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Assessing Long Term Sustainability of Global Supply of Natural Resources and Materials

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1. Introduction

The human population has grown exponentially over the past century and is expected to increase to nine or ten billion by the year 2050 (Evans, 1998). This growth has been accompanied by an increasing rate of consumption of natural resources (Brown & Kane, 1994, Brown, 2009a,b). On several key resources, the use of materials and energy has increased faster than the population growth alone. At present, humans are challenging planetary boundaries and capacities (Humphreys et al., 2003, Rockström et al., 2009). For many fossil resources (energy, most metals and key elements), the rate of extraction is now so high that it can only with difficulty be further increased (Hubbert, 1956, Pogue & Hill, 1956, Ehrlich et al., 1992, Smil, 2001, 2002, Fillipelli, 2002, 2008, Greene et al., 2003, Arleklett, 2003, 2005, Hirsch et al., 2005, Gordon et al., 2006, Heinberg, 2007, Zittel & Schindler, 2007, Roskill Information Services, 2007a,b,c,d, 2008, 2009a,b, 2010a,b,c, 2011, Strahan, 2007, 2008, Ragnarsdottir et al., 2011, Sverdrup & Ragnarsdottir, 2011). In many cases, known resources are dwindling, because prospecting cannot find more. There have been several earlier warnings about the prospect of upcoming future material scarcity (Forrester, 1971, Meadows et al., 1972, 1992, 2004, Graedel & Allenby, 1995), though these have been seen as "interesting", but have generally been shrugged off as academic studies. In the years after world war II, there has been a redefinition of success and wealth to imply increased consumption and material through-put (Friedman, 1962, Friedman & Friedman, 1980, Jackson, 2009). This success, reported as gross national product (GDP), has been adopted by most leaders of the world as a generic measure of success (growth), leading to enormous flows of materials, and as a result, waste. Fossil fuels are arguably the most essential modern commodity that may become scarce during the coming decades (Hubbert, 1966, 1972, 1982, Hirsh, 1992, Graedel et al., 1995, 2002, 2004), but rare minerals and metals, used, for example, in mobile phones, are also not in unlimited supply (Cohen, 2007, Ragnarsdottir, 2008). New technologies, such as transistors, pin-head capacitors, compound semiconductors, flat-screen liquid-crystal displays, light emitting diodes, electric car batteries, miniature magnets and thin-film solar cells therefore need to be developed according to the long-term availability of their key material ingredients.

There are some important facts we need to keep in mind at all times when considering many of our essential resources. Most of them represent inheritance from past geological times, and the amounts regenerated per year are vanishingly small compared to our present use. The global commons has only a one-time allotment for all ages and generations. The amounts are finite, and if we use them all now, then we deprive future generations of many possibilities to support them selves (Norgaard & Horworth, 1991, Ainsworth & Sumaila, 2003, Heinberg, 2007, Brown, 2009b). At present, for every ton of natural resources we remove and waste irreversibly, there will be that amount permanently less in available stock on Earth for future generations.

From limits to accessibility

Around 50 different metals and elements are necessary to produce cars, computer chips, flat-screen TVs, DVD players, mobile-phone screens, hybrid cars, compact batteries, miniature machinery and cameras. For computer chips, this number has increased from around 10 different metals in 1980 to more than 40 metals and elements today. The concentrated ore deposits of these metals that can be easily tapped through mining are finite, even if - overall, the metals are in sufficient supply in the Earth's crust. But are we running out of metals that lie at the heart of our technological society? At an international conference in 2008 (Hall, 2008, Williams, 2008), experts from numerous geological surveys and mining companies claimed that many resources are yet to be mined, arguing that the key is to mine more deeply (up to 2 km) for lower-grade ores and to exploit the ocean floor (up to 7 km below sea level) (Ragnarsdottir, 2008). But deeper mining and refining of lower-grade ores will require more energy (Hall et al., 2001, 2008, Roskill Information Services, 2007a,b,c,d, 2008, 2009a,b, 2010a,b,c, 2011, USGS, 2008), another precious resource. And it remains as a fact, that these views are more wishful thinking than based in any reality. Very few mines go below the 1,500 meter mark in mountains, harvesting the deep seas has not been notably successful, and there is limited technology available at present to undertake such mining. As elements go scarce and hence, expensive, mining will move to also extract from low-grade and ultra-low grade reserves. However, there are limitations to that practice. At some point, the material and energy expenditure exceeds the use that can be obtained out of the extracted resource, thus it does not pay off – usually referred to as EROI (Energy Return On Investment; Hall, 2008). One usual argument for example is that there is theoretically enough phosphorus on earth for all times. However, when we consider that what is available when phosphorus has been dissipated or lost to the sea, the energy and material expenditure to have it extracted is not economically viable. Many new technologies may end up costing too much in metals and energy to build for a mass production scale so that, at least some of them, will never cover the EROI. Even though such solutions may appear as a good idea, they are unsustainable.

Various methods have been developed to analyse material flows through socitety. **Material flow analysis**, MFA (or substance flow analysis, SFA) is an analytical method for quantifying flows and stocks of meterials or substances in a well-defined system. MFA is an important tool to quantify the physical consequences of human activities and needs. It is used in the field of Industrial Ecology for different spatical and temporal scales. Examples include accounting of material use by different societies, and development of strategies for improving the matrerial flow systems as material flow management (Graedel & Allenby, 1995, Brunner and Rechberger, 2003). **Life cycle assessment** (LCA or life cycle analysis, ecobalance, and cradle to grave analysis) is a technique to assess environmental impacts associated with all the stages of a product´s life from cradle to grave. The LCA includes compilation of an inventory of relevant energy and material inputs and environmental releases; the evaluation of the potential impacts associated with identified inputs and releases; and interpretation of results to help make informed decisions (e.g. Guinée, 2002). In the life cycle of a product the life cycle inventory as part of live cycle assessment can be considered an MFA as it involves system definition and balances. Cradle to cradle analysis is a specific kind of cradle to grave assessment, where the end of life disposal step for the product is a recycling process.

In this chapter, we use **systems analysis** and **system dynamics** (Forrester, 1961) as well as **burnoff time** and **Hubbert curve** representation to assess long term sustainability of global supply of natural resources and materials. **Systems Analysis** deals with analysis of complex systems by creating conceptual model structures with the help of **Causal Loop Diagrams** (CLD). CLDs make clear the cause and effect relationships and the feedbacks between different components in a system. **System Dynamics** is a methodology used to understand the behavior of complex systems over time. It deals with internal feedback loops and time delays that affect the behavior of the entire system. With the help of systems dynamics the conceptual model structures are transferred into dynamic numerical models, which can be then used as decision support tools, enabling the user to generate different scenarios and analyze the associated simulation results. Systems analsyis and system dynamics provides a deep insight in identifying interdependencies and feedback processes of dynamic stocks and flows of materiels, population dynamics and recycling rates. Neither MFA nor LCA encompasses these imporant components of systems analysis.

2. Methods of assessment

We use three different types of methods in order to estimate the time horizon of a raw material or metal resource:

1. Burn-off time:

We define burn-off time as known mineable reserves divided by the estimated average annual mining rate. The formula is given as:

$$\text{Burn-off time} = \text{reserves/mining rate [yrs]} \quad (0)$$

2. Hubbert's peak resource estimate:

An oil engineer at Shell Oil Corporation, developed what is referred to as the "Hubbert curve" (Hubbert, 1956, 1966, 1972, 1982) in order to predict the lifetime of oil wells and oil fields. He showed, using observed production data for oil wells as well as metal and phosphate mining, that all finite resource exploitation follows a distinct pattern of the Hubbert curve[1] (Figure 1). The shape of the Hubbert curve has a scientific explanation deriving from the nature of a finite resource, as well as the fact that Hubbert could verify his model on field data several times over. The Hubbert curve is defined by:

$$M = M_{max} / (1 + ae^{-bt}) \quad (1)$$

[1] http://en.wikipedia.org/wiki/Hubbert_peak_theory

where M_{max} is the total resource available (ultimate recovery of crude oil), M the cumulative production, and the coefficients *a* and *b* are constants.

We adapted the Hubbert curve and define the annual production as:

$$P = 2 P_{max} / (1 + \cosh(b(t - t_{max}))) \qquad (2)$$

where P_{max} is the maximum production rate, P is the production at time t, t_{max} is the time of the peak, and the coefficient b is the curve shape constant. Available history for the source, the size of the reserve and $^1/_3$ of the production curve is enough to set the *a* and *b* coefficients (Cavallo, 2004).

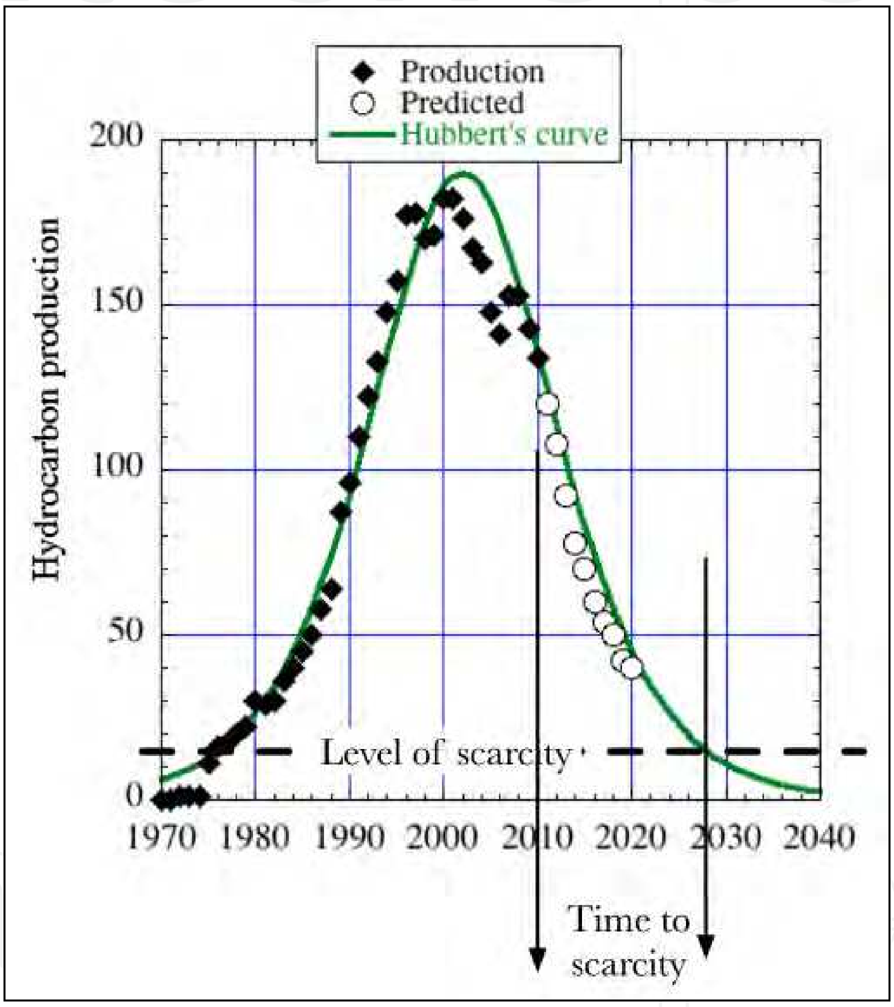


Fig. 1. The extraction pattern for hydrocarbon follows a symmetrical curve common to extraction of all resources. This can be used with observations of production rates to estimate the time to scarcity as shown with an analysis of the Norwegian oil production. The diagram suggests that the time to scarcity for oil produced in Norway is about 15 years. By 2040, the Norwegian age of oil production from Norwegian oilfields will be over.

3. Systems analysis and system dynamics:

Systems analysis with the help of causal loop diagrams is essential for gaining insights into the world metal supply system. With Figure 2, we intend to show that despite the Hubbert

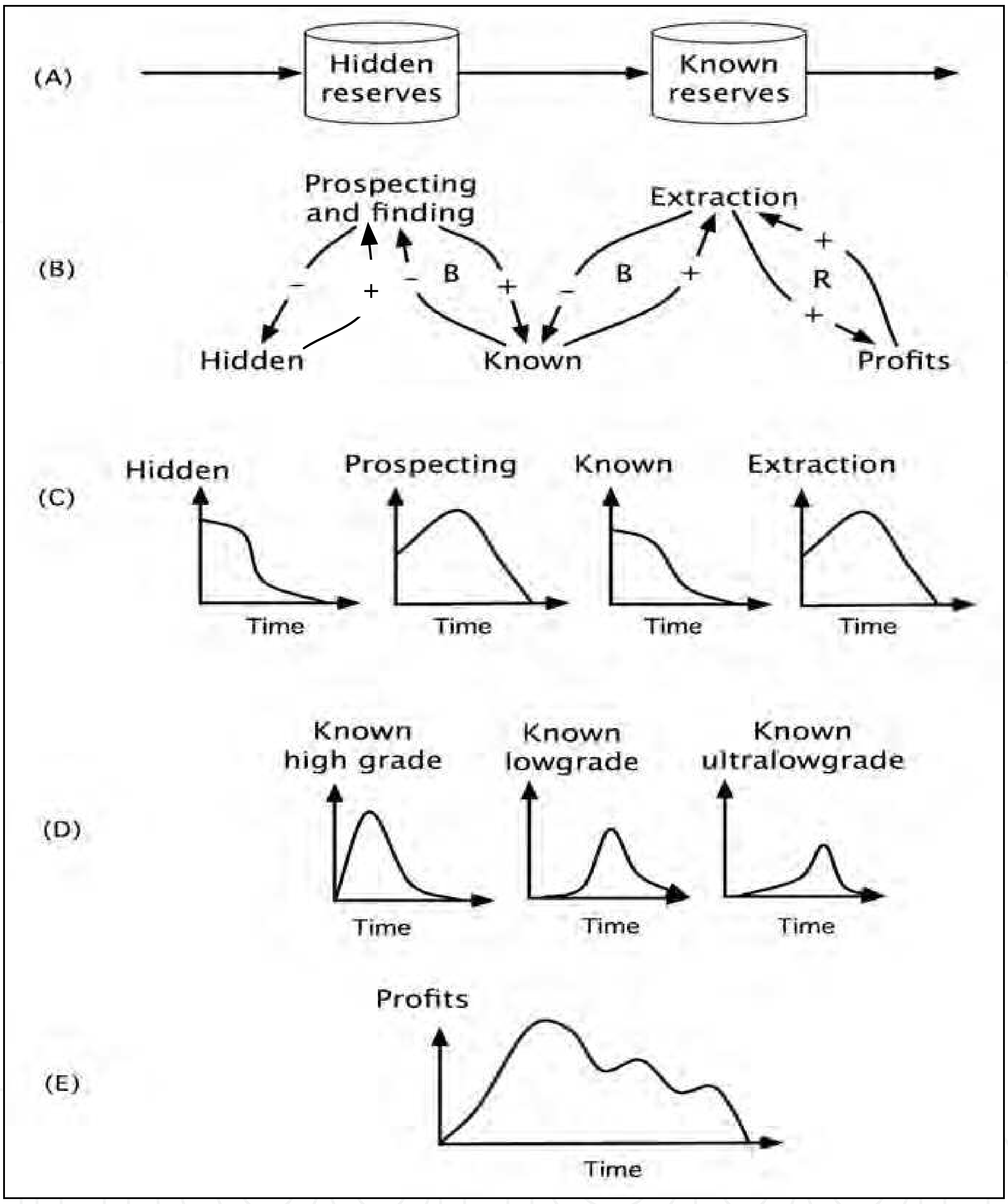


Fig. 2. Flow chart and causal loop diagram that explain the curve-shape discovered by Hubbert (1956, 1982). The system is based on two stocks, one known resource, backed by a hidden resource that can be found by prospecting for it and converting "hidden" to "known" (A). As "hidden" dwindles, "known" does get replenished until "hidden" is exhausted. As the extraction loop exhausts the "known", it gets backfilled, overlying several individual "rise and fall" curves to yield the typical Hubbert curve. The causal loop diagram is shown in (B). The resulting behavior of the components is depicted in (C). If we consider three types of resources in the system; high-grade, low-grade and ultralow-grade, we get three individual peak behavior curves (D), which may be overlaid to the final total production, expressed as profits (E). The results of using the Hubbert curve and using systems analysis and causal loop diagramming yield similar results for time to scarcity.

curve being empirically determined, there is a mechanistic explanation for it. In Figure 2, a flow chart (A) is shown with the corresponding causal loop diagram (B). The system is based on two stocks, one known resource, backed by a hidden resource that can be found by prospecting and finding more resource, converting "hidden" to "known". As the hidden resource, which is finite, dwindles, the "known" resource gets replenished for a short time until the "hidden" resource is exhausted. Thus as the extraction loop exhausts the "known" resource, it gets backfilled a few times by prospecting that brings more "hidden" resource over to "known" (B, C), overlying several individual "rise and fall" curves (D) to yield the typical Hubbert curve (E). The system is driven from the profit side, as mining leads to profits and more profits drives more mining, whereas the exhaustion of the finite stocks terminates it. The diagrams show the relationship between the parameter at the arrow-head over time. The diagrams depict what happens with new resources becoming known after prospecting (D), the bottom diagram (E) shows the sum of all the small diagrams, depicting extraction as a function of time.

The basic functions of our systems dynamics simulation model philosophy are described in the causal loop diagram (CLD) shown in Figure 3. The figure shows that with increased population, the consumption of metals increases, which in turn increases the production. Emissions and waste generated from both the production and consumption of the metals lead to environmental degradation. Increased environmental degradation increases public and governmental concerns and forces society to take necessary policy actions. These actions are shown in the CLD with numbers from 1 to 4 (blue diamonds) in Figure 3. Increasing consumption and population are the two major factors for an increasing demand for metals in the world. An increase in population drives consumption, depleting markets, increasing prices and increasing supply from production to market. This allows for continued consumption augmentation as well as increased resource use. Increased resource use rate and associated waste generation leads to environmental degeneration.

Environmental degradation and declining resources have an effect on political and public awareness. This leads to the development of four different policy options. During the early 1950's, end of pipe solutions (blue diamond no. 1 in Figure 3) were used as a first response to increased concerns over environmental degradation. Instead of draining out wastewater from industrial process to rivers, we built wastewater treatment plants; or instead of emitting hazardous waste gasses into the atmosphere, we installed treatment units in such processes. During the early 90's we realised the economic value of natural resources and waste, and introduced cleaner production and pollution prevention practices (diamond no. 2) to increase the efficiency in the production processes, and thus to decrease the use of raw materials (natural resources), the waste generated and gasses emitted to the atmosphere. In the last decade, we have concentrated on sustainable consumption and production behaviour (diamond no. 3) and begun to question how we can make changes in our life style (and quality) to decrease the demand for goods and food, and consume less, which may in turn eventually decrease the environmental degradation. As a part of sustainable production policy, recycling represents a way to increase metals in the societal material cycle without depleting resources. However, as can be seen from the CLD in Figure 3 - if we trace back the main root cause for today's increasing environmental degradation, it is embedded in the increase in the world's population. We certainly need to introduce sustainable population policies (diamond no. 4) (especially in the developing countries), together with sustainable consumption and production policies (diamond no. 3) (mainly in developed countries) in

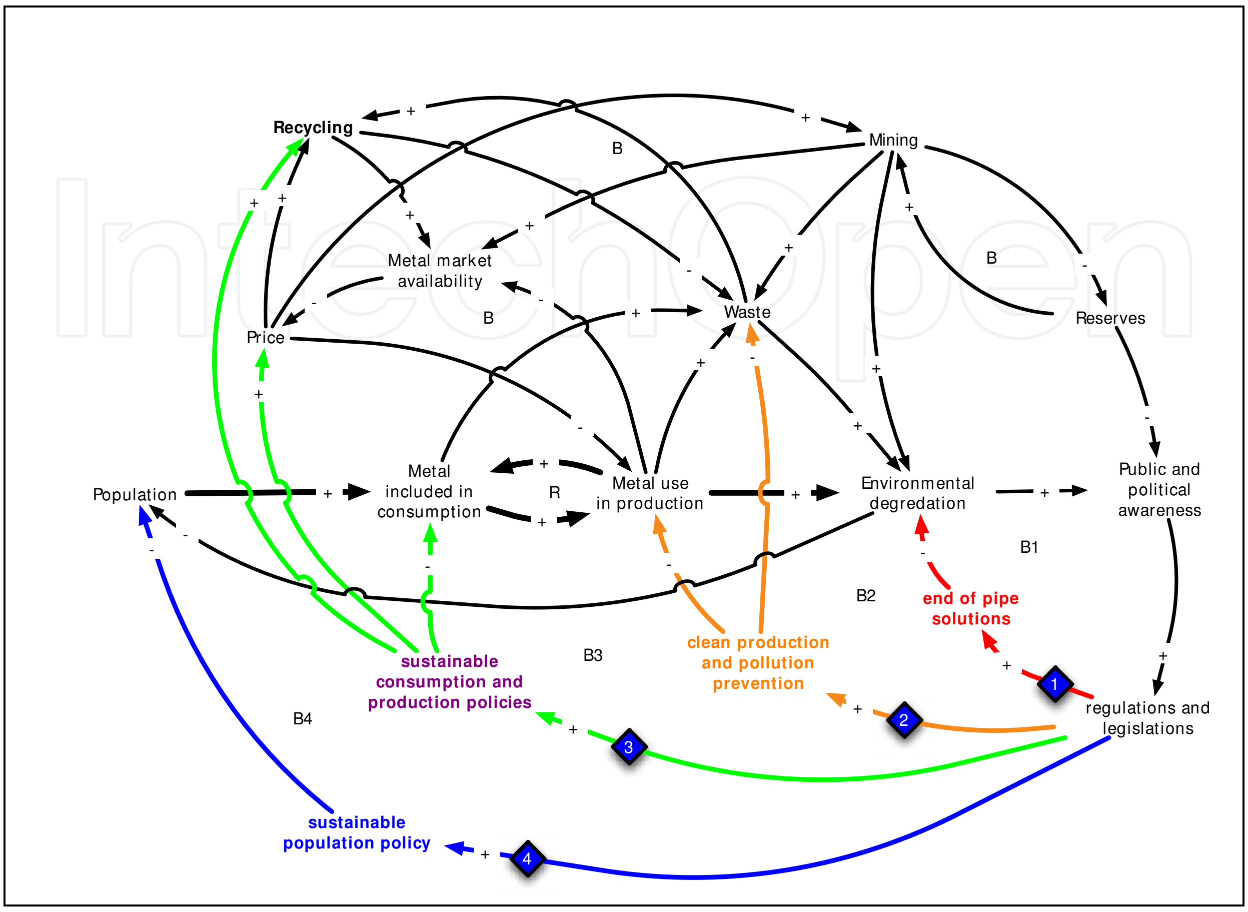


Fig. 3. Sustainability of resource use has moved over many system levels from end-of-pipe (fighting pollution) to root cause (population numbers and their behaviour). Attention has over time moved from end-of-pipe solutions (1) to more focus on clean production (2) recycling, slimmer consumption patterns and sustainable production (3). Ultimately the world must also address the consumption volume as a function of per capita use as well as the number of consumers, directly proportional to the size of the global population (4).

order to decrease over population (demand) and unnecessary wasting (supply). A long-term sustainability policy for the world population will thus be needed, as a part of the total flux outrunning planetary capacities. In this context, Figure 3 presents the problem and displays the different solutions tried so far. Unsustainability in this context arises from: (a) End of pipe pollution output from the system; (b) From unsustainable production or resource use in suboptimal products; (c) From excessive volume consumption of resources; (d) and - From consumption in excess of the carrying capacity of the Earth. In order to address the problems, four different approaches were tested in this study. Potentially, it may be that a global population contraction during the next century must be planned for (Malthus, 1798, Pearson & Harper, 1945, Osborn, 1948, Ehrlich, 1968, Meadows et al., 1972, 1992, 2004, Brown, 2009a,b, Ehrlich & Ehrlich, 1990a,b, 2006, 2009, Bahn & Flenley, 1992, Ehrlich et al., 1992, Daily & Ehrlich, 1992, Brown & Kane, 1994, Daily et al., 1994, Evans, 1998).

The carrying capacity of the world for population has been estimated many times, but with disparate results, primarily because of differences in fundamental assumptions (Cohen, 1995) concerning the following aspects:

1. Energy:
   a. Finite fossil fuels (hydrocarbons, nuclear)
   b. Renewable energy (water, wind, sun, wood, dung)
2. Metals
   a. For infrastructure and tooling (Fe, Al, Co, Zn, Mn, Cr, Ni…)
3. Land
   a. Area suitable for cultivation
   b. Uncultivated land with sustainably harvestable resources
4. Technological food production capability
   a. Technical equipment and machinery
   b. Materials for simple civil construction (brick, wood)
5. Essential resources for sustainable harvest of biomass
   a. Essential trace elements (Co, Mo, Cu, B, Zn, S,….)
   b. Nitrogen
   c. Phosphorus
   d. Water
   e. Base cations (Ca, Mg, K)
6. Social resources
   a. Suitable workforce under sustainable local social conditions
   b. Social conditions conducive to sustained activity through a growing season (absence of warfare, functioning markets, adequate transportation, social accountability, reasonable degree of law and order, personal security sufficient for food storage).

Penck (1925), based on the work of von Liebig (von Liebig et al., 1841, Liebig 1843), defined the basic equation for the number of people that can be fed, the maximum population, called "Liebig's law": *Harvest is limited by the nutrient in least supply*:

Sustainable population =
Total resource available annually / individual annual consumption [persons] (3)

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

Total resource available annually =
Total resource volume / time to doomsday [ton per year] (4)

The time to doomsday is estimated as the time to the end of our consideration, potentially the projected time of eclipse of human civilization (Gott, 1994, Leslie, 1998, Korb & Oliver, 1998, Sowers, 2002, Sober, 2003). We have previously discussed the content and meaning of a long-term time perspective, and we also made an assessment of the impacts of unsustainability of the phosphorus supply with respect to the global population (Ragnarsdottir et al., 2011, Sverdrup & Ragnarsdottir, 2011). There we arrived at the following definitions that we adopt here:

- **Long term sustainable** perspective is when the resource is managed in such a way that a glacial gap can be bridged. Glaciation causes denudation and access to fresh strategic element bearing rock. The average time between glaciations, the room for civilization to prosper, is about 10,000 years. After that geologically large events make conditions for civilizations so fundamentally changed that no standard rules apply. The first urban societies arose 10,000 years ago, the first states emerged 5,000 years ago.
- A **semi-sustainable** timeframe is a time equivalent to how long modern literate and democratic civilizations as we know them have persisted, more than 2,000 years. However, most societies unconsciously want to persist longer than that. The state of Denmark as an entity is about 2,000 years old.
- A **sustainability-oriented** timeframe is the historic time that is set for 1,000 - 2,000 years, the time of continuous historical records and age of the oldest surviving books.
- **Unsustainability** in the intermediate term is 200 - 1,000 years, the time perspective of many monuments and infrastructures that are well built. Unsustainability in the short term is considered to be 100-200 years. This timeframe is bordering on living memory, and often the age of a private house still lived in.
- **Urgent unsustainability** is adopted as the term for time horizons less than 100 years.

Of note is that individual consumption is not seen as the individual physiological requirement, but that it must include efficiencies from first extraction from the deposit until it reaches the individual consumer.

$$\text{Individual supply} = \text{Extracted amount per capita} \times \text{product of all efficiencies in the supply chain} \quad [\text{kg per person}] \tag{5}$$

The extraction steps may be many and the inefficiencies may quickly pile up. The carrying capacity of the Earth under total sustainability will be in sustainable population number (Ragnarsdottir et al., 2011, Sverdrup & Ragnarsdottir 2011):

$$\text{Sustainable population} = \min(\text{Sustainable population estimates (food production limitations (i)))} \quad [\text{persons}] \tag{6}$$

According to Liebig´s principle estimates represent the different aspects that can limit growth (nitrogen, phosphorus, water, light, essential major and trace elements, soil substrate availability). In the short run, many of those can be overrun as long as the system can deplete the available resources. However, in the long run this is impossible, as it would violate mass balance laws. Many studies have considered these resources one by one, a few have done several, but none have done them all (See Table 1 and Table 2 for an overview of different estimates). We also use a simple equation for total consumption of a resource:

$$\text{Total consumption} = \text{Consumption per individual} \times \text{number of individuals} \quad [\text{ton per year}] \tag{7}$$

It is evident that we can take down total consumption by reducing the amount each consumer uses, but also by reducing the number of consumers, and both. It is important to assess the effect of recycling. An integrated assessment over all essential components is needed in the long run, as the studies of Meadows et al. (2004). Thus, what we first estimate is the supply to society, as:

$$\text{Supply to society} = \text{Mining} \ / \ (1\text{-}R) \ \ [\text{ton per year}] \qquad (8)$$

Where R is the degree of recycling on the flux from society. This is what is shown in Figure 4. In the calculations, we take the present mining rate, and use the present recycling degree, to estimate the present supply to society. Then, we calculate the new flow into society for other improved degrees of recycling:

$$\text{Time to scarcity} = \text{Reserves} \ / \ (\text{Supply to society} * (1\text{-}R_i)) \ \ [\text{yrs}] \qquad (10)$$

where we have defined six scenarios (i), including:

1. Business-as-usual, no change in recycling from today's;
2. Improved habits in the market, at least 50% recycling or maintain what we have if it is higher than 50% recycling, and improving gold recycling to 95% recycling;
3. Improve all recycling to 90%, except gold to 96% recycling;
4. Improve all recycling to 95%, except gold, platinum, palladium and rhodium to 98% recycling;
5. Improve all recycling to 95%, except gold, platinum, palladium and rhodium to 98% recycling; assume same per capita use as in 4, but assume that population is reduced to 3 billion;
6. Improve all recycling to 95%, except gold, platinum, palladium and rhodium to 98% recycling; assume one half of present per capita use as in 4, but assume that population is reduced to 3 billion.

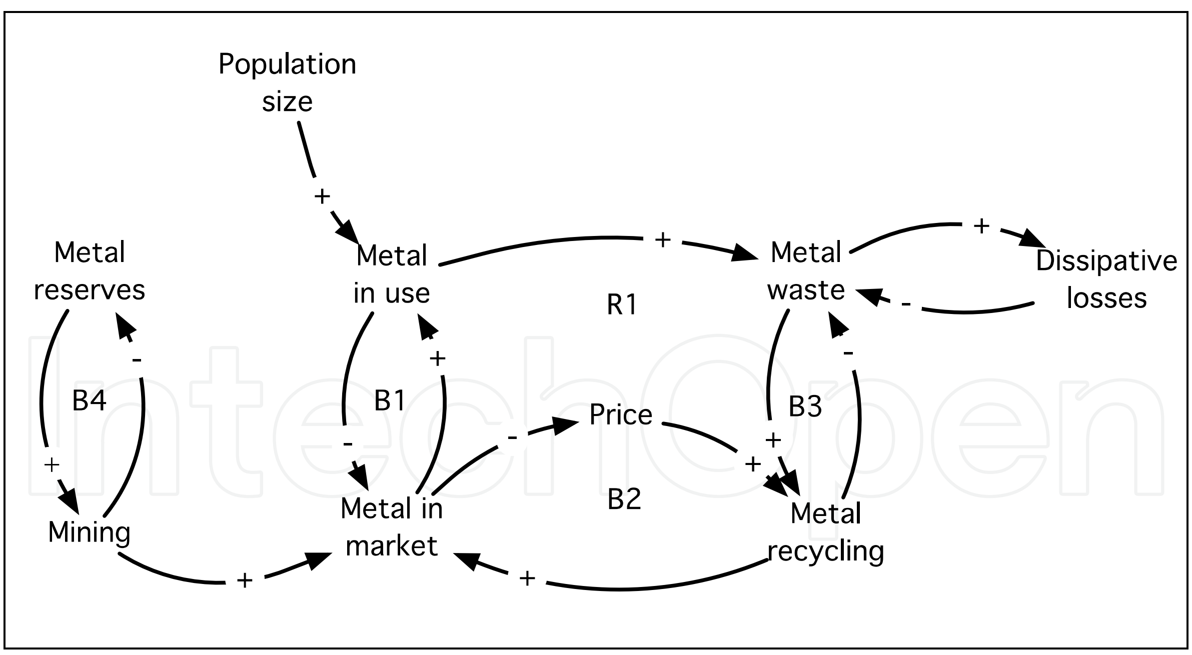


Fig. 4. Market mechanisms for metals. This causal loop diagram explains how supply and demand affect the price of a metal, and how the price feeds back on recycling and use. It can be seen from the diagram, that introduction of recycling creates a reinforcing loop, keeping material in the cycle. The enemy in the system is dissipative losses as they represent a destination for metals with no hope of return. The major driver for metal use is the population size.

Then we calculate the new net supply needed to maintain that societal supply at present level at improved recycling rates, and use that to find the new burn-off time. Figure 5 shows the flow diagram depicting what we explained above in the text, that recycling can maintain the same input to society, but decrease the input from finite resources through mining.

The real flow to society becomes amplified by recycling, because part of the outflow becomes returned to the inflow.

$$\text{Burn-off time for new recycling rate} = \text{reserves} / (\text{supply to society X } (1-R_i))[\text{yrs}] \quad (11)$$

Where R_i is the recycling of scenario *i*. In order to get the Hubbert's methods estimate of time to scarcity, conversion from burn-off based time to scarcity is (based on our results by plotting them):

$$\text{Hubbert's time to 10\% of peak production} = 1.7 * \text{Burn-off time} + 2 \quad (12)$$

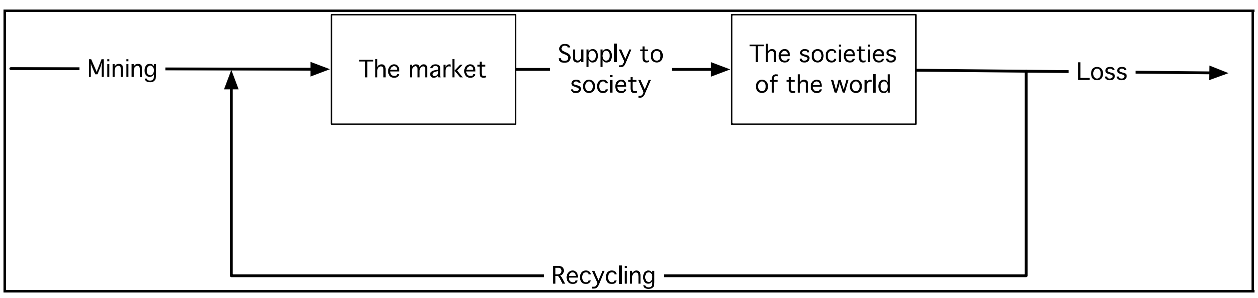


Fig. 5. The recycling effect. A flow diagram showing that recycling can maintain the same input to society, but decrease the input from finite resources through mining. The real flow to society becomes amplified by recycling, because part of the outflow becomes returned to the inflow.

Systems dynamics modelling of material cycles

A CLD neither demonstrates how strong each of the linkages is nor the functional form that the relationship takes. It allows us, however, to develop a better understanding of the overall system, to identify its main components as well as the cause-effect relations between these components and to trace back some main root causes of unsustainability in the system. In a fairly complex system, as the one presented here, there are substantial numbers of feedback loops, all of which result in a complex system behaviour. A model description of the CLD type does not contain all the details necessary for a full understanding of the model's behaviour, but it is possible to identify some overall reinforcing and balancing loops. We do not use neoclassical economic models in this study for analysing trends (Shafik, 1994, Turner, 2008, Goklany, 2009) as these methods do neither use mass and energy balances nor obey thermodynamic principles, thus yielding naïve results of limited value. It is important to state that neither econometricists nor economists can choose whether they believe or do not believe in thermodynamics. Time has come where we stop to be polite and tolerate their ignorance. There is no escape from mass balance, and not internalizing this mass balance has become damaging to society, "….its validity is absolute, leaving those that disbelieve in line for complete humiliation" as Sir Arthur Eddington stated (Eddington, 1928, see Hougen et al., 1959 for further elaboration on the consequence and danger of ignoring mass balances).

In this study, we use causal loop diagrams for finding each metal system connections, important feedbacks and system structures as a part of the generic systems dynamics procedure (Bertalanffy, 1968, Forrester, 1971, Meadows et al., 1972, 1992, 2004, Senge, 1990, Vennix et al., 1992, Sterman, 2000, Maani & Cavana, 2000, McGarvey & Hannon, 2004, Sverdrup & Svensson, 2002a,b, Cavana, 2004, Haraldsson & Sverdrup, 2004) and the learning loop (Haraldsson et al., 2002, 2007, Haraldsson 2007). The method used for constructing the system dynamics model follows a strict scheme, as well as deriving links by empirical-, experimental- and Delphi methods (Adler & Ziglio, 1996). The CLDs uniquely define the differential equations of the system, and together with a flowchart, help to build the dynamic models in the STELLA® modelling software.

Dynamic models are developed for gold, platinum, phosphorus, rare earth elements, lithium, uranium, thorium and oil. The models are then used to estimate time to scarcity, with and without recycling for different alternative scenarios. We define the time to scarcity as the time for the known reserves of high grade and low grade to have decreased to 10% of the original amounts.

The models are constructed into several modules:

1. The global population and consumption module;
2. The mining module with reserves and prospecting;
3. The consumption and market module, including a price mechanism;
4. The recycling module;
5. The social stress module.

Each model is formulated as a series of differential equations, arranged from mass balances for the resource R:

$$dR/dt = \text{inputs - outflows + produced - accumulation in the system [ton per year]} \quad (13)$$

The following 10-12 different coupled reservoirs are considered in the models through coupled differential equations, based on mass balances for a number of stocks in the system:

a. Exhaustible resources (4-6 stocks):
   1. High grade deposits
   2. Hidden high grade deposits
   3. Low grade deposits
   4. Hidden low grade deposits
b. Population model (simplified global) (4 stocks) (0-20 yr, 21-44 yr, 45-65 yr, 65+ yr)
c. Society (2 stocks)
   5. Market stock
   6. Waste stock

For phosphorus, gold and platinum, we also used two additional physical reservoirs, known ultralow grade and hidden ultralow grade, as well as one for social trust in the phosphorous model. The material flow chart for gold including the recycling is shown in Figure 6. The causal loop diagram given in Figure 7 shows the causal chains used in our model on global gold supply. The CLD shows the basics of the market, but for simplicity omitting the derivates trade that also belongs to the model.

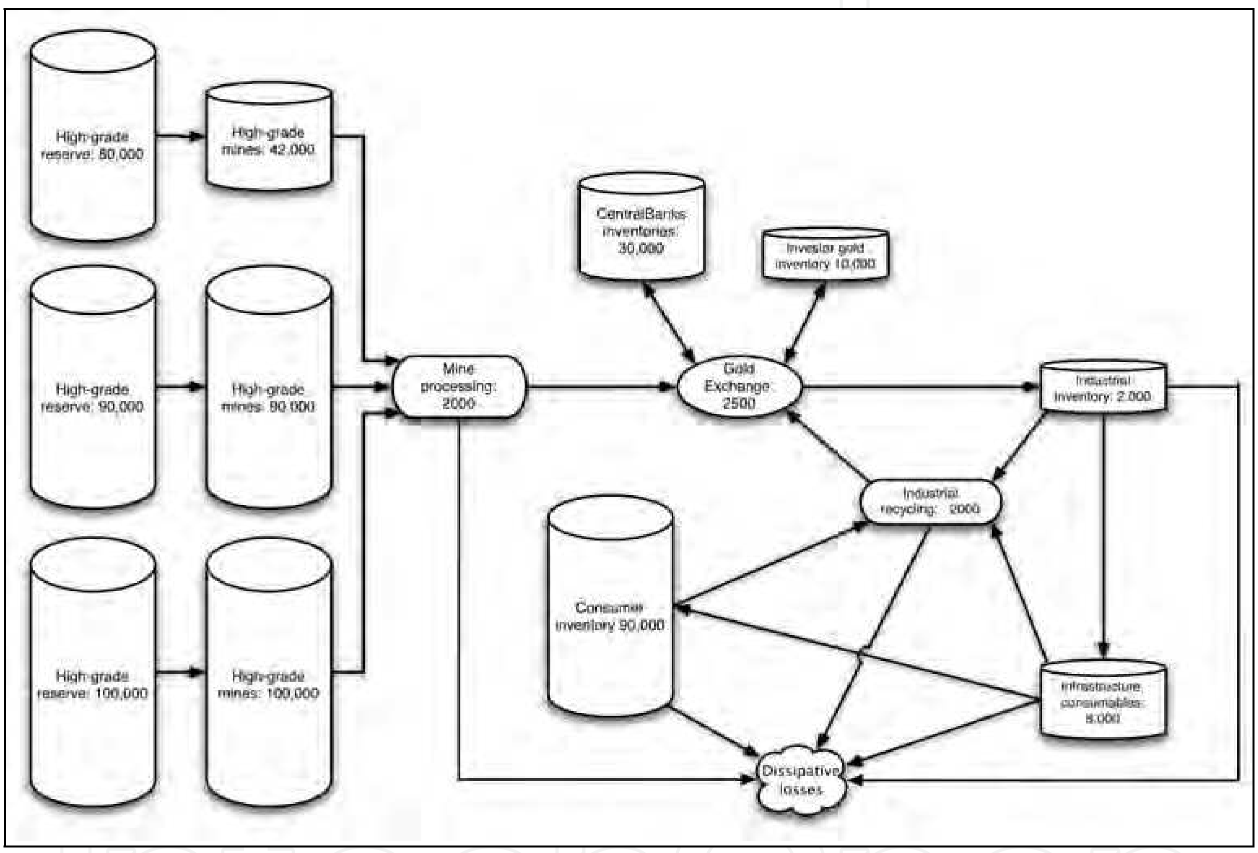


Fig. 6. Flow chart for world gold material fluxes. Actors trade through the market, trade takes place geographically dispersed, but linked through the price systems at the London and New York Metal exchanges. The numbers indicate approximate amounts of gold in metric tons in early 2009. The flowchart layout looks similar for most other metals.

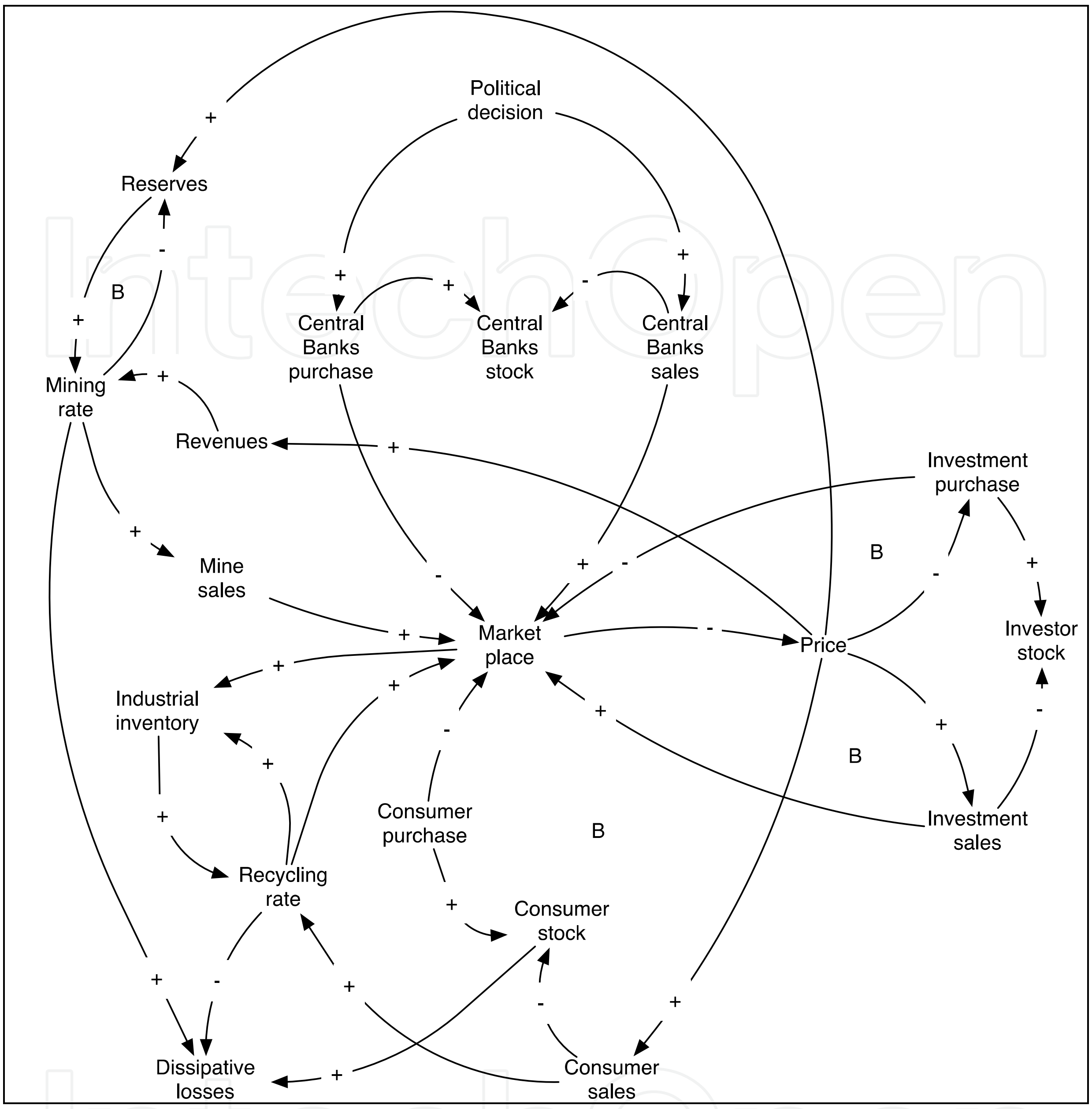


Fig. 7. The causal loop diagram underlying the models used in this chapter. The simplified CLD shows the basics of the market omitting the derivates trade that also belongs in the model.

3. Results

Material cycles and time horizons

Table 1 shows an overview of important metals and elemental resources for running society and human civilizations. The main sources and the main uses are listed, together with indications on the use of the reserves. Comprehensive life-cycle flow assessments are available for few substances. This is primarily a fact because many of the mining companies closely guard their data, making world reserve figures uncertain (USGS, 2008, Roskill Information Services, 2007a,b,c,d, 2008, 2009a,b, 2010a,b,c,d, 2011). However, some

Material	Source country	Main uses
Bulk materials for society		
Iron	India, Russia, Brazil, Germany, France, Sweden	Construction materials, machinery, vehicles, weaponry, household items, containers, building reinforcement (Forester, 1971, Meadows et al., 1972, 1992, 2005, USGS, 2008, Graedel et al., 2004). There is lots of aluminium in solid rock, but this is so tightly bound, that it is prohibitively expensive to take them out. Large losses are to corrosion and in household trash
Aluminium	Guinea, USA Australia, Canada, Russia, Norway	Aircraft, packaging, wiring, lightweight machinery, transport vehicles, electrical consumer durables, cars, rocket fuel, military equipment, soda-pop and beer cans, packaging, wiring (Forester, 1971, Meadows et al., 1972, 1992, 2005, Graedel et al., 2004, Roskill Information services, 2008, USGS, 2008, 2011)
Nickel	Canada, Russia	Steel alloys, galvanizing, tools, coins, LNG tanks, military equipment and weaponry (Forester 1971, Meadows et al., 1972, 1992, 2005, Graedel et al., 2004, International Nickel Study group 2008, USGS, 2008, 2011)
Manganese	South Africa, Brazil	Steel alloys, tools. (Forester, 1971, Meadows et al., 1972, 1992, 2005, Graedel et al., 2004, USGS, 2008, 2011)
Copper	Chile, Russia, Congo, Malawi, Zambia	Wiring, appliances, tubing, household items, major constituent of brass, coins (Forester, 1971, Meadows et al., 1972, 1992, 2005, International Copper Study group 2004, Graedel et al., 2004, USGS, 2008, 2011)
Zinc	China, USA, Austria	Galvanizing, batteries, brass, anti-corrosion., infrastructural items (Forester 1971, Meadows et al., 1972, 1992, 2005, International Lead and Zinc Study group 2003, Graedel et al., 2004, USGS, 2008, 2011)
Strategic metals and elements		
Gold	South Africa, Ghana, Mali, China, Russia, Canada	Investment, jewelry, gold plating, catalyst, coins, electronics contacts, circuit boards, semiconductor wiring, mobile phone antennas, dental materials (Forester, 1971, Meadows et al., 1972, 1992, 2005, Cross 2000, Graedel et al., 2004, Heinberg 2007, Sverdrup et al., 2011a, USGS, 2008, 2011, The Gold Council website, unpublished industrial data)
Silver	Mexico, Bolivia, Chile	Silver plating, industrial conductors, wiring, jewlery, financial placement, coins, hollowware, cutlery (Forester, 1971, Meadows et al., 1972, 1992, 2005, Cross 2000, Graedel et al., 2004, Heinberg 2007, Sverdrup et al., 2011, USGS, 2008, 2011, unpublished industrial data)
Wolfram	China, South Africa	Lamp filaments, high temperature applications, weaponry, cutting materials (Forester 1971, Meadows et al., 1972, 1992, 2005, Graedel et al., 2004, Roskill Information Services 2007b, Ragnarsdottir, 2008, USGS, 2008, 2011).
Helium	USA, Algeria, Qatar, Russia,	Research, superconductors, ballons, protective gas (Forester 1971, Meadows et al., 1972, 1992, 2005, Graedel et al., 2004, USGS, 2008, 2011)
Indium	Canada, China, USA,	LCDs, new generation of solar cells, microprocessors (Ragnarsdottir 2008, USGS, 2008, 2011, Roskill Information Services 2010b). Byproduct of Zn.
Tin	China, Brazil, Malaysia	Cans, solder, paint. (Forester 1971, Meadows et al., 1972, 1992, 2005, Graedel et al., 2004, Ragnarsdottir, 2008, USGS, 2008)
Tantalum	Australia, USA, Brazil, Congo	Mobile phones, camera lenses, DVD players, computers, super-alloys, piping, minor component of brass (Ragnarsdottir 2008, USGS, 2008, 2011, Roskill Information Services 2009a)
Titanium	South Africa, Australia, Norway, Russia, USA	Light and strong metal, and at ambient conditions, it is very resistant to corrosion. It is produced for specialized technologies and as titanium oxide as a white colour pigment. The production is difficult and energy demanding. There is a lot of titanium on Earth, however, the mineral deposits where extraction can be undertaken, are limited. (Roskill Information Services 2010a)
Niobium	Australia, USA, Brazil, Congo	Specialty alloys for high temperatures, engine turbines (Graedel et al., 2004, USGS, 2008, Roskill Information Services 2009b)
Lead	China, Australia, USA	Pipes, batteries, soldering, alloys, weaponry (Meadows et al., 1972, 1992, 2005, International Lead and Zinc Study group 2003, Graedel et al., 2004, USGS, 2008)
Lithium	Bolivia, Chile, Tibet	Batteries, medicine, nuclear bombs (Meridian International Research 2008, USGS, 2002, USGS, 2008, 2011)
Rare earths	Canada, China, South Africa, Australia, Norway, Russia, Brazil	Compact batteries, LED's, miniature magnets, catalysts, new technologies, optics, specialty alloys, steel, lasers (Graedel et al., 2004, Roskill Information Services 2007a, Ragnarsdottir 2008, USGS, 2008, 2011, unpublished industrial data). Rare earths reserves are often associated with co-deposition of phosphates, and part of these reserves represents back-up reserves for phosphate
Yttrium	Canada, China, South Africa, Australia, Norway, Russia, Brazil	Flat screens and cathode ray tube displays and in LEDs. Production of electrodes, electrolytes, electronic filters, lasers, pinhead capacitors and superconductors; various medical applications; as traces in materials as grain size modifier. In superconductors. Yttrium garnets for optic filters, glass for telescopes (Graedel et al., 2004, Ragnarsdottir, 2008, USGS, 2008, 2011, Roskill Information Services 2009, unpublished industrial data)
Platinum	South Africa, Russia, Canada	Jewelry, fertilizer catalyst, car catalyst, car fuel cells, dentistry, implants (Graedel et al., 2004, Johnson Matthey's Platinum Review, 2008, Ragnarsdottir 2008, USGS, 2008, 2011, Sverdrup et al., 2011a,b, Sverdrup & Pedersen, 2009, unpublished industrial data)
Palladium	South Africa, Russia, Canada. Depends on Pt production	Jewelry, fertilizer catalyst, car catalyst, car fuel cells, dentistry, implants, laboratory gear (Graedel et al., 2004, Johnson Mathey's Platinum Review, 2008, Ragnarsdottir, 2008, USGS, 2008, 2011, Sverdrup & Pedersen 2009, Sverdrup et al., 2011a,b, unpublished industrial data)
Rhodium	South Africa, Russia, Canada,	Fertilizer catalyst, car catalyst, car fuel cells (Graedel et al., 2004, Johnson Mathey's Platinum Review, 2008, Ragnarsdottir, 2008, USGS, 2008, 2011, Sverdrup & Pedersen, 2009, Sverdrup et al., 2011a,b, unpublished industrial data). By product of Pt production
Cobalt	Congo, Zambia, Australia, Canada, Russia	Used for magnetic alloys, wear-resistant and high-strength alloys, and as a catalyst in several chemical processes. Blue colour in glass, ceramics, ink and paints (Roskill Information Services 2007c)
Germanium	China, Russia	Electronics, LED, laser, superconductors (USGS, 2008, 2011). Mostly by-product of Zn ores
Gallium	China	Electronics, LED (USGS, 2008, 2011, Roskill Information Services 2011)
Arsenic	China, Chile, Peru, Morocco	Antifouling agent, poison, wood preservative agent, electronics, LED, laser, superconductors, medicine, in copper and zinc-based alloys. We are not dependent on this toxic substance. The use is declining (USGS, 2008, 2011)
Tellurium	Canada, USA, Peru, Japan	Used in alloys, infrared sensistive semiconductors, ceramics, specialty glasses, and photovoltaic solar panels (USGS, 2008, 2011)
Antimony	United States, China	Solder, semiconductors, gunshot substitute (Roskill Information Services 2007d, USGS, 2008, 2011). Alloys with lead, as a flame retardant and as a catalyst in organic chemistry. New uses are in transistors and diodes
Selenium	Japan, Belgium, Russia, Chile	Used in photovoltaic cells and photoconductive action, where the electrical resistance decreases with increased illumination. Exposure meters for photographic use, as well as solar cells and rectifiers, p-type semiconductor and electronic and solid-state applications. Used in photocopying. Used by the glass industry to decolourise glass and to make ruby coloured glasses and enamels. Photographic toner, additive for stainless steel. Mostly by-product of copper ores (USGS, 2008, 2011). http://www.webelements.com/selenium/uses.html. Selenium is an essential nutrient – necessary for a strong immune system
Rhenium	Chile, USA, Kazakstan, Peru	Catalysts, specialty alloys for jet engines (Roskill Information Services 2010c)
Sources of energy		
Oil and Gas	Saudi-Arabia, Emirates, Iraq, Kuwait, Iran, Canada, Russia, Venezuela, Mexico, Indonesia	Energy for transportation, only operational available propellant for aircraft, propellant for ships, propellant for cars, for industry, raw material for plastics, heat source for cement, for steel industry, for domestic heating (Pogue & Hill 1956, Meadows et al., 1972, 1992, 2005, Hubbert, 1982, Arleklett, 2003, 2007, Greene et al., 2003, Hirsch, 2005, Energy Information Administration, 2007, Heinberg, 2007, Strahan, 2007, 2008, Zittel & Schindler, 2007, BP, 2008, USGS, 2008, 2011, unpublished industrial data)
Coal	All continents	Steel and metal production, cement, electricity, heating (Pogue & Hill 1956, Strahan, 2007, 2008, Zittel & Schindler 2007, USGS, 2008, 2011, unpublished industrial data)
Uranium	Russia, Africa, China, Canada	Conventional nuclear energy, atomic weaponry, potentially in breeder reactors (Francois et al., 2004, USGS, 2008, 011)
Thorium	Canada, China, Australia, Norway, India, South Africa	Nuclear energy, potentially in breeder reactors, closed cycle nuclear energy (Jayaram, 1985, Kasten, 1998, USGS, 2008, 2011, unpublished industrial data)
Essential for human life support		
Phosphorus	Morocco, South Africa, China, Russia, Australia	Fertilizer for food production, pesticides (Meadows et al., 1972, 1992, 2005, Fillipelli, 2002, 2008, Oelkers & Valsami-Jones, 2008, USGS, 2008, 2011, Brown, 2009, Ragnarsdottir et al., 2011, Sverdrup & Ragnarsdottir, 2011)

Table 1. Overview of important metals and elemental resources for running society and human civilizations.

material-flow studies detailing a series of life stages are available. Mining and processing, fabrication, use and end-of-life data are documented for copper, zinc and lead (Graedel et al., 2002, Gordon et al., 2003, 2004, 2006, Spatari et al., 2005, Mao et al., 2008), with less-detailed information available for platinum (Råde, 2001). Information is available in special industrial publications (Johnson Matthey's Platinum Review, annual journals 1980-2011 were consulted) for tin, silver and nickel (Gordon et al., 2003, 2006) and indium and gallium (Cohen 2007, Ragnarsdottir, 2008, Roskill 2010b, 2011). Data for gold is available in official and unofficial statistics, and can mostly be found through web searches.

In Table 2 we show some of the outputs of our calculations. They show estimated burn-off times, time to scarcity by using the adapted empirical approach of Hubbert (1966, 1972, 1982), and using integrated systems dynamics modelling for metals and elements of different classes. In Table 2, "#" represents estimates using dynamic simulation models built by the authors, where as "*" represents earlier dynamic model assessments by Meadows et al. (1972, 1992, 2004). The reserve values given represent the sum of estimates for high-grade and low-grade ores. Platinum, palladium and rhodium are being used notably in catalytic converters that make burning of fossil fuels more efficient, and to catalyse a plethora of reactions in the chemical, petrochemical and pharmaceutical industries, and are at the core of ceramic fuel cells. Platinum is key to the production of fertilizer for food production and therefore a part of food security. Platinum group metals have been estimated to be of the order of maximum 80,000 ton, of which about 17,000-25,000 ton are effectively available after taking into account the efficiencies of the different mining, milling and smelting processes (Råde, 2001). With petroleum becoming more scarce and expensive, fuel cells using platinum group elements as catalysts are seen as future sources of alternative energy. But the reserves of these elements will not fuel the world's cars long into this century simply because there is not enough resource to power the cars.

For platinum and palladium, there are dedicated platinum group metal mines (South Africa), but about 30% of the production is a by-product of the nickel production (Russia, Canada). Rhodium production is entirely dependent on the production of platinum and palladium, and when they stop, so does rhodium (Johnson Matthey Platinum Review, 2008). In the systems dynamic modelling output diagrams as shown in Figure 7, we can see dynamic simulations undertaken for platinum, with past and predicted future reserves in geological formations to the left and mining rate to the right. Platinum shows peak behaviour, similar to what many other materials do. Platinum is lost in several ways. Only about 20-25% of the platinum metal used for catalytic converters for cars is recycled every year. This it out of a flux of 40 ton per year, where the global production is 230 ton per year. 40-50 ton is used as catalyst in fertilizer plants; of this 10-20% is lost diffusively into the produced product (4-8 ton per year). Overall global recovery is perhaps in the range 65-75%, which needs to be improved.

Gold has a very special place amongst the metals, as it is the first metal ever used by humans. It is in every day life easy to work with and nearly indestructible. It is traded as money, but has many technical applications, the most common being decorative plating, and plating for protection against corrosion, in jewelry and electronics. It is also special in the sense that the production is well known, it has passed the peak, and we now have more above ground than in geological formations. Gold is very valuable, has always been so, and almost nothing is lost aside from small dissipative losses. It's first and most important use was as money and in prestige jewelry; this remains so to the present. In times of inflation and governmental unaccountability with issuing fiat money, gold is the resort taken by a

Element	Burn-off time, years	Hubbert-time to 10%, years	Dynamic model, years	2008 Available deposits, ton	Estimates 2008 mining rate ton/year	Present Recycling %
Bulk materials for societal infrastructures						
Iron	79	176	200*	150,000,000,000	1,900,000,000	20
Aluminium	132	286	300*	25,000,000,000	190,000,000	30
Nickel	42	95	300*	67,000,000	1,600,000	50
Copper	31	71	120*	490,000,000	15,600,000	50
Zinc	20	38	40*	180,000,000	10,500,00	10
Manganese	19	78	50*	300,000,000	8,800,000	20
Strategic materials for technology						
Indium (Zn-dependent)	25	43		11,000	580	0
Lithium	25	75	330#	4,900,000	200,000	0
Rare earths (Ce, La, Nd, Pr, Sa, Eu, Gd, Tm, Tb, Lu, Tb, Er)	455	400-900	1,090#	100,000,000	120,000-220,000	5
Yttrium (REE dependent)	61			540,000	8,900	20
Hafnium (Zr-dependent)	6200	132		310,000	50	80
Zirconium	67	152		60,000,000	900,000	20
Tin	20	45	60*	6,100,000	300,000	26
Molybdenum	48	120		8,600,000	180,000	25
Rhenium (Mo-dependent)	50	110		2,500	50	75
Lead	23	51	45*	79,000,000	3,500,000	60
Wolfram	32	74	90*	2,900,000	90,000	20
Cobalt	113	255		7,000,000	62,000	20
Tantalum	171	395		240,000	1,400	20
Niobium (Mo-dependent)	45	95		2,700,000	60,000	20
Helium	9	19		7,700,000	882,000	0
Chromium	86	100		18,000,000	210,000	25
Gallium	500			100,000	200	30
Arsenic	31	55		1,700,000	55,000	0
Germanium	100	210		4,000	40	30-35
Titanium	400			600,000,000	1,500,000	50
Tellurium	387			58,000	150	50
Antimony	25	50		5,000,000	200,000	30
Selenium	208			250,000	1,200	0
Precious metals						
Gold	48	37	75#	100,000	2,100	98
Silver	14	44		400,000	28,000	70
Platinum (Ni-dependent)	73	163	50-150#	16,000	220	70
Palladium (Pt-dependent)	61	134		14,000	230	70
Rhodium (Pt-dependent)	44	108	50-150#	1,100	25	60
Fossil energy resources						
Oil	44	100	99#,*	164,000,000,000	3,700,000,000	0
Coal	78	174	220#,*	470,000,000,000	6,000,000,000	0
Natural gas	64	143	100*	164,000,000,000	2,600,000,000	0
Uranium	61	142	180*	3,900,000	64,000	0
Thorium	187	140-470	335#,*	6-12,000,000	64,000	0
Planetary life support essential element						
Phosphorus	80	95-285	230-330#	6-12,000,000,000	145,000,000	10-20

Table 2. Estimated burn-off times (years), time to scarcity using the empirical approach of Hubbert (1966, 1982), and using integrated systems dynamics modelling for metals and elements of different classes. # represents estimates using models built by authors, * represents dynamic model assessments by Meadows et al. (1972, 1992, 2004) using system dynamics. Available deposit values represent the sum of estimates for high grade and low-grade ores.

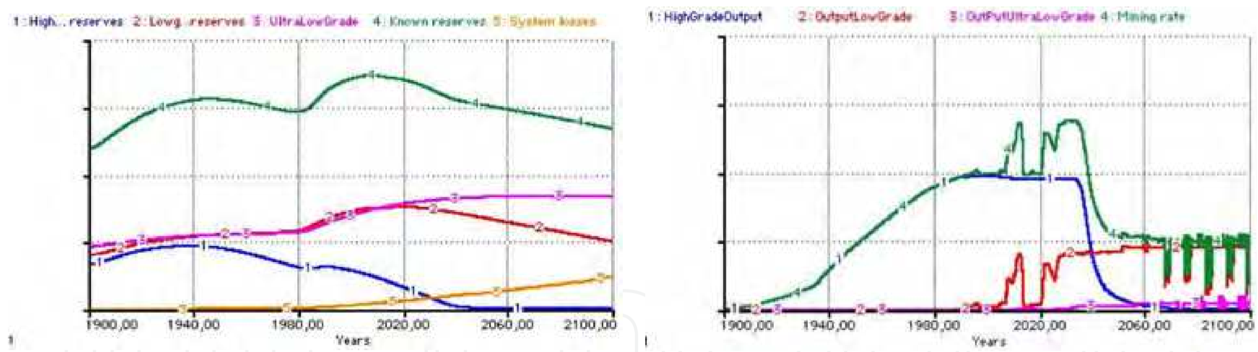


Fig. 8. Peak platinum. Systems dynamics modelling output diagrams showing past and predicted future platinum reserves in geological formations (to the left) and mining rate (to the right).

majority of the world's population. Such practice becomes more prevalent in times of uncertainty. Gold world production peaked in 2005 at 2,500 ton per year, and is expected to decline further from now (now 2,100 ton per year). Overall the recycling degree of gold metal in industrial circulation is better than 92%. In modern times, significant amounts are being lost through gold plated objects and in consumer electronics dumped in landfills and burned in incinerators. Total losses are estimated at 12,000 ton over 5,000 years out of a total mined volume of 160,000 ton (7.5%). A complicating affair with gold is that much has been sold forward as paper gold to investors; this implies that the ownership is sold, but the actual physical metal has not been delivered. This is undertaken by a number of investment and hedge-fund banks that have no significant reserves of physical gold, and thus the gold they sell probably does not exist. They simply assume that they can buy it "somewhere" whenever the need should arise. For a physically limited commodity as gold, that may not be the case at all times. This situation of uncovered gold forward positions will continue to put pressure on the gold price and thus physical supply and demand for decades to come. In the systems dynamic modelling output diagrams in Figure 9, we can see dynamic simulations undertaken for gold, with past and predicted future reserves in geological formations to the left and mining rate to the right.

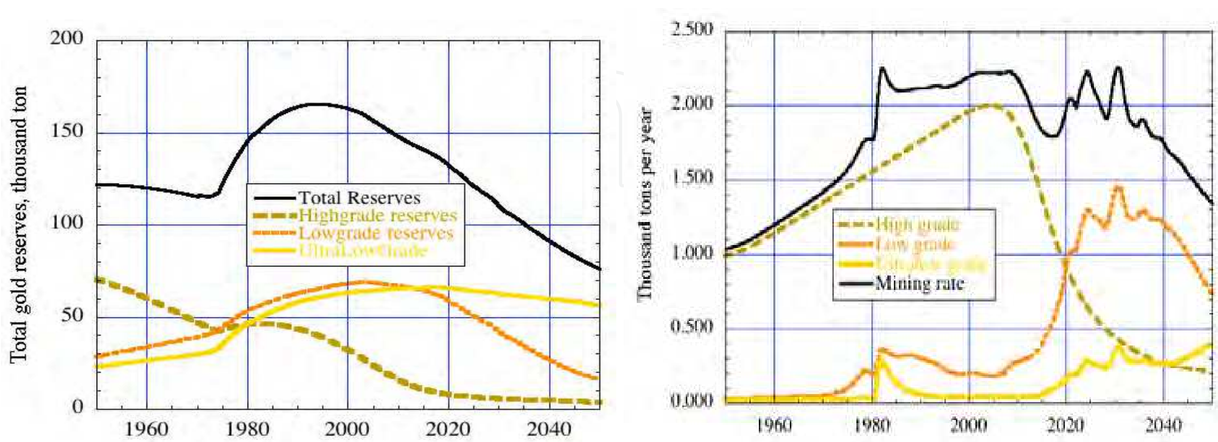


Fig. 9. Peak gold. Systems dynamics modelling output diagrams showing past and predicted future gold reserves in geological formations (to the left) and mining rate (to the right).

Figure 10 shows simulated past and future market price for platinum and gold. The metals will never become unavailable when the resource reserves dwindle, but they will become more expensive as the market availability goes down. The model was validated against observed price as well as on central banks inventory statistics in the past with good success.

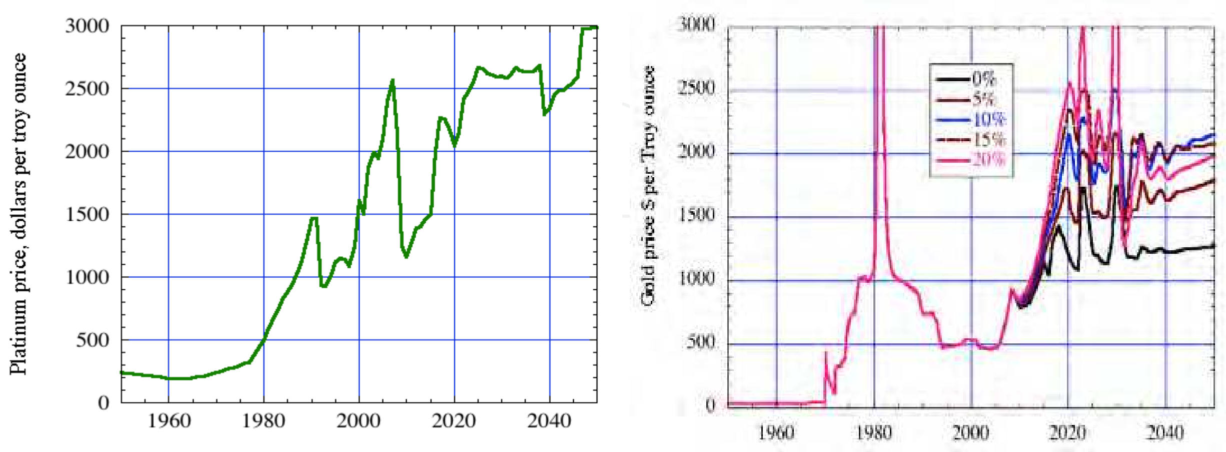
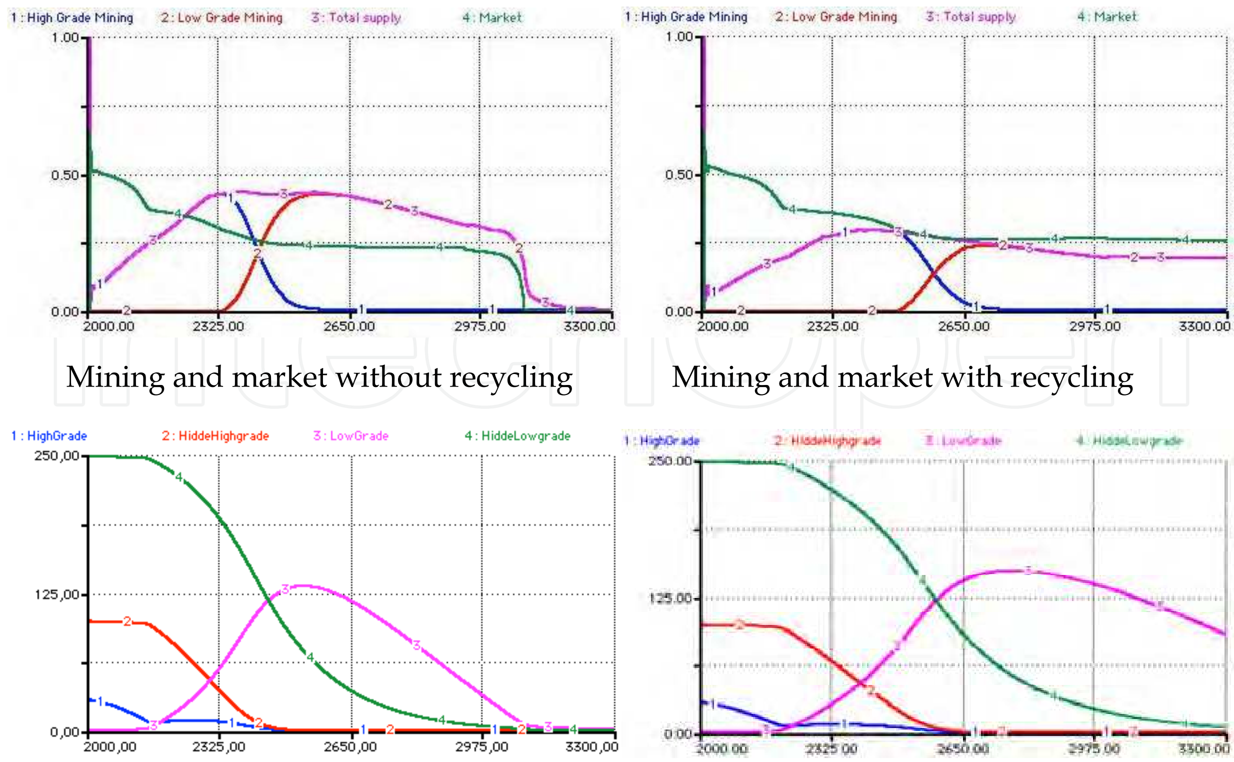


Fig. 10. The price-impact of metal scarcity. System dynamics modelling output diagrams showing past and future market price for platinum (to the left) and gold (to the right). The different % represents at which average rate uncovered forward and short positions are eliminated.

Silver is an important industrial metal, because of its good ductility and conductivity to electricity and heat. As with gold, significant amounts of silver have been speculatively sold forward by banks, and it is uncertain how this is to be found for physical delivery in the future when the contracts expire (OCC, 2009). Silver is lost to diffusive losses, in electronics and silver plating. Cutlery and coinage is mostly recycled. There are considerable amounts of silver stored in private homes all over the world, and a small calculation assuming that in the western world every home has 200 g silver (4 spoons, one in 20 has a full, but simple silverware set) and in the rest of the world there is 15 g silver per person (one teaspoon per household, one in 200 has a full, but simple silverware set), an estimated 400,000 tons is stored in private homes, or about 14 annual global productions.

Rare earths are always mined together as a mix; they are very difficult to separate; with them comes often Y, Sc, Ni and Ta. Figure 11 shows model outputs from simulations for the peak behaviour of rare earth metals without (left) and with (right) recycling. It can be seen that with recycling, we can keep an equal amount available in the market with less mining and that the reserves last significantly longer. With recycling, the availability of the rare earths can be brought to last up to 50 times longer, depending on the degree of recycling.

Lithium is extracted from the salt-beds of certain dried out lakes at some few locations in the world. It has great potential for making light-weight batteries for computers, mobile phones, but possibly cars are also being contemplated. However, the resource base is very small, and mass production of accumulators for cars would quickly finish it off. At present, there is no recycling, and all lithium used at present is lost.



Mining and market without recycling — Mining and market with recycling

Reserves without recycling — Reserves with recycling

Fig. 11. Peak rare earth metals. System dynamics modelling output diagrams showing rare earth metals without (to the left) and with (to the right) recycling. Diagrams on top show the supply and mining rates, where as diagrams at the bottom show reserves over time.

Recycling and replacing

In view of these findings, it is essential that we use metals like copper and zinc, platinum group elements and tantalum as well as all other scarce resources in a sustainable manner. More efficient metal use through better product design and higher durability will also help. But there are limits to recycling; zinc, for example, is used in low concentrations for galvanizing, and is difficult to recycle once it is dissipated across metallic surfaces. Where possible, therefore, scarce resources need to be replaced by more common and easily accessible ones such as aluminium or silicon. A few such technologies are already being investigated. During the past century, industrial production around the world has increased 40-fold. Virgin stocks of several metals seem inadequate to provide the modern "developed world" quality of life for all people on Earth under contemporary technology (Gordon et al., 2006). Of course, there will always be lower-grade metal to exploit, and we can also mine at deeper levels, leading some Earth scientists to reject this more pessimistic view (Williams, 2008). But the price may well prove prohibitive in practice owing to the cost of energy.

Pin-head capacitors in mobile phones that are currently made out of yttrium, tantalum or hafnium, could instead use aluminium[2]. Germanium and indium transistors can possibly be made from silicon or silicon carbide (Juang et al., 2008) or carbon nanotubes (Tans et al., 1998). Solar cells made with silicon polyvinyl chlorides are twice as efficient as thin films solar cells made from the rare metals indium and gallium. For phosphorus there is neither a

[2] http://en.wikipedia.org/wiki/Electrolytic_capacitor

substitute nor any alternative. Economists and economic theorists frequently advocate that technology and science will always develop substitutes, but for phosphorus, we know as a fact that there is none at all because nothing can replace this essential element for life, regardless of what the price might be.

Phosphorus is unique and is demanded for maintaining life in all living organisms in rigidly set proportions. Once elements and metals are dissipatively lost, the energy cost of retrieving them will normally be prohibitive, and if the need is large, the energy needed will probably not be available (Ragnarsdottir, 2007, Fillipelli, 2008, Ragnarsdottir et al., 2011, Sverdrup & Ragnarsdottir, 2011). Extracting phosphorus from the seawater would be energetically unsolvable on a global supply scale. Systems dynamics outputs are shown in Figure 12. The figures show that mining rates from different sources in the longer perspective, show peak behaviour, how the production from high grade, then low grade and last the ultralow grade reserves, peaks (Ragnarsdottir & Sverdrup, 2011).

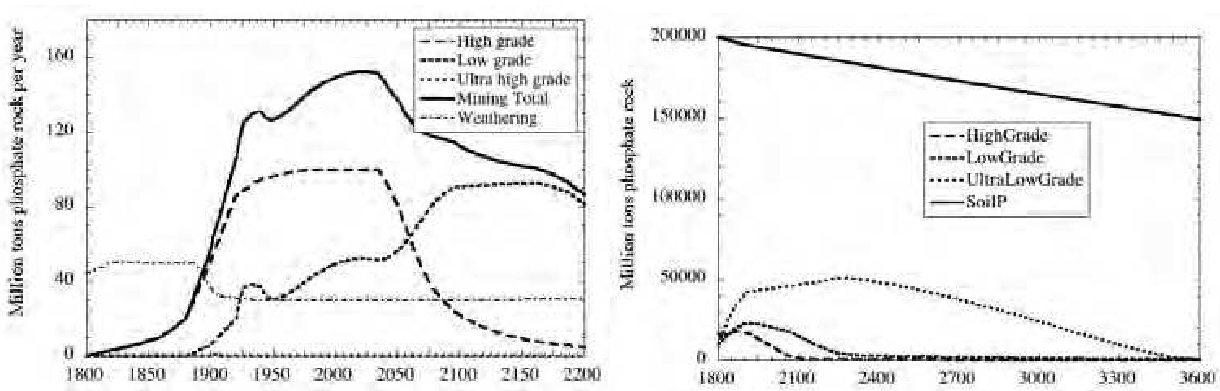


Fig. 12. Peak phosphorous. System dynamics modelling output diagrams showing how the mining rates from different sources peak (to the left) and how the production from high, low and ultralow grade reserves peak (to the right) in the longer perspective.

Job market is affected

It is not only price rises of metals on the world market that give an indication of scarcity: the Denver Post[3] reported in March 2008 that in mining companies, geologists were receiving higher average starting salaries than those with MBA degrees. Similar opportunities apply to skilled oil prospecting geologists and reservoir engineers. At present, these are put to work to make the system even more unsustainable, by finding more of the last hidden reserves, so that they can be finished off as well. However, as times go by and more and more resources can be shown to pass their production peak, the message will have to sink in that recycling is the new kind of mining. The new type of prospecting geologist will have to learn how to mine societal stocks to serve sustainability. Materials engineers and advanced metallurgists have also become rare (difficult subject to master well, few take on this

[3] http://www.denverpost.com/business/ci_8595906

education), and salaries for these are rising. In the near future more systems analysis and sustainability planners as well as material scientists will be needed across the world.

Convergence and contraction needs

From the estimates, using burn-off years, the Hubbert-curve estimate or systems dynamic model runs, we see that we are now challenging the planetary boundaries for supplying most of the materials humans consider necessary for serving civilization. Even metals like iron or aluminium may eventually run out in a few decades. It is of little help to point out that there exists an abundance of these in granite or in the deep crust, as long as there are no reasonable methods or technologies available for winning them. It is also evident from the systems analysis and the dynamic runs, that the market alone cannot cause the use of scarce resources to become sustainable. This is because the market is opportunistic in its function and nature, has no memory, or future vision. The rise in price when a resource becomes scarce will cause recycling to increase, 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, strict governance and policies are needed. Governance must see to that the free market has a well-regulated arena to operate in as well as enforcing that those game rules are obeyed. This is needed to govern responsible use of resources, including starting recycling before the resource becomes scarce. Governments must make policies that look forward with responsibility for generations to come and for the preservation of society.

It is a widely spread misconception that a free market is a market without rules and regulations, with no interference from government; the opposite is the case (Smith, 1776, Friedman, 1962, Forrester, 1971, Friedman & Friedman, 1980, Sterman, 2000, Klein, 2007, Lövin, 2007, Sachs, 2008). The demand for free economy to mean no rules is nonsensical, even if it is cherished by certain political ideologies and taught at many business schools. Games without rules soon deteriorate to anarchy or rule of the strongest, and markets without rules quickly become something that has nothing to do with free markets (Friedman, 1962, Klein, 2007, Sachs, 2008, Jackson, 2009). Sustainability constraints are among some of the most important additions to free market economies if they are to be made long term stable and long term sustainable. The modern world depends on the markets systems for distribution and redistribution of goods, services and wealth, thus functioning markets are an integral part of a sustainable world.

In Table 3, we show the estimates of the maintenance supply from external sources to keep the internal society flux as in 2008, but applying a strict recycling principle. Here we have chosen scenario 4, applying 95% recycling for all elements, except precious metals that we set at 98% recycling. This is a very strict scheme, but it was chosen for the sake of example, to show how large the impact of recycling can be. Obviously, recycling is key factor in going towards metals sustainability. The required external supply can be brought down significantly, once recycling is made efficient. This, together with a contraction of the global population may bring us into the sustainability realm.

In Table 4 we show the outputs on Hubbert-estimates for time to scarcity. The scenarios are as follows; (1) Business-as-usual, no change in recycling from today; (2) At least 50% recycling or maintain what we have if it is higher than 50% recycling, and improving gold recycling to 95%; (3) Improve all recycling to 90%, except gold is improved to 96% recycling; (4) Improve all recycling to 95%, except gold, platinum, palladium and rhodium is

Element	Estimates 2008 mining rate (ton/year)	Recycling now (%)	Real supply to society 2008 (ton/year)	Scenario 4, recycling (%)	Required external supply to keep the real society flux, using scenario 4 recycling (ton/year)
Bulk materials for societal infrastructures					
Iron	1,900,000,000	20	2,300,000,000	95	120,000,000
Aluminium	190,000,000	30	270,000,000	95	13,570,000
Nickel	1,600,000	50	3,200,000	95	160,000
Copper	15,600,000	50	31,000,000	95	1,560,000
Zinc	10,500,000	10	13,100,000	95	656,000
Manganese	8,800,000	20	9,700,000	95	489,000
Strategic materials for technology					
Indium (Zn-dependent)	580	0	580	95	29
Lithium	200,000	0	200,000	95	10,000
Rare earths	220,000	5	232,000	95	11,600
Yttrium (REE dependent)	8,900	20	9,500	95	445
Hafnium (Zr-dependent)	50	80	250	95	13
Zirconium	900,000	20	1,150,000	95	56,250
Tin	300,000	26	405,000	95	20,270
Molybdenum	180,000	25	240,000	95	12,000
Rhenium (Mo-dependent)	50	75	200	95	10
Lead	3,500,000	60	8,700,000	95	437,000
Wolfram	90,000	20	112,500	95	5,625
Cobalt	62,000	20	77,500	95	3,875
Tantalum	1,400	20	1,750	95	88
Niobium (Mo-dependent)	60,000	20	75,000	95	3,750
Helium	882,000	0	882,000	95	44,100
Chromium	210,000	25	280,000	95	14,000
Gallium	200	30	285	95	14
Arsenic	55,000	0	55,000	95	2,749
Germanium	40	30	57	95	3
Titanium	1,500,000	50	3,000,000	95	140,000
Tellurium	150	50	300	95	15
Antimony	200,000	30	282,000	95	14,200
Selenium	1,200	0	1,200	95	24
Precious metals					
Gold	2,100	80	14,000	98	280
Silver	28,000	70	93,300	98	1,867
Platinum (Ni-dependent)	220	70	733	98	15
Palladium (Pt-dependent)	230	70	766	98	15
Rhodium (Pt-dependent)	25	60	83	98	2
Planetary life support essential element					
Phosphorus	145,000,000	20	187,500,000	95	50,000,000

Table 3. Estimates of the maintenance supply from external sources to keep the internal society flux as in 2008, but applying a strict recycling principle. The required external supply can be brought down significantly, once recycling is made efficient. The maintenance needs after this much recycling amounts to approximately 1/10 of the 2008 mining. This, together with a contraction of the global population may brings us into the sustainability realm.

Element	(1); BAU	(2); 50%	(3); 90%	(4); 95%	(5); 95%+3bn	(6); 95%+3bn+ ½
Bulk materials for societal infrastructures						
Iron	158	254	1,285	2,574	6,007	12,014
Aluminium	132	372	1,876	3,756	8,764	17,528
Nickel	82	82	424	851	1,986	3,972
Copper	61	61	317	638	1,488	2,975
Zinc	38	72	372	748	1,745	3,490
Manganese	35	58	306	616	1,437	2,874
Strategic materials for technology						
Indium (Zn-dependent)	35	74	385	771	1,798	3,597
Lithium	47	97	496	997	2,325	3,597
Rare earths	924	1,759	8,809	17,622	41,117	82,235
Yttrium (REE dependent)	120	616	1,235	2473	5,770	11,541
Hafnium (Zr-dependent)	12,649	12,649	25,303	50,609	118,087	236,174
Zirconium	133	214	1,085	2,173	5,071	10,142
Tin	38	58	304	611	1,425	2,850
Molybdenum	94	289	728	1,459	3,405	6,809
Rhenium	99	99	252	507	1,183	2,365
Lead	43	47	181	365	852	1,703
Wolfram	62	102	523	1,049	2,447	4,894
Cobalt	227	365	1,840	3,683	8,594	17,188
Tantalum	346	556	2,795	5,594	13,053	26,106
Niobium (Mo-dependent)	88	143	731	1,466	3,420	6,841
Helium	14	32	175	353	823	1,647
Chromium	175	262	1,310	2,600	6,100	12,200
Gallium	1,017	1,425	7,139	14,282	33,325	66,650
Arsenic	60	123	627	1,258	2,936	5,872
Germanium	201	282	1,425	2,854	6,659	13,317
Titanium	813	813	4,078	8,160	19,039	38,079
Tellurium	784	784	3,942	7,888	18,405	36,809
Antimony	48	68	354	711	1,658	3,317
Selenium	422	8,500	10,600	21,200	49,600	99,200
Precious metals						
Gold	94	94	142	725	1,693	3,385
Silver	26	26	90	434	1,012	2,024
Platinum	145	145	442	2,223	5,187	10,400
Palladium	121	121	369	1,860	4,340	8,679
Rhodium	86	86	266	1,343	3,135	6,269
Fossil energy resources						
Oil and gas	100	-	-	-	330	660
Coal	174	-	-	-	574	1,150
Uranium	121	240	1,215	12,184	28,400	56,900
Thorium	379	747	3,746	37,500	87,500	175,000
Planetary life support essential element						
Phosphorus	160	258	1,303	6,527	15,200	30,460
Colour legend						
TTS range, years	0-100	100-200	200-1,000	1,000-2,000	2,000-10,000	>10,000
Colour code						

Table 4. Outputs on Hubbert-estimates for time to scarcity. (1) Business-as-usual, no change in recycling from today's values, (2) Improved habits in the market, at least 50% recycling or maintain what we have if it is higher than 50% recycling, and improving gold recycling to 95% (3) Improve all recycling to 90% except gold to 96%. (4) Improve all recycling to 95%, except gold, platinum, palladium and rhodium to 98%. (5) Improve all recycling to 95%, except gold, platinum, palladium and rhodium 98%, assume same per capita use as in 4, but assume that population is reduced to 3 billion. (6) Improve all recycling to 95% except gold, platinum, palladium and rhodium to 98%, assume one half of present per capita use as in 4, but assume that population is reduced to 3 billion.

improved to 98% recycling; (5) Improve all recycling to 95%, except gold, platinum, palladium and rhodium to 98% recycling, assume same per capita use as in 4, but assume that population is reduced to 3 billion; (6) Improve all recycling to 95%, except gold, platinum, palladium and rhodium to 98% recycling, assume one half of the present per capita consumption with respect to scenario 4, but assume that the global population is reduced to 3 billion (Brown, 2009, Sverdrup & Ragnarsdottir, 2011). The colour code in the table shows the time to scarcity years. Degree of sustainability can be assessed as 'very unsustainable' for red and orange colours, 'unsustainable' for light orange, 'problematic for future generations' for yellow, 'approaching sustainability' for light green and 'fully sustainable' for green colours.

For fossil energy resources, we see no possibility of ever becoming sustainable, the same applies to use of thorium and uranium in conventional nuclear power stations. However, if the technological and security challenges of breeder reactor designs and fuel recycling are overcome, then the perspectives for uranium and thorium may be widened to the order of 50,000 years.

From Figure 13 we can see a comparison of the different estimates with present recycling rates as repeated to the empirically based Hubbert-estimate. Making system dynamic models and running them may take some time to do. The Hubbert-estimate is fast, providing the right historical records are available. The plot of Hubbert-estimates versus the times obtained with dynamic modelling (Figure 13) shows good correlation; this means that we can make some observations and empirical rules:

1. Burn-off times multiplied by two is a good estimate for the time to scarcity. The burn-off estimate can be made on the back of an envelope, so that it is practical for quick calculations.
2. The Hubbert estimates of time to scarcity and system dynamic modelling estimates of time to scarcity give comparable results. The Hubbert method is a quicker way to get a rough estimate of time to scarcity.
3. System dynamic modelling estimates of time to scarcity makes a more detailed overview and allows for less sweeping generalizations and more specific adaptations to the situation of the specific element and the feedbacks that affects it's fate. Dynamic modelling allows for inclusion of systemic feedbacks and sensitivity analysis, as well as lending it self to policy optimization through back-casting.

It is therefore imperative that we start on a path towards sustainable development worldwide. Whether new technologies use components that will still be available in a few decades, should be a key criterion for their development, not an afterthought. Lack of resources is a dangerous situation globally; there are many convincing examples where this is indirectly or directly the cause for social crisis and potentially also war (Hardin, 1968, Bahn & Flenley, 1992, Ehrlich & Ehrlich, 1992, Haraldsson et al., 2002, 2007, Diamond, 2005, Klein, 2007, Lövin, 2007, Tilly, 2007, Zhang et al., 2007, Brown, 2009b). The solutions to our sustainability problems are as much in the social domain as in the technology domain. Engineering and economics must learn to deal with the functions and mechanisms of the social machinery, and realize that people and feedbacks from social processes control and shape human behaviour. Behaviour is what controls decisions, and these are not always conscientious, nor openly rational. The notion of "the rational economic man" as a foundation for economic behaviour is a mythomania, and it has never been shown to be

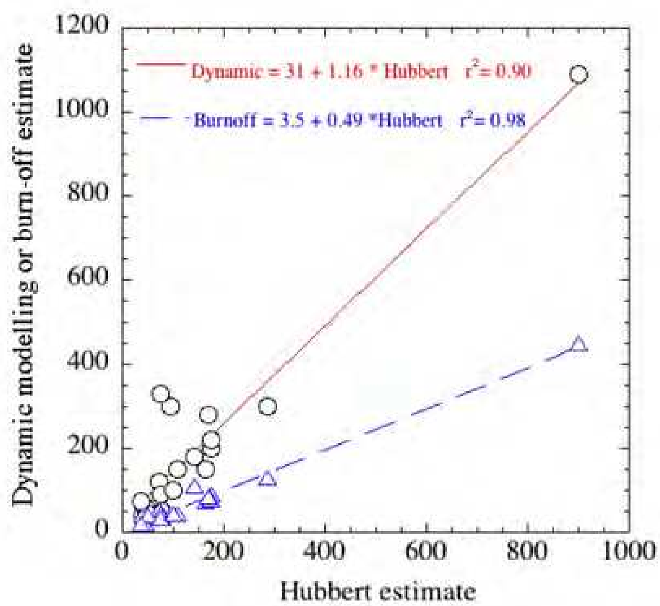


Fig. 13. The plot of Hubbert-estimates time to scarcity (years) versus the times obtained with system dynamic modeling (years) shows good correlation. The burn-off estimates are roughly 50% of the real time to scarcity, and thus underestimates the time to scarcity.

valid. The sustainability challenge is thus a social challenge and centres around the willingness of populations to change behaviour. The use of all resources available to us at maximum rate, probably possesses a threat or significant limitation to future generations, and carries large moral and ethical problems with them (Norgaard & Horworth, 1991, Costanza & Daly, 1992, MacIntosh & Edward-Jones, 2000, Ainsworth & Sumaila, 2003).

4. Conclusions

Our analysis of the length that resources will last into the future allows us to make the following conclusions:

1. Society is outrunning the global resource supply rate for key resources rapidly and has struck upon the planetary boundaries for resource supply for many materials.
2. With the prevailing one way-use paradigm, implying little or no recycling, the Earth cannot feed and sustain 7-9 billion people for very long. We show that there are some important end-times within 100-200 years from now, unless some paradigm changes have occurred.
3. The paradigm change includes policy-changes involving both convergence (efficiency, reduce losses, recycling) and contraction (population contraction, less intensive resource use, smaller extraction rates).
4. It will be possible to feed and supply approximately 2.5 - 3 billion people on Earth if we carefully recycle most of the resources (90-95% should be a target), making sure that we can keep enough material in the cycle, having low restocking demands, because of low losses.
5. Our bulk energy strategies are at present based on unsustainable thinking and still, inefficient use, and partly inadequate technologies.

  a. We are currently in a chicken-race to consume all oil, gas and coal, with no honest thought for future generations. Many reserves are extracted very fast, involving poor recovery efficiencies.
  b. For air transport there is at present no substitute fuel available, nor any alternative planned for. No trials are being undertaken. No viable technical proposal is on the drawing board. There is no plan B.
6. When it comes to public policies and strategic planning for the national states, a complete rethinking must take place in order to step out of a self-destructing behaviour. For approaching a sustainable situation in our world, recycling must be raised to levels between 80% and 95%; these are very challenging tasks both technologically and behaviourally.

It is important to realize that we cannot base any of our planning on miracles to happen in the future. When problems escalate towards crisis, we cannot assume that "someone smart" will show up with a magical solution that liberates us from all problems. Some researchers like to consider energy and material resources to be endless and unlimited, hoping for some yet undiscovered miracle. This is an inadequate attitude for future planning of sustainability, and there are many examples where such approaches failed in the past (e.g. Bahn & Flenley, 1992). At conferences we sometimes hear haggling over the exact numbers in the reserves tables, however this appears to the authors of this chapter as irresponsible, because doubling all our reserves estimates will not make the fundamental underlying problem go away. Neither does sustainability come around from talking about it; what we really need to do is to plan for real change to paradigms, social functions and human consumption patterns that allow us to become demonstrably sustainable. We must plan to become sustainable with the technologies that already exist and are available now, and with significant changes in societal and consumer behaviours. We must plan to change and set out with actions, even if it implies changing our behaviour, our lives, social standards for value, and our laws and policies. It now appears that unsustainability will soon challenge us, our daily lives and put democratic governmental form to tough tests. We need to get ready for real change, because if we do not then future generations do not have a chance to live on our Earth.

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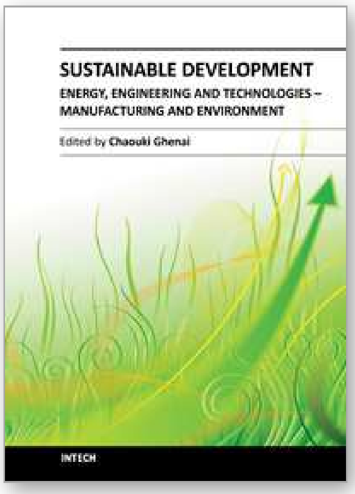

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The technological advancement of our civilization has created a consumer society expanding faster than the planet's resources allow, with our resource and energy needs rising exponentially in the past century. Securing the future of the human race will require an improved understanding of the environment as well as of technological solutions, mindsets and behaviors in line with modes of development that the ecosphere of our planet can support. Some experts see the only solution in a global deflation of the currently unsustainable exploitation of resources. However, sustainable development offers an approach that would be practical to fuse with the managerial strategies and assessment tools for policy and decision makers at the regional planning level. Environmentalists, architects, engineers, policy makers and economists will have to work together in order to ensure that planning and development can meet our society's present needs without compromising the security of future generations.

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