{max} /(1 + \cosh(b*(t-t_{max}))) \quad [ton/yr] \qquad (3)$$

   where P_{max} is the maximum production rate, P is the production at time t, t_{max} is the time of the peak, and the coefficient b is the curve shape constant. Parameterization for other elements is shown in Table 1. They are set using the available history for the source and production capacity estimates. Once t_{max} and M_{max} have been empirically measured, then the predictions are quite accurate and robust. Using that $\cosh x = (e^x-e^{-x})/2$, we can rearrange the equation (3) and get the timing of the time to scarcity (t_S) as Equation (4):

   $$t_S= t_{max} + \ln((P_{max}/P)-1) / (2 *b) \quad [yrs] \qquad (4)$$

   where t_s is the time for scarcity in years AD, P_{max}/P is at what fraction of the peak production we consider the resource to have become scarce, t_{max} is the timing of the peak and b is the same coefficient as b in equations 2 and 3. Geological surveys in different countries normally focus on estimating M_{max} for the key resources in their countries. The time of the peak, t_{max} is given by Equation (5):

   $$t_{max} = t_{now} - \ln((P_{max}/P)-1) / (2 *b) \quad [yrs] \qquad (5)$$

   where t_{now} is the present time. The Hubbert's curve model is robustly verified on field data from oil, coal, phosphorus and metal mining (copper, gold, silver, individual mines), demonstrating that it works well (Hubbert 1956, 1966, 1972, Greene et al. 2003, Cavallo 2004, Hirsh et al. 2005). We have chosen to define scarcity as the point in time when the production has declined to 10% of the peak production. Exponential growth and market price mechanisms are empirically captured into the Hubbert's estimate in a lumped way.

3. **Dynamic modeling estimate of time to scarcity** as estimated by systems analysis we define as time for the known reserves of high grade and low grade to have decreased to 10% of the original amounts. 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, either using an environment such as STELLA® or it is coded in FORTRAN. We have developed these kinds of sustainability assessment models since 1988; (agricultural systems; FarmFLOW, natural or managed ecosystems; ForSAFE, PROFILE, precious metals; GOLD, PGM, rare earths; FoF, global phosphorus; FoF, lithium) in our research team (Sverdrup and Warfvinge 1988, 1992, Warfvinge and Sverdrup 1993, Sverdrup et al., 1996a,b, 2006, 2007, 2011a,b, 2012, Ragnarsdottir et al. 2011, Sverdrup and Ragnarsdottir 2011, Öborn et al., 2005). Models for global supply of iron, aluminium, silver, lithium and rare earth metals are under development at present (2011-2012). Exponential growth and market price mechanisms are mechanistically incorporated in our process-oriented models.

We have compared these methods in earlier studies (Ragnarsdottir et al. 2011a,b, Sverdrup and Ragnarsdottir, 2011, Sverdrup et al., 2011a) and they are compatible and mutually translatable.

Recycling

The resources can be divided into two parts, where most metals and materials are recyclable, whereas nuclear fuels, oil and coal, which all are burned, suffer from dissipative losses and small possibilities for significant recycling. The flow diagram in Figure 6 shows how recycling can maintain the input to society, but decrease the input from finite resources through mining. We also may use the simple equation for total consumption of a resource. This is given [ton/year] by Equation (6):

Total = Consumption / individual * individuals (6)

It is evident that we can reduce total consumption by reducing the amount each consumer uses, but also by reducing the number of consumers, and both. When we assess the effect of recycling we first estimate the supply to society [ton per year] using Equation (7):

Supply to society = Mining / (1-R) (7)

Where R is the degree of recycling on the flux from society. In the calculations, we take the present mining rate, and use the present recycling degree, to estimate the present supply to society. Then we calculate the new flow into society for other improved degrees of recycling. We then estimate time to scarcity, this is given by Equation (8):

Time to scarcity = Reserves/(Supply to society *(1-R) (8)

Then we calculate the new net supply needed to maintain that societal supply at present level at improved recycling rates, and use that to find the new burn-off time. The real flow to society becomes amplified by recycling, because part of the outflow becomes returned to the inflow. In Equation (7), R is the recycling fraction of the internal supply to society. In order to get the Hubbert-time to scarcity, conversion from burn-off based time to time to scarcity as 10 % of maximum production is (Equation 9):

Time to scarcity = 1.7 * burn-off + 2 (9)

The equation, was developed using earlier results from a parallel study (Sverdrup et al. 2011).

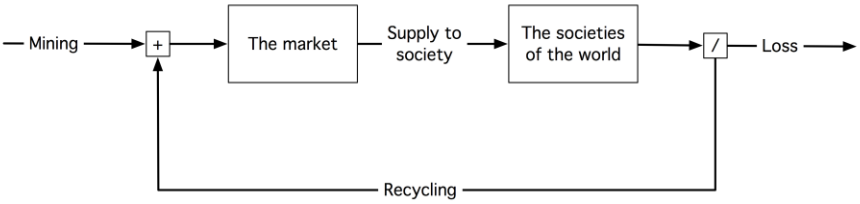


Figure 6. *The effect of recycling. This flow diagram shows that recycling can maintain input to society, but decrease the input from finite resources through mining. The real flow to society becomes amplified by recycling, because part of the outflow becomes returned to the inflow.*

Energy and material return on investment

An important aspect for all natural resource extraction or harvesting is the net energy return on investment, (EROI) or the net material return on investment (MROI), or both (EMROI). We look at it from the perspective of the first origin to the final point of use in Equation (10):

EROI = energy supplied /energy consumed (10)

And for materials the same principle was applied (Material Return On Investment) in Equation (11):

MROI = material supplied / material consumed (11)

It implies that when energy and materials are invested to harvest energy or materials or both, then we cannot spend more energy nor materials than we get out unless we want to end up with an overall negative balance. One such example is the extraction of tar sands in Alberta, Canada, or brown coal in Germany, where the energy input is very large, the materials needed are very large, and the benefit from these resources occasionally may cover the material and energy costs, but often run with a net deficit.

In discussion with colleagues, we sometimes have to listen to comments like "….we will win it up from seawater, there is plenty there, new technology will solve that…". Technically, phosphorus can be extracted from seawater, however, in the amounts society needs phosphorus, the task has a prohibitively high energy cost per unit phosphorus extracted, with huge material resources to be committed. Such comments do not consider the energy costs of extracting materials from ultralow contents. Unless very large new energy resources can be found for the work, the thermodynamic barriers cannot be passed. The same applies to extraction from many ultra-low grade resource deposits on land or the sea floors. The energy and material return on investment may be negative. This is why we are not taking aluminium out of solid granite, as there is more aluminium in granite globally than we could ever consume. But it will require unreasonable amounts of energy, water and chemicals to get it out, thus it would no longer be a cheap metal. When cheap and abundant oil is a thing of the past, i.e. the wealth of the current golden age, then the Energy Return on Investment (EROI) or material return on investment (MROI) or both will be negative, making many extraction efforts for energy and materials unsustainable. Without gas, oil and coal, many of the tasks can no longer be powered and are thus out of reach for society. Figure 5 shows the effect of Energy Return On Investment (EROI); when it becomes too low, then the investment cannot be paid back. The same reasoning applies to Material Return On Investment (MROI). For many projects today, the activities are approaching negative EROI. That is the main reason why we cannot mine the seawater for gold or phosphorus, thermodynamically the returns cannot pay the recovery beyond a certain dilution. It is simple thermodynamics, and there is no known rhetoric that can win over thermodynamics (Eddington 1926). If we let resource reserves slip down to scarcity, we are up against negative EROI for future extraction, and then we will have lost in the economic game. This brings in huge ethical issues for current Earth citizen for future generations. In Figure 5, Assets are produced as a result of work directly derived from the net raw materials or energy (the stippled line) and accumulation of infrastructure that is done with that gain, (the whole line), and the incurred costs of systems maintenance (dotted line) on those infrastructure. Energy is the main resource for this, but materials and phosphorus are also important drivers. The industrial material stock grows to a level that requires an enormous input of resources for maintenance in terms of material and employed humans. In the process of creating GDP growth, the resource reserves available are depleted, destroying the foundations for growth. As resource prices rise and mines are depleted, more and more capital must be used for obtaining resources, leaving less to be invested for future growth. The outcome is that investment cannot keep up with depreciation, and the industrial base erodes, taking with it the service and agricultural systems, which have become dependent on industrial inputs. The final wealth creation equation is (Equation 12):

$$\text{Wealth creation} = a*\text{Energy}+b*\text{Materials}+c*\text{Work} \quad (12)$$

where the values are $a=0.6$, $b=0.2$ and $c=0.2$ in a very approximate estimation by the authors.

The world model

A comprehensive WORLD5 model is being built by the author team, integrating a large number of world system aspects. An outline of the model is shown in Figure 15. The green coloured boxes are modules already developed and included into the integrated model structure (Oil, phosphorus, people, food, agricultural soils, market). Yellow boxes are modules developed and ready (metal mining, ecosystems, industrial production, but not yet integrated. The turquoise box called social systems module is undergoing development and a simple version has been integrated into the World Model. The magenta boxes are models in early stage of development that will be included at a later date when they have been finalized. The phosphate and population modules have been published earlier (Ragnarsdottir et al., 2011a, Sverdrup and Ragnarsdottir 2011a), the model is derived from a standard model originally developed at the IIASA at Laxenburg. The market model and part of the financial system was published in Sverdrup et al., (2012, and in Sverdrup et al., (2011a). The metal mining appears in Ragnarsdottir et al., (2011b), and in Sverdrup et al 2011b). The ecosystems model is partly published in Sverdrup et al., (2007) and Belyazid et al., (2010). The market module also appears in Haraldsson et al. (2012), where it is applied to the Chinese grain market and the Easter Island natural resources exhange in a tribal society in past history. WORLD5 shares many of the general features of the models used for the Limits to Growth study, which generated 3 versions of a model called WORLD1 to WORLD3. A preliminary version of WORLD5 was used for some of the assessments used in the final evaluation of our results. The present model is not yet published as it is in development. Figure 7 shows the organization of the World5 Model.

5. Results

The results of this study are of different types. They consist of a number of causal loop diagrams, which are important for interpreting and understanding the dynamics of material extraction and sustainable use of natural resources. The results are outcomes from calculations and these were combined with results from the synthesis we can do from understanding the systems. The calculation results are based on the three types of estimates, burn-off times, Hubbert's curve fittings to get times to scarcity and use of outputs from earlier systems dynamics model assessments developed by the authors (Ragnarsdottir et al., 2011, Sverdrup and Ragnarsdottir, 2011, Sverdrup et al., 2012).

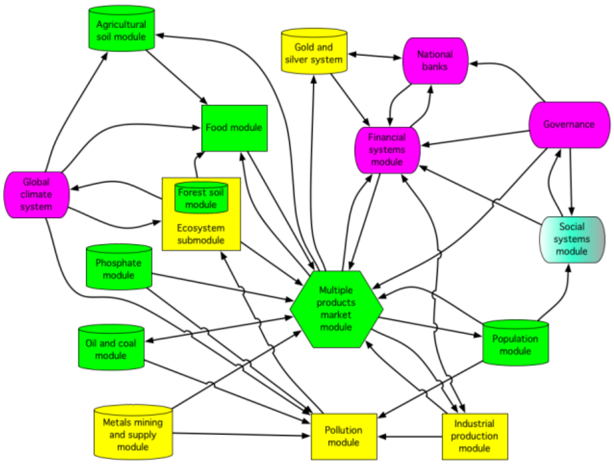


Figure 7 The organization of the World5 Model. The green colored boxes are modules already developed and included into the integrated model structure. Yellow boxes are modules developed and ready, but not yet integrated. The turquoise box called social systems module is undergoing development and a simple version has been integrated. The magenta boxes are models in early stage of development.

In Figure 8, the Hubbert-curve fittings for gold (a) and silver (b), copper (c), zinc (d) lead (e), indium (f), iron (g), molybdenum (h), chromium (i), nickel (j). We can see that the data suggest gold already passed the peak in 2000. Time to scarcity for gold would be about 2070. Equation (3) was used for the Hubbert's-curves. We have adapted four different Hubbert's-curves for the existing gold data and postulated in the future to consume up the high-grade reserves and the low-grade reserves, but to leave a part of ultra-low because of money return on investment limitations. These can be partly allocated to known gold-rushes of the past (Laherrere 2009a,b, 2010). Qualitatively, the same conclusions will be reached by adapting a single curve. Iron is found in abundance on Earth, but in limited supply for extraction of the metal at reasonable cost. The first iron production peak will appear in 2030, probably a secondary peak may occur in 2060 as a response to increased prices, recycling and the after-effects of a probable global recession. After that iron will become a scarce resource, unless recycling rates are improved significantly. Iron will not really run out completely, but after 2060, it will be a valuable metal, where today's material loss rates will appear as very wasteful. Running into scarcity of iron would lead to a very serious situation, and it is difficult to foresee the consequences.

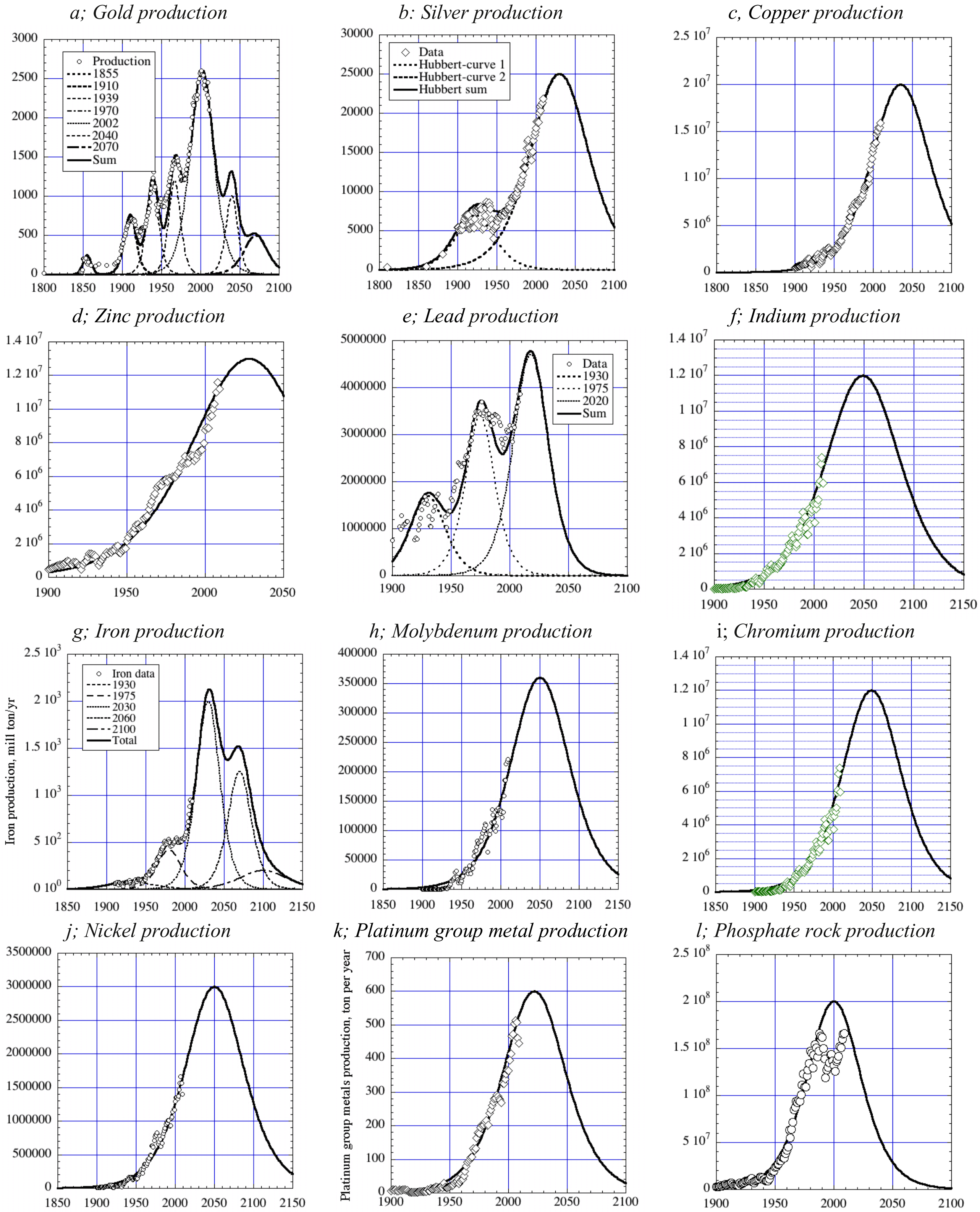
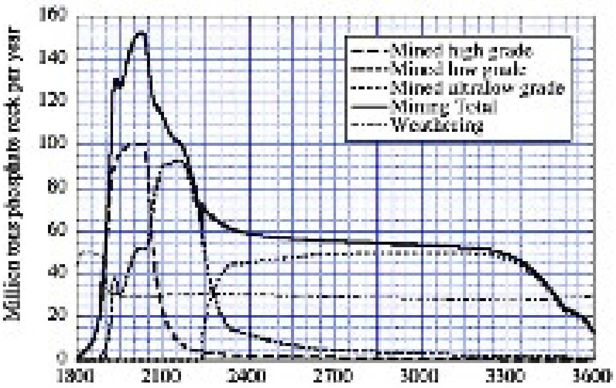


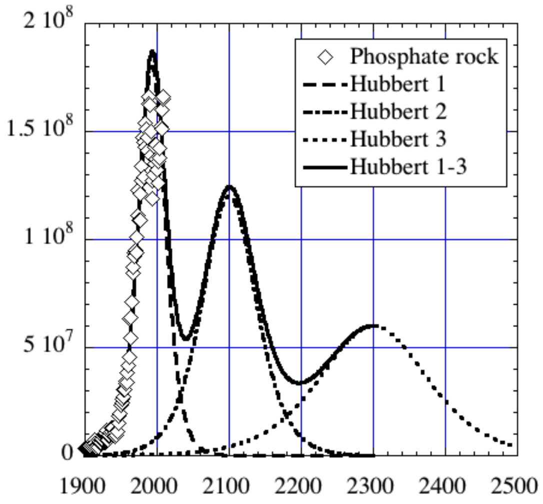
Figure 8. *Hubbert-curve fittings for gold (a) silver (b), copper (c), zinc (d) lead (e), indium (f), iron (g), molybdenum (h), chromium (i), nickel (j), platinum group metals (40% Pt, 43% Pd, 5% Rh, 5% Ru, 5% Ir, 2% Os) (k) and (l) that shows a one-curve phosphorus plot. We can see that the data suggest gold already passed the production peak. The scale on the Y-axis is production in ton per year, the x-axis is the year. Data: http://minerals.usgs.gov/ds/2005/140/*

Hubbert's-curve fittings for chromium (c) is shown. The parameters for the chromium curve were determined, and we may report that the peak time is t_{max}=2049 and that the total reserve is converging on approximately 1.9 billion ton. This amount is set by the shape of curve derived from the available data on production over time. Equations (2) and (3) were used. Hubbert's-curve fittings for nickel and molybdenum production rates were also made by the authors.

a; Phosphorus production



b: Phosphorus production



c; Phosphorus prospecting history

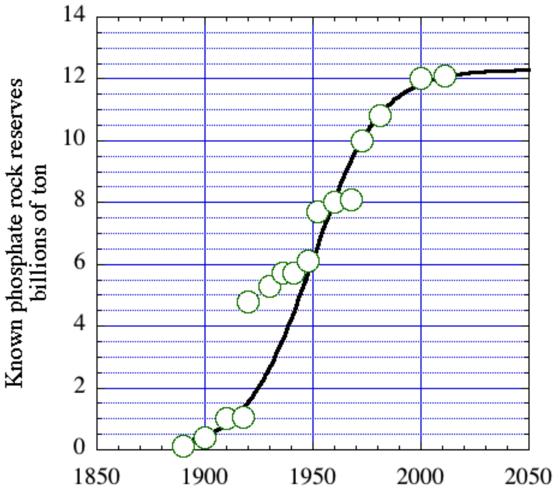


Figure 9. *Hubbert curve phosphorus and phosphorus reserve discoveries (a,b and c). (a) shows the output from a systems dynamics model by Sverdrup et al., (2011). The diagram in (Fig 8.k) was used to calibrate Equation (4) for phosphorus based on the prospecting history, yielding a maximum reserve of 12,4 billion ton (b, c). By 1945, 50% of the reserve had been discovered. The scale on the Y-axis is production in ton of material or per year or ton of phosphate rock per year, the x-axis is the year Data:* http://minerals.usgs.gov/ds/2005/140/

The curves are similar and nickel and molybdenum appear to peak at the same time as chromium, t_{peak}= 2050. They are simple shapes that are easily modelled with one single Hubbert's-function, (k) shows the fitting for the platinum group metals, suggesting a peak production of 550 ton per year and a total reserve of 39,000 ton when it all started in 1900. t_{max}=2022, and b=0.056 for platinum.

Table 1. Major global phosphate reserves (adapted from Ehrlich et al. 1992, Smil 2002, Fillippelli 2008, USGS 2008), and scaled for use in the integrated assessment model.

Deposit type	**Phosphate rock, tons**
High grade deposits	16,000 million
Low grade deposits	25,000 million
Ultra low grade deposits	50,000 million
Sum known reserves 1800	**93,000** million
Hidden high grade 1800	4,000 million
Hidden low grade 1800	20,000 million
Hidden ultralow grade 1800	50,000 million
Sum unknown reserves 1800	**74,000** million
Stored in soils of all kinds	200,000 million

The estimated stocks used in the systems dynamics modelling of phosphorus are shown in Table 1. Figure 9 shows the systems dynamics simulations (a), the Hubbert's-curve fittings (b) for phosphorus and phosphorus prospecting and production rates (c) (Sverdrup et al., 2011) or several Hubbert's curves. Using one single curve is shown in Fig. 8, diagram (l). We can see that the data suggest phosphorus already passed the peak in 1997. Then, possibly, half the reserved had been taken out. Time to scarcity for phosphorus will possibly go through two bottlenecks (in 2040 and in 2190) and into a third sometime after 2440, unless the global population has come down significantly by then (Ragnarsdottir et al., 2011a,b, Sverdrup et al., 2011). In diagram (f) we can see the prospecting data fitted to the integral Hubbert curve (Equation 2). Together these two Hubbert's-curve fits set the parameters of the Hubbert model for phosphorus in a narrow window. The curves sum up to the total reserves suggested by the diagram (f). Prospecting results for phosphorus reserves peaked in 1945, by then, 50% of the reserve had been discovered. Diagram (f) was used to calibrate Equation (4) for phosphorus based on the prospecting history, yielding a maximum reserve of 12,4 billion ton, and the curve parameter b=0.65. The reserve is estimated to be in the range 12-65 billion tons. Having the prospecting data and the production data, confines the parameters well. Recently USGS has reported a large upscaling of the Moroccan deposits to 51 billion tons of phosphate rock (UNEP 2011, Cordell et al., 2009, 2011). That would perhaps be good news if it is true, and it would postpone the phosphorus scarcity problem by about 50 years, but in no way solve it as our systems dynamic assessment showed taking such quantities into the scenario analysis (Ragnarsdottir et al., 2011a,b, Sverdrup et al., 2011). It would have to be verified properly and assessed tow what degree it can also be recovered at a reasonable return on investment for energy and materials.

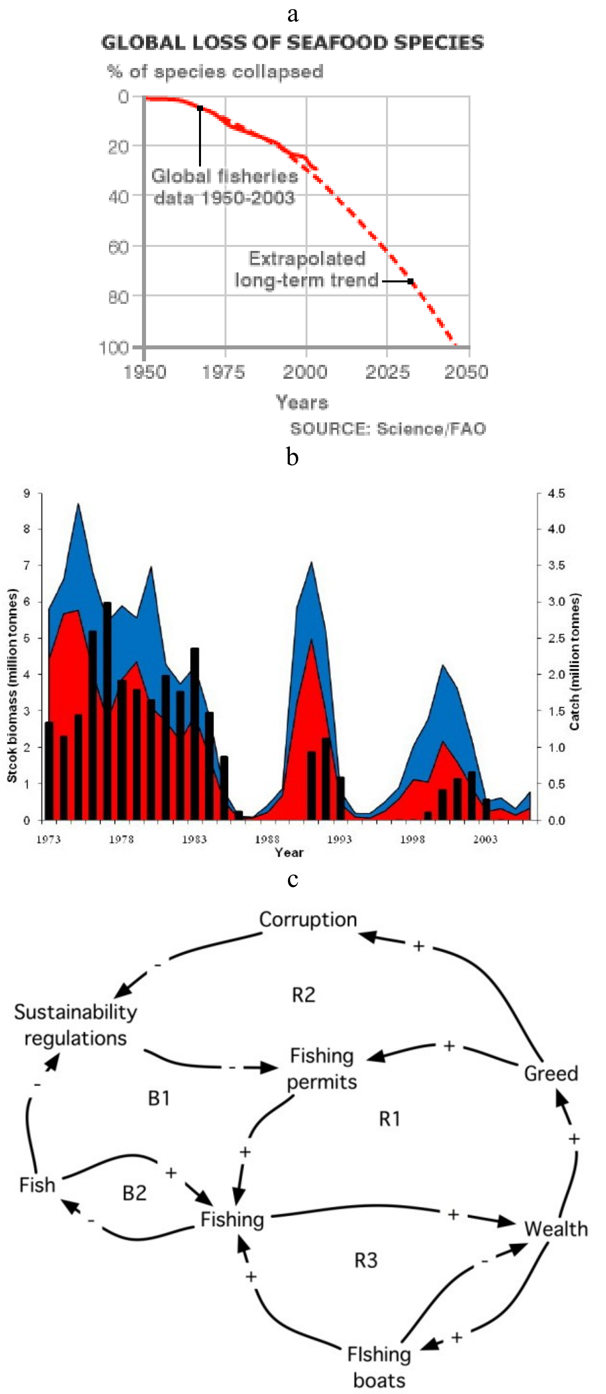


Figure 10. *Example of a renewable resource that is being fished to near extinction from capelin catches and stocks in the Barents Sea. (a) depicts that the fish species have declined globally. In (b) we can see the situation in the Barents Sea. The black bars represent catches, the colour bands are the fish stocks. In (c) we present the causal loop diagram that explains what is going on. Fishing leads to wealth, the wealth allows building of more fishing boats, leading to more fishing, but governance and fishing permits is supposed to limit the extent. Wealth leads to greed that leads to corruption that leads to larger fishing quotas, even if the fishing is far too high. Fishing leads to decreased ocean fish stocks, which in turn will ultimately limit fishing.*

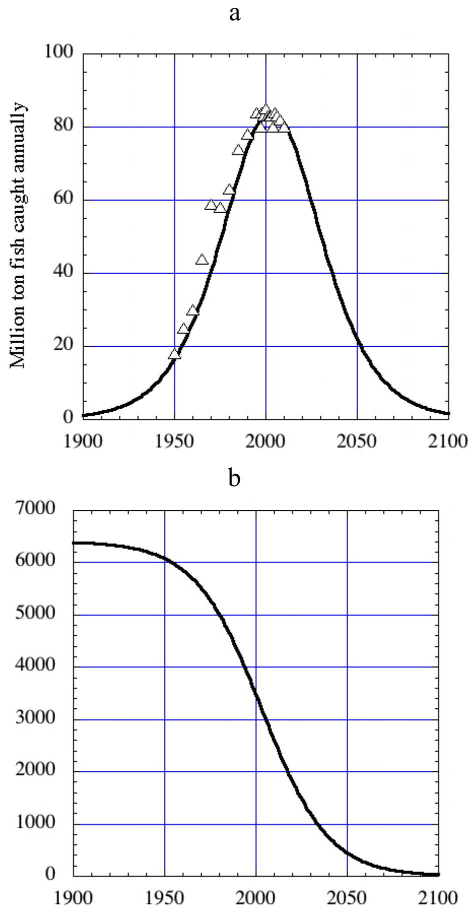


Figure 11. *The global fish production peaked in 2002-2003 as is shown in (a). In 2060, the catch will have sunken to 10% of the maximum. (b) shows the cumulative distribution of remaining stock in million ton, showing total global fish stock remaining in the world's oceans. (Data from FAO curves by the authors).*

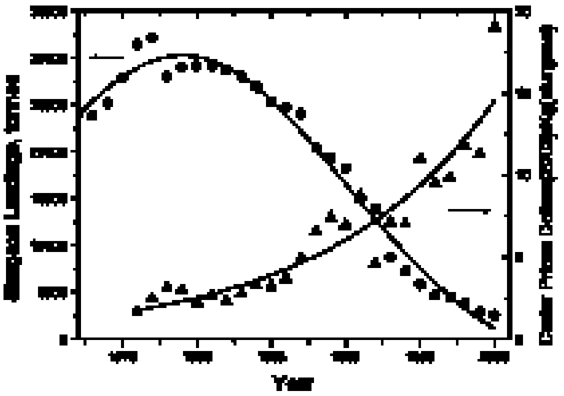


Figure 12. *A diagram taken from Bardi and Yaxley (2005) shows how the price goes up, when the amount of sturgeons in the market go down, but when the demand is constant. The price rises exponentially. In principle, all freely traded commodities have this behaviour.*

If it is true, it would for a short while allow for a higher global population, which would result in significant worsening of most other supply problems and make the inevitable final contraction more drastic and painful. The curve has a distinct S-shape, diagnostic for the fact that there are not very much more phosphorus rock reserves to be found.

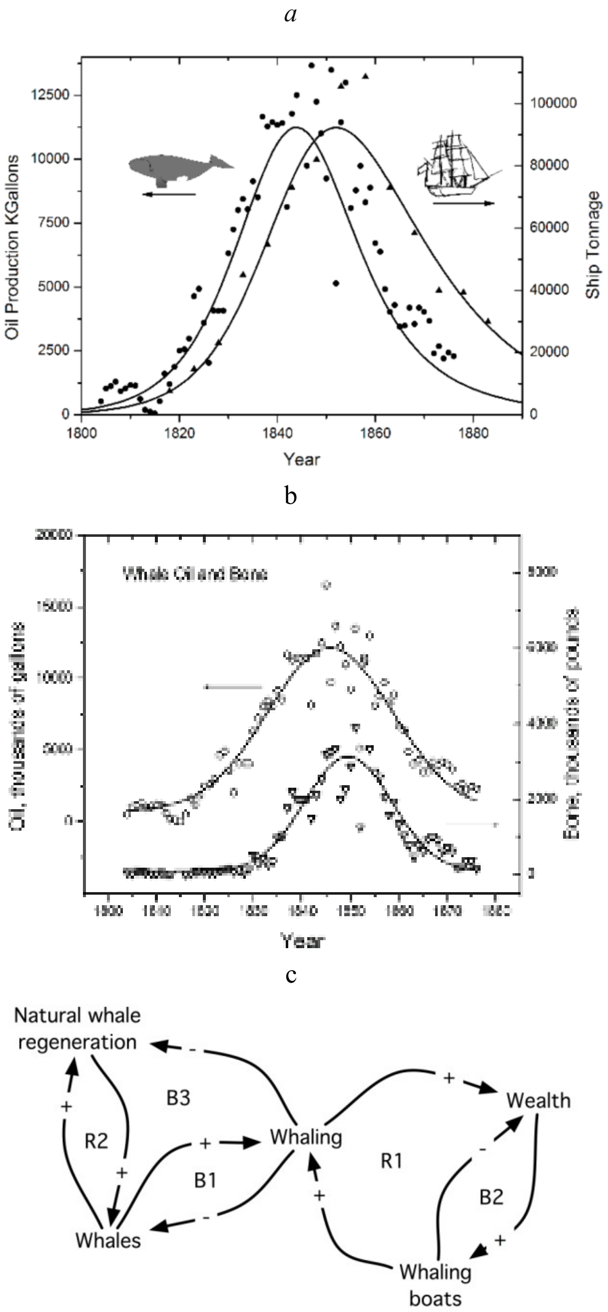


Figure 13. *A simulation by Bardi and Yaxley (2005), Bardi (2009a), using a simple predator prey model (Lotka-Volterra), and shows that if we have "peak resource", we will have "peak income". The dots represents numbers of whales caught to the left and number of whaling vessels to the right. We can see that a peak occurs in whale catch about 1848 and a peak in whaling vessesl occur about 10 years later. The causal loop diagram shown that explains the dynamics. "Peak whale", leads to "peak whaling".*

This implies that there was a 52-year delay between the peak in prospecting and the peak in production. Use of a systems dynamic model yield a much more sophisticated assessment (Ragnarsdottir et al., 2011, Sverdrup and Ragnarsdottir 2011). Phosphorus is one of few substances that has no substitutes, indicating that the price may potentially rise without any obvious limit if it is undersupplied. Phosphorus is an essential ingredient for all living organisms, and lack of phosphorus is equivalent with lack of food. We can see that the data suggest phosphorus already passed the peak in 1997-2000.

Figures 9-12 shows the Hubbert's curves for global fisheries. The global fish production peaked in 2002-2003 as is shown in diagram (a), (b) shows the cumulative stock estimated by us to remain in the oceans. In 2060, the catch will have sunken to 10% of the maximum, and fish as a food will be a rarity for the rich. Diagram (b) shows the cumulative distribution, showing to total global fish stock. Having once been at 6,4 billion tons of fishable fishes in the oceans, this has now sunk to approximately 2,2 billion ton fish, or about 33% of the original stock. These data demonstrate that existing national and international fishing policies are great failures, and that the failure to admit this fact has disastrous consequences for the global fish stock.

Figure 11 shows the global fish production peaked in 2002-2003 as is shown in (a). In 2060, the catch will have sunken to 10% of the maximum. (b) shows the cumulative distribution of remaining stock in million ton, showing total global fish stock remaining in the world's oceans. Having once been at 6,4 billion tons of fishable (Data from FAO curves by the authors).

Figure 12 shows a diagram taken from Bardi and Yaxley (2005) shows how the price goes up, when the amount of sturgeons in the market go down, but when the demand is constant. The price rises exponentially. In principle, all freely traded commodities have this behaviour.

Figure 13 (a) and (b) shows the correlation between whale catches and the number of whaling ships. (c) shows the causal loop diagram shown that explains the systems dynamics. More whaling leads to less whales, but in the process, sales of dead whales products yields wealth. More wealth leads to more investment in whaling boats, and thus on to more whaling, this is a reinforcing loop (R). Building whaling boats will decrease the wealth because of the costs, but it will promote more whaling. Finally, industrial scale whaling knocks out the natural regeneration of whales, the catch rate is simply overwhelming the natural reproduction rate, which is very low. Whales become a finite resource that is mined to exhaustion. Very similar data can be used to construct a similar picture for Norwegian whaling and wealth generation. The example is here with whaling and whales in the New Foundland Banks. "Peak whale", leads to "peak whaling", however with an overshoot and collapse archetype. This is fully predicable from what we know today. The examples shown in Figures 10-13 also illustrate that resources that have a natural regeneration rate may still be converted to a mining system, when the rate of extraction widely exceeds the natural or managed regeneration rate. This is particularly evident for forestry, where there are serious attempts ongoing to make long term harvest fit inside the constraints of natural regeneration (Warfvinge et al., 1992, Sverdrup and Rosen 1996, Sverdrup et al., 2002, 2006,). Sweden is such an example, where the Swedish forests may support an annual harvest of about 80-90 million cubic meter of roundwood per year, based on sustainable soil support and sustainable land management (Warfvinge et al., 1992, Sverdrup and Rosen 1996, Sverdrup et al., 1996, 2002). In this sector there is still a power-struggle going on, and there are many that still refuse to accept that a forest system may be destroyed by overexploitation. Because of their large forests resources, Sweden and Finland are very fortunate countries, and we conclude (Warfvinge et al. 1992, Sverdrup and Rosen 1996, Akselsson et al., 2002, 2006, Sverdrup et al., 2002) that with sustainability management, their forests could be sustainable possibly forever.

Building and ruining nations

Tainter (1988, 1996) starts off his analysis of the stability of nations by defining collapse, when an empire, nation, chiefdom or tribe experiences a "significant loss of an established level of socio-political complexity", manifesting itself in decreases in vertical stratification, less occupational specialization, less centralization, information and simpler trade flows, less literacy, decreased artistic achievement, shrinking territorial extent and less investment in the "epiphenomena of civilization" (palaces, granaries, temples, etc). He summarizes a large number of historic collapses. Figure 14 shows the example "Rise and fall of the Roman Empire" taken from (Bardi 2009, Bardi and Lavacchi, 2009, Fukuyama 2011). The content of silver in the coinage went down steadily from the time of Augustus until the end of the empire, by 300 AD, it was largely over in the Western part, the silver content taken to represent the availability of wealth in the form of silver. Resources dried up for the Romans as old resources became exhausted and the new territories could not deliver or the expansion stopped, and this seems from visual inspection to follow the shape of a Hubbert's curve reasonably well. The extent of human activity in the Roman Empire, in Italy, as reflected by abundance of archaeological artefacts, is shown in diagram (b). The manpower of the Roman army is shown in diagram (c), to illustrate how much surplus they could divert to defence and expansion (Tainter 1998, Diamond 2005, Bardi and Lavacchi, 2009, Fukuyama 2011) is shown in diagram (c). Resources lead to wealth that leads to more people and in the continuation that may lead to larger military might. That leads to larger territory and more resources in the resource base. By acquiring more new territories, implies that the same army must hold more land, thus it becomes weaker and more stretched. Wealth is extracted from the resources of the newly acquired territories, thus they decreased. Peak resource for the Roman Empire came in the years of Emperor Augustus, in 14 AD, imperial peak wealth seems to have occurred about 120 AD, the imperial expenses peaked in 270 AD, the Western Roman Empire perished a century after. In 410 AD, Rome was sacked by the Visigoths and their king Alariks, and the Roman economy was wrecked. It stayed as a theoretical empire another 60 years, but not in reality.

The Eastern Roman Empire had a wealth revival and income peaked under Justinian in the 600 AD, with a peak in state costs about half a century later. The state income and costs of the Eastern Empire (Byzantines) peaked for the second time 1000 AD. The collapse was precipitated with the sack of Konstantinopel in 1204 AD by the 4th crusade (Henrikson 1988, Tainter 1988, 1996, Greer 2005, Bardi 2009a).

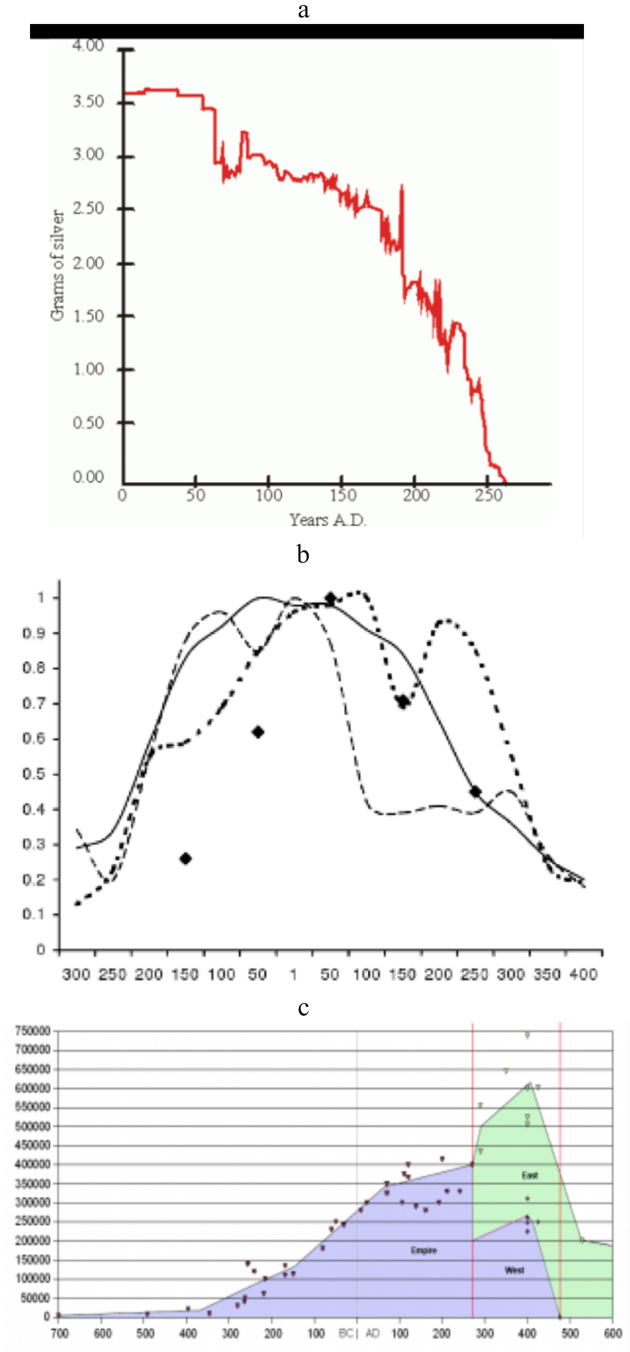


Figure 14. *The rise and fall of the Roman Empire. (a) shows the depletion of the content of silver in Roman coins 0-270 AD, (b) the habitation intensity as reflected by different archeological artifacts found as a function of time and (c) the manpower of the Imperial Roman Army (Blue and the Eastern Roman Army, (Green). The content of silver in the coinage went down from 0-270 AD, and this is taken to represent the availability of wealth in the form of silver (a). The extent of human activity in the Roman Empire, as reflected by abundance of archaeological artefacts reflect how much wealth came to the population 350 BC-450 AD, (b), as well as the size of the army (c) illustrating state expenditures on defence.*

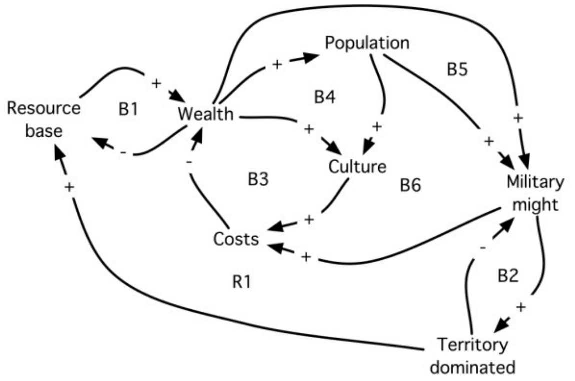


Figure 15. A simple causal loop diagram, to illustrate why the Roman Empire collapsed and disappeared. The causal loop diagram is a logical variant of Figure 2 discussed earlier.

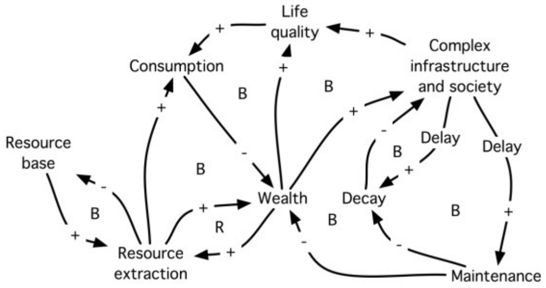


Figure 16. A causal loop diagram that explains a part of the reasons for the fall of the Roman Empire. As the Roman Empire developed and grew in size, it developed a state and society organization with increasing complexity. It will need maintenance in terms of replacement of key people at regular intervals, providing them with training and education. The backlog in terms of maintenance costs will eventually catch up with the stock of infrastructure, and may in the period after a large infrastructural expansion, become large enough to exceed the available income for maintenance and thus undermine the whole economy. If the overshoot is too large, it may lead to maintenance shortage and potentially collapse.

For the Western Roman Empire, the delay between resource peak and wealth peak seems to be about 100-200 AD, and the delay between the wealth peak and the cost peak seems to be approximately 100-200 years. We assume the time of maximum cost to be the time of maximum army size (400 AD). Thus, the collapse began 400 years after the resource peak. It never revived properly after that, as the resource base for a recovery was no longer present. The fall of the Roman Empire, has been much debated, from Gibbon's "Rise and fall of the Roman Empire" where he suggests that it came from a progressing moral inadequacy caused by the introduction of Christianity and the rise of decadence and corruption (Gibbon, 1776-1789). Later the reason has been suggested that it was a resource collapse (Diamond 2005), to a systemic collapse of a complex organization (Tainter 1988, Greer 2005, Heinberg 2005, 2011, Fukuyama 2011). In Figures 15 and 16, causal loop diagrams have been assembled that attempts to explain some of the reasons for the fall of the Roman Empire. To us it appears that the two first reasons are partial causes involved as components of a larger systemic collapse. There are several balancing loops in the causal loop diagrams in Figures 15 and 16 but only a few reinforcing based on resources. This illustrates why an empire with a good resource base can achieve great might, but that it almost inevitably also must decline and run out of resources. When complex systems fall out of their stable envelope of operation, the structural collapse of the complex organization may be catastrophic with respect to the structure and complexity. As the Roman Empire developed and grew in size (population and area), it also developed a state and society organization with increasing complexity. More and more complex structures, such as sewer systems, water supply systems, including complex piping in the cities, aqueducts, storage dams and cisterns, roads, road construction organizations, materials sub-suppliers, maintenance organizations, state agencies, offices for this and that, etc. But also complex structures in terms of complex organizations, like roads, canal and communications organization inside a larger empire, will need a coordinating organization with complex tasks. This would imply physical infrastructures, organizational structures for trade, security, finance and education, and personal networks between organizations and between people. All of that will need maintenance in terms of replacement of key people at regular intervals, providing them with adequate training and education, etc. The maintenance backlog inside the system 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 for large, well constructed, projects. The backlog in terms of maintenance costs will eventually catch up with the stock of infrastructure, and may in the period after a large infrastructural expansion, 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 potentially the collapse of structures.

For the Roman Empire, we can see how it evolved through different stages (Tainter 1988, 1996, Fukuyama 2011):

1. Expansion of the area of dominance with a very simple and low-cost organization, efficient for the specific task. As new territories are acquired, they are harvested for resources, energy, labour and skilled people at a high return on investment, and the energy and material return on investment (EROI/MROI) values are high.

2. The increased area of dominance, increase the running costs of operations, the increased access to low cost wealth leads to specializations and increased complexity of the organization of society. Increases in EROI/MROI stops and the EROI/MROI trend turns at this stage. That is the early warning signal for those that have done their systems analysis homework. The Imperial leaders at that time did not see it.

3. The continued expansion of the Roman Empire created a backlog of cost that slowly built up in the system. The further expansion, after the acquisition of the best resource reserves, ran into diminishing returns on further effort, the EMROI value fell. The exploitation of internal domestic resources stagnated and declined as they approach exhaustion. For the Roman Empire, this implied that local mines went empty, the landscape was deforested and the agricultural soils eroded away. This reduced the domestic resource base, and increased reliance on resources harvested far away or new conquests they could no longer afford.

4. As the energy and material return on investment (EROI/MROI) continues to decrease, growth stagnates as a result of falling EROI/MROI, and all the maintenance cost backlog catches up, deficits develop throughout the whole structure.

5. As the reserves inside the Imperial system structure run out, the system experiences broad-front systemic collapse.

The Roman Golden Age as defined by classical authors, actually occurred in 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 (Tainter 1988, 1996, Fukuyama 2011). These include Mycenaean Greece, with strong central authority, palace-oriented kingdoms with literacy, Greek City states (Athens), Chinese Empires, Persian Empire, Minoan state, but later states like the British Empire, the Soviet Empire, the American Empire.

Let's rock and roll!

Figure 17 shows co-correlation between quality rock music and peak oil in United States. Now, what are the authors up to? What does it really show? Are we joking with the reader? Not at all, we are serious and using an example found by Bardi (2009a). The ability to create rock music probably depends on several things, but mostly on an affluence in society, enough to create resources to create music with expensive equipment, to indirectly pay people to do it and resources to consume this luxury product. There may be some bias in the data, caused by tastes and maturity of opinion as well as exhaustion of a finite number of combinations that will lead to a quality product. So produced and successful rock music is a very rough simplification for wealth. Oil was the main driver of the United States economy after World War II, American oil production peaked in 1975, the global 3rd oil peak in production was in 1975. The decline of the domestic United States production is closely connected to the internal generation of wealth in the United States. After 1973, there has been little or no true economic growth in the United States, once we subtract for accelerated indebtedness, externalities and other incurred social and economic deficits (Max-Neef 1995, Daly 1996, Anielski et al., 2001, Anielski and Soskolne 2001, Lawn 2003, Erickson et al., 2008, Jackson 2009, Fukuyama 2011). What they believed was growth, was not growth in wealth production, it was growth of debt. This is not adequately reflected in the GDP estimates, because progress is better expressed by the Genuine Progress Indicator (GPI, Eriksson et al., 2008), as an alternative to the GDP. What is recorded as growth and progress in many countries, based on GDP, is in reality debt-driven and does not represent progress well. It would appear that the directors of the United States Federal Reserve and the United States Treasury (as well as many other large financial institutions) do not understand this well; in effect the government had consumed their assets to a rate of 100% of GDP by 2011, in addition comes the private indebtedness that is larger.

Global considerations

The recent global economic crisis and the still ongoing global debt crisis is such a systemic crisis where we are now in the last stages for systemic collapse (Tainter 1988, Bardi 2009a). Large deficits have been building up in many states of the modern western world, and these have temporarily been offset by loans against assets inside the system. When these loans exceed the value of the assets being placed as security, then the internal resource stocks within the systems will be gone, and the system has then lost its financial resilience.

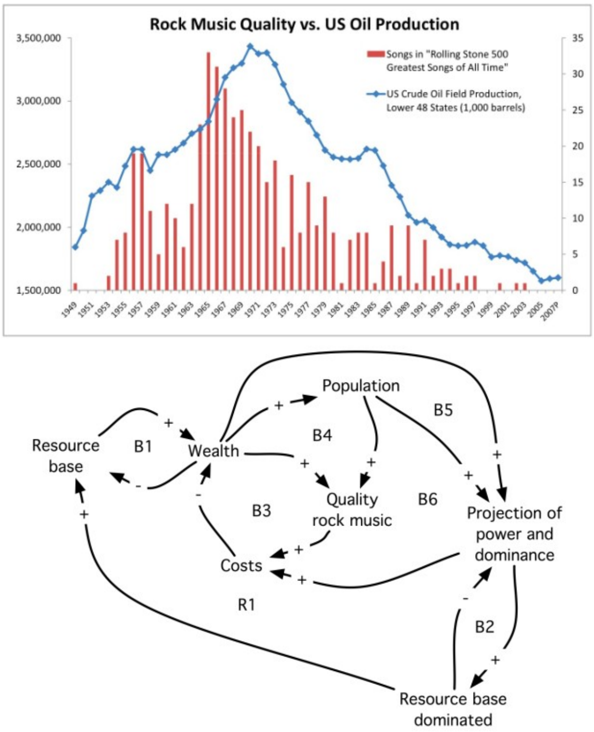


Figure 17. *Co-correlation between quality rock music and peak oil in the United States (Bardi 2009b). The causal loop diagram is attempting to explain what is going on. This causal loop diagram is the same as the one we used for the Roman Empire, the variables just have different commodity names. In the United States, oil was the dominant wealth provider.*

That means that no more money can be raised for the necessary change that will be needed to get out of the problematic situation. Figure 18 shows that peak oil occurred 2008-2010. Other, more detailed studies using a multi-cycle Hubbert model confirm this picture (Nashawi 2010). The curve for global oil production was prepared by the ASPO institute in 2009, and this particular figure was derived from their website in 2011. The global oil production follows the shape of a Hubbert's curve very well and the resulting global wealth production as well. When this occurs on a global scale, then there will be no extra global resource reserve left. Then the situation could become very difficult to steer way from a grand scale systemic collapse. The authors think we see signs that this is in fact taking place right now. Figure 19 shows how the Hubbert's equation (Eq. 3) was fitted to the Norwegian oil and gas production for the period 1970-2040, using official production statistics. In the diagram, we can see the typical "peak" behaviour, how the Norwegian oil and gas production peaked around year 2000. Diagram (b) in Figure 17 suggests that the time to scarcity for oil and natural gas produced from Norwegian oilfields is only about 20 years away (2030). If the market is left alone to put in recycling of energy or materials based on price only, then this will be too late. Normally, the price will rise with increasing scarcity, and thus the peak in value production will occur later than the physical production peak.

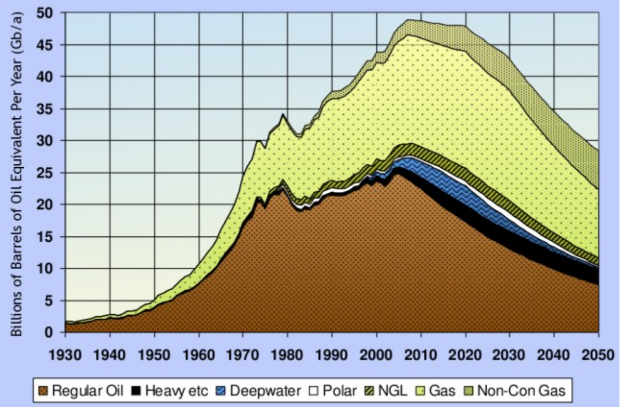


Figure 18. *We are now at global peak oil. The curve was prepared by the ASPO institute 2009, and derived from their website. The unit of production is gigabarrel of oil equivalents per year, or* 10^{12} *barrels per year, which is corresponding to 110 billion tons oil equivalents per year.*

Fossil hydrocarbons are not recycled, but the energy produced from it can be partially recycled after certain uses through heat exchanging, provided it is valuable enough. The Norwegian hydrocarbon production peak occurred in 2002-2003, the Norwegian oil-related income peak is predicted to occur in the years 2012-2014. However, when oil was supplied in surplus to the market, the price was low, and the oil was priced far below the real value. Thus, oil was squandered in those years, with little thought on how to save it or if the right price was obtained. Figure 19 suggests, that for Norway, there is a 30-year lag between peak resource and peak wealth.

Figures 18 and 20 shows that we probably passed global peak oil 2007-2008, so it already happened. If the same principles as were valid for the Roman Empire or the British Empire, also apply to the whole world, then peak global wealth should occur around 30 years later, 2037-2040. Norway has stored large part of that resource as capital in a special "oil" fund (approximately 70% of the value of the revenue stream from the oil fields), but now the government needs to think how that monetary resource should be managed in the best way for long-term benefit for the society in the future. A world of limits seems to be catching up with us all. Figure 21 shows the world coal production, distributed among different main producing regions (Source: Oil Drum, Bardi 2009b). The curve is based on observed production data and the production estimates for the next decade. From the empirical data, it looks like peak coal should be expected in the time period 2035-2045.

Figure 22 presents data and predictions for past and present United States coal production. Coal is more abundant that oil, but also a finite resource, with a low regeneration rate. In the past most of the high quality coal has been excavated, leaving the remaining reserves in the low-grade category. There have been four instants where the coal production has peaked for the economical growth periods. In 1992, around 50% of the United States coal reserve had been burned (Statistical peak year), however, the shape of the curve at that time did not show it as obvious.

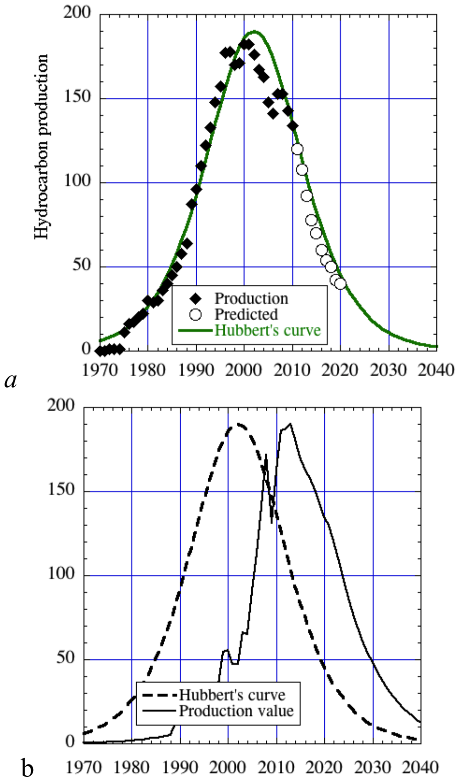


Figure 19. *"Peak oil" and "peak oil money" for the Norwegian hydrocarbon production.* ***a****: For the Norwegian hydrocarbon peak production occurred in 2002, the value peak will probably occur in 2012-2015.* ***b****: There is a delay of 30 years between resource extraction and peak wealth from that resource. Y-axis is production in ton per year (a) and billions of dollars, Data:* http://www.norway.org/ARCHIVE/business/businessnews/oilproduction/

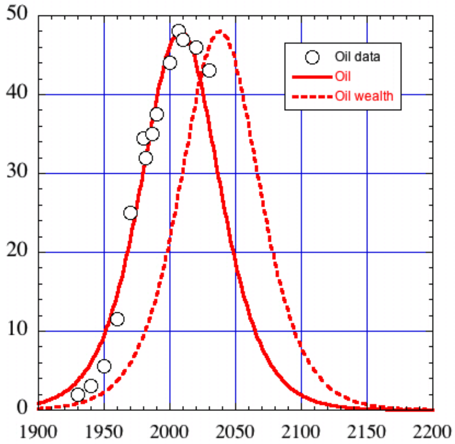


Figure 20. *Applying a Hubbert's curve to global oil production in Fig. 18, and using the oil price projections to suggest the oil wealth trajectory.*

The peak years are indicated by our analysis at the following dates: t_{max}=1928, 1955, 1980, 2020. The Hubbert's coefficients are: b1=0.05, b2=0.05, b3=0.05, b4=0.15, This dataset spans several major business growth periods, the economic period that lasted from about 1900 and culminated with the financial crash in 1929, the post World War II economic boom that rebuilt Europe, and that culminated in 1955, the modern economic boom that culminated in 1980, and the last boom that will be based on coal as the major energy source and culminate in 2020.

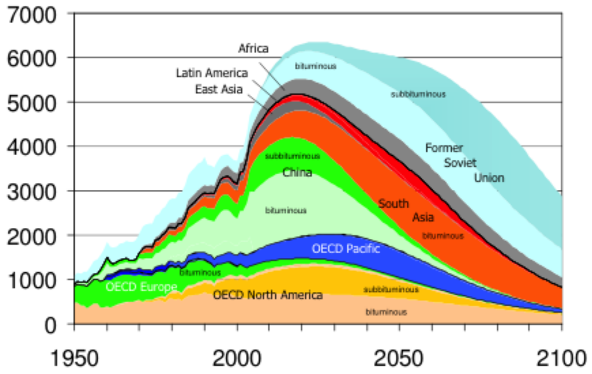


Figure 21. *The world coal production is shown, distributed among different main producing regions (Source: Oil Drum, Bardi 2009b). The global energy peaks in 2015.*

Then the coal reserves known today will be mostly consumed. That would comprise all known and anticipated coal reserves in the Unites States. The detectable S-shape of the prospecting curve (Bardi 2009b) suggests that hoping for new sensational discoveries of large coal-fields in the United States are vain hopes. Figure 23 shows the cumulative Hubbert's curve for world coal production (a). The coal production had by 2011 extracted 35% of all extractable coal in the world. In Figure 23, diagram (b) shows the world coal production, past and future (Adapted after Höök et al., 2008), with our analysis using multiple Hubbert's curves. Triangles represent observed data. By 2150, the worlds coal reserves will be for the purpose of mass production be exhausted. The world coal production and reserves follows a very similar pattern, total reserves are estimates at 710 billion tons, the peak year occurs in 2035 (b=0.045).

Table 2 shows the systematic delay between peak in reserve discovery and peak production. The data suggest an average delay of 50 years between peak discovery and peak production. The Hubbert's curve approach has been verified for a number of fossil resources (coal, oil, gas, phosphorus rock, gold, fisheries), and the data verify that the approach reconstructs the observations of the past with good accuracy. It is thus a verifiable concept (Fischer-Kowalski et al., 2011). For the global energy resources, the bulk comes from fossil sources, mainly oil, coal, gas and the nuclear fuel uranium. The renewable natural 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.

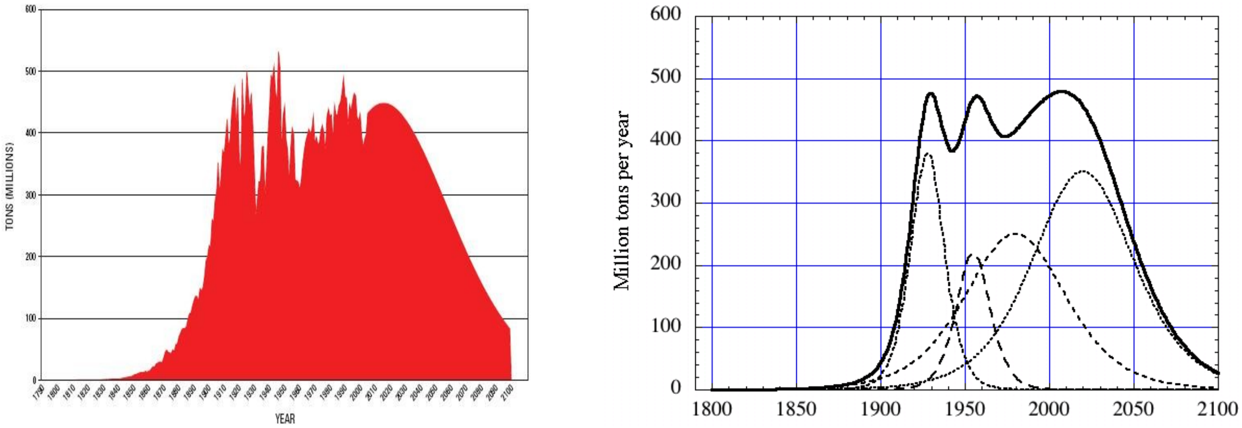
6. Discussions

The role of the free market

It is evident from the systems analysis and the dynamic runs undertaken for this study, that the market alone cannot cause the use of scarce resources to become sustainable in time. This is because the market is opportunistic in its function and nature; it has no memory and no future vision. At best, the market only partly optimizes for the instant. The rise in price when a resource becomes scarce will cause recycling to increase after a certain delay, but this occurs when too much of the resource has been consumed without significant recycling, and thus allows a large part of it to have become wasted. In addition to a well functioning market, proper governance is needed.

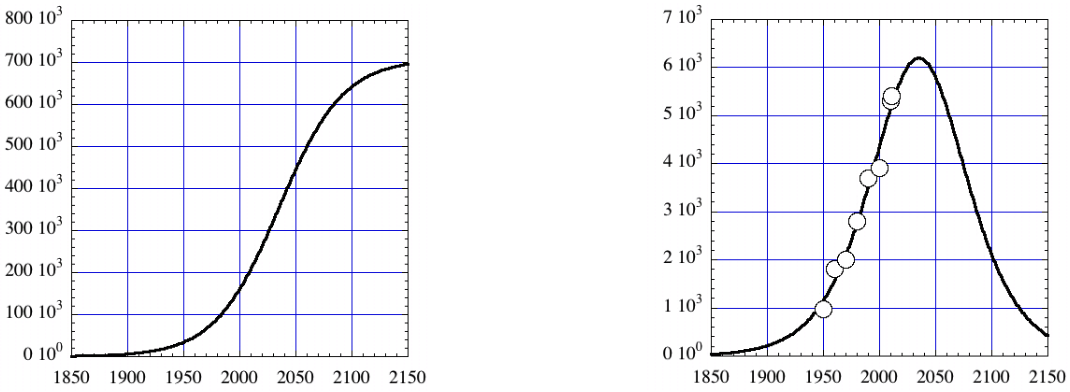
Also policy makers and the public do not understand the effect of exponential growth of extraction, and indeed the mathematician Arthur Allen Bartlett from the University of Colorado has stated that the "the greatest imperfection of mankind is that it does not understand the consequences of exponential growth." Interestingly his colleague and economist Kenneth Boulding (1956) argued that "anyone who believes that exponential growth can go on for ever in a finite world is either a madman or an economist." One can only imagine their vivid discussions and wish for everyone´s better understanding of the exponential function.

Governance must see to that the free market has a well-regulated arena to operate in as well as enforce that those game rules are obeyed. In such a role for governance lay also the long-term rules that govern responsible use of resources, such as recycling before the resource becomes scarce. The government must make rules that look forward with responsibility for generations to come and for the preservation of society. It is a widely spread misconception that a free market is a market without rules and regulations, with no interference from government, but the opposite is the case (Smith 1776, Friedman 1962, Forrester 1971, Friedman and Friedman 1980, Sterman 2000, Klein 2007, Lövin 2007, Sachs 2008). The demand for free economy to mean no rules is nonsense, even if it is cherished by certain political ideologies and even taught at many business schools. All games without rules soon deteriorate to anarchy or rule of the strongest, and markets without rules quickly become something that has nothing to do with free markets at all (most children know this as generic knowledge, but grown-ups seem to need references for it: Keynes et al. 1932, Friedman 1962, Klein 2007, Sachs 2008, Jackson 2009). Thus, we need a free, well functioning market, but not an unregulated, wild market. Sustainability constraints are among some of the most important additions to free market economies if they are to be made long term stable and long term sustainable. The modern world depends on the market systems for distribution and redistribution of goods, services and wealth, thus functioning markets are an integral part of a sustainable world. Figure 24 shows the total energy use per capita in different groups of countries. It seems like all that extra expenditure in materials and energy is for nothing and is just used because of poor consumer habits, regionally very low social trust between persons, poor public policies and poor policy planning. It is evident that Canada and United States uses twice the amount of energy as compared with the most prosperous European countries. For material throughput, the relationship is closer to 3:1. Canada and United States are not able to deliver any better life quality to its citizens than for example Sweden, Denmark, Netherlands, Switzerland or Austria - rather the contrary is the case (Fischer-Kowalski et al. 2011). Whereas Switzerland has a metabolic materials rate (MMR) of 12 relative units and Norway of 14 units, the United States has 24 units. At the same time Switzerland has a GDP of per capita 35 units, Norway has a GDP per capita of 38 units and the United States has a GDP per capita of 36 relative units. The ratio MMR/GDP per capita of Norway is; 0.37, for Switzerland it is 0.34 and for the United States it is 0.66. This tells us that using the most materials per produced unit is definitely not to be considered as a success story (Fischer-Kowalski et al. 2011). The United States demonstrably do deliver an inferior quality of life in comparison to the other nations mentioned above over a number of life quality parameters. Alternatively, with social and governance reforms that would improve United States governance to the North/Central European standard, the United States should be able to cut its energy use to half without reducing the quality of life, as well as cutting their cost of energy imports and state administration significantly. However, then a number of political hang-ups in the United States political establishment and electorate must be overcome, as well as American lobbyism (an important kind of legalized corruption to change the democratic process) would need to be strongly curbed.


a

b

*Figure 22. United States coal production analysis. Data (**a**) and predictions for past and present United States coal production (**b**). Hubbert's curves for the US coal production (The statistical peak year), Source: casafoodshed.org/archives/2008/12/,blogs.wvgazette.com/. ../category/peak-coal/*


a

b

Figure 23. *Global coal reserves and peak prediction. **a** shows the cumulative Hubbert's curve for world coal production, the data points have been omitted. **b** shows the world coal production, past and future (Adapted after Höök et al., 2008). Triangles are observed data. Adapted from USGS statistics 2010.*

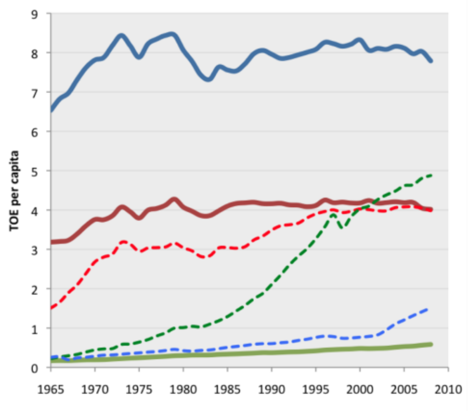


Figure 24. Total energy use per capita in different groups of countries. It is evident that Canada and United States uses double the amount compared to the most prosperous European countries. Canada and United States are not able to deliver any better life quality to its citizens despite this larger supply of energy.

Table 2. *Hubbert's curve parameters used in this study. The key elements of global energy supply show peak behaviour. P_{max} is oil equivalents for all energy sorts, but mass for fish.*

Energy sort	Hubbert's constant b	Peak year	P_{max} mill ton	Assessment of sustainability
Oil and gas	0.050	2008	6,200	Fossil, finite, peak 2008. Dwindling EROI
Coal	0.044	2035	3,000	Fossil, finite, peak within 20 years. Dwindling EROI
Fish	0.055	2003	84	Renewable, vulnerable to overexploitation. Dwindling EROI.
Nuclear, conventional	0.080	2080	160	Fossil, finite, will peak in 70 years. Intermediate EROI.
Nuclear, new thorium breeder paradigm	0.020	2200	6,000	Fossil, finite, High efficiency, peak in 10,000 years, mining and processing may be oil limited. Intermediate to high EROI.
Hydropower	0.020	2100	500	**Renewable**, Finite but inexhaustable, materials limited. Persistently high EROI.
Photovoltaics		2050	50	**Renewable**, materials limited, energy-intensive production. Low EROI,
Wind energy		2050	50	**Renewable** Finite but inexhaustable, installations may be materials limited. Low EROI
Bioenergy		2200	800	**Renewable**, capacity limited,

Times to scarcity under different scenarios

In Table 3 we present the burn-off time for different materials and the classification of the degree of urgency, for a number of scenarios. For the assessment made here we have considered a number of scenarios for the future. These are as follows:

Target 1:	Business-as-usual, (BAU) no change in recycling from today.
Target 2:	Improved habits in the market, at least 50% recycling or maintain what we have higher than 50%, improving gold recycling to 95%.
Target 3:	Improve recycling to at least 70% for all elements.
Target 4:	Improve all recycling to 90%, except gold to 96%.
Target 5:	Improve all recycling to 95%, gold, platinum, palladium, rhodium to 98%.
Target 6:	Improve all recycling to 95%, except gold, platinum, palladium and rhodium to 98%, assume same per capita use as in Target 4, but assume that population is reduced to 3 billion.
Target 7:	Improve all recycling to 95%, except gold, platinum, palladium and rhodium to 98%, assume ½ of the present per capita resource use in Target 4, but assume that population is reduced to 3 billion.

The abbreviations within brackets are found on top in Table 3. The cells red, orange and light orange represents scenarios for individual materials where the present extraction rates and materials handling can in no way be considered to be sustainable. Cells coloured in yellow, implies we have sufficient time to improve towards sustainability, cells coloured green are different degrees of soft or hard sustainability. The outputs are burn-off estimates in years. The burn-off rate suggests the year when the materials price starts to rise sharply. The Hubbert's estimate time to scarcity is about twice the burn-off time estimate as estimated in our earlier study (Ragnarsdottir et al., 2011b). For some elements that are major infrastructural elements, the significant corrosion rate was considered to be non-recoverable. The metals concerned with large bulk losses from corrosion are iron, aluminium and zinc. The colour shows the classification of the degree of urgency in Table 3. The scenarios corresponding to squares coloured in red, orange and light orange can in no way be considered to be sustainable. Yellow, implies we have sufficient time for mitigation, green are different degrees of soft or hard sustainability. However, if the technological and security challenges of breeder reactor designs and fuel recycling are overcome, then the perspectives for uranium and thorium may change significantly.

Peak world and the end of the golden age

Figure 25, diagram (a), shows that both oil and coal will peak in the near future, the oil peak was passed in 2008, the coal peak comes in 2018, and wealth peak will arrive in 2035. From then on no more global growth of GDP will be possible, and a new economic paradigm for supply of life quality to the citizens must be in place. The simulation is made according to the assumption that wealth is caused by oil and coal mainly (Hubbert's curve parameterization; the Hubbert's curve coefficients b1=0.044, b2=0.044, b3=0.050, the peak time estimates t_{max}= 2018, 2038, 2100). The wealth curve is especially interesting to discuss. Oil has peak and coal will peak in the near future, the oil peak was passed in 2008, the coal peak comes in the period 2020-2035, and oil wealth peak will arrive in 2035, coal wealth will take place around 2050-2060. By combining the curves, we get the result that the peak energy will occur in 2018, and the peak wealth from energy will occur in 2045.

Table 2. Estimated **burn-off times** according to the different recycling, materials use and populations scenarios, output estimates of burn-off times are in years. The time to scarcity as estimated with the Hubbert's curve or a systems dynamics model (Sverdrup and Ragnarsdottir 2011) would be the double of this estimate. All values are years counted from 2010 and forwards.

Element	BAU	50%	70%	90%	95%	95%+3bn	95%+3bn+½
The structural metals							
Iron	79	126	316	316	632	1,263	2,526
Aluminium	132	184	461	461	921	1,842	3,684
Nickel	42	42	209	419	838	1,675	3,350
Copper	31	31	157	314	628	1,256	2,512
Zinc	20	37	61	61	123	245	490
Strategic metals and materials							
Manganese	29	46	229	457	914	1,829	3,668
Indium (Zn)	19	38	190	379	759	1,517	3,034
Lithium	25	49	245	490	980	1,960	3,920
Rare Earths	455	864	4,318	8,636	17,273	34,545	69,000
Yttrium	61	121	607	1,213	2,427	4,854	9,708
Zirconium	67	107	533	1,067	2,133	4,267	4,554
Tin	20	30	150	301	602	1,204	2,408
Cobalt	113	135	677	1,355	2,710	5,419	10,838
Molybdenum	48	72	358	717	1,433	2,867	5,734
Rhenium (Mo)	50	50	125	250	500	1,000	2,000
Lead	23	23	90	181	361	722	1,444
Wolfram	32	52	258	516	1,031	2,062	4,124
Tantalum (Nb)	171	274	1,371	2,743	5,486	10,971	22,000
Niobium (Ta)	45	72	360	720	1,440	2,880	5,760
Helium	9	17	87	175	349	698	1,396
Chromium	225	334	1,674	3,348	6,697	13,400	26,800
Gallium	500	700	3,500	7,000	14,000	28,000	56,000
Arsenic	31	62	309	618	1,236	2,473	4,946
Germanium	100	140	700	1,400	2,800	5,600	11,200
Titanium	400	400	2,000	4,000	8,000	16,000	32,000
Tellurium (Cu)	387	387	1,933	3,867	7,733	15,467	30,934
Antimony	25	35	175	350	700	1,400	2,800
Selenium	208	417	5,208	10,417	20,833	41,667	83,000
Precious metals							
Gold (Ag)	48	48	71	357	714	1,429	2,858
Silver (Cu)	14	14	43	214	429	857	1,714
Platinum (Ni)	73	73	218	1,091	2,182	4,364	8,728
Palladium (Ni)	61	61	183	913	1,826	3,652	7,304
Rhodium (Pt)	44	44	132	660	1,320	2,640	5,280
Uranium	61	119	597	5,972	11,944	23,887	47,500
Thorium	187	367	1,837	18,375	36,750	73,500	147,000
The limiting nutrient for all life							
Phosphorus	80	128	640	3,200	6,400	12,800	25,600
Legend, yrs	0-50	50-100	100-500	500-1,000	1,000-5,000	>10,000	

After 2045, no more global growth of GDP will be possible, and a new economic paradigm for supply of life quality to the citizens must be in place and operating if political problems are to be avoided. The colour graph in Figure 25 (a) is taken from the Oil Drum webpage. Next is a diagram below it with three curves (b). The first curve (whole black line) is the Hubbert's curve for world energy production, including data (Δ). The second curve (dotted curve) is the wealth creation from this energy production, taking price dynamics into account. The third curve (tightly dotted line) is the cost curve that is resulting from investing the wealth at the normal rate into physical and social infrastructures, if a substantial part of the revenues are invested into energy or organizational infrastructures, with a delay of 50 years between initial investment, and the cost of maintenance for infrastructural renewal increasing by 1.5 % per year. In area A in Fig 25 (b), the global EROI is positive but declining towards 2030. After point A (2030) and in area B (2030-), the wealth production has decreasing energy backing, and this is compensated only by price rises. After point C (2075) and in area D (2075-), costs are larger than wealth production. A global society that is in D must rapidly contract or risk thermodynamically driven collapse. Critical points in future policy development are in 2015-2020 when it is predicted that peak energy occurs, in 2030 when it is predicted that wealth creation becomes undersupplied with energy, in 2060 when the infrastructural costs in energy cannot be met and in 2075.

The integrated world system simulation model used to produce the runs used for this study are similar to the approach taken by Meadows et al. (1972, 1992) in their World3 model in the limits growth study. However, they lumped energy and all material resources, missing the dynamics of having them coupled but separate.

Table 4. *Delay between peak in reserve discovery and peak production. The data suggest an average delay of 50 years between peak discovery and peak production.*

	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
Coal, United States	1950	1992	42
Phosphorus, global	1955	2000	45
Coal, Great Britain	1880	1922	42
Chromium, global	1944	2050	106
Iron, global	1978	2025	45
Global copper	1996	2035	39
Global silver	1995	2030	35
Whales	1842	1860	18
Roman Empire	28 AD	140 AD	112

Materials can be recycled very well, whereas much of energy use is in it's fundamental function dissipative. We have taken on the development of a new world resource model. In the new global model, we have lumped the metals into some categories according to their importance and role in society (structural, strategic, financial and energy-related). The strategic financial metals gold, strategic materials platinum group metals, silver are classified as precious metals we hold apart in the assessments. The strategic metals lanthanides, indium, we see as one group, the infrastructural metals iron, aluminium, zinc, and copper, and we have specifically kept phosphorus and fossil carbon-oriented energy substrates separate. We have lumped oil, gas and coal all into general hydrocarbons. Lack of resources is a very dangerous situation globally, there are convincing examples where this 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: Hardin (1968), Ehrlich (1968), Meadows et al. (1972, 1992, 2005), Tainter (1988), Ehrlich and Ehrlich (1992), Leslie (1998), Haraldsson et al. (2002, 2007), Diamond (2005), Greer (2005), Klein (2007), Tilly (2005, 2007), Lövin (2007), Sachs (2008), Brown (2009b), Rockström et al. (2010), Fukuyama 2011). The solution to our sustainability problems are as much in the social domain as anywhere else, engineering and economics deal with social machinery, however, people and social processes control and shape behaviour.

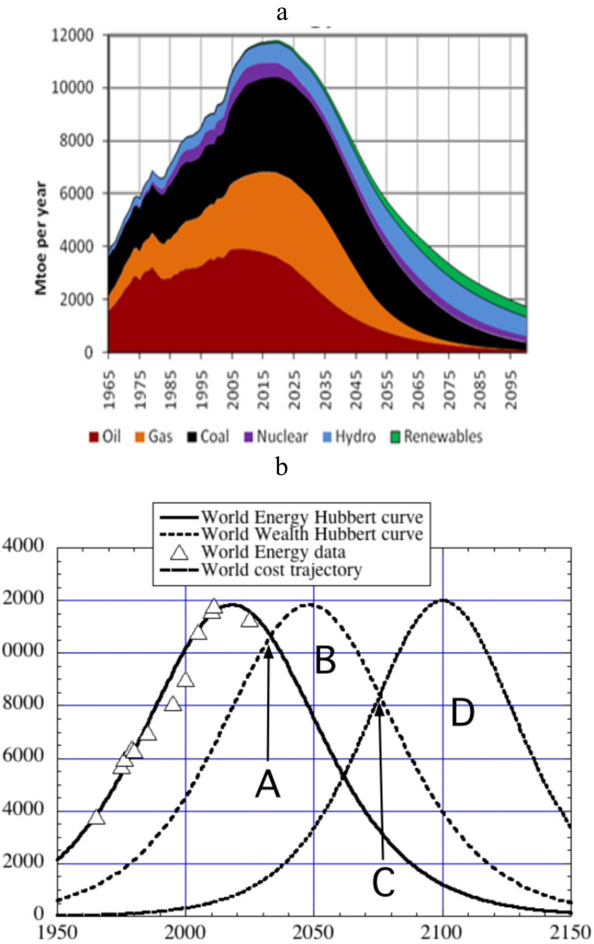


Figure 25. *(a) is a graph redrawn from the Oil Drum webpage, showing past global energy use and a future projection. (b) is a diagram with 3 curves; The first curve is the Hubbert's curve for world energy production, Δ are data points. The next curve is the wealth creation from this energy production, taking price dynamics into account. The third curve is the cost curve that is resulting, if a substantial part of the revenues are invested into infrastructures and the maintenance costs for renewal are increasing by 1.5 % per year. In area A, the EROI is positive, and wealth is oversupplied with material. After A and in area B wealth production has decreasing resource backing, compensated only by price rises. After C and in area D, the costs are undersupplied with wealth.*

The sustainability challenge is thus a social challenge and the willingness to change behaviour. The use of all resources available to us at maximum rate, probably do possess a threat or significant limitation to future generations, and carries moral problems with them (Norgaard and Horworth 1991, Costanza and Daly 1992, Beder 2000, MacIntosh and Edward-Jones 2000, Heinberg 2001, 2005, Ainsworth and Sumaila 2003).

In Figure 26, the apparently linear world has been made partially circular with respect to resources. At the end of the golden age (Meadows et al., 1972, 1992, 2005, Tainter 1988, 1996, Greer 2005, Heinberg 2001, 2005, 2011, Sverdrup and Ragnarsdottir 2011, Sverdrup et al. 2012a,b), the world will come back to being circular for humans. This will happen as a consequence of the principles of mass balance. When fossil natural resources finally give out, then any material will have to come from renewable resources or from recycling of what we already have. There are simply no other sources to tap energy and resources from.

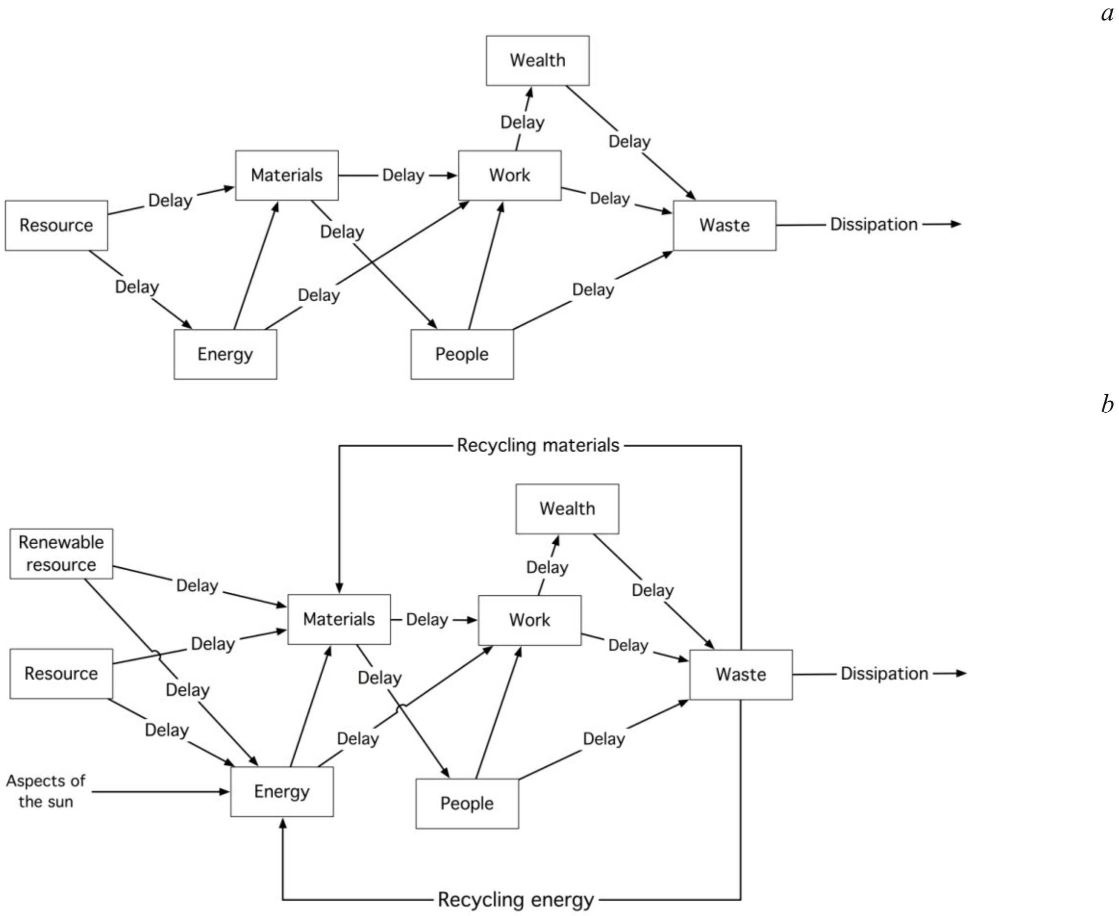


Figure 26. (a) *Present behaviour makes the world apparently linear. This illustrates in the top drawing how resources, after a delay, are converted to materials, which after a delay will be converted to population, and work and wealth which all after a delay becomes waste, which after a delay becomes dissipated and lost.* (b) *We need to make the apparent linear world into a circular world. The cycle must be complemented with recycling loops for materials and energy, where materials and energy are recycled to a large degree as possible. Then output is returned as input. However, not at any cost, energy and material return on investment must be positive (EROI>0 and MROI>0).*

When fossil natural resources finally give out, then any material will have to come from renewable resources or recycling of what we already have. There are simply no other sources to tap from. Figure 26 illustrate that before the end of the golden age, the cycle must be complemented with a recycling loop, where materials and the energy are recycled to a large degree as possible, if a decline is to be avoided. A decline in the resource base will with a delay, result in a less complex society when the society is starved on food and adapts by reducing maintenance costs and reduce infrastructures to maintain. Exploitation of resources will normally increase wealth as exploitation increases. This in turn will lead to more infrastructure and property in ownerships. Wealth and assets also are used in debt expansion, causing further economic expansion. However, as time goes by, decay will catch up with the infrastructures, property and maintenance costs will come in. When resources are in decline, then exploration of resources will also decline, decreasing available wealth in the end. However, the maintenance costs and the costs of the debts will still be there. If the debts and infrastructures to maintain have been allowed to grow too large, costs will exceed income and problems will follow. This process is what we see as being the root cause of the problems behind the economic problems of Netherlands in the 1970'ies after the decline of the natural gas fields (peak gas), Sweden in the 1980'ies due to state overspending on public welfare (too large money handout-structures, declining metals and wood prices an industrial recession, a real estate bubble), and currently in the United States, Greece, Ireland and other countries (gross overspending, maintenance backlogs, eroding taxation, cost of unsustainable warfare) coming into full force after 2007.

The punishment for not listening to early warnings

During the 1700's, the global community made a terrible and now a bitter mistake, by not listening to Malthus projections (Malthus 1798), and allowing the global population slip above 700 million and into a pathway towards not being sustainable (Ehrlich 1968, Forrester 1971, Meadows et al., 1972, 1992, 2005, Brown 2009, Ragnarsdottir et al., 2011, Sverdrup and Ragnarsdottir, 2011). Unfortuneatly, human societies were not up to the task at those times, because at that time democracy in most countries was a rarity, and religious totalitarianism was common, intolerance and oppression was rather the norm than the exception, and, then as now, future planning in politics, business and society was grossly insufficient. In 1973, when the United States went through peak oil, and started importing large amounts of oil from the Middle East, the world had a last warning of what happens when peak oil is passed. That coincided with the assessment mad by the Club of Rome with their "Limits to growth" report that was published in 1972 (Meadows et al. 1972, 1992, 2005). The report was heavily criticized by the free market fundamentalists of mainly the United States and Britain, however, all of that criticism has been utterly disproven by hard field facts (Friedman 1980, Tainter 1988, 1996, Kelsey 1995, Boetteker 1997, Soros 1998, 2008, Petsoulas 2001, French-Davies 2006, Albers 2007, Klein 2007, Kozul-Wright 2007, Jackson 2009). Despite this, the erroneous opinion of the critics have remained as the general public impression, causing loss of time that in the end may prove damaging to many. Sadly, the lesson was not properly learned, it was only shortly heeded by some and then fast made to be forgotten by the public. The key designers for this were mainly the free market fundamentalists of the United States and Britain, and at that point politicians in America and Europe slipped significantly in their statesmanship and their strategic planning and leadership. The economic science failed grandly in not doing systems thinking, and they all failed to see the ramifications of a world that is limited and finite in capacity and extent. This has lead to a credibility crisis towards national economists in the public eye. Soon, the time is reached when the damage done to society and the national economies will be irreversible (Tainter 1988, 1996, Greer 2005, Heinberg 2005, 2009, 2011, Fukuyama 2011, see also the discussion of Figure 25) and these leaders and thinkers will go down in history as some of the worst statesmen we ever had, at a time when we needed a totally different quality of leadership.

How long can we wait?

With what we know today, we know what we need to do to plan for the future, and that we have the technology to do it. It is in these next 50 years we will have the energy resources to do the work that is required, while when the resources all have become scarce, and the global population larger, then our possibilities will be far less or possibly gone (Meadows et al. 1972, 1992, 2005, Greer 2005, Heinberg 2005, 2011). However, the lead-time to plan and start many of the necessary measures are quite long and in some important cases may be 10-20 years in order to get them right. A simple thing as just finding a new phosphate rock deposit and starting a new mine normally takes about 7-10 years, all-in-all. The process of going from first idea to a ready built factory in full production operation takes the same amount of time. We can get a warning from declining discoveries, when they occur, there will be about 40 to 50 years left before the peak, and about the same time until scarcity. This is exemplified in Table 4.

We experience similar lead times when it comes to changing social and political conditions. The development of critical loads policy under the LRTAP and also adopted partly in the EU directive, consumed a lot of time, it started in earnest in 1987 and continued through to 2007. From first idea (Grennfelt and Nilsson 1987) to concept (Sverdrup and Warfvinge 1988a,b), to first signing of the protocol (Göteborg protocol 1999), ratification by a majority of members (2004) and implementation (2007), in all it took 20 years. If we are serious about sustainability and its implications and care about our future quality of life, our safety, our freedom embedded in the functioning democratic state, then we better start now, because if not, then we will not be ready in time. Many very complex challenges in the economic arena, the social arena, the population issue and in the engineering arena all will take substantial time and much research in order to create the sustainable policy measures require. We must have respect for the large amount of work that will go into adequate planning and development of national action plans. None of the present international policy committee processes existing today are really adequate. A new initiative is needed and the process needs solid reinforcement from professional scientists.

Discussing policy advice

Developing policy advice is a long process, and our recommendations made here have not been quality-checked against multiple runs using integrated assessment models, partly because adequate integrated assessment models do not yet exist. However, the process needs to start with some kind of initial proposals. As demonstrated in this communication it is imperative that we start on a path towards sustainable development worldwide. The information in Table 1 tells us that both resource per capita use and the number of consumers are globally far too large. Soon it is not about the rich to contract and the poor to converge, it will be about that all must contract. The sustainable population from a perspective of metals and materials, is rather on the order of 1.5-2 billion people on Earth, than the projected 9 billion people on Earth. The model assessments we have done, suggests that there is no way 9 billion people on Earth can be sustained for any longer period of time. The peoples of the world must take extraordinary efforts to prevent that from happening (Ragnarsdottir et al., 2011a, Sverdrup and Ragnarsdottir, 2011). The procrastination done so far by different religious groups, certain official circles, autocratic regimes and conservative political groups at every population policy assessment meeting that tries to discuss the population issue, is utterly destructive and damaging to our global future. They are part of the major obstacles and the real problem, and they have only misery in the long term to offer those that believe in them, as well as causing serious problems for all others.

Politicians now stand before a new situation they have not realized before, where decisions made today may have little effect before a century has passed, and it may decide over survival conditions, over life and death of humans several centuries from now. This demands moral stature and strong characters far beyond what we see today, with stamina to ignore what is opportune for the moment, and insight to see what would be dangerous in the long term. The human world has so far been mentally linear, but also with the advent of fossil hydrocarbons, and it has been seen as linear, even if it evidently is in exponential growth. Humans in general have no nature-given understanding of exponential growth that is an acquired skill that comes from advanced training. We will have a hard time explaining it to the general public, as is necessary in a democracy. The next 500 years will offer some of the hardest political challenges of modern times, and will require statesmanship and proper understanding of systems thinking and social and natural systems simultaneously. If necessary, present higher education would have to be substantially reformed. It will probably be unwise to elect politicians and statesmen that do not hold such skills. Eternal economic growth is a doomed concept, and it is basic elementary knowledge that this is so. Thus, when peak material and peak energy resources have been reached, then the growth of the material economy we desire, becomes the core cause of problems, and the enemy of prosperity.

The causal chain we invoke for material and energy handling at present are illustrated in Figure 26. Here we see how resources, after a delay, are converted to materials, which after a delay will be converted to population, and work and wealth, which all after a delay become waste, which after a delay becomes dissipated and lost. As long as the humans were few, the fluxes were small compared to global fluxes and the whole process would basically be possible for multiple millennia. Today the material fluxes are no longer small as compared to geological fluxes, and the fact is that the fluxes are sometimes larger than any naturally caused fluxes. We therefore have a huge problem. We are challenging the planet and the limits set by thermodynamics, and only humiliation will be the final result, unless we heed the message. We need to make a linear world circular. The cycle must be complemented with a recycling loop, where materials and the energy are recycled to a large degree as possible.

Time has now come for action in those societies and nations that will want to redesign themselves to sustainability, in order to prevail into the future. For those that wait until a crisis is evident to see even for the simple and ignorant, it will normally be too late, history tells us very clearly a message on that fact (Gibbon 1776, Kennedy 1985, Tainter 1988, 1996, Diamond 2007, Fukuyama 2011). Those nations that use up all their resources go into decline, with almost no exceptions. Smaller nations that go bankrupt, end up in dependency, get assimilated into other countries or just simply vanish. Larger nations may crumble, fall apart or make very damaging wars. The worse their situation is, the likelier it is that they loose any wars they eventually may start.

Conclusions

The world is fast moving towards a world of limits. We see peak behaviour in most of the strategically important metals and materials and finally also in wealth and population. A too large population in a world of physical limits for resource extraction will most likely be a world of great poverty. This puts us in front of the largest challenge ever faced by mankind:

1. Wealth creation is strongly coupled to conversion of resources (metals, materials, energy, renewable crops from agriculture and forests, mining of ecosystems in the terrestrial wilderness and oceans for biomass).

2. Economic growth based on growth in material- and energy consumption will with 100% certainty stagnate and decline when the underlying resources decline. When resources peak, so do wealth, only with a delay of a few decades.

3. Economic growth based on debt growth is national suicide in the long run. Such debts can never be paid in a world of resource limits. These nations that do not stop in time will disappear. The lessons of history are crystal clear at this point.

4. A world with many people and small resources is a world of limits for everybody.

5. We need to act before resource limitations reduce our possibilities and when we still have the minimum required capital still available.

6. Change takes time, and there is not much time left. 20-30 years is not a long time available for the changes that humanity needs to make.

Of note is that in this analysis we have not taken into account the threats of climate change and biodiversity loss. These challenges along with material scarcity and population is such a large a challenge that many would prefer not to hear, not to see, not to know. Today, the use of the strategically important metals and materials is wasteful, and the recycling of them is far too low. The market is evidently not able to household in a responsible way with metals until too much has been already consumed, and the future governments must take a stronger grip on this. Plans and measures for material use must be taken. The population issue must also be addressed properly. For any strategic metal or element, there will be no sustainability worth while discussing at any recycling below 70%. Significant approaches to global materials sustainability will be made when the average recycling is above 90%. The corresponding alternative measure would be to have a significantly smaller global population.

Our policy recommendation is that governments must take the issue seriously and start preparing for legislation that can close material cycles and minimize losses as soon as possible. Forceful programs promoting extensive recycling will be needed as well as special care in closing loops and reducing irreversible losses. Research efforts in this field needs to be based on systems thinking and a concerted effort is needed. Several things stand out as important aspects to consider for reaching a sustainable society:

1. Close all material cycles and keep extraction of renewable resources below the critical extraction rate by a good margin. Strong incentives and regulation will be needed, international coordination will be helpful.

2. Make all extraction of renewable resource stay within the limits of sustainability, disregarding all complaints and nagging for higher extraction rates. Strong regulations to protect the regenerative capacities is needed, with proper enforcement.

3. Base all energy production on a multitude of methods for harnessing the power from the sun directly (heat collection, photovoltaic) or indirectly (wave, wind, waterpower, photosynthetic bioenergy) with a positive EROI and MROI larger than 3. Limit the use of all fossil fuels to a time-to-doomsday perspective of 4,000 years (uranium, thorium, oil, gas, coal, geothermal energy). Stimulus to scientific research will be able to speed up the process.

4. Reduce to insignificance corruption and abuse of power in governments globally, general society and make all foreign aid conditional on this. A global convention on abolishment of corruption is needed. Close overseas tax-havens and abolish secure shelters for illegal money.

5. Promote the liberal form of democracy with adequate balancing of the powers, demanding accountability of all offices of power. Marginalize all non-democratic modes of governance and create open information governance and a liberal and secular society.

…And then we have not even touched upon global overpopulation, global climate change, global pollution, large scale loss of biodiversity, soil erosion and lots of other very serious challenges to the survival of civilization. But that will be the topic of a later study.

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