Journal of Environmental Science and Engineering B2 (2013) 189-222
Formerly part of Journal of Environmental Science and Engineering, ISSN 1934-8932

Peak Metals, Minerals, Energy, Wealth, Food and Population: Urgent Policy Considerations for a Sustainable Society

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Received: December 25, 2012 / Accepted: January15, 2013 / Published: April 20, 2013.

Abstract: Several strategic metals, elements and energy resources are about to run into scarcity in the near future under the present paradigm of use. A global systems model has been developed (WORLD) to assess the issue of scarcity and its implications for society. We show that scarcity may lead to "peak wealth", "peak population", "peak waste" and "peak civilization", unless urgent counter-measures are systematically undertaken. Materials that underpin modern society may become 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 resources will go up in price. The future resource supply is unsustainable without comprehensive recycling. The creation of wealth from conversion of resources and work, as well as the current extensive borrowing from the future, cause concerns that peaking energy and materials production may lead to "peak wealth" and the end of the golden age we live in. Our policy recommendations are that governments must take this issue seriously and must immediately start preparing legislations to close material cycles, optimize energy use and minimize irreversible material losses. Research efforts need to be based on systems thinking and a concerted effort is needed.

Key words: Sustainability, scarcity, integrated modelling, burn-off time, peak resources, peak phosphorus, peak wealth.

1. Introduction

The peak production rate phenomenon (best 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 including national economies [1-13]. Peak resources imply that the resource production considered goes through a maximum and then production declines to insignificance over time as the reservoir is depleted. This common production behaviour is 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 [14-21]. There has never been a lack of prophets predicting aspects of doomsday, however, the gloomy estimates presented here of resource depletion are based on scientific calculations that are underpinned by robust field data foundation. Early warnings include the first essay by Malthus in 1798 [22], followed by Ehrlich [23, 24], Forrester in 1971 [25], taken out fully by Meadows, Meadows, Randers and Behrens in the book "Limits to Growth" in 1972 [1] and with updated versions in 1992 and 2004, Ehrlich et al. [24] and Brown [26], however, these warnings have so far gone unheeded and necessary policy actions on the ground are 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 the public and governments to

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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 [27], resource evaluations [20, 28-44], general systemic studies [1-4, 25] as well as the studies of others pioneers in this field [14-17, 23-25, 31-44].

2. Objective and Scope

The objective of this study is to assess the degree of sustainability of the present global material and economic paradigm and the potential for future survival of human society as it appears now. We present some preliminary outputs from a causal-chain-based dynamic simulation model that will become valid after passing peak fossil fuels, peak phosphorus and peak metals and use it to investigate the connection between resource extraction and wealth generation in society. The results of the assessments are used to initiate a framework for developing future scenarios and policy advice for sustainable societies across the globe.

3. Methods of Assessment

This study uses generic systems thinking, systems analysis and systems dynamics procedures found in Refs. [1, 25, 45-50]. The method used for constructing the model followed a strict scheme, as well as deriving links by empirical, experimental and Delphi methods [51]. 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 Fig. 1 [20]. 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 augments public concerns and forces governments to take necessary policy actions. Increasing population and affiliated consumption are the two major factors for a growing resource demand in the world. Anincrease in population drives consumption, depleting markets, driving up prices and increasing supply from production to markets in response. This allows for continued consumption rise and enhanced resource use. Increased resource use rate and waste generation leads to resource depletion and environmental degeneration. Recycling represents a way to increase materials in the consumption cycle without increasing extraction. Policy interventions have evolved through time to reduce environmental effects. End of pipe solutions (Fig. 1) were initially used as a first response to environmental degradation. Instead of draining out wastewater from industrial process to rivers and coastal zones, wastewater treatment plants were built; or instead of letting off smoke through chimneys into the atmosphere, removal of hazardous waste gases and particles was undertaken. Later, the economic value of natural resources and waste was realized, and clean 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 gases emitted to the atmosphere. Recently, focus has shifted to sustainable consumption and production behaviour. These life style changes must decrease the demand for goods, and lead to less consumption in total [52], decreasing the global resource overconsumption, reducing resulting environmental degradation and putting society on a path towards sustainability. It can be seen from the causal loop diagram in Fig. 1 that we can trace back the main root cause for today's increasing environmental degradation and impending degradation and impending resource exhaustion to the rise in the world's population.

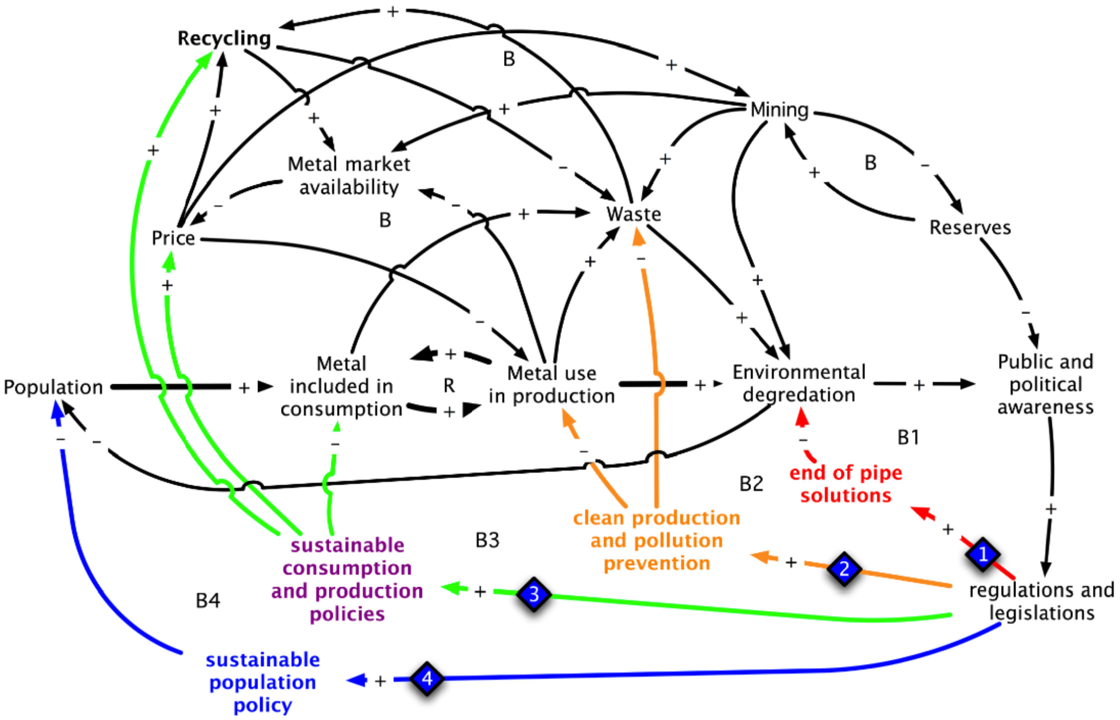


Fig. 1 Sustainability of resource use has moved from end-of-pipe solutions (fighting pollution<1>) to the root cause (overpopulation<4>). Attention has over time moved from end-of-pipe solutions to more focus on recycling, slimmer consumption patterns and sustainable production. B1-B4 are different balancing loops that can be introduced into the system by policies [20].

The authors 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 outrun 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 [1, 17, 22, 26, 30]. Lack of sustainability in the context of world population arises from several factors:

1. End of pipe pollution output from the system;
2. Unsustainable production or resource use in products and services;
3. Excessive volume consumption of resources in products, service production and vanity for display (fuelled by advertising);
4. The total global number of consumers in excess of the carrying capacity of the Earth.

Impact is determined both by number of consumers (n), consumption per individual (U) and the resource use efficiency (E), where ($1—E$) is the fraction not used, as well as the impact efficiency k, per unit resource used [23]:

$$I = n \times k \times u \times (1 - E) \qquad (1)$$

In relation to Fig. 1, society first addressed I by end-of-pipe, then focus was shifted to U, then society addressed E and only partially and in exceptions n. That implies that even if consumption per individual (U) goes down and efficiency (E) goes up, if populations increase (n) enough, impact (I) may still rise. This has been the case in the last decades. The carrying capacity of the world for population has been estimated many times, but with varied results because of differences in fundamental assumptions [28, 53]. In Fig. 2, the authors 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 [1, 14, 16, 17, 32, 40, 44, 54].

Hoping for some yet undiscovered resource and/or technological miracle to solve all problems of shortages is an irresponsible attitude to future planning of sustainability. There are many examples of where such approaches failed in the past [34, 55, 56]. Total systemic sustainability assessments on the essential components in the world system is needed in the long run, and the study of Forrester [25] and Meadows et al. [1-3] are the pioneering studies that came the closest to achieve this.

The authors propose that the concept of convergence (by some of the undeveloped nations) and contraction (by some of the undeveloped and most the developed nations) may be an important part of the solution to the global sustainability issue to fit human civilization inside the worlds limits. 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 refers to minimizing per capita use of resources per utility produced, as well as the number of capita using the available resources, assuming equitable access to resources of the world population, coupled to a personal responsibility for conservation.

4.2 Resource Use and the Connection to Wealth

The basic principle behind the need for convergence and contraction is illustrated in Fig. 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 are driven by resource availability, and growth of elements mined from the Earths crust and surface, there generative capacity is millions of years (or nearly insignificant for present and future generations).

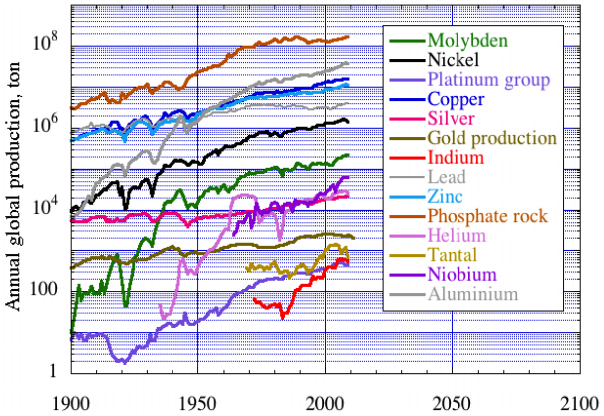


Fig. 2 During the period 1900-2010, metal and element output from the world's mines increased exponentially (straight line on a logarithmic graph).

The regenerative feature is important and represents a reinforcing loop in the system (R4).

A sustainably managed fishery or sustainably managed forestry, both based on renewable resources, works in this way, and principally may give a supply forever. Growth is normally defined as increase in total transaction volume (gross domestic product—GDP) and is normally not well connected to the quality of life of citizen. Prosperity, wealth and happiness are better correlated the quality of life, and are therefore used more in our assessments when possible. 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 Fig. 4. The regenerative capacity (Fig. 3) is insignificant for fossil resources and is here replaced by recycling. This introduces a reinforcing loop (R4) that can partly replace the effect of the regenerative capacity. Early in the exploitation of a 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 reduces replace newle extracted material, and reduce irreversible natural reserve losses significantly and considerably extends the lifetime of the available reserves. Constrained by thermodynamics and mass-balance,

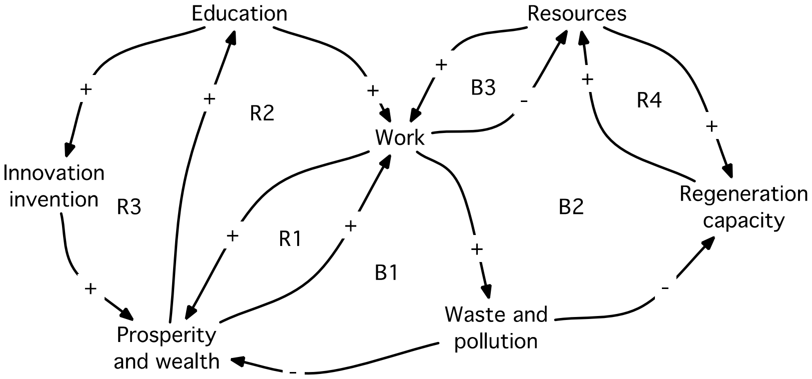


Fig. 3 **The basic economic engine in a system based on natural renewable resources. The carrying capacity is determined by the regenerative capacity, and when this is exceeded, the system deteriorates and the regenerative capacity decreases. In a natural system, the extraction may be adjusted to be covered 100% by regeneration. That is the definition of sustainability, a process that can go on forever.**

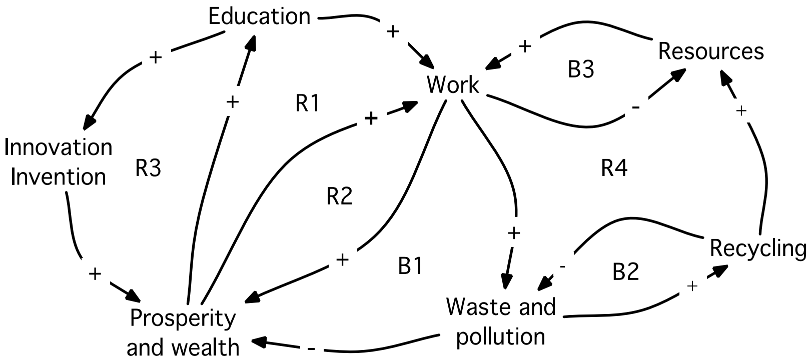


Fig. 4 **For fossil resources the regenerating capacity is initially seen as insignificant early in the extraction phase. Early in the exploitation of the resource, the loops R1, R2, R3 dominate and the authors have exponential growth. Later as the reserves get depleted, R1 will dominate and become limited by B1, B2, but supported by R4 if recycling is kept on a significant level. How early and how efficiently recycling is implemented determines the time to resource exhaustion.**

Material growth on a finite planet as a foundation for society is something that can not be sustained forever. Resources can be obtained from finite resources, but also by recycling what resources we already have in our societal and industrial systems. Recycling levels of materials are 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 reduces waste. But as the supply of recycled material reaches the market, it may cause prices to fall. Energy is a prerequisite for metal, phosphorus and material extraction from reserves.

Wealth creation in a society arises from the extraction and use of oil, coal and gas to produce energy and produce metals and phosphorus products that become food and people 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 as long as it depends of finite fossil resources. Prosperity and welfare for the individual and the family is what people want to obtain from the economic growth driven resource use, but resource extraction volume growth is not necessarily a prerequisite for prosperity. True wealth can only be created by:

1. Converting natural resources to valuable products or work;
2. converting social resources to benefits or services;
3. work, innovation and intellectual achievement.

Wealth can be brought in in addition to the above by taking loans against future potential income. This does not create wealth, but rather bets on the possibility that the wealth will be made in the future, in time to cover the loans made. In summary, there are the following sources of wealth:

- Existing wealth:
    - Taking loans by appropriating with acceptance from the owners present existing wealth for later repayment.
- Non-existing wealth: It has several sources:
    - against future earnings resulting from an investment in a future profitable activity, with some calculated risk for success;
    - taking loans against own future income from work, with security in the asset purchased;
    - taking loans with no mortgages but interest, by appropriating, with acceptance from the owners, wealth believed to exist in the future, committing the future generations to pay it, and without seeking their consent, based on the assumption that they will simply find a way to do it. These are include things referred to as futures;
    - taking loans against collateralized expectations of a value appearance or increase in the future. These are generally referred to as derivatives or futures and have no fundamental difference from bets and gambles;
    - by calling into existence money that does not exist, neither now nor in the future, except in the minds of those that created the deception.

A long-term loan is based on the assumption that wealth materializes in the future and thatfuture generations stay with the obligation to pay the loan. 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 significant manipulations causing inflation and imaginary wealth, but is also substrate for graft and corruption in the system. In a future society, local economic growth need to be present and it is locally necessary for progress. However, overall growth must stay within the resource capacity of the system, or be matched by contraction somewhere else. The same principle applies to other imbalances in society, where a fair share implies a redistribution of wealth and resources. 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. Fig. 5 shows how material and energy metabolism structure of society is similar to an ecosystem with different trophic levels. Resources are the nutrients of this human social ecosystem, the fuel that runs it. With diminished resources and the subsequent simplification of society, the upper levels will shrink or even vanish, lowering the number of levels. Corruption and crime are human designed losses in the system, other losses are there because of conversion inefficiencies, sometimes unavoidable. Every trophic level of society has significant losses because transformation efficiencies are always less than 100%. The normal social model of a civilized society is one of rights, solidarity, responsibility and duties, where those with means help share the burden of those with less means, respecting the integrity of the individual. If well organized, benefits are coupled to duties and responsibility. With the principle of contraction and convergence, systemic corruption represents a difficult problem that canderail the

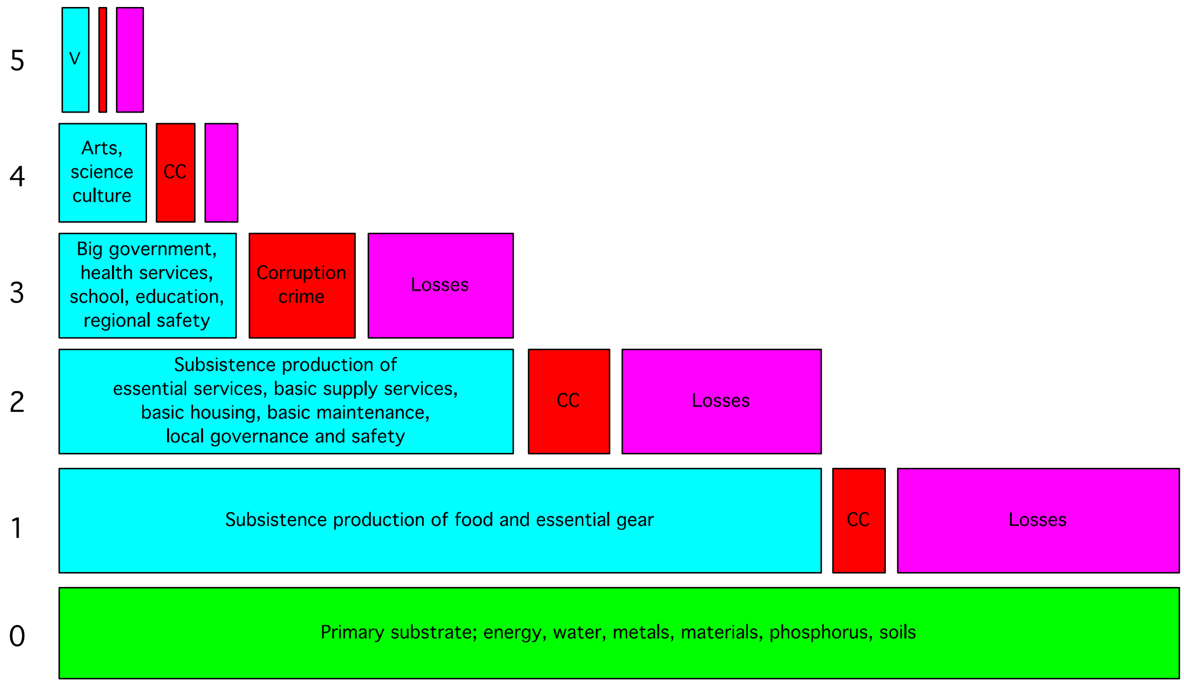


Fig. 5 The material and energy metabolism of society is like an ecosystem with different trophic levels. Resources are the nutrients of this human social ecosystem. Useful social outputs are marked in blue, corruption and crime in red and losses in magenta. V = vanity and social display.

redistribution process through graft, lack of transparency and well as sidestepping democratically made decisions. Local growth is needed in a societal economy to secure the creation of new businesses to secure the necessary business structures, innovations, develop better 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). There can not 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. Fig. 6 shows what we refer to as Tainter's principle [57] of rise and fall of empires. As any empire develops and grows in size, it will develop a state and societal organization with increasing complexity.

It needs 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. We may thus legitimately ask "where does wealth really come from?".

Fig. 7 illustrates the origin of wealth in modern society'ssociety consistent with Fig. 5. In principle, wealth is made from metals and materials, oil and gas, coal, nuclear energy, biomass and food, and transformed through work to people and society. 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 and the monetization of existing collateral property. The flow diagram in Fig. 7 is a logic consequence of what is shown and understood with the trophic pyramid shown in Fig. 5.

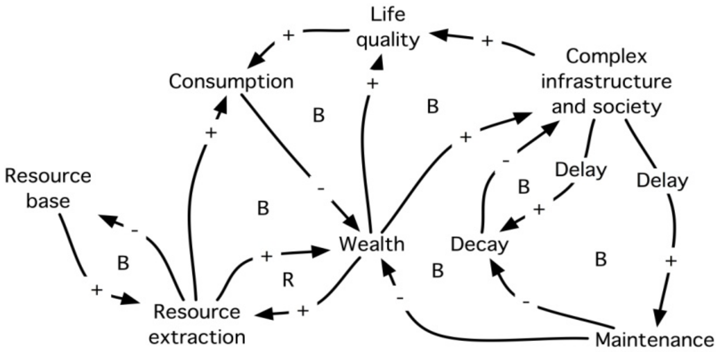


Fig. 6 Tainter's principle of rise and fall of empires. It explains why prosperity leads to overshoot in consumption, initializing a contraction or collapse. "R" means a reinforcing loop in the system, "B" means a balancing loop in the system.

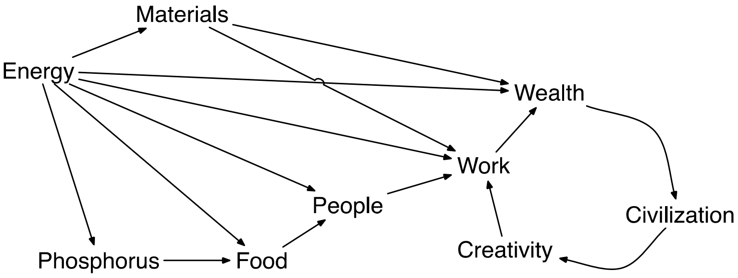


Fig. 7 Where does wealth really come from? The flow of wealth and its precursors and output in society and the core system for doing so are illustrated in this figure.

Fig. 8 shows the qualitative development that can be read out of the causal loop diagram shown in Fig. 6 and the flow diagram in Fig. 7, as well as Figs. 3 and 4, assuming the recycling rate 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. Initially, the process is driven by maximizing resource extraction, leading to exponential growth in primary profits. Increase in available money normally leads to increased spending into investments, infrastructure and consumption. Increase in infrastructures and bureaucracies leads to exponential growth in maintenance costs. As the resource is depleted, the exponential growth can no longer be sustained, we get "peak" behaviour where the resource output declines. However, the infrastructure stock has grown to a level that requires a large input of resources, which at some points exceed incomes. As reserves are depleted, more and more capital must be used for obtaining resources, leaving less to be invested for future maintenance and development. In the initial growth period, income outruns costs and spending is driven upward. In this phase debts are incurred and interests and mortgages are easily paid as the economy grows. When income stagnates while costs are still rising, a point is reached where the interest payments onthe debt taken during the growth phase can be paid, but the mortgages can not be paid. Later with the income entering in sharp decline, and when the cost reductions are significantly lagging behind, then neither interests nor any mortgages can be paid on the debt. Then debt defaults and economic crisis will take place. The final result of this process is an economic contraction, where the whole system downsizes to return to a balance, but at a far lower level, where there again is balance between income and expenses. Some call this "austerity", in reality it is about shrinking the expenses down to the same size as the long term income level.

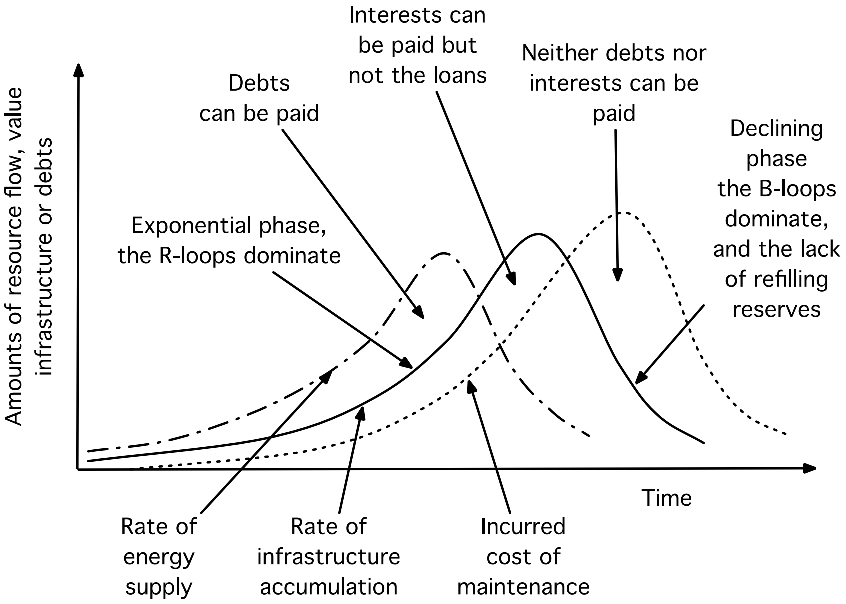


Fig. 8 The system output can be read out of the causal loop diagram which is given in Fig. 6. Initially, the system is driven by maximizing resource extraction, leading to exponential growth in primary profits. Increase in available money normally leads to increased spending into investments, infrastructure and consumption. Increase in infrastructures and bureaucracies leads to exponential growth in costs and maintenance costs. As the resource base is depleted, the exponential growth can no longer be sustained, and we get "peak" behaviour when the resource output declines. However, the infrastructure stock has grown to a level that requires a large input of resources, which at some point exceed incomes. As reserves are depleted, more and more capital must be used for obtaining resources, leaving less to be invested for future maintenance and development. Adapted after the narrative of Tainter [57-59].

In a situation with declining income, further creating "growth" by taking huge loans is a receipt for disaster. Tainter [57] states that the whole system is simplified as a result of shedding costswith fewer and simpler systems.

We use different types of methods to estimate the time horizon of raw material or metal resource scarcity [20].

1. Burn-off time is a worst-case scenario, and it is given a worst case estimate. It does neither consider exponential growth nor market price mechanisms. The burn-off time is defined as the estimated extractable resources divided by the present net extraction rate. This is an accurate estimate in a stagnate economy, but an overestimate in a growing economy and gives approximate time frames:

$$Burn-off = \frac{reserves}{extraction \cdot rate} \quad (2)$$

2. Peak discovery projections: Earlier work has shown that there is a systematic shift of 40 years between the peak discovery and the production peak. This is a purely empirical observation, but it is consistent across many cases [8, 20, 14, 15, 16, 28]. Thus we have:

$$Peak\ production = Peak\ discovery + 40 \quad (3)$$

In the results section, we give the basis for adopting 40 years in relation [3].

3. Modified Hubbert's-curve estimate of peak production and time to scarcity: The Hubbert's curve is defined by the simple equation for cumulative production is:

$$m(t) = \frac{URR}{1+e^{-b\cdot(t-t_{\max})}} \quad (4)$$

where M is the sum of all resource produced to time t, t_{max} is the time of the peak, URR is the size of the whole resource, and b is the curve shape constant. The production is given by:

$$P = \frac{2 \times P_{MAX}}{1 + \cosh(b \times (t - t_{\max}))} \qquad (5)$$

Where P_{max} is the maximum production rate, P is the production. Time to peak can be estimated using:

$$t_{\max} = t + \frac{1}{b}\ln(\frac{4 \times P_{MAX}}{b \times m(t)}) - 1 \qquad (6)$$

Once t_{max} and URR have been empirically measured, then the predictions are relatively accurate and the Hubbert's curve model has been robustly verified on field data from oil, coal, phosphorus and metal mining, demonstrating that it works well [12, 32, 39, 41, 60-62]. The URR (ultimately recoverable reserve) is equal to:

$$URR = 4 \times \frac{P_{\max}}{b} \qquad (7)$$

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.

4. The last calculation method is based on dynamic modelling [1, 2, 3, 20, 29, 30]. 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, here using STELLA®. This method gives more detail, demands more insight and can include more factors, but is more difficult to parameterize. Aspects of exponential growth and market price mechanisms are mechanistically incorporated in our process-oriented models [30].

4.3 Recycling

The resources can be divided into two parts. While most metals and materials are recyclable, nuclear fuels, oil and coal—which all are burned—suffer from dissipative losses and small possibilities for significant recycling. The flow diagram in Fig. 9 shows how recycling can maintain the input to society, but decrease the input from finite resources through mining. The total resource consumption is given as:

$$Total = consumption\ per\ person \times persons \qquad (8)$$

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 at best both. When we assess the effect of recycling, we firste stimate the supply to society by:

$$Supply\ to\ society = \frac{Mining}{1 - R} \qquad (9)$$

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 can calculate the new flow into society for other improved degrees of recycling:

$$Time\ to\ scarcity = \frac{Reserves}{Supply * (1 - R)} \qquad (10)$$

We calculate the new net supply needed to maintain the societal supply at present level at improved recycling rates, and use that to find the new burn-off time as given above.

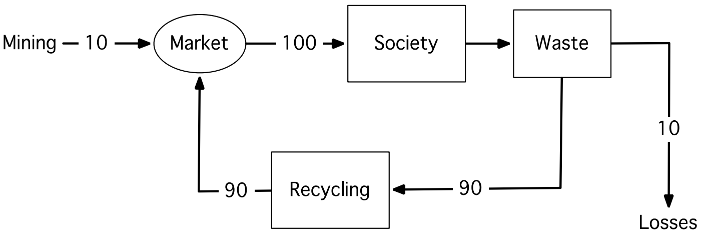


Fig. 9 The effect of recycling. This flow diagram shows how recycling can maintain input to society, but decrease the input from finite resources through mining. The authors can maintain a flow inside the system if the authors recycle 90 units, thus we loose only 10 units and thus only need to top it up with the losses, 10 units. The real flow to society becomes amplified by recycling, because part of the outflow becomes returned to the inflow. Market refers to manufacturing and market; losses refers to dissipation, burial in landfills and pollution of the atmosphere.

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 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 can not keep up with depreciation, and the industrial base erodes, taking with it the service-and agricultural systems, which have become dependent on industrial inputs.

4.4 The World Model Development

A comprehensive global model assessment is being built by our team (WORLD), integrating a large number of world system aspects. An outline of the WORLD model is shown in Figs. 10-12. The coloured boxes refer to modules in various stages of development. The phosphate and population modules have been published earlier [19, 28, 30], and it is derived from a standard model originally developed at the IIASA (International institute for applied systems analysis) at Laxenburg. The market model and part of the financial system appears in Refs. [29, 30] and Refs. [19, 20]. The metal mining part appears in in Refs. [29, 30]. The ecosystems model is partly published in Ref. [27]. The market module—including futures and derivatives trade—also appears in Ref. [48] and Refs. [28, 30], where it is applied to the Chinese grain market and in another context, to the Easter Island exchange system for natural resources in a tribal society in past history. WORLD shares many of the general features of the models used for the Limits-to-Growth study [1], which generated three versions of a model called WORLD1 to WORLD3, but also has important improvements and modules not found in the earlier models. The social modules presented here are new and to a large part not yet published. A beta version of the WORLD model was used for some of the assessments used in the final evaluation of our results.

5. 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 [19, 20, 28, 30].

5.1 Time to Scarcity under Different Scenarios

In Table 1, the authors 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. The abbreviations within brackets are found in the caption to Table 1. For some elements that are major infrastructural elements, significant corrosion rates were considered to be non-recoverable. The metals concerned with large bulk losses from corrosion are iron, copper and zinc. The colour in Table 1 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 sustainability. Of the 31 metals and materials listed, 21 have a burn-off time of less than 100 years, and 15 shorter than 50 years. The burn-off time is a diagnostic parameter, suggesting when this material will become too expensive for mass consumption.

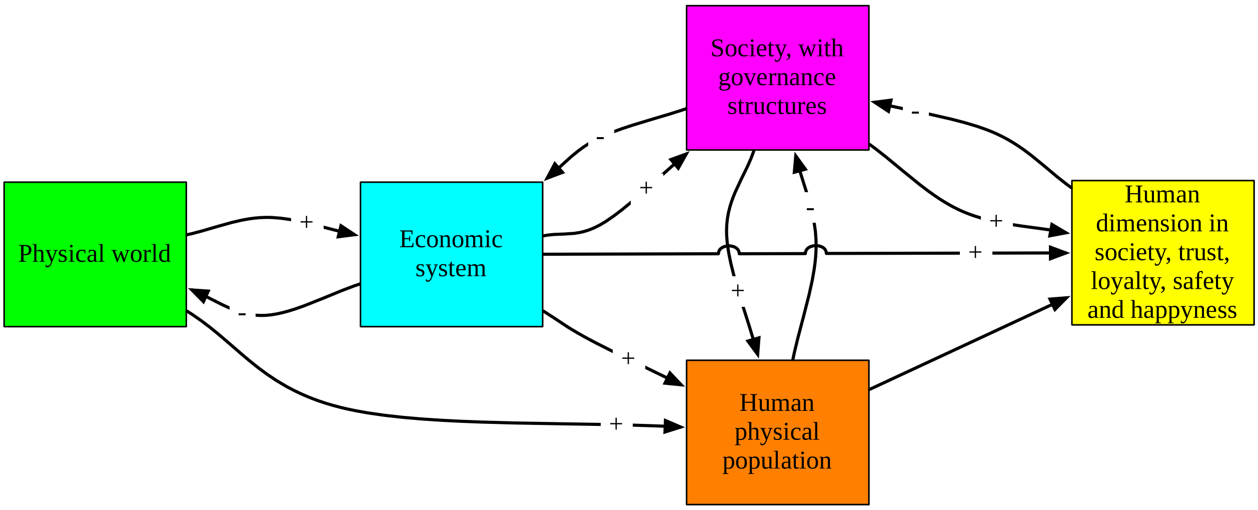


Fig. 10 **The WORLD model concept. The organization of the WORLD model on an overview level, show the connection from the physical world through the economy and society, includingaspects of well being, trust and happiness of citizen.**

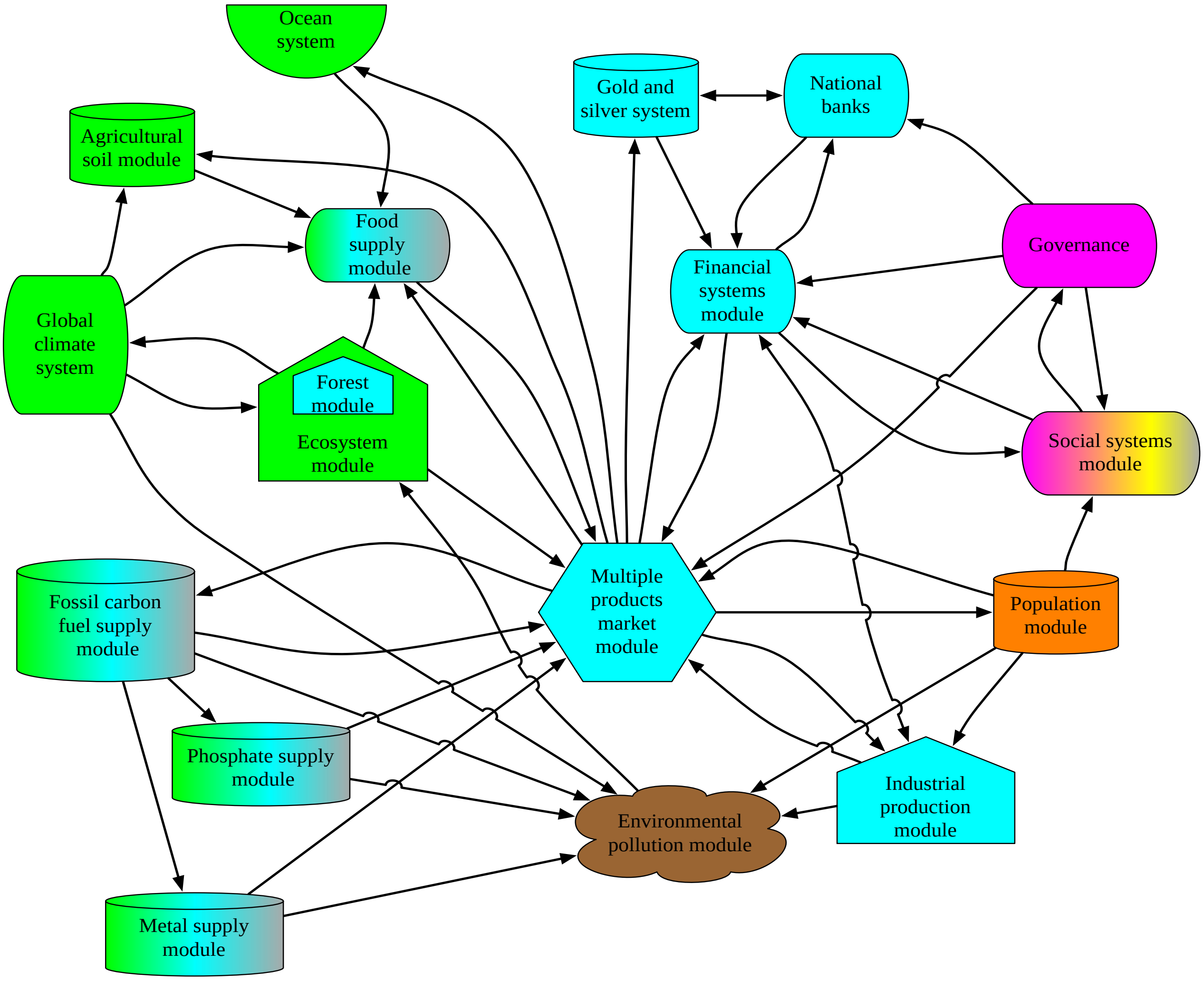


Fig. 11 **The organization of WORLD model is ingreater detail. The social systems module is undergoing development and a simple version has been integrated in the version used for this study. Important is that the model also gives for the first time outputs for social parameters like social trust, corruption levels and happiness in the population.**

Table 1 Estimated burn-off timesin years for a selection of important materials and metals, considering the different recycling, materials use and populations scenarios. Output estimates of burn-off times are in years. All values are years counted from 2010 and forwards. BAU = BAU (business-as-usual) with recycling as today. 50% = improved habits in the market, at least 50% recycling or maintain what we have higher than 50%, improving gold recycling to 95%. 70% = improve recycling to at least 70% for all elements, gold to 95%. 90% = improve all recycling to 90%, except gold to 96%. 95% = improve all recycling to 95%, gold, platinum, palladium, rhodium to 98%. 3bn = 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. 1½bn = 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. All numbers are years after 2010.

Element	BAU	50%	70%	90%	95%	3bn	1½bn
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
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
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
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	

5.2 Assessment Using Peak Discovery Projection

Table 2 shows delays between peak in reserve discovery and peak production that we have found by surveying data in the literature. The data suggest an average delay of 40 years between peak discovery and peak production. Thus, peak discovery is a useful diagnostic tool for detecting an impending production peak.

5.3 Assessment Using Hubbert's Curves

In Fig. 11, the Hubbert's-curve fittings for the metals gold, silver, copper, iron, platinum group metals and indium is shown, further details can be found in Refs. [20, 30], which assessed 38 major materials and metals. We can see that the data suggest gold already passed the peak in 2000. Time to scarcity for gold would be about 2070 [13]. 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, iron 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 problem, and it is difficult to foresee the consequences. Fig. 11 also shows the fitting for the platinum group metals, suggesting a peak production of 550 t per year and a total reserve of 89,000 t when it started in 1900.

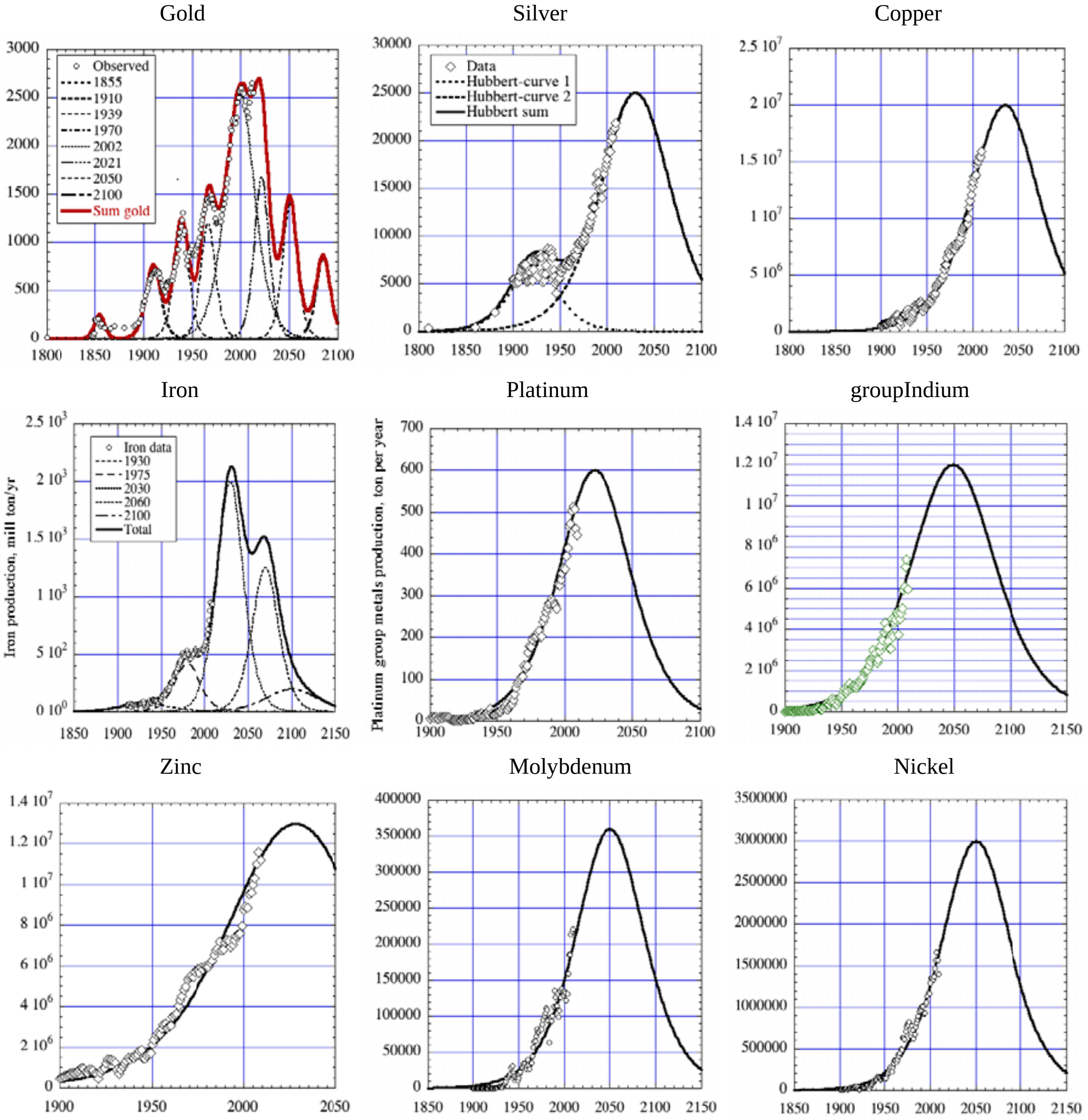
5.4 Peak Phosphorus

Peak phosphorus and soil could mean peak food and possibly peak people. Fig. 12 shows the systems dynamics simulations (Fig. 12a), the Hubbert's-curve fittings (Fig. 12c) for phosphorus and phosphorus prospecting and production rates (Fig. 12d) [28] as several Hubbert's curves. We can see that the data suggest phosphorus already passed the peak in 1990-2010 (Fig. 12c), with a flat plateau to 2050 with a sharp decline into scarcity after that.

The total mineable reserve in 1900 is estimated at 167 billion ton. By 2010, an approximate half of this had been consumed [28], with 80 billion ton remaining, mostly in low grade and ultra-low 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. Fig. 13 shows some data on the area of tilled soils of the Earth. By applying the Hubbert's model to soil data, we assume that we are mining a resource where the mining rate by far exceeds the regeneration rate. The Hubbert's model fits the data well, suggesting that we may view our soil resource to be under going mining through erosion. It is apparent from the curve that the global soil resource appears to have peaked in 2005. We should interpret this a diagnostic indicator something being very unsustainable in how we are at present managing the soils as a resource. This could potentially be the single largest identified threat to general survival of civilization on the planet because soils form very slowly of the order of millimetres per 100 years.

Table 2 Delay between peak in reserve discovery and peak production. The data suggest an average delay of 40 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
Oil, Russia	1961	1989/1998	37
Oil, Saudi Arabia	1958	2002	44
Coal, United States	1950	1992	42
Coal, Russia	2030	2070	40
Phosphorus, global	1955	2000	45
Coal, Great Britain	1880	1922	42
Iron, global	1978	2025	45
Global copper	1996	2036	39
Global silver	1995	2030	35
Average			40



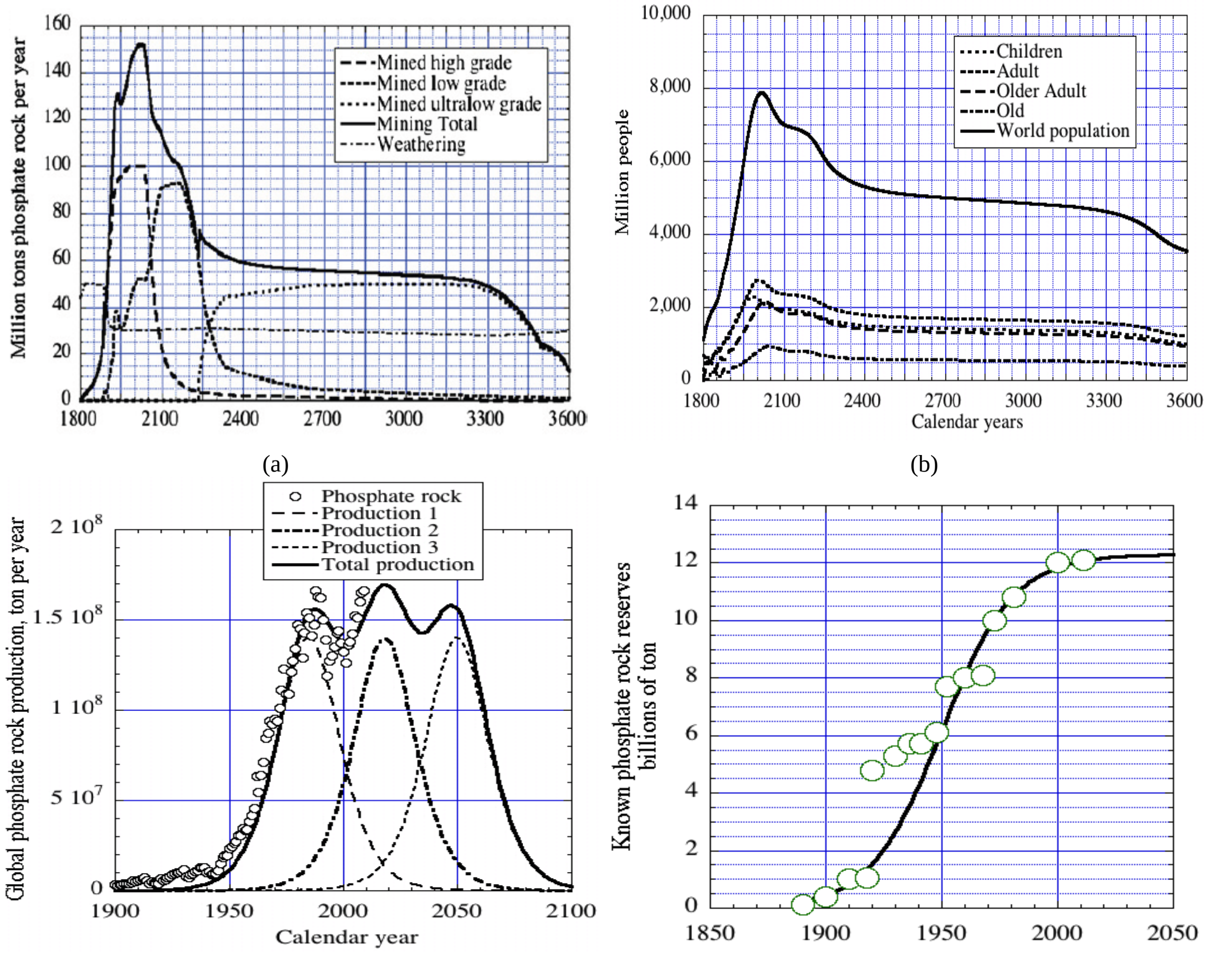
Gold Silver Copper

Iron Platinum groupIndium

Zinc Molybdenum Nickel

Fig. 11 Hubbert-curvesare fittings for different metals. Silver and copper is essential for electronics, platinum for a number of key chemical processes, including artificial fertilizers, indium for computers and electronics, and iron for almost everything humans do to run society. The scale on the Y-axis is production in ton per year, the X-axis is the calendar year. Data: Published literature, industrial unpublished databases, USGS [63-67].

Without soils, many areas can not 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 [19, 28]. In Fig. 12c, the authors 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's model for phosphorus in an arrow window. The curves are sum up to the total reserves suggested in the diagram (Fig. 12c). USGS [63, 66] has reported an up-scaling of the Moroccan deposits to 51 billion tons of phosphate rock that is a significant increase compared to earlier [64-66]. That estimate would be very good news if it was true, and it would postpone the phosphorus scarcity problem by about 50 years [19, 28].



(a) (b)

(c) (d)

Fig. 12 (a) Phosphorus production, dynamic FoF-model developed by the authors [19, 28]. (b) Global population scenario, resulting from applying a phosphorus limitation to the standard UN population dynamics model when it is limited by phosphorus availability [19, 28]. (c) Hubbert's curve phosphorus rock production in million ton phosphate rock and using phosphorus reserves of 12.4 billion tons. (d) The phosphorus prospecting history according to available data is shown. Major discoveries came in three pushes. By 1945, 50% of the phosphorus reserve had been discovered. Being able to see a clear s-shape suggests we have found most of what is there.

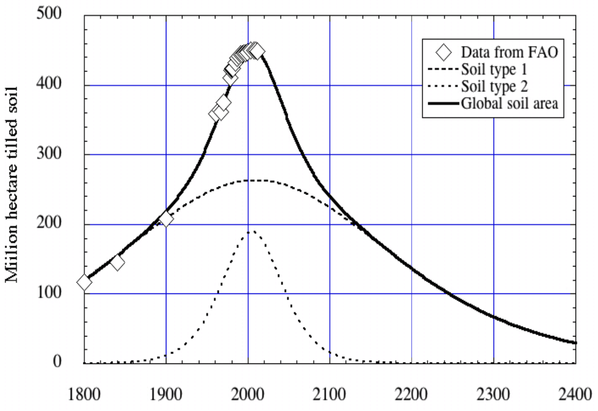


Fig. 13 The area of agricultural soils of the earth peaked in 2005. That is a serious observation for humanity.

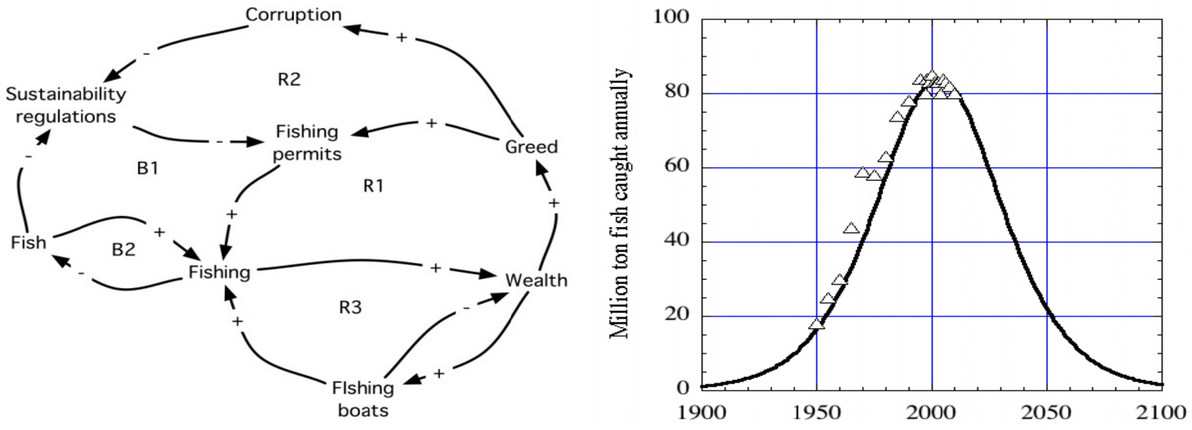
Whether this is wishful thinking and how much of it is recoverable remains undefined at present. The latest up-scaling of the reserves does not properly address how much of this phosphate will be eventually extractable and if so at what cost, and until this is done, it represents no more than an unverified claim. It needs to be verified adequately and assessed to what degree it can also be recovered at a reasonable return on investment for energy and materials. If the increase in phosphate resource is real, 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 world has an emergency of the most serious type on its hands, though there does not seem to be much political recognitions of what may lay ahead in the near future. This occur after 2040 according to the model output in Fig. 12a, after 2050 according to Fig. 12b, this is only 25-35 years away at the time of writing. Phosphorus is a substance that has no substitutes, indicating that the price may potentially rise without any obvious upper limit if it is significantly undersupplied. Phosphorus is an essential ingredient for all living organisms, and lack of phosphorus is equivalent with lack of food, unless closed cycle agro-ecological approaches are adopted [26, 27, 35, 68-69].

The cumulative prospecting curve (Fig. 12d) has a distinct S-shape, a certain diagnostic trait for the fact that there are not much more phosphorus rock reserves to be found, casting the last USGS up-scaling of reserves into serious doubt [67]. This implies that there was a 50-year delay between the peak in prospecting and the peak in production for phosphorus. The use of a systems dynamic model yields a much more sophisticated assessment [19-20, 28], but qualitatively comes to a same type of conclusion. Add to this Fig. 13 that shows that the area of tilled soils of the earth peaked in 2005, and it becomes obvious that we have a severe challenge to global food supply in the future. Understanding the serious consequences of a global food shortage does not need further elaborations here.

5.5 Fisheries are at Stake

Fig. 14 shows the Hubbert’s curves adapted for global fisheries [8, 10]. The global fish production peaked in 2002-2003 as shown in Fig. 14b. Fig. 14a is a causal loop diagram explaining the causalchain leading to exponential increase in fishing, an overshoot and collapse of the stock. In 2060, the catch will have sunk to 10% of the maximum and fish as a food will be a rarity for the rich. The total stock having once been at 6.4 billion tons of fishable fish in the ocean 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 cold fact has had disastrous consequences for the global fish stock. Fig. 14b shows how the global fish production peaked in 2002-2003.



(a) (b)

Fig. 14 Fish is a renewable resource that is near extinction in our times. The diagram (a) depicts the causal loop diagram that explains the overall system. Fishing leads to wealth, the wealth allows building of more fishing boats, leading to more fishing, but governance and fishing permits are supposed to limit the extent. Wealth leads to greed that leads to corruption that leads to larger fishing quotas, even if the fishing limits are far too high. Fishing leads to decreased ocean fish stocks, which in turn will ultimately limit fishing. The diagram (b) shows some data gathered from official sources. The global fish production peaked in 2002-2003 as shown in (b). In 2060, the fish catch will have sunken to 10% of the maximum (data from FAO, curves by the authors).

In 2060, the catch will have sunken to 10% of the maximum, and ocean fish as we know it today will definitely be over for the foreseeable future. There is unknown uncertainty in this figure, but the warning is clear enough and it would be unforgivably reckless to ignore it.

5.6 Building and Ruining Nations

Tainter [57-59] 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". It manifests 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.) and he summarizes a large number of historic collapses. Fig. 15 shows the example "rise and fall of the Roman Empire" taken from Kennedy [70], Tainter [57], Bardi [10], Bardi and Lavacchi [12], Fleming [71] and Fukuyama [72]. The content of silver in the Roman coinage went down steadily from the time of Augustus until the end of the empire. By 300 AD, the Empire 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 today's Italy, as reflected by abundance of archaeological artefacts, is also shown in Fig. 15. The manpower of the Roman army is shown in Fig. 15 to illustrate how much surplus they could divert to defence and expansion [12, 55-57, 72]. Resources lead to wealth that leads to more people and in the continuation that may lead to larger military might (Fig. 15). That leads to larger territory and more resources in the resource base. By steadily acquiring more new territories, it implies that the same army

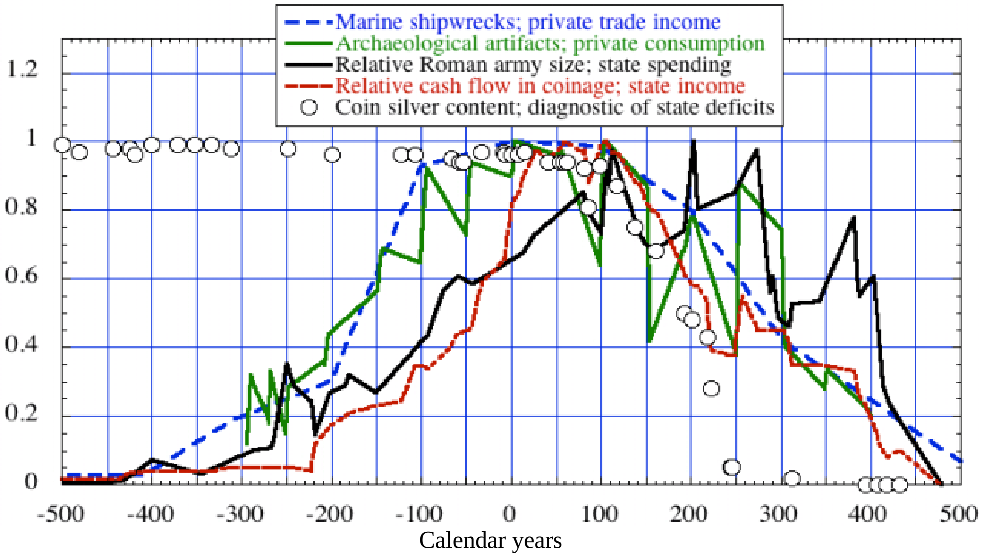


Fig. 15 The rise and fall of the Roman Empire in observed numbers. The depletion of silver in Roman coins 0-270 AD shows the inflation as the coin silver content was reduced, the archaeological artefacts reflect household income and the manpower of the Imperial Roman Army reflect Roman state costs. The 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. All parameters shown have been rescapeled to the same unitless scale, with 1 being the maximum value.

must hold more land, thus it becomes weaker and more stretched, unless it is correspondingly increasedand thus increasing running costs as well. 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, the imperial peak wealth seems to have occurred about 120 AD, the imperial expenses peaked in 270 AD, the Western Roman Empire perished as a state a century after. In 410 AD, Rome was sacked by the Visigoths, and then a real Roman Empire no longer existed.

For the Western Roman Empire, the delay between resource peak and wealth peak seems to be about 100-200 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 (280 AD). The collapse of the Roman Empire began 170 years after the resource peak (270 AD). It never revived properly after that, as the resource base for a recovery was no longer present. The reasons for the fall of the Roman Empire have been much debated. Gibbon’s “rise and fall of the Roman Empire” suggests that it came from a progressing moral inadequacy caused by the introduction of Christianity and the rise of decadence and corruption. Later it was suggested that it was a resource collapse [56], or a systemic collapse of a complex organization [14-17, 57-58,72]. In Fig. 16, a causal loop diagram is shown that attempts to explain some of the reasons for the fall of the Roman Empire. To us it appears that the decadence and corruption (”culture”) are partial causes that are involved as components of a larger systemic collapse. There are several balancing loops in the causal loop diagram but only one reinforcing loop-based on resources. This illustrates why an empire with a good resource base can achieve great might, but that it 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 power elite, the imperial structure and complexity. As the Roman Empire evolved and grew in size, it also developed a state and societal organization with increasing complexity. More and more complex structures were built, such as sewer systems, water supply systems, including complex piping in the cities, aqueducts, storage dams and cisterns, roads, road construction organizations, materials sub-suppliers, maintenance organizations, state agencies, bureaucracies and offices for various operations [10, 11, 34, 44, 57-59].

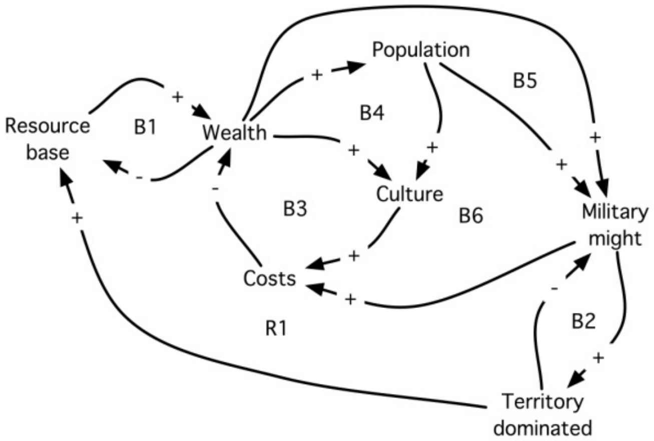


Fig. 16 A simple causal loop diagram, to illustrate why the Roman Empire disappeared. The causal loop diagram is a logical variant of Tainter’s principle as shown in Fig. 7 and discussed in the text. In short, surplus wealth drives up consumption into overshoot, where the income no longer can support the activity, whereupon a contraction (in a peaceful environment) or in the worst case a collapse (as in a conflict environment) follows.

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. 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 [57-58, 72]:

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 profit return on monetary investment, and the energy and material return on investment values are high;
2. The increased land area with military dominance, augmented the running costs of military operations in consolidating gains, the increased access to low cost short term wealth that leads to specializations and increased complexity of the organization of society gaining that extra wealth;
3. The continued expansion of the Empire created a backlog of cost that slowly built up in the system. The further expansion of the domain, after the acquisition of the best reserves for resources, ran into diminishing returns on further effort. The exploitation of internal domestic resources stagnated and declined as they approach exhaustion, compensated by unsustainable taxation to fill the gap. For the Roman Empire, this implied that local mines (e.g., silver) went empty, the landscape was deforested (and fuel was depleted) and the agricultural soils eroded away. This reduced and depleted the domestic resource base, and increased reliance on resources harvested far away and new conquests they could no longer afford;
4. The maintenance cost backlog catches up, income declines and as a result, huge budget deficits developed throughout the whole structure. As the reserves inside the imperial system structure run out, the system experiences broad-front systemic decline that may under stress accelerate to 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 [1-3, 10, 14-17,26, 44, 55-59, 70, 72].

5.7 Fossil Energies

There are several sources of fossil energies, stored energies from the past. The main fossil sources available for energy production are:

1. Hydrocarbons—oil, tar sands, bitumen, natural gas, shale gas, oil shale;
2. Carbon fuels—coal, brown coal, peat, and carbon-rich shale;
3. Conventional nuclear power generation based on uranium and thorium;
4. Fossil geothermal heat

They all have in common that they are mined, and once they are gone, then they are gone forever from a human civilizations perspective. Breeder reactors are not yet ready technologically, but may extend the lifetime of thorium-based reactors to 50,000 years with some additional development [73, 74]. Research for fusion reactors for power generation are on-going at present, but nowhere near anything useful for energy production for the foreseeable future [75, 76].

5.8 Global Considerations

The recent global economic crisis and the still on-going global debt crisis are claimed to be a similar systemic crisis to the Roman Empire, where we are now proclaimed to be in the last stages before systemic collapse [10, 57]. Here we will examine these claims. Large deficits in running budgets 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. The situation may potentially be dangerous for the stability of the state it affects. Figs. 17-18 shows the world fossil fuel production, distributed among different fossil fuel types.The curves are based on observed production data from the open literature and the oil and coal corporation production estimates for the next decades [7, 20, 24, 26, 28-29, 33, 35, 39-43, 53, 61, 63-64, 66-67, 74, 77-82]. The global coal production will peak soon, and the numbers suggest 2015-2020. The ranges arise from the issue of how much of the remaining coal that can actually be extracted [77-78, 84]. Coal is more abundant than oil and also a finite resource, the regeneration rate is insignificant.The global oil production and the resulting global wealth production follow 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. In the past, most of the high quality coal has been mined and burned, leaving the remaining reserves in the low-grade category.Peak oil already occurred 2008-2010. Other studies using a multi-cycle Hubbert's model confirm this depiction [79]. At that point the situation could become difficult to steer away from a grand scale systemic collapse, which would potentially cause a lot of problems.

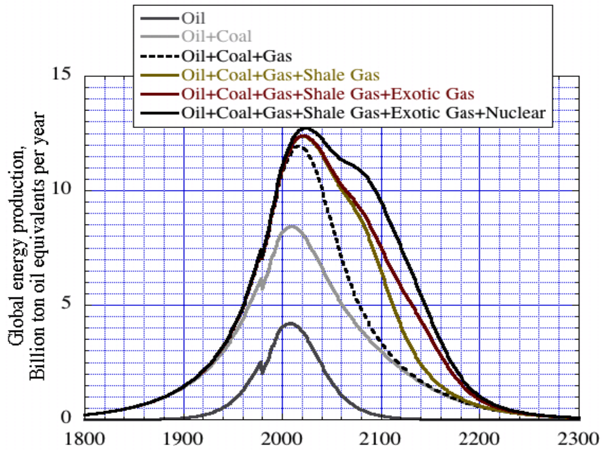


Fig. 17 Production of many different types of fossil fuels, including some new types claimed "to remove the problem of peak oil". The estimates of extraction rates show this to be a very naïve opinion, as all fossil energy use must obey mass balance, and there is no escape in this universe from that principle. And as we extract, less will be left in the reservoir. Conventional nuclear energy is also a fossil fuel and with present use it will not last any longer than oil. Hubbert's curves were estimated by the authors.

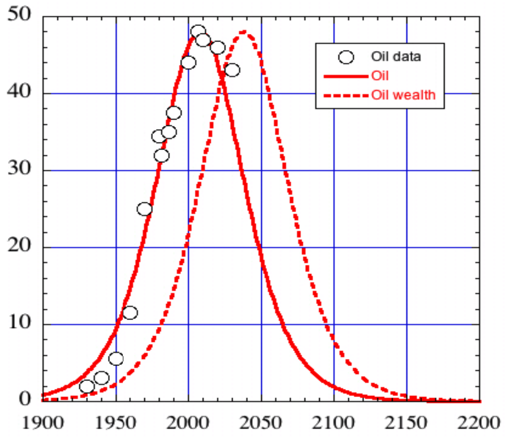


Fig. 18 Applying a Hubbert's curve to Norwegian oil production with time we can see the maximum year, and using the oil price projections to suggest the oil wealth will peak some years later. Circles are observed data, the data has been formatted to a relative scale in order to fit the same diagram. Numbers on the x-axis are calendar years. Adapted from USGS statistics [67]. Data assembled, modelling and drawing by the authors [80-84].

We conclude that we see signs that this is taking place right now. Energy from fossil hydrocarbons is not recycled, but it can be partially recycled after certain uses through heat exchanging, providing that it is valuable enough. 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 some decades 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. The Norwegian hydrocarbon production peak occurred in 2002-2003, the Norwegian oil-related income peak is predicted in Fig. 19 to occur in the years 2012-2014.

For Norway, there is approximately a 15-year lag between peak resource and peak wealth. There have been four instants where the coal production has peaked for economic growth periods. The detectable S-shape of the prospecting curve for coal, shows thathoping for new sensational discoveries of large coal-fields, are vainhopes [10-12].

The coal mining industry had by 2011 extracted 35%-40% of all extractable coal in the world. The world coal production and reserves follows a very similar pattern as oil, total coal reserves are estimated at 710 billion ton oil equivalents, the peak production year occurs in the interval 2020-2035. The data on delay between peak in reserve discovery and peak in production rates suggest an average delay of 40 years between peak discovery and peak production (Table 3). The Hubbert’s curve approach has been verified for a number of fossil resources (coal, oil, gas, phosphorus rock, gold, fisheries) [5-7, 10], and the data demonstrate that the approach reconstructs the observations of the past with good accuracy and is thus a proven concept [79]. 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.

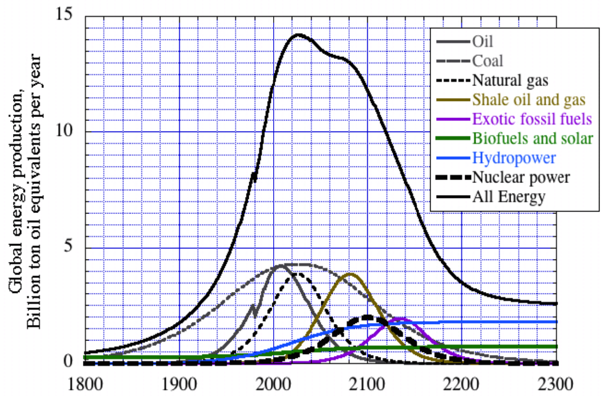


Fig. 19 Graph showing the production over time for all energy sorts, fossil, and renewable, but excluding thorium energy from breeder reactors. Data was assembled and drawing by the authors [80-83].

Fig. 18 shows the different energy types used to supply the world. It suggests 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. Without a paradigm shift, this is what we can get. By 2200, we will have to have adjusted to about 20% of the energy supply we have now. Not easy, but not impossible with a big rethink. Fig. 20a and 20b show past global energy production and a future projection. The diagrams are based on historical data and the predictions are assembled from published projections of the major energy companies.

5.9 Alternative Energy Sources

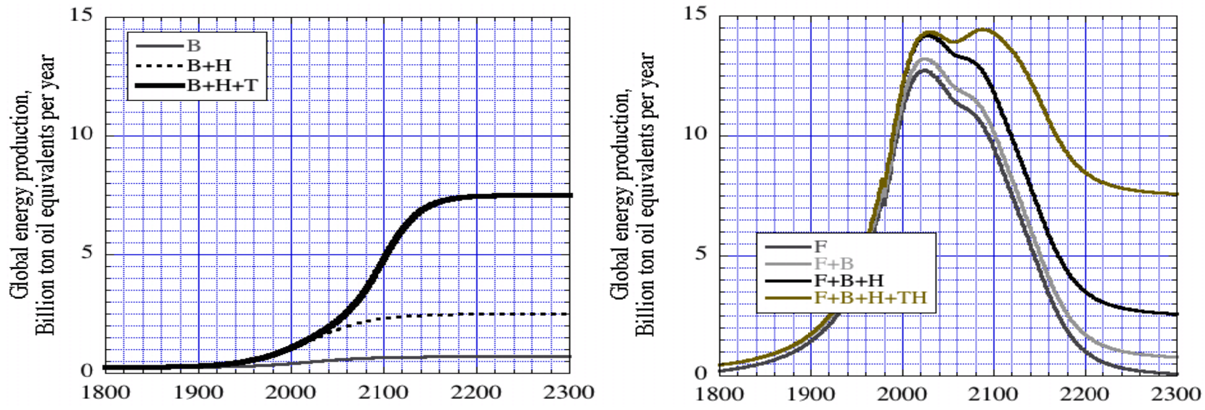
Fig. 20b show a future possible scenario where alternative technologies and renewable energies are used to replace fossil fuels. They are further described below:

- Hydropower is by far the largest sustainable source of long-term renewable energy, next comes biofuels, very important in less developed and in northern arctic countries with large forests.

Central Asia and the mountains of the Americas still have areas with un-harvested hydropower available;

- Biomass may potentially provide a large amount of fuel and substrate for synthetic oils, however, this would compete with other present uses of biomass in a way that may prove problematic. Much of the potential is already taken up by production of food and materials for wood and paper. How large the potential is after a detailed assessment remains uncertain, however, the potential for extra biomass for fuel from forests is limited as long as we intent to harvest sustainably, avoiding mining out forests [27]. So far, the potential has been overstated to levels that are not sustainable [38]. Hydro and Bio energy types can support long term 20% of the present global supply when fully developed, however have some challenges to be tackled;
- Huge amount of long term energy can be added by introducing thorium breeder nuclear reactors based on thorium as fuel with nuclear fuel recycling, a system that would be able to yield about 50% of the global energy production that was produced in the year 2010 [60, 61, 74, 85, 86]. Thorium in such use may be estimated to last at least 4,000 years, possibly more [19, 20]. The weapons proliferation issue is limited for thorium technologysolution, one major advantage is that it generates limited waste problems (3%-10% volume of uranium wastefor the same energy production, much can readily be reprocessed to fuelof the comparable) [73]. We need to remember that there are very serious safety and radiation challenges that will require a huge effort to make thorium installations safe and reliable. The recycling technologies required are in general available, but still require more development to be safe [87]. These challenges are not yet solved and will take time and effort to develop. The implication is that upwards to 50% of today’s energy use may come from the biofuels, hydropower and breeder nuclear reactors. Fig. 20b shows the adding up of all possible energy types, including the potential from new technology thorium recycling reactors;
- The technology-based solar energy harvesting strategies (photovoltaic, wind energy harvesting, active or passive heat harvesting, wave power harvesting) all have significant technological and social challenges and require rare materials that may become scarce or volume-limiting and thus require very strict recycling [88-91].

Potentially, all these alternatives may be able to sustain the present energy production level (but not increase it) until 2080, after which a convergence and contraction to about 50% of 2010 production levels will have to occur regardless of what we do. This is a best-case scenario that requires a substantial effort in research and societal preparation, however the advantage with thorium-based nuclear power is that it produces no material useful in nuclear arms and thus prevents nuclear arms proliferation. In the best case we will at best end up with 50% of 2010 energy production level, but more likely something like 18%-25% of 2010 energy production level. In the best case (-50%), it will be possible to adapt to with serious and determined efforts, the more likely scenario (-75% to-82%) is a tough challenge that will require a huge effort, including major political and cultural adaptations and changes [16-17, 44, 55-59, 70-72, 90, 100, 112].



(a) (b)

Fig. 20 Diagram (a) shows different long term energy sources and what they can yield in the next 300 years. B implies biofuels, solar power harvest and wind power. B+H is the energy added from hydropower. These energy types can support long term 20% of the 2010 global production. B+H+T indicates the energy that can be added by introducing breeder reactors based on thorium and fuel recycling, yielding about 50% of the 2010 global energy production. The implication is that 50% of today's energy use may come from these three sources. Diagram (b) shows adding up all the energy types, including new technology thorium recycling reactors. This may be able to sustain the 2010 energy production level until 2080, after which a convergence and contraction to about 50% of 2010 production level will have to occur. *F* = fossil fuel energy generation, *B* = biomass based energy, *H* = hydropower, *TH* = thorium-based power generation. Data from diverse sources [79] and drawing are assembled by the authors. Thorium potential was estimated by the authors [84].

Table 3 Assumption underlying the assessment. These are basic numbers behind the simulated curves (Figs. 17 and 20) with estimates for energy reserves in 2010. The numbers for coal and shale gas vary widely, depending on at which quality the cut-off is made. Much of the higher estimates include reserves of very low quality where it is highly questionable if they will ever be or can be extracted. Exotic fuels are metanedeep sea condensates, sea floor coal beds and other reserves presently out of technical reach. Data were assembled to a database and analysed by the authors using Hubbert's model and dynamic modelling (WORLD model early versions). The table shows data for shale gas and oil, and hydrocarbons released through shale frackinghave been included.

Fossil energy source	Ultimately recoverable reserves in 2010	Initial reserves in 1840	Estimated production peak time (this study)
	Billion ton oil equivalents		
Oil	355	650	2005
Coal	750-1,400	1,600-3,000	2020-2055
Natural gas	310-330	690	2015
Shale gas	320-450	500-700	2040-2080
Exotic fuels	100-210	100-210	2130
All energy	1,795-2,745	3,540-5,250	2015-2020

6. Discussions

6.1 The Role of the Free Market

It appears from the analysispresented here 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 neithera future vision nor a magic source of materials. At best, the free market only partly optimizes for the present instant. Important is to realize that a free market is not a market without rules. A free market is a regulated market where the actors are free to act within the guardrails set by the rules defining fair play. 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 [54] argued that "anyone who believes that exponential growth can go on for ever in a finite world is either a madman or an economist."

6.2 Peak World and the End of the Golden Age

Figs. 17-20 show that both oil and coal will peak in the near future, peak oil production was passed in the period 2008-2010, the coal peak comes in the period 2015-2020, peak energy will occur in 2015-2020 and thus wealth peak will arrive around 2035. From then on global growth of GDP will be possible, and a new economic paradigm for supply of life quality to the citizens must be in place. There is a delay of 50 years between initial investment, and the cost of maintenance for infrastructural renewal was assumed to increase by 1.5% per year. The integrated world system simulation model (WORLD) used to produce the runs used for this study [30] is similar to the approach taken by Meadows et al. [1-3] in their World3 model in the Limits-to-Growth study. However, they lumped energy and all material resources, missing the dynamics when having them coupled but separate, as shown here. Materials can be recycled very well, whereas much of energy use is in its fundamental function non-recyclable. We have taken on the development of a new world resource model.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. [92], for Easter Island see Bahn and Flenley[34], but also more general considerations [1-3, 17, 23-24, 26, 44, 50, 52, 55-57,72, 93-99]. Lack of resources is a potentially dangerous situation globally. The solutions to our sustainability problems are as much in the social domain as any other domain, and engineering and economics 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 creates a significant limitation for future generations, and carries ethical problems with such behaviour [14-17, 100-106]. At the end of the golden age [1-3, 19, 28, 30, 57, 58], 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 extracted from the Earth.

6.3 Not Listening to Early Warnings

In the 18th century the global community made a mistake by not listening to Malthus projections [22], and allowing the global population slip above 700 million and into a pathway towards notbeing sustainable [1-3, 19, 23, 25, 26, 44]. 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. In 1973, when the United States went throughlocal peak oil, and started importing largeamounts of oil from the Middle East, the worldhad a last warning of what happens when globalpeak oil is passed. The assessment made by the Club of Rome, the "Limits-to-Growth" report was published in 1972 [1-3], predicted the coming of resource scarcity and the ramifications following. The lessons were not learned, they were only shortly heeded by a few and then fast forgotten by both the public and politicians [21, 101]. At that point politicians slipped in their statesmanship and their strategic planning and leadership, by listening to and believing the talk of endless growth. Economic "science" failed in not applying systems thinking, not understanding the basics of exponential growth, not understanding limits, applying faulty models, and in their ignorance of mass balance as well as thermodynamic laws, and not learning from past historical experiences with collapses and declines [14-17, 57, 58, 72]. The WORLD model was used in this study to estimate the rise, peak and decline of some empires and check this against available data to assess the exactness of our predictions. Table 4 shows data on rates of resource discovery, resource extraction and wealth creation over time, cost over wealth overshoots and predicted civilization declines, an attempt at a preliminary prognosis.Resource peaks are for land, coal, oil and metals. The decline dates assume that governance and society continues along the practice of business as usual, without any consideration of effective measures to attain sustainability.

6.4 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 that we will have the energy resources to do the work that is required, while when all the resources have become scarce, and the global population larger, then our possibilities will be far less [1-3, 14-17].

Table 4 Knownresource discovery, resource extraction and wealth creation peaks, cost over wealth overshoots and predicted civilization declines, a preliminary prognosis. Red numbers are predicted dates, black dates areobserved dates from historical data.

Empire	Predicted with meta-model prototype based on the WORLD-model, outputs in calendar year					Observed decline
	Discovery peak	Resource peak	Wealth peak	Cost > wealth	Predicted decline	
Roman Empire	14 AD	80-120	120-160	180-220	240-280	First 287 Final 370
British Empire	1888	1928	1938-1943	1958-1963	1978-1981	Dismantled 1947-1965
Spanish	1520	1550	1565	1580-1600	1620-1660	1700-1750
Soviet	1932	1948	1960	1985-1990	1995-2005	1990-1993
Russia	1880	1993	2005	2020-2025	2035-2045	n.a.
American	1955	1971	1983-1986	1991-2006	2010-2030	2008-2012
Chinese	2000	2020-2025	2035-2040	2050-2060	2060-2080	n.a.
Indian	1990	2030-2040	2045-2055	2068-2080	2077-2090	n.a.
Global	1975	2007	2017-2022	2040-2060	2060-2080	n.a.

n.a. = not available

It is in these next 20-40 years that we will have the energy resources to do the work that is required, while when all the resources have become scarce, and the global population larger, then our possibilities will be far less [1-3, 14-17]. 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. We can get a warning from declining discoveries, when they occur, and there will be about 40-50 years left before the peak, and about the same time until scarcity. This is presented in Table 5. 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 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. A new initiative for future development is needed and the process needs solid reinforcement from professional scientists from all disciplines.

7. 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 running of oursocieties. The crisis we experienced 2007-2009 in the western world was not only a financial crisis, but a crisis that showed the first symptoms of resource-backed economic growth that

Table 5 How deep is the plunge when fossil fuels are no longer available?

	Fossil	Hydro	Bio	Alternative technologies	Agriculture and bio	Forestry and bio	Now	Future reduction
	Attribution to primary sources of value, %						Level of value creation	
Sweden	35	30	4	1	10	20	100	-31%
Norway	35	55	1	1	2	6	100	-26%
Britain	89	0	0	1	10	0	100	-85%
USA	55	10	5	0	20	10	100	-53%
Russia	40	10	10	0	20	20	100	-38%
China	55	10	10	0	20	5	100	-55%
Germany	61	2	2	5	20	5	100	-66%
Bangladesh	58	2	5	5	30	0	100	-58%

can not be sustained because of the physical limits ofthe world [1-3, 17-16, 57, 106, 108, 111, 112]. In a world of limits, planning for further growth is a fools policy that we now know will fail [1-3, 16, 44, 62]. There are still very influential people stuck in full denial of the finite nature of resources, in full contempt of fundamental principles of thermodynamics. A too large global population in a world of physical limits for resource extraction will most likely be a world of great poverty. When the resources continue to decline at the same time as the population rises, the situation will get worse. This puts in front of humanity one of the largest challenge ever faced by mankind [17, 44, 112]. We conclude that:

1. The time of cheap energy, and affluent supply of materials, food, water and metals is over in this era. This is a matter of mass balance and basic thermodynami claws;
2. Wealth creation is strongly coupled to conversion of non-renewable resources (metals, materials, fossil-based energy, phosphorus and oil) and renewable resources (crops from agriculture and forests, mining of ecosystems in the terrestrial wilderness and oceans for biomass) to produce the food needed to run the workforce;
3. Economic growth based on growth in material and energy consumption will stagnate and decline when the underlying resources decline in the coming decades. When resources peak, so does wealth, but with a delay of a few decades;
4. A world with many people and constrained resources is a world of limits for everybody. The global population is still rising, measures are neither being taken, nor discussed on population reduction, and time is running out fast;
5. We need to act before resource limitations reduce our possibilities and we need to act when we still have the minimum required capital and energy still available. We need to act before problems in society rise to a level where proper governance and democracy is at risk;
6. Changes take time, and there is not much time left. Twenty years or so is the window of time available for the changes that humanity needs to make in order to have a managed contraction process. The window is already closing as can be seen in rising materials, energy and food prices.

Of note is that in this analysis we have not taken into account the threats of climate change and biodiversity loss. Today, the use of the strategically important metals and materials is wasteful, and the recycling of them is far too low. The market reacts with increasing the commodity price once it becomes scarce. However, that is too late for having any warning, and when scarcity sets in, it also means most of the resource has already been lost. Thus, the market is not able to manage in a responsible way with metals until too much has been already consumed, and governments must take a stronger grip on this matter.

8. Developing Policy Goals and some Advice

8.1 Policy Advice

As demonstrated in this communication, it is imperative that we start on a path towards sustainable development world wide. In the best of cases there will be both a convergence and a contraction necessary on a local to global scale. As efficiently as we used globalization to expand, we must now use it for the required convergence and contraction. We may define goals for closing the present sustainability gap we can observe and have described here [19, 26, 28, 30, 55-59, 110, 112]:

- Create sustainable basic materials, metals, energy and phosphorus cycles in human society;
- Make sure that the measures that are taken are socially sustainable within the basic framework of democracy and free society;
- The sustainability principles are applied with a long term perspective, with fairness towards coming generations without limiting their possibilities nor forward appropriating their freedom or fundamental resources for subsistence.

Renewable energy supply will be important to compensate for the huge shortfall created when fossil fuels have been consumed. The most promising are listed in order of ability to deliver:

1. Hydropower
    a. Develop more hydropower where this is sustainable in ecological and social context. Hydropower has low environmental impact and lasts virtually forever;
2. Biofuels
    a. Use existing biofuel potentials in secondary wastes, recycling and garbage;
    b. Be careful not to compete with important food production potential or strategic materials production;
3. Technological renewable energy solutions — promote the use of:
    a. photovoltaic systems;
    b. solar heat harvesting
    c. heat pumps
    d. wave and wind energy harvesting designs.
4. Reducing overall per capita energy use; The alternative is to reduce demand per capita, it may amount to as much as 20%-30% of 2010 global energy use: reduce frivolous, wasteful or vanity driven energy use. Different literature sources produce widely varying estimates, however all agree that the potential is large, and the average end up in the range 20%-30% [16-17, 41, 44, 83, 101, 112].

Both long-termhorizons of substaintially more than 500 years for sustainability assessments as well as short term emergencies of climate change and peak everything set limitations and demand an urgent agenda [3, 27, 57]. Hydropower constitutes at present 6.5% of the 2010 global total production but has potential for more without causing intolerable damage (10%-12%). Special attention must be made that biofuels are truly sustainable when done correctly, but extractive mining when done unsustainably. We need to take care that we are not just shifting the resource issue around. The whole chain from technology to effect on society must be included, as well as detailed sustainability assessments with respect to energy, materials and return on monetary, energy and material investments. Biofuels are already used to a large degree, however, it is at present only 1%-2% of the total global energy production. This issue must be dealt with carefully as it interacts with other ecosystem services harvested from the forests, local fuel, food crops, biomass for pulp and paper, wood for construction, ecosystems for nature conservation and production of recreational services[26-27]. People in developing countries depend to a large degree on biomass for fuel. Biomass for energy has a limited potential, and a huge downside if done wrong and short-sightedly. Research and impact assessments are required. Soil degradation and erosion remain since millennia as an unmitigated problem that may again cause global system collapse.Technological renewable energy solutions apply when these can be shown to be energy-effective (with respect to EROI (Energy Return on Investment)) and material effective (sustainable supply and recycling of essential ingredients). At present they account for 0.1%-0.2% of the global total energy production.

8.2 Population Size is a Neglected Issue

The information in Table 1 demonstrates that both resource use per capita and the number of consumers are globally too large. Soon it is not about the affluent to contract and the poor to converge, it will be about that all must contract with respect to net materials and net energy use per capita or face serious societal crisis. The concept of net use emphasizes the importance of energy and material conservation in closed loops, making recycling of everything one of the mantras for survival of society. The sustainable population from a perspective of energy and phosphorus is on the order of 1.5-2.5 billion people on earth, rather than the projected 9-10 billion people on earth [19, 28, 30, 110]. The model assessments we have done suggest that there is no way 9 billion people on earth can be sustained for any longer period of time [19, 28, 30, 35]. 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 or energy [19, 28, 111-112]. The most effective measure for achieving this is simple [23, 109-112]:

1. Emancipation of women, including good education and full civil rights;
2. Reduction of infant and child mortality.
3. Socially dignified care of the elderly.

The procrastination done so far by different religious groups, political groups, autocratic regimes and conservative political groups at every global population policy assessment meeting during the last decades that tries to discuss the issue which is destructive and damaging to our global future. These groups are a part of the major obstacles and part of 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 ecosystems. Corruption remains throughout the world a major obstacle for good governance and democracy, and it is used for siphoning off wealth to tax havens, both in developed and underdeveloped countries. Eternal economic growth is a doomed concept in a limited world, and it is elementary scientific knowledge that this is so. There is no more time to waste on discussions with those that lack the ability or will to understand, big changes take time and actions need to be taken while there is still time. We must find a way to promote prosperity without growth and within the limits of the planet [16, 112]. For any strategic metal or element, recycling reaching 70%, is needed at present, but the recycling rates are far below that [20]. 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. Governments need to 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. Some countries have realized this and have initiated planning like India, Japan, Germany and China. Other countries have so far done nothing at all, and stand so far very unprepared for what may come. In the US this is understood in research, but has little or no impact through to business or federal policy.

8.3 Policy Goals

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 regulations will be needed, and international coordination will be helpful. Make all extraction of renewable resource stay within the limits of sustainability. Strong regulations to build up the recycling capacities of resources are needed, with enforcement. Put special emphasis on closing cycles of these 5:
    a. phosphorus;
    b. iron and steel;
    c. copper and zinc;
    d. platinum group metals
    e. aluminium
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).
3. 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). Stimulus and funding for scientific research will be able to speed up the process. All the energies to be distributed short distances, through smart and autonomous grids. Disaggregate large scale grids for resilience.
4. Systematic and pervasive energy-efficiency programmes as well as curbing of wastefulness of energy and materials.
5. 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.
6. Close overseas tax-havens and stop all bonuses on fictive financial deals (futures, derivatives) and abolish secure shelters for illegal money. Separate savings and loans banks from investment banks. Create ethical value-based banks.
7. Regulate and limit the credit practices to match resource availability for wealth generation. Declining growth implies limited credit possible. Debts at the root cause level lay a claim on resources to be extracted and sold. Thus, debt overshoot will put a huge pressure on resources.
8. Promote the participatory form of free 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.

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 fundamental survival conditions, over life and death of humans several centuries from now. This earlier unparalleled era of growth may have come to an end for what should be very obvious reasons. The next 20 years will offer some of the hardest political challenges of modern times, and will require statesmanship and systems thinking in social and natural systems simultaneously. In light of these huge challenges, it is imperative that present higher education be substantially reformed and changed.

And then we have not adequately touched upon many important issues including global climate change, global pollution, large scale loss of biodiversity and lots of other very serious challenges to the survival of civilization. That will be the topic of later studies.

Acknowledgments

The authors are indebted to many for useful and insightful discussions—including members of the Balaton Group, the members of the UNEP International Resource Panel. This study had financial support from the CONVERGE project, a part of the EU 7th Framework Programme.

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