The World 5 model; Peak metals, minerals, energy, wealth, food and population; urgent policy 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, and most elements within some centuries. A new global systems model was assembled to analyse this scarcity as a continuation of the model used in the Limits-to-Growth World3 model. We 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 is thus unsustainable as long as resource use continues as today. The creation of money from conversion of resources and work, as well as the current 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 currently have for developed nations. Our policy recommendations are that governments must take this issue seriously and immediately start preparing for legislations that can close material cycles, optimize energy use and minimize all types of irreversible material 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.

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 such 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 implies that the resource production considered goes through a maximum and then production declines to insignificance over time. These findings become a practical tool for evaluation of finite resources that are being exploited at present. 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 present behaviour and national and global policies are 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 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 and actions on the ground are glearingly lacking. This paper presents several serious challenges in terms of scientific research that must be undertaken now. 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 paper on our 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).

2. Objective and scope

The objective of this study is to assess the degree of sustainability of the present economic paradigm and its potential for future human survival. We present a follow-on causal chain that will be valid after peak fossil fuels, peak phosphorus and peak metals and we investigate the connection between resource extraction and wealth generation in society. The results are used to initiate a framework for developing policy advice and future scenarios for sustainable societies across the globe.

3. Methods of assessment

In this study we use several methods:

1. Simple back-of-the-envelope type of calculations to estimate the order of magnitude of resource burn-off times and Hubbert's "peak production" curve responses.
2. 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 resource availability and identify the key components of what constitutes the real problem.
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 systems models are made to secure model output quality that is verified against the ability to predict resource availability 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.

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 resource 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 natural 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. In 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.

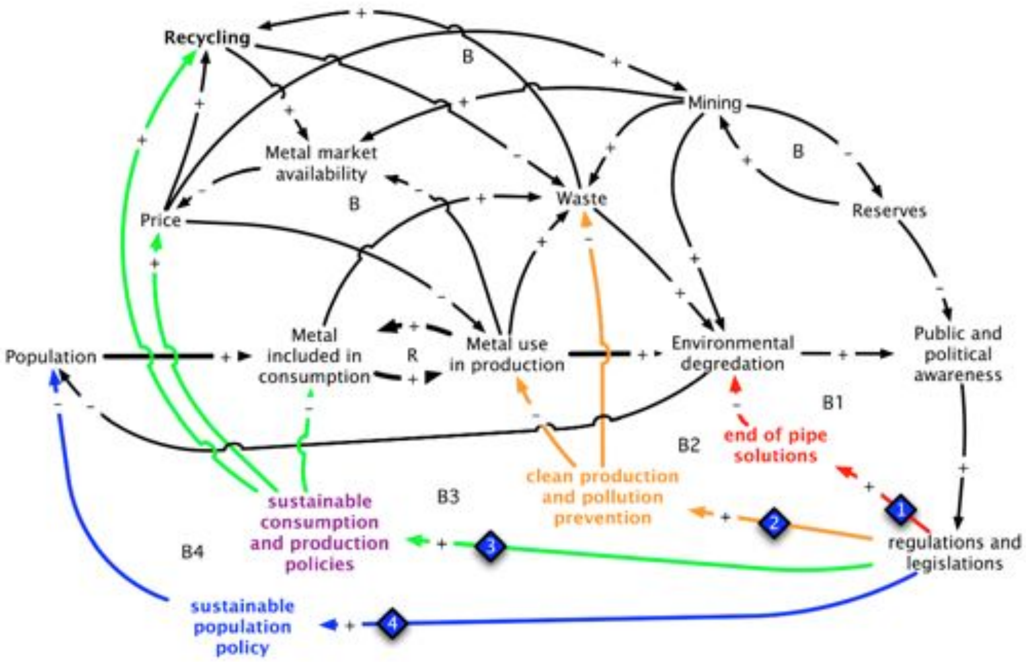


Figure 1. *Sustainability of resource use has moved from end-of-pipe (fighting pollution) to the root cause (overpopulation). Attention has over time moved from end-of-pipe to more focus on recycling, slimmer consumption patterns and sustainable production. Adapted from Ragnarsdottir et al. (2011). B1-B4 are different balancing loops that can be put into the system by governance.*

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 varied results because of differences in fundamental assumptions (e.g. Cohen 1995, Sverdrup et al. 2011). We propose that the concept of convergence (by the South) and contraction (by the North) 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. Recycling 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.

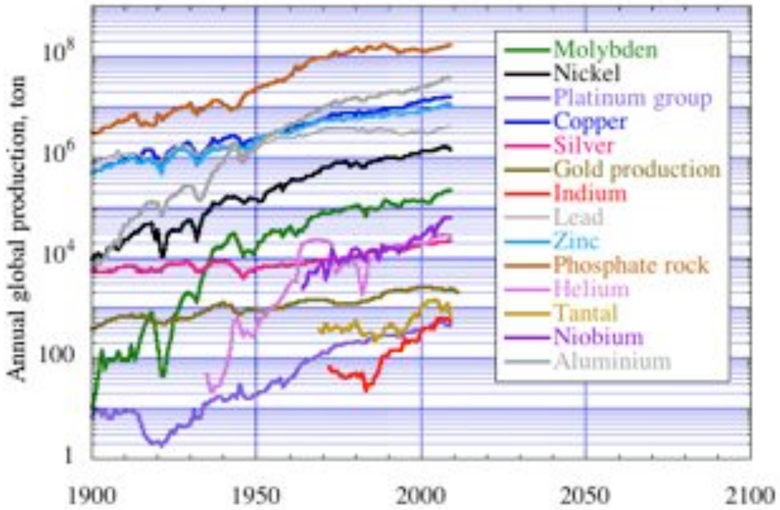


Figure 2. *During the period 1900-2010, metal and element output from the world's mines increased exponentioally (straight line on a logarithmic graph).*

In Figure 2, we show how during the period 1900-2010, metal and element output from the world's mines increased exponentially. In a finite world, exponential growth forever is impossible (e.g. Boulding 1956). 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 reource and/or 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 in the world system is needed for 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.

Resource use and wealth, an analysis

The basic principle behind the need for convergence and contraction is illustrated in Figure 3. The figure shows the basic engine of societal economic growth as a causal loop diagram. The R's represents reinforcing loops, and the B's 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 millions of years (or nearly insignificant). 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 therefore used here. Resource-use causes waste and pollution, which in turn may damage regenerative functions when they are in operation.

The causal loop diagram for non-renewable fossil resources is shown in Figure 4. Here we have further regenerative capacity (Figure 3), which is insignificant for fossil resources (except some carbonates). Instead, we have introduced recycling as a partial regenerative feature. This introduces another reinforcing loop (R4) 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, R1, R2 and 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 R4 if recycling is kept on a significant level. There is no new resource generation from recycling, but the recycling may reduce irreversible natural reserve losses significantly and considerably extend the lifetime of the available reserves.

Constrained by thermodynamics and mass-balance, material growth on a finite planet as a foundation for society is something that cannot be sustained forever. Resources can be obtained from finite resources, but also by recycling what resources we already have in 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 and this leads to exponential behaviour. As the natural resource is depleted, 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.

Energy is a prerequisite for both phosphorus and material extraction. The fundamentals of wealth creation in a society, is arising from extraction of extraction and use of oil, coal and gas to produce extract and produce phosphorus-, and metal reserves with input of productive work. All of these resources are finite 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 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 by:

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 wealth, 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 by appropriating:
    a. with acceptance from the owners, present wealth for later repayment;
    b. wealth believed to exist in the future, committing the future generations to pay it, and 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.

A sustainable loan obeys is based on the assumption that wealth materializes and that future generations 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.

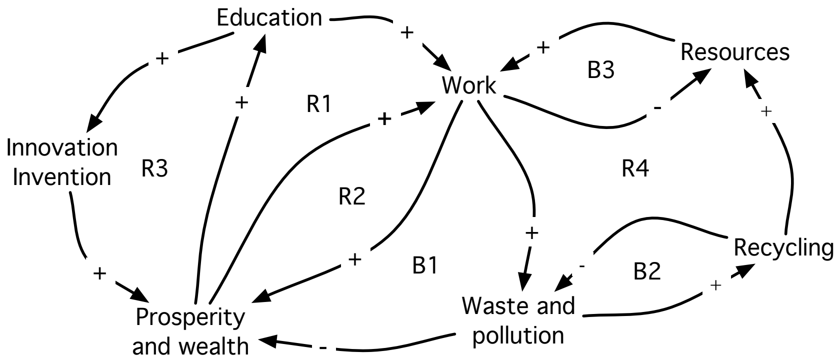


Figure 4. *For fossil resources the regenerating capacity is generally insignificant. All material that is lost is to be considered as lost forever for society. Early in the exploitation of the resource, the loops R1, R2, R3 dominate and we have exponential growth. Later as the reserves get depleted, R1 will dominate and become limited by B1, B2, but supported by R4 if recycling is kept on a significant level.*

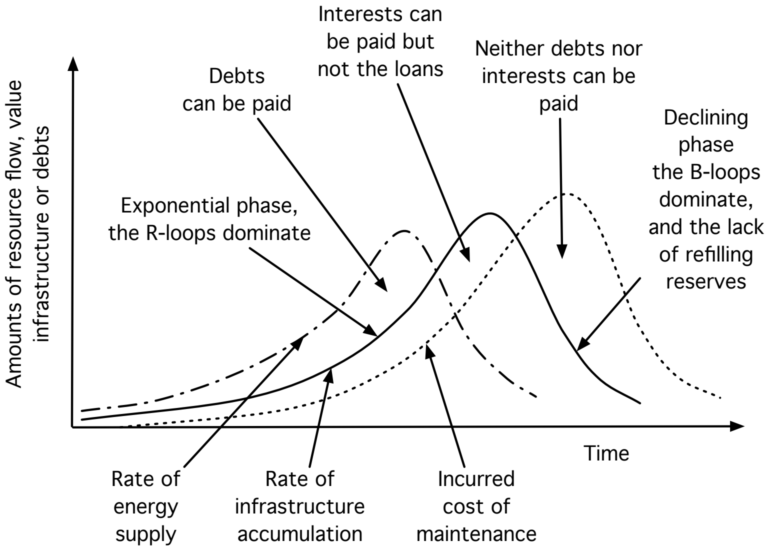


Figure 5. *The system output that can be read out of the causal loop diagram given in Figure 3. Initially, the process is driven by maximizing resource extraction, which leads to exponential growth. As the resource is depleted, the exponential growth can no longer be sustained, we get "peak" behaviour and the system is depleted. "R" means a reinforcing loop in the system, "B" means a balancing loop in the system. 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.*

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 a 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 along with growth of use of local currencies that lock the money flow locally and are supported by parallel currencies (i.e. for trade) and time (exchange between people) (Lietaer et al. 2010). 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 innovative businesses, but kill off 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) by calculating the burn-off time (reserves/mining rate): **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) **Modified Hubbert's-curve estimates** of **peak production** ($t_{max} = t_{now} - \ln((P_{max}/P)-1)/(2 *b)$ and **time to scarcity**. The Hubbert's curve model is robustly verified on field data from oil, coal, phosphorus and metal mining, 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)** The third calculation method is based on **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 coded in FORTRAN. We have developed these kinds of sustainability assessment models since 1988 (see Ragnarsdottir et al. 2012 and references threrein). Exponential growth and market price mechanisms are mechanistically incorporated in our process-oriented models.

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. This is given as (Total = Consumption / individual * individuals [ton/year]). 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 by (Supply to society = Mining / (1-R) [ton per year]).

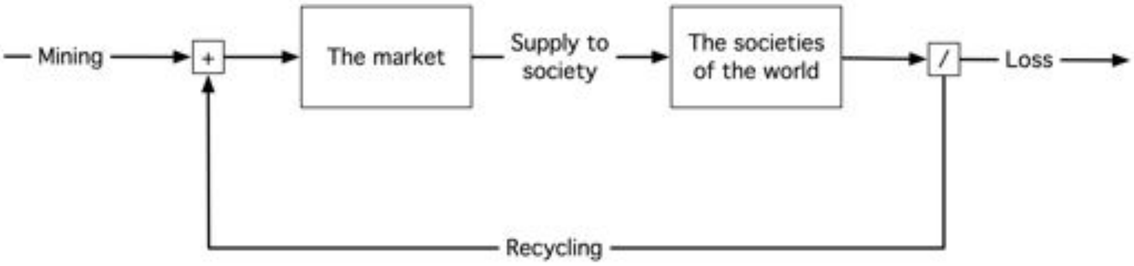


Figure 6. *The effect of recycling. This flow diagram shows that recycling can maintain input to society, but decrease the input from finite resources through mining. The real flow to society becomes amplified by recycling, because part of the outflow becomes returned to the inflow.*

Here 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 (Time to scarcity=Reserves/(Supply to society *(1-R))). 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. 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 (Time to scarcity = 1.7 * burn-off) as estimated in the systems dynamics calculations (see Ragnarsdottir et al. 2012).

In the process of creating GDP growth, the resource reserves available are depleted, thereby 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 assumes energy to contribute 60%, materials 20% and phosphorus 20%.

The world model development

A comprehensive global model assessment is being built our team (WORLD5), integrating a large number of world system aspects. An outline of the model is shown in Figure 7. The coloursed boxes refer to modules in various stages of development. The phosphate and population modules have been published earlier (Ragnarsdottir et al., 2011, 2012, Sverdrup and Ragnarsdottir 2011a), and 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. (2011, Ragnarsdóttir et al. 2011, 2012). 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 (Forrester 1971, Meadows et al., 1972), 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 an overview of the organization of the World5 Model.

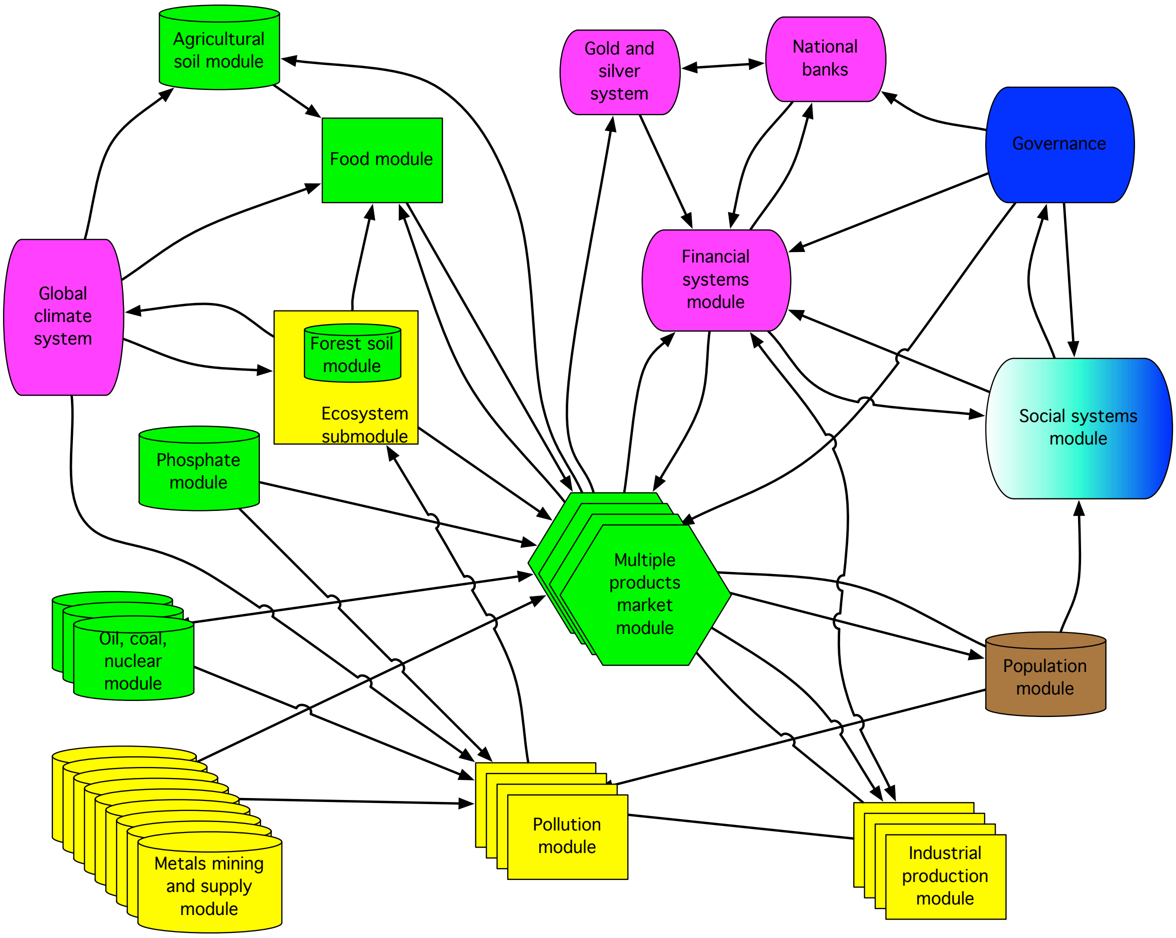


Figure 7 The organization of the World5 Model used here. The green are modules already developed and included into the integrated model structure. Yellow are modules developed and ready, but not yet integrated. The social systems module is undergoing development and a simple version has been integrated.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

Results

The results of this study are of varied nature. 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, Ragnarsdottir et al. 2012).

Times to scarcity under different scenarios

In Table 2 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 (Table 1).

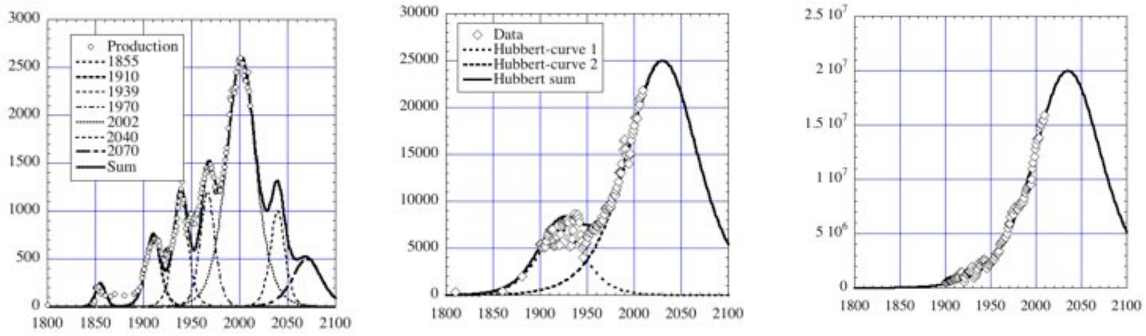
Table 1. Listing of assumptions taken in various model scenarios presented in Table 2.

Target 1: Business-as-usual, (BAU) recycling as 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, gold to 95%.
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 2. 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 estimated in our earlier study (Ragnarsdottir et al., 2012). 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 in Table 2 depicts the classification of the degree of urgency. 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. It is evident from the Table 2, that human society is not sustainable with respect to most materials and metals. This represents a serious diagnostic warning that our present paradigm for creation of wealth is about to expire. Only by drastically increasing recycling and possibly bringing down populations numbers, may a semi-sustainable situation be created that could be sustained for centennials.

Assessment using Hubbert's curves

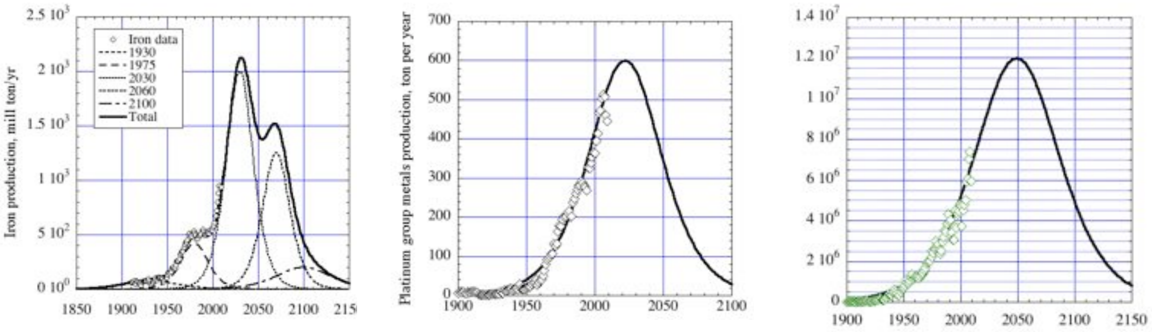
In Figure 8, the Hubbert-curve fittings for gold (a), silver (b), copper (c), indium (f), iron (g),. We can see that the data suggest gold already passed the peak in 2000. Time to scarcity for gold would be about 2070 (Laherrere 2009a,b, 2010). Iron is found in abundance on Earth, but in limited supply 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. 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 infrastructure situation, and it is difficult to foresee the consequences. They are simple shapes that are modelled with one single Hubbert's-function, (e) 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 started in 1900.



a; Gold production

b: Silver production

c, Copper production



d; Iron production

e; Platinum group metal production

f; Indium production

Figure 8. *Hubbert-curve fittings for gold (a) silver (b), copper (c), indium (f), iron (g), platinum group metals. 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/*

Peak phosphorus could mean peak food
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 1990-2010. Then, possibly, half the reserve had been mined. The total mineable reserve in 1800 is estimated at 167 billion ton, by 2010, an approximate half of this had been consumed (Sverdrup and Ragnarsdottir 2011), with 80 billion tons remaining, mostly in low grade and ultralow grade deposits. However, being able to produce food also depends on having a soil substrate to grow food in and the phosphorus supply from soils is significant when considering food security. Figure 10 shows some data on the area of tilled soils of the Earth. As is apparent from the curve, the soil resource peaked in 2005. This is perhaps the single largest identified threat to general survival of civilization on the planet because soils form very slowly (of the order of several mm/year – Brantley et la., 2007). Without soils, many areas cannot be resettled after economic collapses, as there will be no way to feed the population. This augments the gravity of the situation created by peak phosphorus. 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., 2011, 2012, Sverdrup et al., 2011). In diagram (c) in Fig. 9, we can see the prospecting data fitted to the integral Hubbert's curve. 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 in the diagram (c).

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 (Ragnarsdottir and Sverdrup 2012) would be the double of this estimate. All values are years counted from 2010 and forwards.

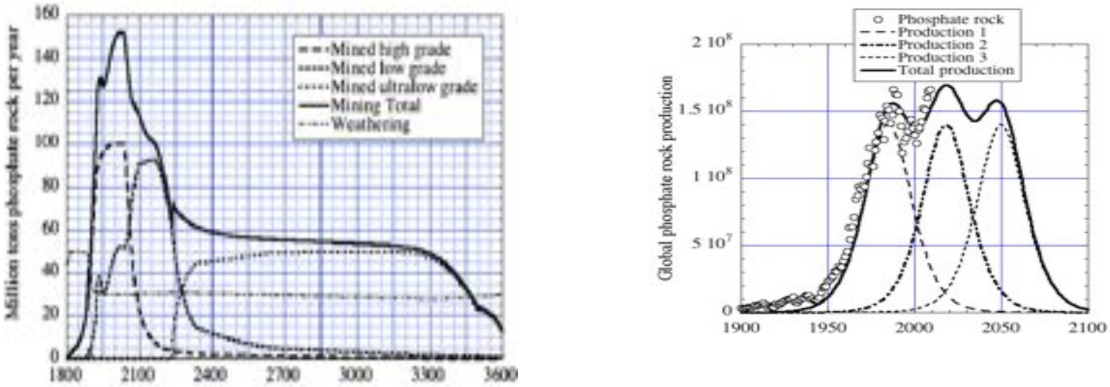
Element	BAU	50%	70%	90%	95%	95%+3bn	95%+3bn+½ the use
Iron	79	126	316	316	632	1,263	2,526
Aluminium	132	184	461	461	921	1,842	3,684
Nickel	42	42	209	419	838	1,675	3,350
Copper	31	31	157	314	628	1,256	2,512
Zinc	20	37	61	61	123	245	490
Manganese	29	46	229	457	914	1,829	3,668
Indium	19	38	190	379	759	1,517	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
Lead	23	23	90	181	361	722	1,444
Wolfram	32	52	258	516	1,031	2,062	4,124
Tantalum	171	274	1,371	2,743	5,486	10,971	22,000
Niobium	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	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
Gold	48	48	71	357	714	1,429	2,858
Silver	14	14	43	214	429	857	1,714
Platinum	73	73	218	1,091	2,182	4,364	8,728
Palladium	61	61	183	913	1,826	3,652	7,304
Rhodium	44	44	132	660	1,320	2,640	5,280
Uranium	61	119	597	5,972	11,944	23,887	47,500
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	

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 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., 2011, 2012, Sverdrup et al. 2011). It would have to be verified properly and assessed to what degree it can also be recovered at a reasonable return on investment for energy and materials. 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 (Figure 9c) has a distinct S-shape, diagnostic for the fact that there are not very much more phosphorus rock reserves to be found. 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.

Figure 11 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.

a; Phosphorus production, dynamic FoF-model developed by the authors (Sverdrup and Ragnarsdottir 2011)

b: Phosphorus production, 3-way Hubbert's curve



c; Phosphorus prospecting history real data

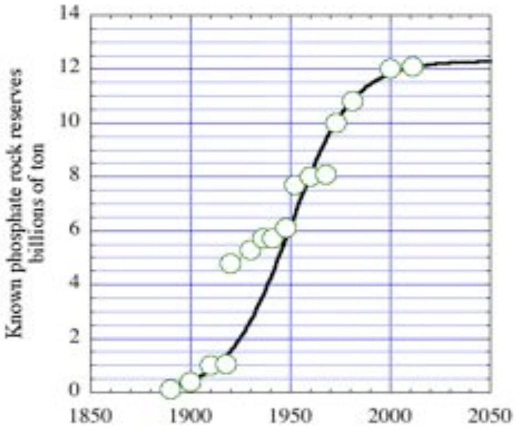


Figure 9. *Hubbert curve phosphorus and phosphorus reserve discoveries (a,b and c). (a) shows the output from a systems dynamics model by Sverdrup et al., (2011). The diagram in (c) was used to calibrate for phosphorus based on the prospecting history, yielding a maximum reserve of 12,4 billion ton (b, c). The dynamic model is based on a resource estimate shown in Table 3. By 1945, 50% of the phosphorus reserve had been discovered. The scale on the Y-axis 8b) 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/*

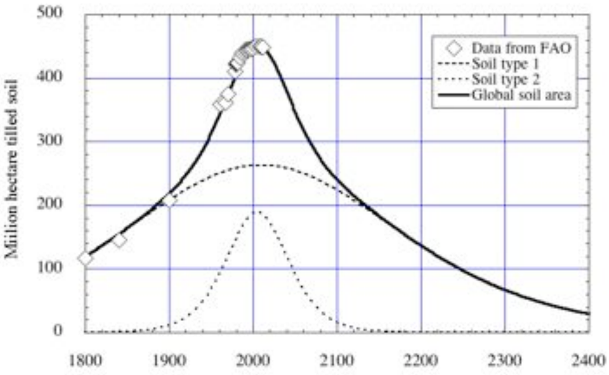


Figure 10. *The area of tilled soils of the Earth peaked in 2005.*

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(d) shows the global fish production peaked in 2002-2003. In 2060, the catch will have sunken to 10% of the maximum. Figure 11(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, the curves by the authors).

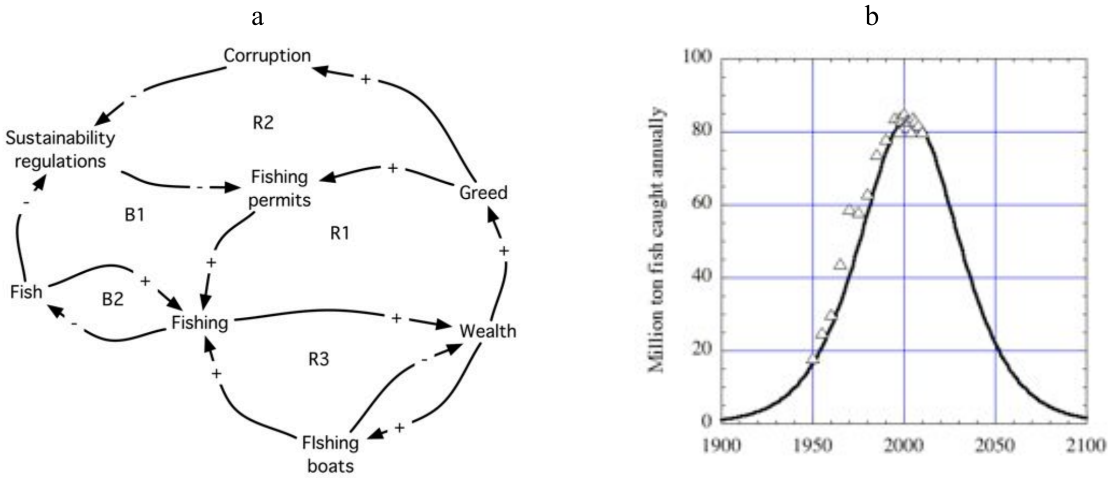


Figure 11. *Example of a renewable resource that is being fished to near extinction from capelin catches and stocks in the Barents Sea. (a) depicts the causal loop diagram that explains what is going on. Fishing leads to wealth, the wealth allows building of more fishing boats, leading to more fishing, 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. (b) The global fish production peaked in 2002-2003 as is shown in (a). In 2060, the fish catch will have sunken to 10% of the maximum. (Data from FAO curves by the authors).*

Building and ruining nations

Tainter (1988, 1996) analysed 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 centralization and information as well as simpler trade flows, poorer 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 12 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 also shown in Figure 12. The manpower of the Roman army is shown in the Figure 12 to illustrate how much surplus they could divert to defence and expansion (Tainter 1998, Diamond 2005, Bardi and Lavacchi, 2009, Fukuyama 2011). Resources lead to wealth that leads to more people and in the continuation that may lead to larger military might (Figure 13). 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.

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 was suggested that it was a resource collapse (Diamond 2005), or a systemic collapse of a complex organization (Tainter 1988, 1995, 1996, Greer 2005, Heinberg 2005, 2011, Fukuyama 2011).

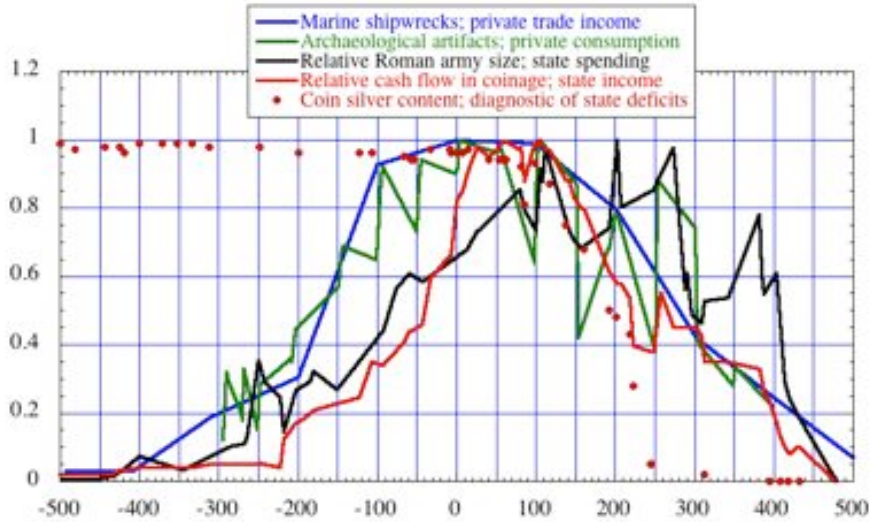


Figure 12. *The rise and fall of the Roman Empire. The depletion of silver in Roman coins 0-270 AD shows the inflation as the coin silver content declines, the archaeological artefacts reflect household income and the manpower of the Imperial Roman Army. The extent of human activity in the Roman Empire, as reflected by abundance of archaeological artefacts reflect how much wealth came to the population 350 BC-450 AD, as well as the size of the army illustrating state expenditures on defence.*

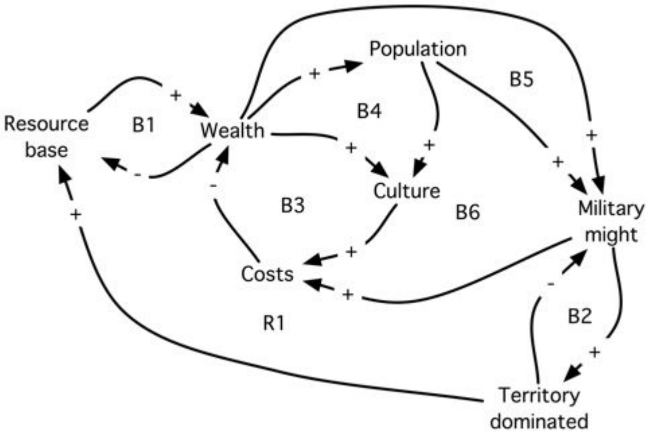


Figure 13. A simple causal loop diagram, to illustrate why the Roman Empire collapsed and disappeared. The causal loop diagram is a logical variant of Figure 12 discussed earlier.

In Figures 13 and 14, causal loop diagrams are assembled that attempt 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 both figures 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 societal 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.

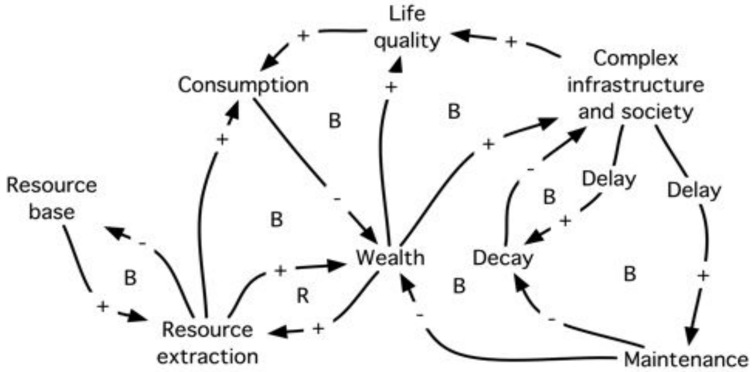


Figure 14. As the Roman Empire developed and grew in size, it developed a state and society organization with increasing complexity. It needed maintenance in terms of replacement of key people at regular intervals, providing them with training and education. The backlog in terms of maintenance costs 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.

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. 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 values are high.
2. The increased area of dominance, augment the running costs of operations, the increased access to low cost wealth leads to specializations and increased complexity of the organization of society.
3. The continued expansion of the 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 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. The maintenance cost backlog catches up, deficits develop throughout the whole structure. 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).

Global considerations

The recent global economic crisis and the still ongoing global debt crisis is claimed to be a similar systemic crisis to the Roman Empire, where we are now proclaimed to be 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. 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 15 shows that peak oil occurred 2008-2010. Other, more detailed studies using a multi-cycle Hubbert model confirm this depiction (Nashawi 2010). The curve for global oil production was prepared by ASPO (Association for the Study of Peak Oil) in 2009, and this particular figure was derived from their website in 2011. The global oil production and the resulting global wealth production follows the shape of a Hubbert's curve well. When peak occurs on a global scale, then there will be no extra global resource reserves left. Then the situation could become difficult to steer away from a grand scale systemic collapse. We conclude that we see signs that this is taking place right now.

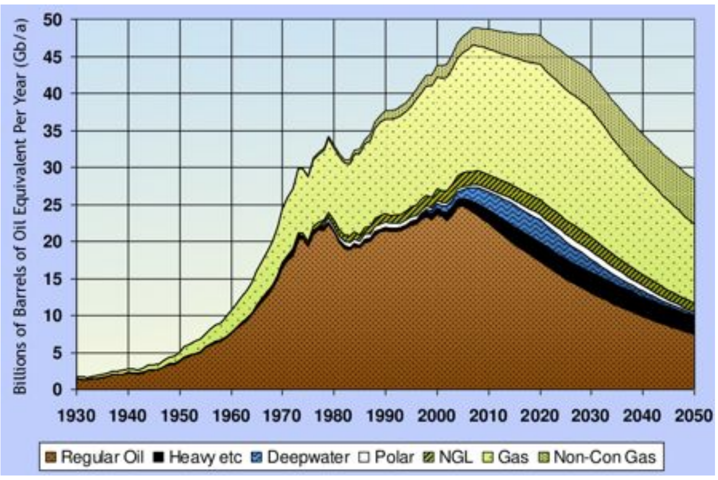


Figure 15. *We are now at global peak oil. The curve was prepared by the ASPO institute 2009, and derived from their website. The unit of production is gigabarrels of oil equivalents per year, or* 10^{12} *barrels per year, which is corresponding to 110 billion tons oil equivalents/year.*

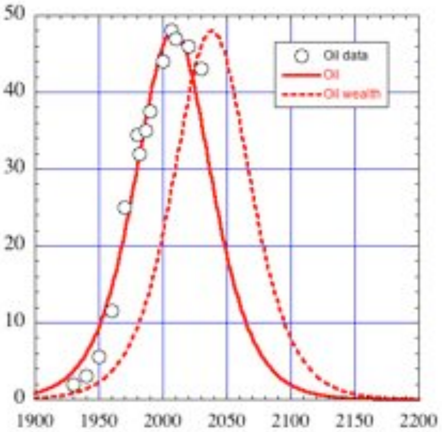


Figure 16. *Applying a Hubbert's curve to global oil production in Fig. 15, and using the oil price projections to suggest the oil wealth trajectory.*

Energy from fossil hydrocarbons is not recycled, can be partially recycled after certain uses through heat exchanging, provided it is valuable enough. Figure 16 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 10-20 years later, 2017-2027. Norway has stored large part of the oil revenue in a special "oil" fund (approximately 75% 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 future generations. A world of limits seems to be catching up with us all. Norwegian hydrocarbon production peak occurred in 2002-2003, the Norwegian oil-related income peak is predicted to occur in the years 2012-2014. For Norway, there is a 15-year lag between peak resource and peak wealth.

Figure 21 shows the world oil production, distributed among different main producing regions (Source: Oil Drum, Bardi 2009b). The curve is based on observed production data and the oil corporation production estimates for the next decade. From the empirical data, it looks like peak oil should be expected in the time period 2010. Figure 22 shows the global coal production, it is evident that the peak is near, 2025-2035 or 10-20 years delay from resource peak.

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 mined and burned, leaving the remaining reserves in the low-grade category. There have been four instants where the coal production has peaked for economic growth periods. The detectable S-shape of the coal prospecting success curve show that hoping for new sensational discoveries of large coal-fields in the United States are vain hopes (Bardi 2009b) (See Figure 9 for a similar curve for phosphorus). Figure 19 shows the cumulative Hubbert's curve for world coal production (a). The coal production had by 2011 extracted 35-40% of all extractable coal in the world. Figure 19 (b) shows the world coal production, past and future (Adapted after Höök et al., 2008), with our analysis using multiple Hubbert's curves. Circles represent observed data. By 2150, the world's coal reserves will, 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. The data on delay between peak in reserve discovery and peak production 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 (Figure 20). 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. The figure shows that renewable energy will never be replaced by the current "cheap" fossil energy that we are using up at a record rate at the present moment with little or no thought for future generations.

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. 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."

Peak world and the end of the golden age

Figures 15-20, 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. 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 peak wealth from energy will occur in 2045. 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 and societal problems are to be avoided.

The colour graph in Figure 19 (a) is taken from the Oil Drum webpage. In Figure 19 (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. There is a delay of 50 years between initial investment, and the cost of maintenance for infrastructural renewal increasing by 1.5 % per year. 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-to-growth study. However, they lumped energy and all material resources, miss the dynamics when having them coupled but separate, as shown here. 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 our new global model (World5), 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 such as platinum group metals and silver are classified as precious metals we hold apart in the assessments. The strategic metals lanthanides, indium, we see as one group, as are 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 hydrocarbons. 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). Lack of resources is a very dangerous situation globally. The solutions to our sustainability problems are as much in the social domain as anywhere else, and engineering and economics deal with social machinery. However, people and social processes control and shape behaviour. The sustainability challenge is thus a social challenge and the willingness to change people´s and society´s behaviour. The use of all resources available to us at maximum rate as we do now, probably 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). 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 in terms of material use 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.

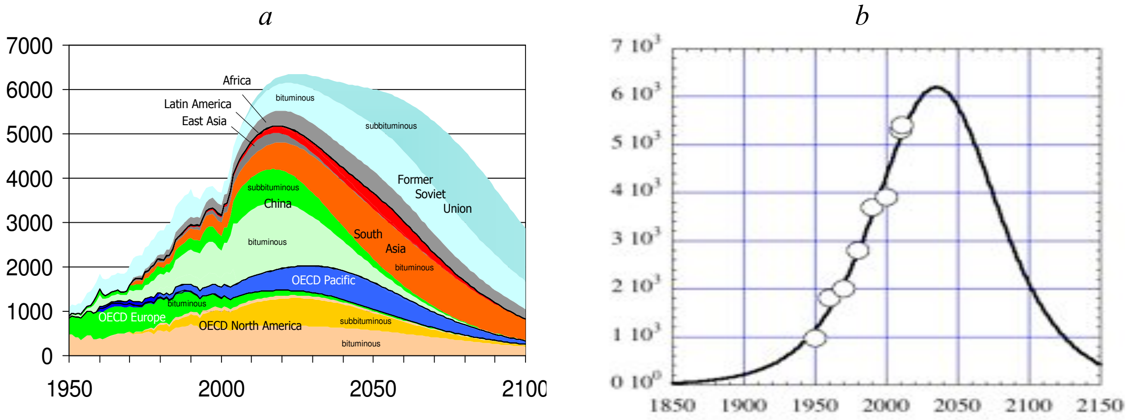


Figure 19. *Global coal reserves and peak prediction.* ***a*** *The world coal production is shown, distributed among different main producing regions (Source: Oil Drum, Bardi 2009b). The global energy peaks in 2015.* ***b*** *shows the world coal production, past and future (Adapted after Höök et al., 2008). Circles are observed data. Adapted from USGS statistics 2010.*

Figure 21 illustrates that before the end of the golden age the linear material use 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.

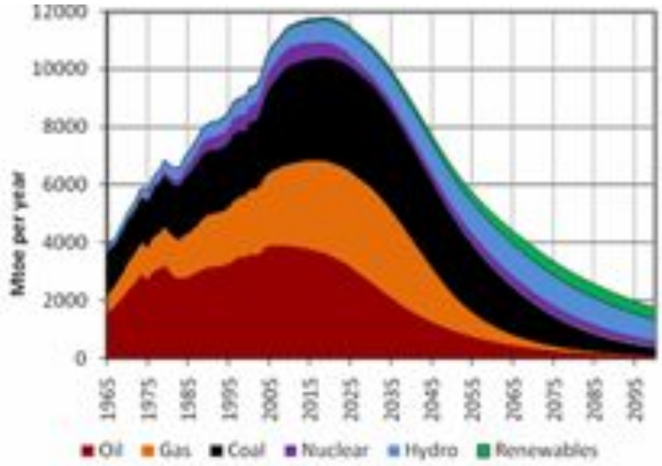


Figure 20. *(a) is a graph redrawn from the Oil Drum webpage, showing past global energy use and a future projection.*

The punishment for not listening to early warnings

During the 1700's, the global community made a 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 in the 18th century because systemic insight was a rarity, religious totalitarianism was common, intolerance and oppression was rather the norm than the exception. 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 the global peak oil is passed. The assessment made by the Club of Rome, the "Limits-to-growth", report was published in 1972 (Meadows et al. 1972, 1992, 2005). Sadly, the lessons were not properly learned, they were only shortly heeded by some and then fast made to be forgotten by both the public and what would seem like "smart" economists. The key designers for this nonsense 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. Economic "science" failed grandly in not doing systems thinking, not learning from past collapses 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 as well as the principles of their science basis 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) 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.

Table 3. Known resource discovery, resource extraction and wealth creation peaks, cost over wealth overshoots and civilization collapses. Red numbers are predicted dates, black dates are the observed based on historical data. Resource peaks are for land, coal, oil, metals. The collapse dates assume that governance and society continues along the practice of business as usual, without any consideration of effective measures to attain sustainability.

Empire	Predicted with meta-model based on the WORLD5-model, calendar year					Observed collapse
	Discovery peak	Resource peak	Wealth peak	Cost larger than wealth	Collapse	
Roman[1]	14 AD	80-120	120-160	180-220	240-280	First 287 Final 400
Norwegian[1]	1066-1100	1220-1280	1292	1330	1340	1349-1450
Swedish[4]	1520	1632	1688	1712	1732-1750	1788-1809
British[2]	1888	1928	1938-1943	1958-1963	1978-1981	Dismantled 1947-1965
Spanish[1]	1520	1550	1565	1580-1600	1620-1660	1700-1750
United Kingdom[3]	1965	1988	2000	2010-**2020**	**2025-2040**	?
Soviet[2]	1932	1948	1960	1985-1990	1995-2005	1990-1993
Russian[3]		1993	2005	**2020-2025**	**2035-2045**	?
American[3]	1955	1971	1983-1986	1998-2006	**2010-2030**	?
Chinese[3]	2000	**2020-2025**	**2035-2040**	**2050-2060**	**2060-2080**	?
Indian[2]	1990	**2040-2048**	**2052-2065**	**2068-2080**	**2077-2090**	?
Global[3]	1975	2007	**2017-2022**	**2040-2060**	**2060-2080**	?

How long can we wait?

With the knowledge we have today, we know that we need to plan for the future, and that we have the technology to do it. It is in these next 20-40 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 issue as finding a new phosphate rock deposit and starting a new mine normally takes about 7-10 years, from discovery to planning. The process of going from first idea of planning 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, and there will be about 40 to 50 years left before the peak, and about the same time until scarcity. This is exemplified in Table 3. 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 Air Quality 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 own future quality of life and future generations, 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 that required. We must have respect for the large amount of work that will go into adequate planning and development of national and international action plans. On tope of that none of the present international policy committee processes existing today are 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, 2 and 3 tells us that both resource use per capita 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 or face society crisis. The sustainable population from a perspective of energy and phosphorus, 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 UN and IIASA global population projections towards 9-12 billion people on Earth in 2050 can only be allowed if the models have no limitation on food (United Nations 2003). This one of the least plausible assumptions, and these projections are not suitable for any policy recommendations.

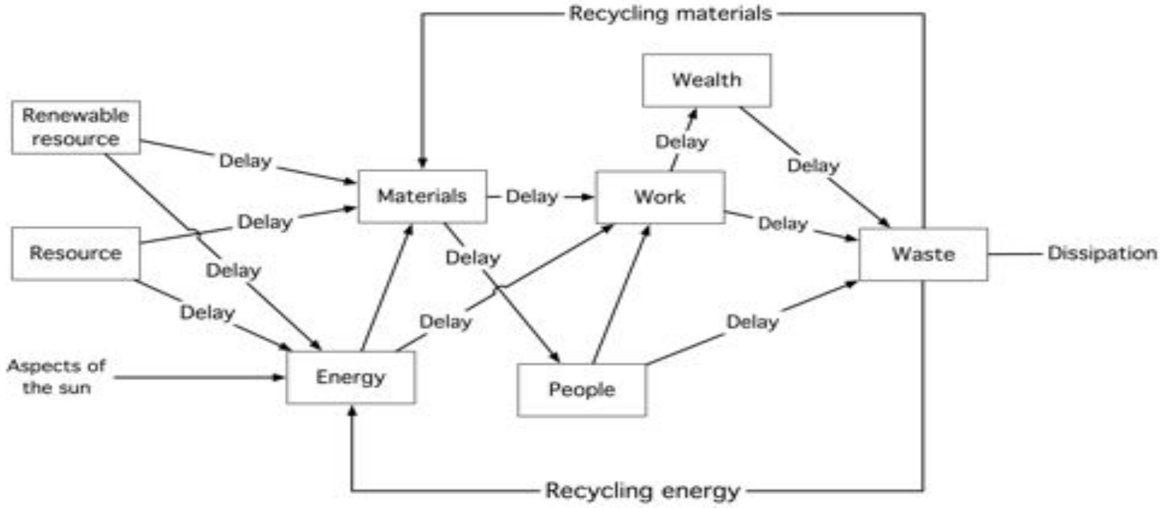


Figure 21. *Present behaviour makes the world apparently linear. This illustrates how resources, after a delay, are converted to materials, which after a delay will be converted to population, and work and wealth which all after a delay becomes waste, which after a delay becomes dissipated and lost. 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.*

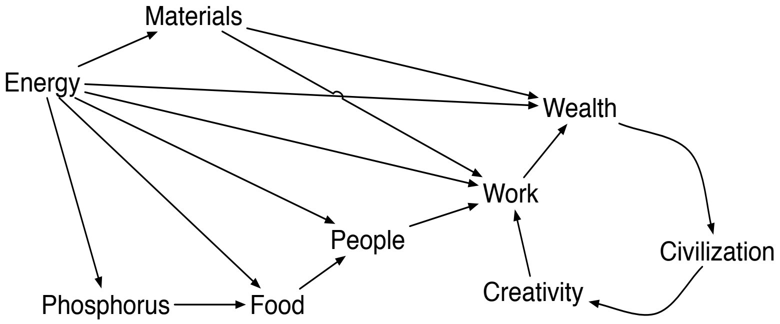


Figure 22. *Where does wealth really come from? The flow of wealth and its precursors or perpetuation in society are illustrated. In principle, wealth is made from oil, coal, nuclear energy, biomass and food, transformed through work. On this wealth, society is founded. Note that "financial services" have a very small role in real wealth generation beyond reducing costs of resource conversion transactions.*

The peoples of the world must take extraordinary efforts to prevent that from happening (Ragnarsdottir et al. 2011, 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 during the last decades that tries to discuss the population issue, is destructive and damaging to our global future. They are a 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, not to mention the destruction of nature and ecosystem..

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 plentiful fossil hydrocarbons, it has been seen as linear, even if it evidently is in exponential growth. 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. It is imperative that present higher education be substantially reformed. Eternal economic growth is a doomed concept in a limited world, and it is 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 as we see it today. We must find a way to promote prosperity without growth and within the limits of the planet (Jackson 2009).

Conclusions

The world is fast moving towards a world of limits. We see peak behaviour in most of the strategically important metals and materials that are fundamental to society as we know it today and also in linked wealth all driven by population and consumption. The crisis we experienced 2007-2009 in the western world was not only a financial crisis, but a crisis where the first symptoms of resource-backed economic growth that cannot be sustained because of the physical limits of the world (Jackson 2009). In a world of limits, planning for further growth is a fools policy that we already now know must fail.

A too large global population in a world of physical limits for resource extraction will most likely be a world of great poverty. When the resources continue to decline as the same time as the population rises, the situation will get worse. This puts in front of humanity one of the largest challenge ever faced by mankind. We conclude that:

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, phosphorus and oil to produce the food needed to run the workforce).

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 des wealth, but 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. The nations that do not stop in time will disappear. The lessons of history are crystal clear at this point as seen for example with the decline of the Roman Empyre.

4. A world with many people and constrained 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 and energy still available.

6. Change takes time, and there is not much time left. Twenty to thirty years is the window of 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 numbers is such a large a challenge that many would prefer not to hear, not to see, and/or 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 matter. 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%, at present, the recycling rates are far below that (Ragnarsdottir et al 2012). 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. Once phosphorous is depleted, we need both measures.

Our policy recommendation include that governments must take these resource limitations and population growth seriously and start preparing for legislation that can close material cycles and minimize material 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 need 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, and 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 recycling capacities of resources 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 an 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 and funding for scientific research will be able to speed up the process.

4. Reduce to insignificance corruption and abuse of power in governments globally in society and make all foreign aid conditional on this measure. A global convention on abolishment of corruption is needed. Close overseas tax-havens and bonuses on fictive financial deals (futures, derivatives) and abolish secure shelters for illegal money.

5. Promote the liberal form of democracy with adequate balancing of 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. That will be the topic of a later study.

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