9. The WORLD6 Integrated System Dynamics Model: Examples of Results from Simulations

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Abstract

The WORLD6 model is a fully integrated dynamic world systems model. It includes a biophysical global economic model, based on first principles of physics and thermodynamics, forcing it to be fully consistent with the underlying mass- and energy balances. The WORLD6 model first creates value from extraction of natural resources, input of human labour, the efficiency effect of mechanization and automation, the effect of innovation and their use in manufacturing of goods and services, and the secondly does monetization through market mechanisms and debt financing. The model includes 7 different capital stocks for: (1) industrial resource extraction, (2) industrial manufacture, (3) social service capital, (4) agricultural capital for land use and food production, (5) military capital, (6) speculative capital tied up in derivatives, real estate, consumer credits, (7) criminal or illegal capital. There are 3 different debt pools; (1) general, (2) speculative and (3) pensions. These are all linked through a number of feedbacks in the system to resource extraction, energy production, population dynamics, food production and phosphorus extraction, manufacture of consumer goods and services. The WORLD6 model connects to environmental pollution with feedbacks and inputs to human health and climate change inside the model. The model includes money flows, stocks as well as debt dynamics and how this is connected to the capital base and the governance. The WORLD6 model has earlier been extensively tested on natural resource extraction rates, resource ore grades, supply volumes and market price for resources with very good success. The WORLD6 model system was tested in its economic aspects against observed GDP for the period 1850 to 2015 and GDP per capita, commodity prices, extraction rates and resource supply rates with good success. These results were obtained from first principles only and without calibrating the model to any type of data time-series.

Keywords: WORLD6 Model, Economic Model, Society, Natural Resources, Environment, Base Case Scenario, Policy Development.

Introduction

The WORLD6 model is a fully integrated dynamic world systems model. It includes a biophysical global economic model, based on first principles of physics and thermodynamics for consistency. It goes beyond stock-and-flow consistent models, by forcing it to be fully consistent with the underlying mass- and energy balances. There are efforts to achieve several goals for the decades to come:

1. A long term sustainable energy supply and to be independent as far as possible from fossil fuels by 2040.
2. The future energy visions needs the assessment of long term natural resources suppy. Alternative energy technologies and ways in using energy, demand larger use of rare metals and materials. Will there be enough?
3. On synthesizing measures and solutions to address the challenges, it emerges the necessity to consider what constitutes sustainable society and resource use, and what the implications are in terms of energy, natural resources, social, cultural and political aspects. Changes may be of technological nature, but also on consumer behaviors and habits areas.

The WORLD6 was run to investigate what it would take to make some of these policy visions a reality. Simulations were run for the period 1850 to 2400 and it was checked on historical performance. The system delays are significant for many of the processes involved, from short term (a few years, business cycles), via intermediate (10-30 years, generational times) to long delays (100 or more years, carbon cycle, population dynamics, extraction cycles, lock-in into fundamental heavy infrastructures).

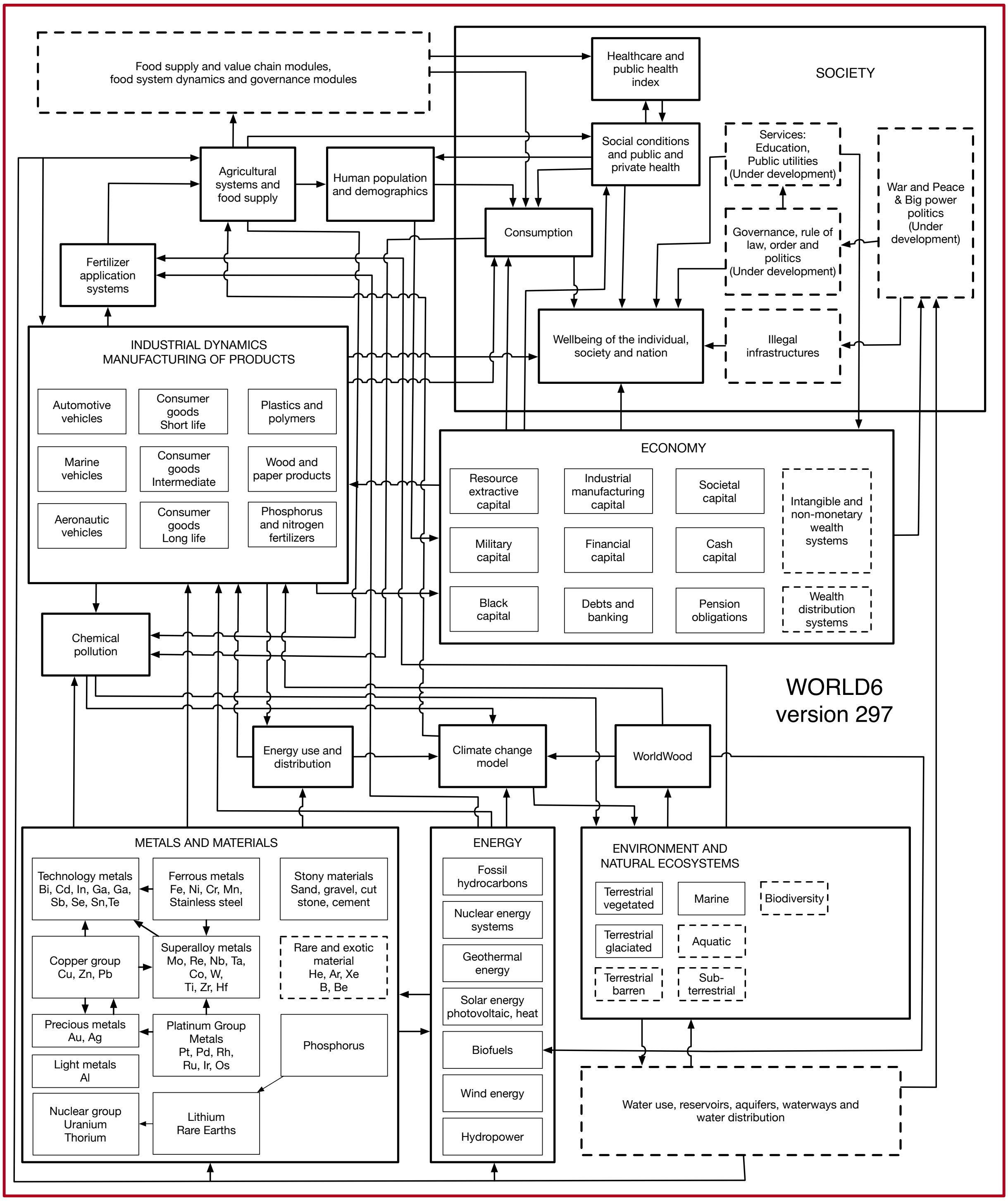


Figure 9-1: *Overview of the WORLD6 and its submodules in Version 297. In the model, nearly everything is connected. The model links the biophysical world, and the social world of humans, and from them generate the economy within the bounds of the world.*

Outputs dealt with from the WORLD6 model

The peak curves for the key resources are as described in the following. The key large scale resources are:

1. Fossil hydrocarbons; oil, gas, coal
2. Fertilizers and proxies for food: Phosphorus global supply (The food module also deals with land area for agriculture and soils per land area unit. Phosphorus is used as a proxy for food)
3. Stony materials; sand, gravel, stone, cement, concrete
4. Woody materials and paper
5. Polymers and plastics
6. Metals; iron, steel, stainless steel, nickel, chromium, manganese, aluminium, copper, zinc, lead, antimony, bismuth, cobalt, indium, gallium, germanium, selenium, gold, silver, tellurium, molybdenum, rhenium, niobium, tantalum, wolfram, tin, lithium, rare earth elements, platinum, palladium, rhodium

The technology metals are quite small in volume, and sometimes modest in production value. However, they hold key positions for many different key technologies that are essential for making a transit to a new sustainable society with respect to energy and materials. In former work we reported on the extraction, supply, price, and depletion of different metals, such as silver (Sverdrup 2014a), copper (Sverdrup 2014b), lithium (Sverdrup 2016a), and cobalt (Sverdup 2016b). The assessment of global metal supply sustainability was also discussed by Sverdrup et al. (Sverdrup 2017). In the model, all losses and wastes in each transformation are counted up. Waste is the starting point for recycling. Recycling is driven by market mechanisms in the model. That implies technical capability (which change over time) and profitability, depending on price and cost of recycling. In the WORLD6 model, a number of interdependencies are made between different modules and sectors. These are:

1. Demand linkages
   a. For many energy production technologies, special materials are needed. When this is the case, they are included in the demand, and taken away from their extraction module and taken to the energy module. Examples of this are: silver, gallium, germanium, indium, rare earths for alternative energies. Stainless steel requires nickel, manganese and chromium. Production is reduced when demand cannot be fulfilled.
   b. The extraction of all materials require energy and this energy is taken from the markets in the energy module. Production is reduced when demand cannot be fulfilled.
   c. Demands in some modules are taken from other modules
2. Supply linkages
   a. For the dependent materials, secondary extraction is done from mother metals, and the rate depend on the extraction rate of the mother metal.
   b. When actual supply to a module is less than demand, then the production is reduced.
   c. When more energy is demanded by resource extraction, than what is available, then resource extraction is reduced.
3. Recycling
   a. Recycling is done for all metals and materials
4. Economy
   a. Resource extraction generate income, costs and profit, a basis income in the economic model. This income makes up about 40-50% of all value generated. The rest comes from human labour and knowledge input.

Figure 9-1 shows an overview of the WORLD6 model and its submodules in Version 6.260. WORLD6 runs on a daily time-step in the integration.

Modelling energy extraction, production and consumption

Energy is an important resource as it allows for use of machinery that greatly amplifies the human effort. This justifies its prominence in the WORLD6 model. The energy module in the WORLD6 model considers the following sources of energy for distribution :

1. Fossil fuels: (1) Hydrocarbons (2) Nuclear fuels
2. Renewable energies (1) Biofuels to heat or to electricity, (2) Hydropower to electricity
3. Technology energies: (1) Photovoltaic solar harvest to electricity, (2) Wind power to electricity (3) Geothermal power to heat or electricity

In “oil” are all types of oil contained; crude oil, tar sands, tight oil, shale oil, heavy oil, offshore etc. This variety is taken care of into the ore grade classification. The same principle applies to natural gas and coal of all kinds being extracted. It is also considered the production of gas from oil, gas conversion to oil and the production of synthetic gas and crude oils from coal, when this is profitable or done by necessity.

Economic modelling in the WORLD6 model

In WORLD6, a simple economic model has been constructed, based of biophysical principles. Mass and energy balances apply, and money flows with the materials, commodities and the services. The economic module in the model is simplified, and under development and steady upgrading (Figure 9-2). In it, we take into account industrial capital (To produce goods and food), social service capital (To provide public services), resource industry capital (To extract resources), military capital and illegal black capital (money outside the regular society), as well as a global capital stock (Cash to pay bills) and a stock of debts. Debts are incurred as a part of any investment and for replenishing the capital stock of liquid cash. The debts taken are paid down over 30 years in the model and incur interest payments at an average rate of 3%. All capital is subject to wear (depreciation) and all capital stocks such as industrial capital, resource industry capital, social capital or military capital, requires maintenance, which all come as a cost. Debts cannot be taken of the debt to GDP ratio is more than 150%. Each step in the supply chain is demanded to run at a profit. When the profit declines, the production decrease, and if supply falls below the demand, immediately rising the price, keeping profits up as long as there is demand, and supply can be done. The increase in price along the supply chain, is determined by the required profit margin and the resource use efficiency.

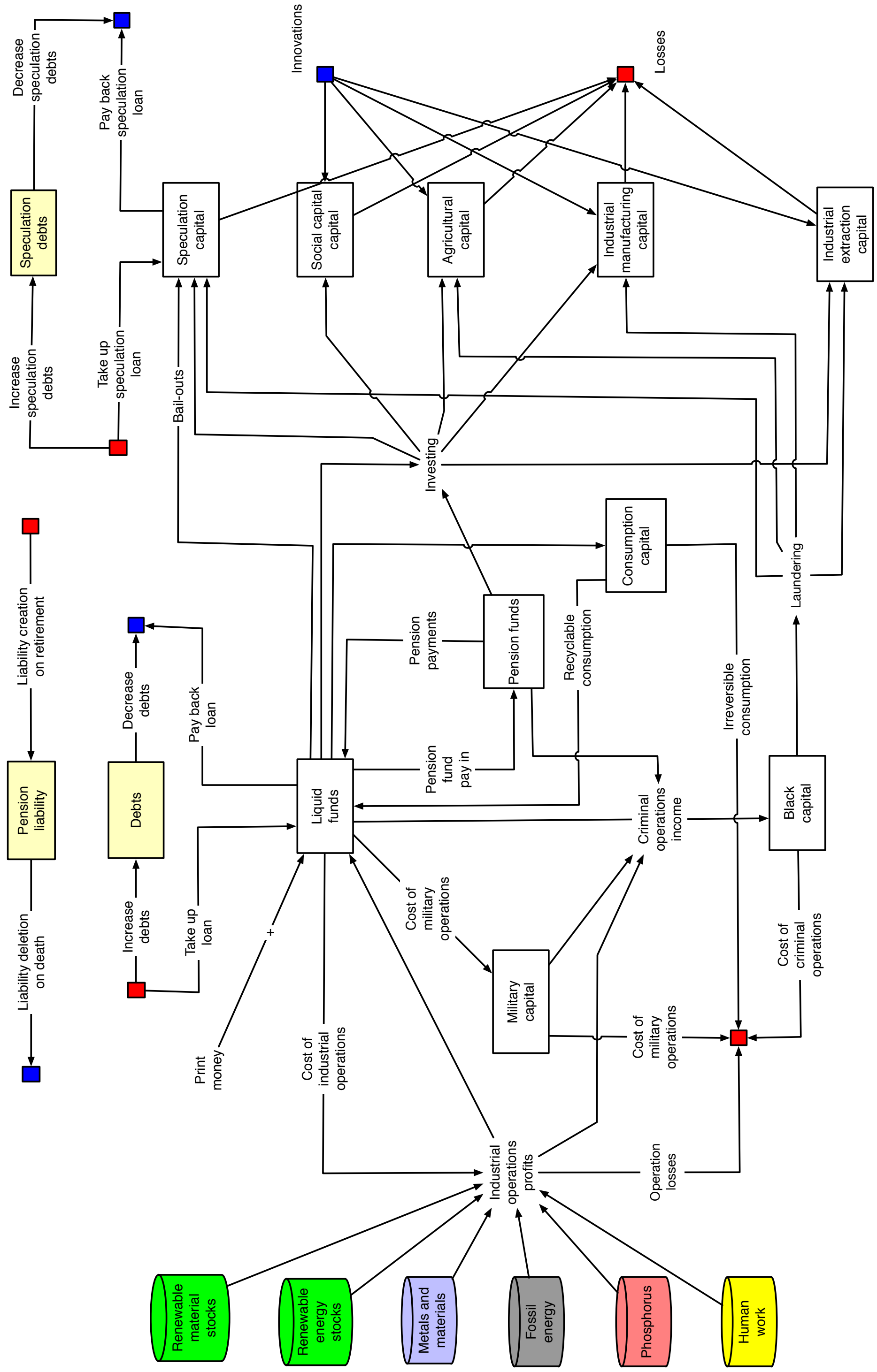


***Figure 9-2:** Overview flow chart of the economic module included in WORLD6.*

The resource use efficiency is made up of the production yield and the production losses. The basic principles in the economic model used are as follows:

1. Income arise from resource extraction and input of human labour and innovation in the supply chain from raw material to commodities and consumables. Profit is generated along supply chains, as the difference between sales income and cost of production.
2. Resource supply: Raw material (resources) costs come from extraction, treatment, refining and supply costs to the market for raw materials. Raw material income is the amount supplied to the market times the market price at that point in time. The profit is the income minus the cost of extraction and supply.

3. Commodity supply: For commodities, the costs come from amount of raw materials used, their market price and cost of input of human labour and innovation. For commodities, the income is the amount supplied times the market cost. The profit is the income minus the production costs as outlined above. Resource use efficiency and yield factor for each transformation is used.
4. Service supply: Services also use resources and commodities, and require certain infrastructures to be present, even when the target supply is only a service. Income is generated by delivery of the service times the market price for that service.

Resource conversion is the most important source of revenue. Important other sources of value generation are inventions, innovations, organization of production and service provision and input of human labour. Important sinks are material losses, infrastructure and commodity wear or depreciation of capital. The WORLD6 model has used simplified supply chains for some commodities and materials. In the primary production, profits arise as the difference between income from sales and extraction costs. In the next step, sales of commodities and services become the source of income, whereas the resources used or used and lost are costs, profits being the difference (Figure 9-2). This way, the economic model is tied to biophysical flows and events.

The base scenario and its outputs

The base case scenario in WORLD6 does not introduce any new policies that involve active interventions, beyond the already built-in feedbacks. These feedbacks are part of the systems, and operate endogenously in the model. Important such feedbacks are the following:

1. Extraction increases as a response to increased profit. Profits increase when prices rise more than extraction costs do. When the profit drops to zero or below, the extraction stops. Over time, extraction cost decrease because of technological advances.
2. The demand declines with increasing price
3. The price increase when the tradable amount in the market decline, and decrease when the market tradable amount increases.
4. Recycling increases with increases in market price or when the profit of recycling increases. Recycling costs goes down with time, as the recycling technology improves.
5. The extraction module has some built-in scaling functions.
    a. A mining and extraction efficiency with time function, based on data from literature.
    b. Extraction costs increase with decline in resource quality, both in terms of work requirements (Extraction costs) and energy requirements (EROI).

The basic scenario is capable of reconstructing the past observations of mining rate, market price, and when data is available, ore grade, stock-in-society, known reserves. The model is not calibrated to any dataset, it is not data-driven, but operates up from basic physics and ecology, confined by mass- and energy balances. Important are to get good estimates of all technically feasible extractable resources, regardless of extraction cost, as the model decides internally over what will get extracted, based on what is the most economically profitable.

Assessing resource access per person on the global level and other simulation outputs

For the assessment of risks for scarcity, two types of diagrams are central to the evaluation of scarcity and whether it an apparent challenge or a real challenge that demands a policy consideration and potentially measures to be taken: Supply as amount per person per year and stock-in-use per person. Supply per person will be used for replacing irreversible losses, new investment to stock-in-use for new persons added by population growth, and growth of present standard. These indicators have been calculated for all resources investigated. Stocks-in-use per person is an indicator of the service provision.

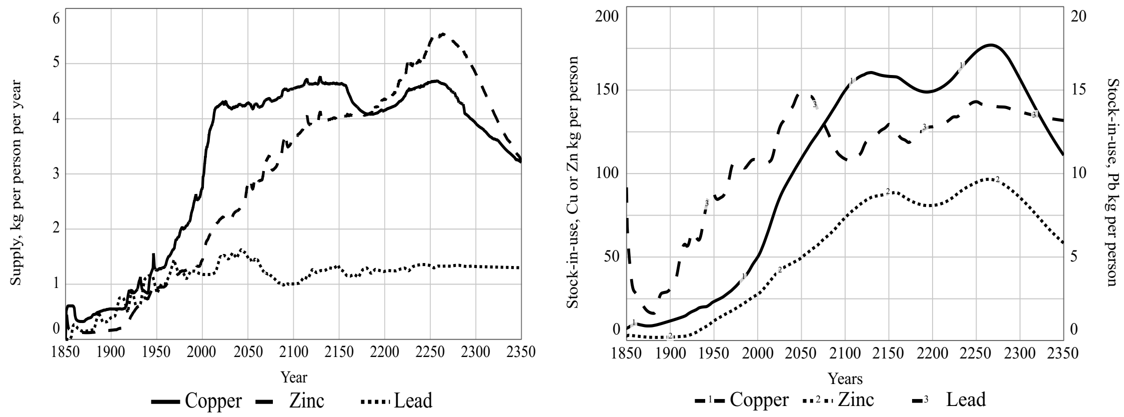


Figure 9-3: *The supply in kg per person and year (left) and the stock-in-use (right), kg per capita, for copper (-1-), zinc (-2-), and lead (-3-) as calculated using the WORLD6 model.*

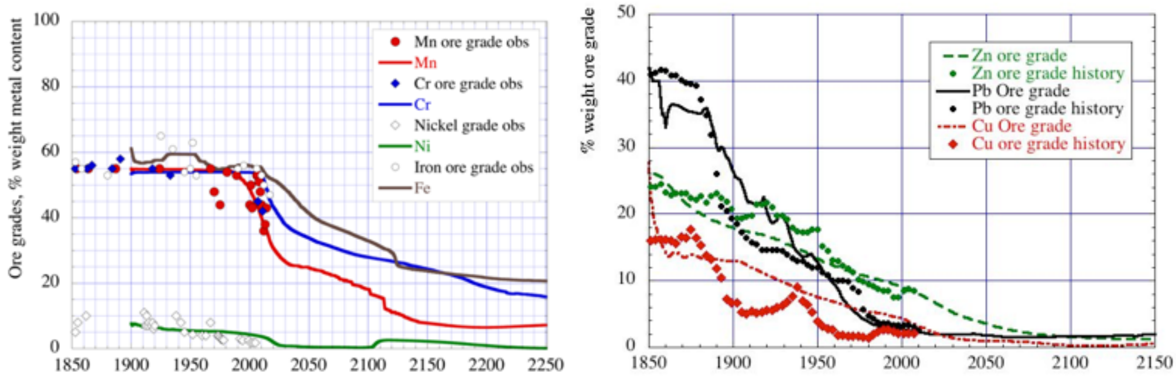


Figure 9-5: *Ore grades for iron, manganese, chromium and nickel as simulated using the model (left), and ore grades copper, zinc and lead (right), as compared to the observed ore grades. Declining ore grades are a very powerful signal that the resources are becoming exhausted.*

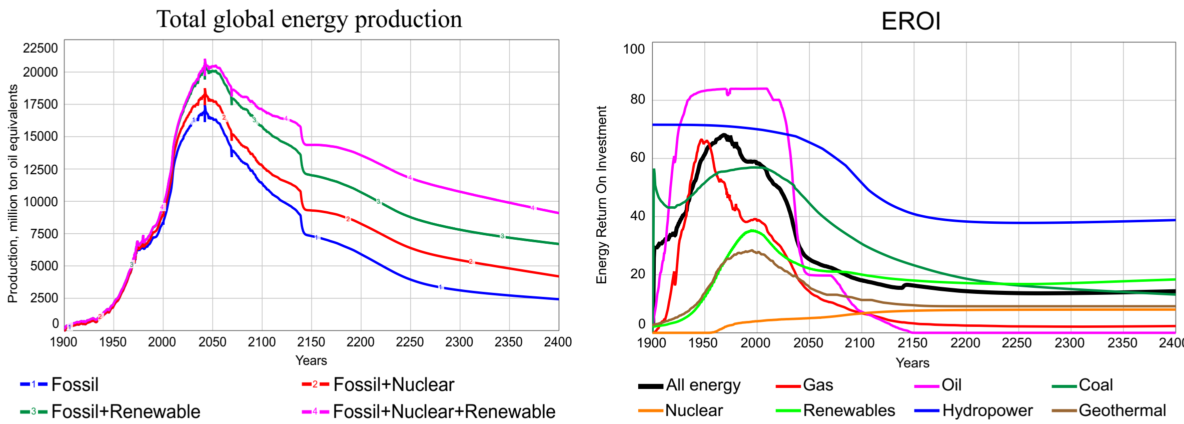
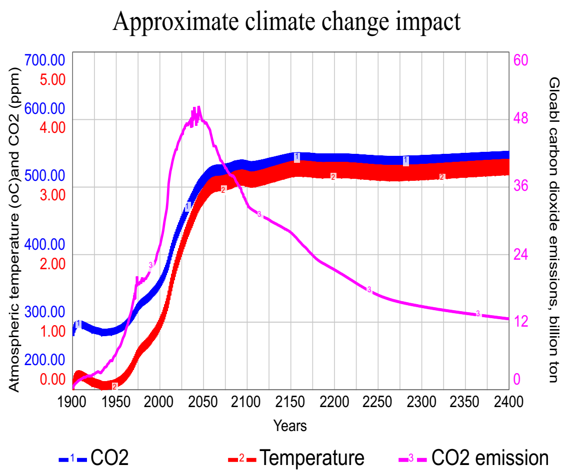


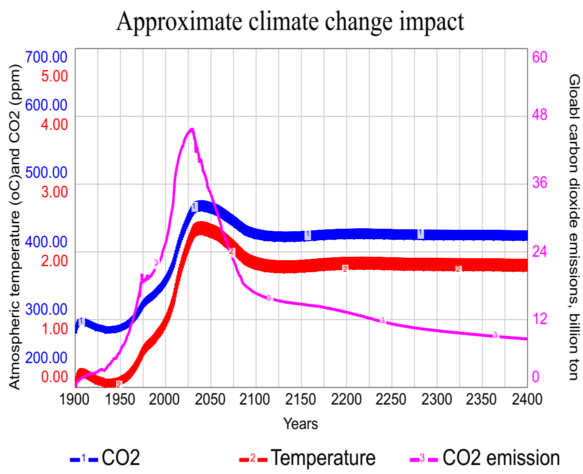
Figure 9-6: *Overview of the energy produced in the WORLD6 model (left) and the Energy Return on Investment for different energy types (right).*

Growth in stock-in-use per person is correlated to material standards and a decline, suggests a decline in the degree of provision, suggesting a decline in provision of material quality of life. Efficiency of service provision per unit stock-in-use has not yet been developed but would be the next natural step to take. A significant part of the large, but ultralow grade coal resources will not be fully extracted due to low energy return on investment and high extraction costs that cannot compete with more cost-efficient renewables. The results from the scenario runs are as follows:

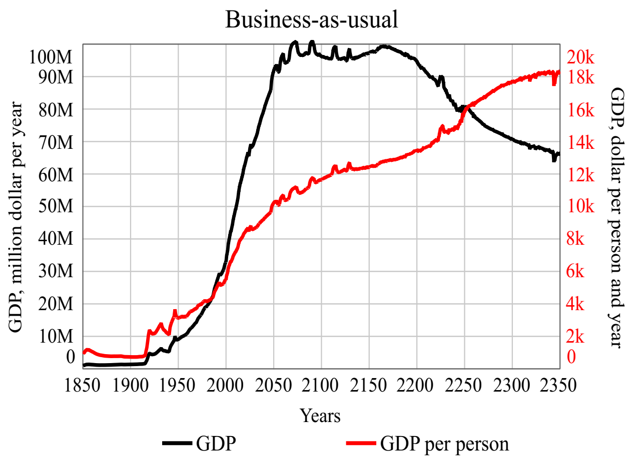
1. **Base case scenario** for GDP is shown, with and without climate change damages counted. The climate change damage was estimated as land inundation and city flooding damaging costs. Costs of conflicts and war were not counted.
2. **Maximum 2°C climate change**, done by shutting down fossil hydrocarbon extraction by 90% in 2020-2060. GDP is first reduced by 3% during 2030-2060 because of already incurred damages before 2020 and the loss of oil revenues. The scenario is letting the GDP level off at a value above the level of the base scenario. Thus, mitigating climate change and resource scarcity is beneficial to industry.
3. **UN population scenario** The GDP is higher for the larger population, because of the way GDP is defined. Climate and pollution damages are subtracted from the GDP. The UN population scenario, leads to a CO_2-polluted, and heavy metals-contaminated, overcrowded and a worn-down Earth, with massive climate change ecological and economic damages. This prevents an economic recovery, and GDP stabilize at a significantly lower level than the Maximum 2°C scenario and the base case scenario.



a: WORLD6 Base case scenario.



b: Max 2°C warming Draw down fossil fuels 90%.



c: GDP for base case scenario.

Figure 9-8: *Climate change outcomes for 4 different scenarios tested with the model. The climate change model is internal to the WORLD6 model. Estimated GDP for the base case scenario. Estimated GDP for maximum 2°C climate change, done by stepping down fossil hydrocarbon extraction 2020-2060 is nearly identical to the base case scenario, but ends slightly higher. Phasing out fossil fuels do not lower the GDP, but create a small increase.*

Policy implications

The purpose of the model is to assist in policy development towards a long term sustainable society, where all aspects are linked; economy, *natural resources, environment* and society. This is not really the case today, and the model is an alternative to economic models based on statistics, of which some have little or no connection to any reality. The present simulations show that many natural resources will peak in the period from 2040-2070, creating a number of simultaneous supply crisis. Increased recycling or resource efficiency may be used to drag the supply peaks out in time, softening the problems. The resource peak can be moved with several parameters using policy instruments:

1. Total resource use with less CO_2 impact: Limit extraction of carbon-based energy resources, Limit calcination of fossil carbonates (Cement production and carbonate ores). Use of more wood materials for infrastructures which sequester CO_2 in their production and use
2. Resource use efficiency can be improved in the extraction step, by decreased losses in every transaction and less losses in recovering and recycling. Important is better utilization efficiency in the consumption step and smaller material and energy consumption overall
3. Recycling implies that the material is reused and less net supply is required from primary sources, extending the life-time of our natural non-renewable resources.
4. Efficiency of use: Better use efficiency, based on better durability, repair, retrofit or design for recycling during or after consumption. Reduction of irreversible losses in the system: extraction, refining and supply, manufacturing and transaction losses, use losses, recycling losses

Some of these are already somewhat promoted in the market system, but several can be significantly improved on by policy measures. For several of the technology materials, this appears to be necessary. Either as supportive or constraining regulations and stimulants. It would appear that taking initiatives to become market leaders and in several segments will create a position of priority in the market. The model runs suggests that a horizon of 2040-2050 for a phasing out 90% of all fossil fuels is challenging but realistic.