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Dynamics in the Extended Cass-Koopmans-Ramsey Growth Model

Dissertation

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Statement:

I declare that I have elaborated this dissertation thesis on my own using only sources cited in the chapter References.

Hradec Králové Ing. Lukáš Režný

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Content

List of Abbreviations

BTU…British Thermal Unit

dmnl…Dimensionless

EROEI…Energy Returned on Energy Invested

GDP…Gross Domestic Product

GNP…Gross National Product

PV…Photovoltaics

TOE…Tonne of Oil Equivalent

SD…System Dynamics

1989$...Constant dollar of the year 1989

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Abstract

This thesis deals with the expansion of the Cass-Koopmans-Ramsey model of economic growth with the energy sector. Firstly, the current problems presented by declining quality and limited quantity of fossil fuels together with the properties of the new renewable energy sources are analysed. Next, the relationship between economic growth and energy consumption is introduced. The paper then briefly describes the advantages of using system dynamics for an extension and analysis of economic models. The main content is the description of the expansion of the selected model of economic growth with the energy sector and resulting analysis of its dynamics. The impact of the varied quality of renewable energy sources on the future economic performance is being studied.

Keywords: economic growth model, fossil fuels, renewable energy sources, EROEI, system dynamics.

Abstrakt

Tato práce se zabývá rozšířením Cass-Koopmansova-Ramseyho modelu ekonomického růstu o energetický sektor. Nejprve jsou přiblíženy současné problémy představované klesající kvalitou a omezeným množstvím fosilních paliv spolu s vlastnostmi obnovitelných zdrojů energie. Dále je přiblížen vztah ekonomického růstu a spotřeby energie. Práce stručně popisuje výhody použití systémové dynamiky pro rozšiřování a analýzu ekonomických modelů. Hlavním obsahem je popis rozšíření vybraného modelu ekonomického růstu o energetický sektor a analýza jeho dynamiky. Je zkoumán vliv rozdílné kvality obnovitelných zdrojů energie na budoucí ekonomickou výkonnost.

Klíčová slova: model ekonomického růstu, fosilní paliva, obnovitelné zdroje energie, EROEI, systémová dynamika.

1 Introduction

Humanity is currently facing gradually worsening resource depletion and environmental degradation problems, the so called 'perfect storm', as UK's Chief Scientific Advisor John Beddington referred to an extensive list of converging environmental problems, above all climate change and increasing scarcity of key energy resources[1]. The term 'Peak oil', announcing an irreversible decline of conventional oil production, entered mainstream debates after many years of various controversies when the price of oil almost quadrupled in the last decade [2-4][1]. The recent price collapse is sometimes presented as proof that there are no problems with oil scarcity. Considering recent announcement that in the year 2015, oil discoveries were lowest since 1947, replacing only six percent of quantity of oil drilled in the same year, the aforementioned conclusion is indeed invalid[5]. Other fossil fuels also face imminent availability problems, including coal[6]. Non-energy minerals like copper, zinc, nickel are being extracted in rapidly diminishing ore grades, requiring more and more energy to be used in extraction process, further worsening humanity's pollution and energy availability problems [7]. These problems have serious economic consequences. James D. Hamilton, examining relationship between oil price spikes and recessions in the USA noted [8]: "*The correlation between oil shocks and economic recessions appears to be too strong to be just a coincidence*". Some authors have also argued that oil supply limit appear to be a primary cause of the 2008–2009 recession[9], while others went even further and announced end of economic growth[10]. These worrisome trends led some to argue that the possibility of imminent collapse of the human society is indeed real [11-12].

Curiously, leading figures in the field of economics were not amongst them, despite unpleasant current economic trends, when major developed countries are fighting with high unemployment and extremely slow or no growth. Paul Krugman recently announced that saving the planet would be cheap, even free[13]. Particularly interesting is his following note[13]: *"…they don't understand what economic growth means. They think of it as a crude, physical thing, a matter simply of producing more stuff, and don't take into account*

[1] During the period of 1990-1999, the average price of oil was 28, 44$ while the average price in the year 2012 was 111, 67$ (Brent prices in constant 2012 US dollars).

the many choices — about what to consume, about which technologies to use". This change in production from 'crude, physical things' and 'simply producing more stuff' to intangible assets lies at the heart of the Cobb-Douglas production function with constant returns to scale, which allows for smooth, endless substitution between inputs (typically, only labour and capital are considered as inputs). Adoption of the Cobb-Douglas production function consequently led to formulation of the Solow-Swan model of economic growth, which does not acknowledge any importance to natural resources or energy in the growth process.

It is a well-documented fact that economic growth defined as a growth of real gross domestic product is accompanied by increased energy consumption and increased consumption of natural resources in general[14-17].

On the same note, professor Steve Keen pointed out recently[18]: *"The abiding weakness of all schools of economics, ever since the Classicals—including today's Neoclassical and Post Keynesian schools, which are normally at pains to point out how superior one is to the other—is this failure to acknowledge the key role of energy in production."*

This blindness is in stark contrast to the modelling approach of System Dynamics, which carefully considers various interactions between economy and its environment, its inputs in form of stocks of non-renewable and renewable resources, outputs and sinks (e.g. greenhouse gases dumped into the atmosphere) during model development.
The seminal study Limits to Growth concluded that limited availability of non-renewable natural resources combined with various pollution problems will halt economic growth [19]. The study was never widely accepted by most economists, with the exception of ecological economists, being subject of various criticisms over the years. But as Graham Turner pointed out recently, comparing the study scenario called Standard run with the real-world data, study was surprisingly precise[20]. Professor Ugo Bardi in his analysis also pointed out that at least some of the critics did not really understand the original study and thus their criticism was unjustified [21].

Since 1972, many more models used the System dynamics approach, illustrating problems of resource depletion and climate change caused by continuing economic growth[22-25]. But these models failed to change the economic theory in any appreciable way, despite the fact that they were representing empirical facts of the relevant fields of science.

Takuro Uehara summed the problem concisely[26]: *"While system dynamicists may not rely heavily on economic theory because of the seemingly unrealistic assumptions employed, economists are indifferent to models that seem to disregard economic theory".*

2 Purpose and Aims

The purpose of this dissertation is to bridge the gap between mainstream models of economic development and system dynamics models incorporating environmental feedbacks to economic process.

For this task, dissertation first analyses existing representative models which deal with the issues of resource depletion and climate change while using system dynamics methodology. Analysis will be focused on the common model's assumptions and conclusions as well as on the form of used production functions.

The Next step will comprise of selecting a representative model of economic development, its conversion into system dynamics format and its extension by energy sector, comprised from selected important feedbacks and stocks, to represent ongoing energy transition. Energy transition currently only mildly influences economic growth, but it will play decisive role in the future. The model created in this dissertation will help to shed some light on the conflicting debate presented in the introduction. Can the current rate of economic growth be maintained with currently available renewable energy sources? For how long can the current stock of fossil fuels support economic growth? These and other questions should be answered by the model.

The model should also be as simple as possible, to be relatively easily interpretable and understandable, in compliance with the term coined by professor Bardi, model should be "mind sized"[27]. In this form, it should convey to readers selected challenges which economic growth process faces in the 21st century.

The scope of the proposed dissertation fits very well into the field of Information and knowledge management. Derivation of new stylized facts about economic growth and energy consumption from the empirical literature and existing integrated assessment models represents an acquisition of new information and their inclusion into the Ramsey-Cass-Koopmans model of economic development represents knowledge creation. Furthermore, system dynamics is an advanced tool of management, which is used to analyse complex nonlinear dynamic feedback systems for the purposes of generating insight and to help to design policies that should improve their performance [28].

3 Methodology

One of the aims of this dissertation is to extend an existing model of economic development using the System dynamics framework, implementing new stylized facts about economic growth. Why such a model should not be developed using standard economic tools, namely various general or partial equilibrium models? Professor Keen succinctly puts it [29]:"*…from neither general equilibrium nor microfoundations, but from the very sound rejection of both these concepts decades ago, by almost all the intellectual disciplines that build mathematical models apart from economics. In the mid-20th century, other modelling disciplines developed the concept of "complex systems", along with the mathematical and computing techniques needed to handle them. These developments led them to the realisation that these systems were normally never in equilibrium—but they were nonetheless general models of their relevant fields. … Economics needs to embrace the reality that, even more so than the weather, the economy is a complex system, and it is* ***never*** *in equilibrium*"

According to Radzicki [28], System dynamics is a computer simulation modelling methodology that is used to analyse complex nonlinear dynamic feedback systems for the purposes of generating insight and designing policies that will improve system performance. It was originally created in 1957 by Jay W. Forrester of the Massachusetts Institute of Technology as a methodology for building computer simulation models of problematic behaviour within corporations. The models were used to design and test policies aimed at altering a corporation's structure so that its behaviour would improve and become more robust.

Radzicki further states that there are three principle ways that system dynamics is used for economic modelling. The first involves translating an existing economic model into a system dynamics format, while the second involves creating an economic model from scratch by following the rules and guidelines of the system dynamics paradigm. The former approach is valuable because it enables well-known economic models to be represented in a common format, which makes comparing and contrasting their assumptions, concepts, and behaviour easy. The latter approach is valuable because it usually yields models that are more realistic and that produce results that are counterintuitive. The third way that system dynamics can be used for economic modelling is a "hybrid" approach in which a well-known economic model is translated into a system dynamics format, critiqued, and then improved by modifying it so that it more closely adheres to the principles of system dynamics modelling. This approach attempts to blend the advantages of the first two approaches, although it is more closely related to the former. Existing economic models that have been created in an ordinary differential equation format can be translated into system dynamics very easily, and in Fig. 3 in his article Radzicki presents the Robert Solow's ordinary differential equation growth model in a system dynamics format [28].

That is very fortunate, because it is the very model of economic growth for which Daron Acemoglu used the term "workhorse" of dynamic macroeconomic analysis [30]. The model is also relatively simple, which favours his adoption for the purpose of the proposed dissertation thesis. Therefore, the model to be modified by the inclusion of the new stylized growth facts is the Solow-Swan growth model.

3.1 Short note on the general structure of System Dynamics models

3.1.1 Stocks and flows

Radzicki describes the structure of a system dynamics models as follows: From a system dynamics perspective a system's structure consists of stocks, flows and feedback loops. Stocks can be thought of as bathtubs that accumulate/de-cumulate a system's flows over time. Flows can be thought of as pipe and faucet assemblies that fill or drain the stocks. Mathematically, the process of flows accumulating/de-cumulating in stocks is called integration. The integration process creates all dynamic behaviour in the world be it in a physical system, a biological system, or a socioeconomic system. An example of a stock and flow in the economic system can be a stock of the value of a total capital present in the economy and its inflow of investment spending and its outflow of depreciation [28].

Stock is represented as a rectangle, S. Its value (level) is determined by the changes in s', as is determined by the 'pipe', the thick straight arrow leading to S. The change of S from t to $t+1$ is represented by s'. There can also be auxiliary variables and constants, which are represented by the circles in the graph. Auxiliary variables use the calculation between stocks, flows, constants and other variables and can change in each period t. Constants are exogenous and independent of the time. In the Figure 1 below, there are no auxiliary variables and only one constant, t.

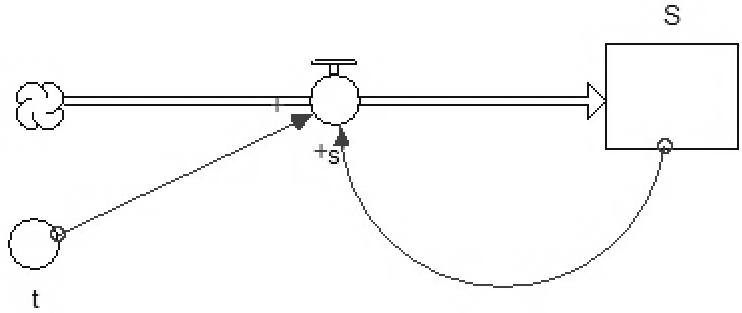

Figure 1 - Exponential growth systems archetype. Source: own work.

The relation of the variables, stocks and flows to each is shown by the arrows. A "+" on the arrow tip means identical direction or reinforcing behaviour. Figure 1 depicts a situation where an increasing growth rate t increases inflow *s'* into stock *S*, as is represented by a "+" sign. A "-" sign symbolizes exactly the opposite, therefore if a variable increase, it leads to a decrease in the dependent variable. The strength of this relationship is determined mathematically and cannot be indicated only by the previously mentioned graphical representation. The large advantage of a graph instead of a pure mathematical representation is to be sure that the observer can optically recognize, which relations form the model [31]. Figure 1 describes a pattern of exponential growth (reinforcing feedback structure), which is a recurrent archetype in the mainstream models of economic growth.

3.2 Solow-Swan Growth model

Solow-Swan growth model consists of three stocks – the capital stock *K*, the population stock *L* (model assumes that all people work, therefore it also represents total labor supply) and third stock, *A*, represents technological progress.

Economic product *Q* is represented by the Cobb-Douglas production function

$$Q = AK^{\alpha}L^{\alpha-1}$$

Where α is the capital elasticity in production. The model employs pattern of exponential growth on two places – in the growth of labor force and technology.

$$L = L_0 * e^{lt}$$

$$A = A_0 * e^{at}$$

Where L_0 and A_0 are the stocks initial levels and *l* and *a* are their respective growth rates, *t* represent time step in the model. Capital stock is influenced by the Savings *S* and depreciation rate *D*. Constant share of product is saved

$$S = s * Y$$

and model assumes closed economy, therefore

$$I = S$$

Depreciation rate *D* is defined as a constant rate of capital degradation

$$D = d * K$$

Models scheme in system dynamics notation is placed below alongside the representative model output.

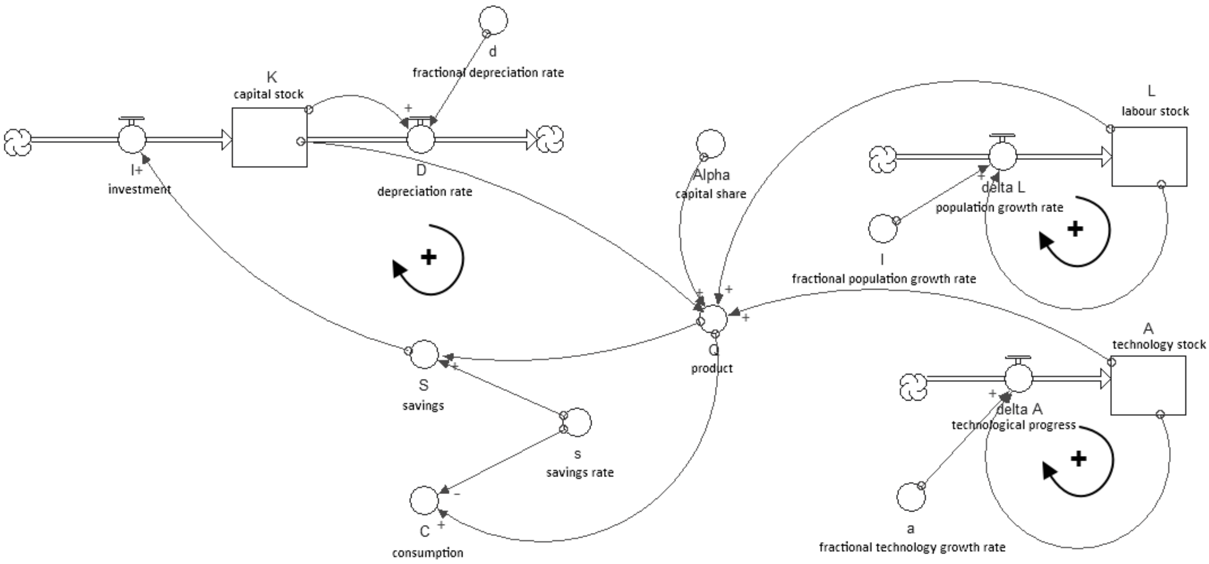

Figure 2 - Solow-Sawn growth model in system dynamics notation. Source: own work.

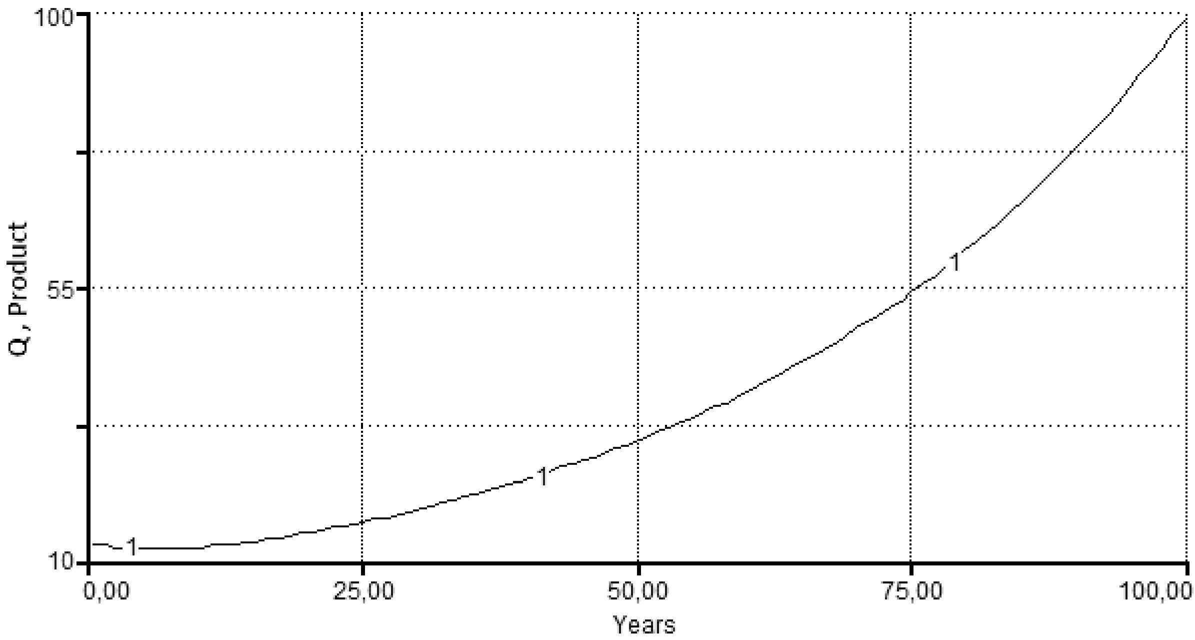

Figure 3 - Representative output of the Solow-Swan growth model. Source: own work.

3.3 Ramsey-Cass-Koopmans model

One of the simplifying assumptions of the Sollow-Swan model is that the savings rate is constant. Ramsey-Cass-Koopmans model allow households to make optimal consumption/saving decisions as a reaction to their environment. Capital stock then reflects interactions between households supplying savings to the firms, which demands it – savings rate is no longer constant. Households face the problem of maximizing utility subject to certain budget constraint. For this problem, economics employs the method of dynamic optimization in continuous time. Unfortunately, it is not possible to use this method in a purely system dynamics model.

Fiddaman proposed a different solution, which is also used in this dissertation thesis[23]: *"…simple behavioral savings rule, which may be substituted for the optimal investment allocation of the DICE model. The fraction of investment devoted to output is an increasing function of the ratio of the marginal product of capital, net of depreciation, to a normal return or interest rate. This creates two additional feedback loops governing the capital stock (R2 and B2). Because output grows less than proportionately to the capital input, the negative loop dominates; increasing capital lowers the marginal product of capital, reducing investment, and slowing the increase of capital. While this rule can be parameterized to match the optimal investment behavior of the DICE model almost exactly,* *it does not in general allocate investment optimally over time. Also, this rule is subject to steady-state error; it does not guarantee that the marginal return to capital eventually reaches the normal return in equilibrium. "*

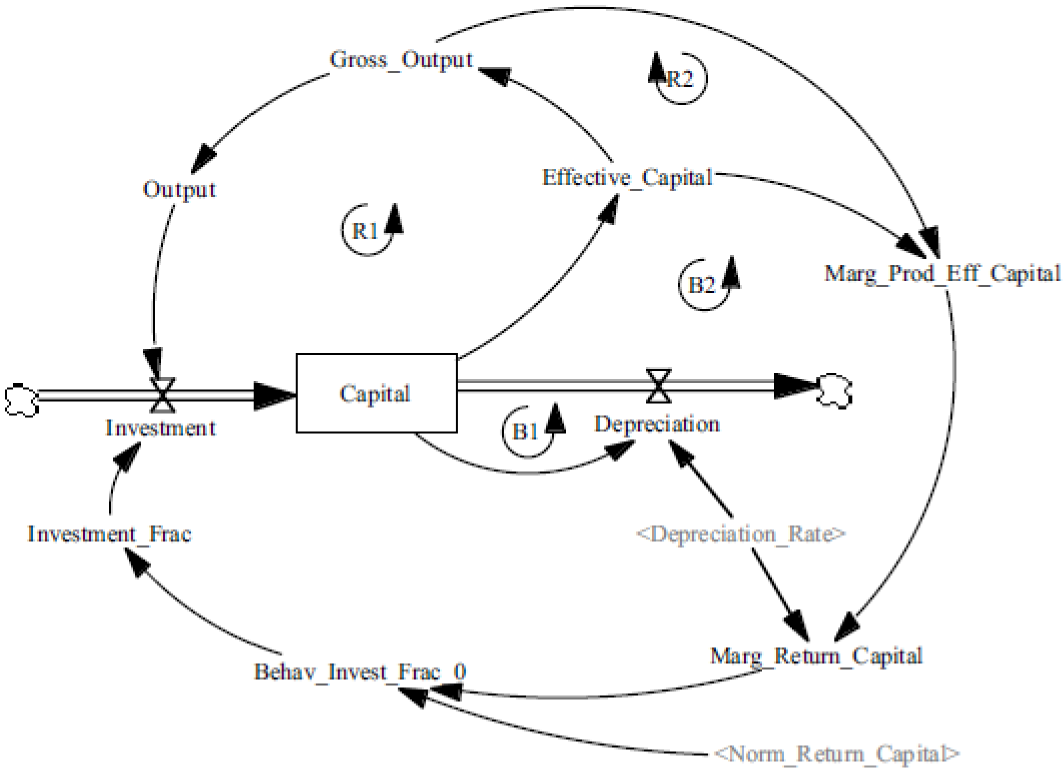

Figure 4– Structure of the behavioral investment rule for the capital investment. Source: Fiddaman [23]

In the circumstances of the model developed in this dissertation, it is important for the population to have the opportunity to suddenly change their savings behaviour, i.e. as a reaction to growing energy scarcity, when it is necessary to invest more into the capital stock in the energy sector.

4 Review of Literature

This chapter is focused on two main topics, critical for the dissertation thesis – existing models exposing interactions between economy and its natural environment during growth process and also empirical literature identifying main feedback mechanisms which influence economy during energy transition. This part is similar to the work of Nicholas Kaldor and his definition of stylized facts about the economic growth [32].

Models using framework of System dynamics are presented with their assumptions and obtained results which are also important for the dissertation, but their feedback structure itself is of paramount importance. Purpose of this chapter is not to present all existing system dynamics models of the selected problem, but only representative, important ones.

4.1 Identified Feedback Mechanisms from the Literature

4.1.1 Relation of Economic Growth and Energy consumption

It is a well-documented fact that economic growth defined as a growth of real gross domestic product is accompanied by increased energy consumption and increased consumption of natural resources in general. One example is depicted in the chart 1 below for the economy of USA, where in the period of 1949 – 2009, correlation between GDP growth and growth of energy consumption was equal to 0,934 [17]. Smil found the similar result for the economy of Japan[16]. Brown et. al. analysed the data for 220 nations over the 24 year long period (1980-2003) and found a strong correlation between per capita energy use and per capita GDP[33].

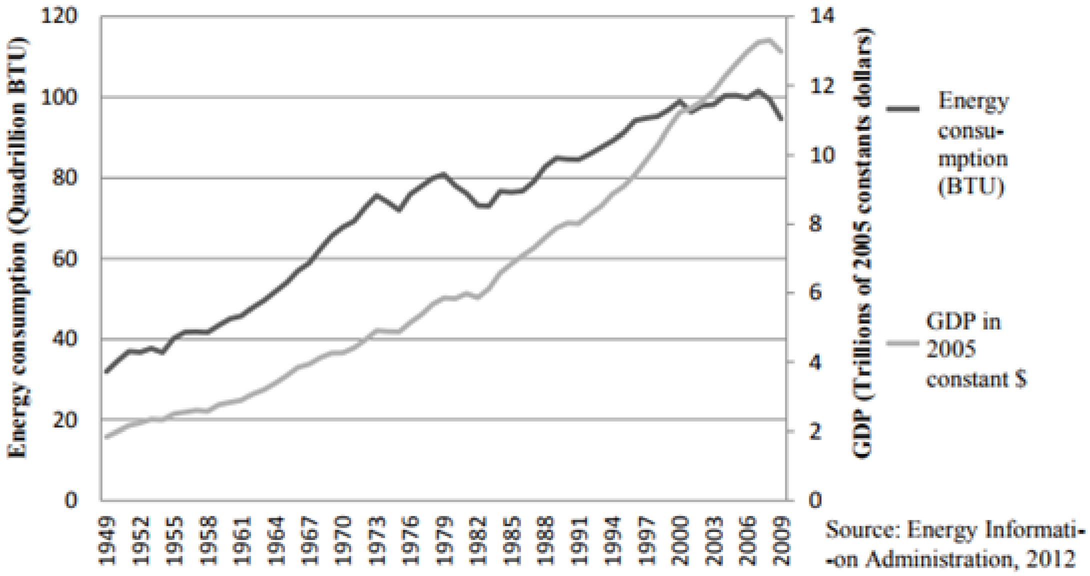

Figure 5 - GDP growth and energy consumption in the USA (1949-2009), Source: Režný and White [17]

Explanation for this phenomenon is the augmentation of human labor with capital. Most of capital goods currently used are in one way or another dependent on various inputs of energy resources, be it gasoline or electricity, to be actually usable in the production process. Human labor has been reduced mostly to the role of operating capital, or serving as sensory input, supervisory and decision making roles [34]. From that viewpoint, Fossil fuels were the enablers of industrial revolution and subsequent continuing economic growth. When energy is scarce it imposes a strong constraint on the growth of the economy but when energy is abundant its effect on economic growth is much reduced [35]. This is also a conclusion of a study of the 200 years of data for the Swedish economy[36].

Hamilton notes that four out of the five recessions experienced since 1970 in the USA can be explained by examining oil price shocks. On the account of the last, which contributed to the global recession, he clarifies: "*Whereas historical oil price shocks were primarily caused by physical disruptions of supply, the price run-up of 2007-2008 was caused by strong demand confronting stagnating world production. Although the causes were different, the consequences for the economy appear to have been very similar to those observed in earlier episodes, with significant effects on overall consumption spending and purchases of domestic automobiles in particular. In the absence of those declines, it is unlikely that we would have characterized the period 2007:Q4 to 2008:Q3 as one of economic recession for the U.S. The experience of 2007-2008 should thus be added to the list of recessions to which oil prices appear to have made a material contribution.*"[37]

On the basis of analysis of 99 countries in the period of years 1971 – 2010, Stern and Csekeleyi formed these stylized facts about energy and economic growth (not all stylized facts are listed here, see the original publication)[38]:

- A stable relationship between energy use per capita and income - Increasing energy use per capita over time as incomes grow. Decreasing energy intensity with income and over time in terms of the global mean
- The cost share of energy declines over time (only based on empirical evidence from three countries – Sweden, the UK, and the USA).
- Increasing energy quality with income.

4.1.2 Exhaustion of resource stocks

The Hubbert curve describes the extraction rate of specific non-renewable resources during a certain period of time. It is a result of interactions between a growing economic system and a finite resource base upon which it is dependent.

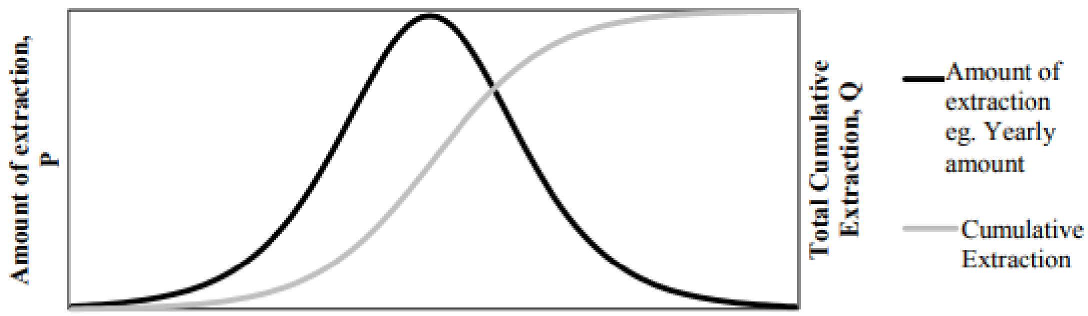

Figure 6 - Hubbert's curve, Source: Režný and White [17]

The bell-shaped extraction curve is known as the Hubbert curve for its characteristic shape. However, charting resource discovery and extraction is not deterministic, so curves in the graph above are only model examples. Real resource extraction curves are deformed in many ways, marked by many different real-world events, but usually remain similar to model cases presented above. The Hubbert curve can be used to model extraction of non-renewable resources, including predictions of peak extraction but it should be used with extreme caution. Correct computation of the precise peak date requires exact knowledge of how much resource is still in the ground, which is simply impossible. But it is possible to estimate how much of the resource is still in the ground, so the result then is a time interval in which peak extraction should occur. This is a more appropriate application of the curve and it is how Hubbert used it in 1956. He estimated the total recoverable reserves of crude oil for lower 48 U.S. states to be somewhere between 150 – 200 billion barrels. According to that range, he placed peak crude oil production in lower 48 U.S. states between the years 1965 – 1970 [39]. In 1970, the region really experienced a peak in crude oil extraction, proving the first successful application of Hubbert's model. There is no breath-taking precision in this; the peak was predicted in the year 1956 and placed it within a 5-year range, roughly ten or so years before it happened. But still, we should not forget that at that time it was a rather heretical prophecy. Adam Brandt thoroughly tested Hubbert curve in his work. He tested sets of 139 oil extraction curves from local, regional and national examples to explore the validity of Hubbert's model. Results of his work were in general favorable for Hubbert's model, but some regular deformities were also identified on the selected set of extraction curves [40]. Recently, Patzek and Croft used multi-hubbert cycle analysis to predict that peak of global coal extraction is imminent [41]. Ugo Bardi noted that even renewable resources, when extracted beyond their regenerative abilities, tend to have bell-shaped extraction curves. He presented cases of wood extraction in 19th century Ireland and recent case of Atlantic cod [42].

The important conclusion from the Hubbert model is not that non-renewable resources should have symmetrical, bell-shaped curves: the important conclusion is that extraction of resources tends to rise along with a growing economy, but later this process is reversed when the ultimate limit of scarcity is approached. It is important to note that this occurs only in the free market conditions. In other cases, resource extraction curves can have different shapes, e.g. under rare political conditions, like in Russia, where we can see second peak for oil extraction curve after the dismantling of USSR.

4.1.3 EROEI

Energy return on energy invested (EROEI) is the major characteristic of our energy sources. The higher it is, the more energy is free to fuel human economic activities. On the other hand, its decline indicates that proportionately higher share of obtained energy from a given source has to be used in energy extraction process instead of powering other economic activities. This usually means higher price of a given energy source and more extensive use of capital during the production process itself. Recent meta-analysis performed by Hall and colleagues points out to rapidly declining EROEI of major fossil fuels, with renewables having only fraction of EROEI previously bestowed by high quality fossil fuels century ago [43-44]. The ongoing transition to renewable energy sources thus might have serious long term economic consequences.

Energy return on energy invested is a means of measuring the quality of various fuels by calculating the ratio between the energy delivered by a particular fuel to society (E_{output}) and the energy used in the capture and delivery of this energy (E_{input})[44].

$$EROEI = \frac{E_{output}}{E_{input}}$$

Relationship is thus seemingly straightforward, but in reality, various studies adopts different system boundaries, which leads to different results obtained for the same fuels, caused by variability in denominator[44]. The wider the system boundaries selected, the lower EROEI tends to be, as more energy inputs are accounted for. Fortunately, there are efforts to push the common framework for calculations, so this issue should no longer cause confusion.

Table 1 sums EROEI values of currently used major energy sources. It is clearly visible that EROEI of fossil fuels declined sharply from the values of around 100:1 to a more recent 18:1. From the renewable energy sources, only the Hydropower has EROEI comparable to early fossil fuels, but its extensibility is limited, probably to not more than 80% above its current capacity [45]. Modern renewables (Solar PV and Wind power) have lower EROEI than Fossil fuels, with the exception of imported oil and gas, which seems to be comparable with Wind power.

Resource	Year	EROEI (X:1)
Oil and Gas	1930	>100
Oil and Gas	1970	30
Oil and Gas	2005	18
Coal	current mean value	46
Hydropower	current mean value	84:1

Wind	current mean value	20:1
Solar PV	current mean value	10:1

Table 1 - EROEI values for various energy resources. Source: Hall et al. and Murphy and Hall [44], [46]

It is important to note that there are few important caveats. Studies focused on modern renewables adopting wider boundaries, including even necessary back-ups in the form of batteries to counter intermittency of these energy sources, usually come with much lower EROEI values then presented in the table above. On example study by Ferroni and Hopkirk came to a conclusion that Solar PV is an energy sink based on analysis of Solar PV installations placed in Switzerland and Germany [47]. Pedro Prieto and Charles Hall also came to a much lower number for solar PV analysing the comprehensive available data for the case of Spain. According to their conclusion, EROEI of solar PV installations in Spain is only around 2,45:1[48-49].

On the other hand, it is also important to note that most of modern renewables sources are not mature technologies, so they are still in the phase of development, which means that their EROEI has the potential to increase.

Concept used to show the progression in development of a certain energy source is the experience curve. Experience curve shows reductions in price of a unit of installed capacity related to its cumulative installed capacity. Experience curve reflects learning ratio, which is achieved reduction in price of installed capacity unit per doubling of installed cumulative capacity. In other words, experience curve depicts economies of scale without taking into account other possible influences, e.g. changes in the prices of raw materials used in production of any given renewable energy source.

Figure 7 depicts experience curve for the solar PV price, which displayed a historic learning rate of 22% in the years 1976 - 2003.

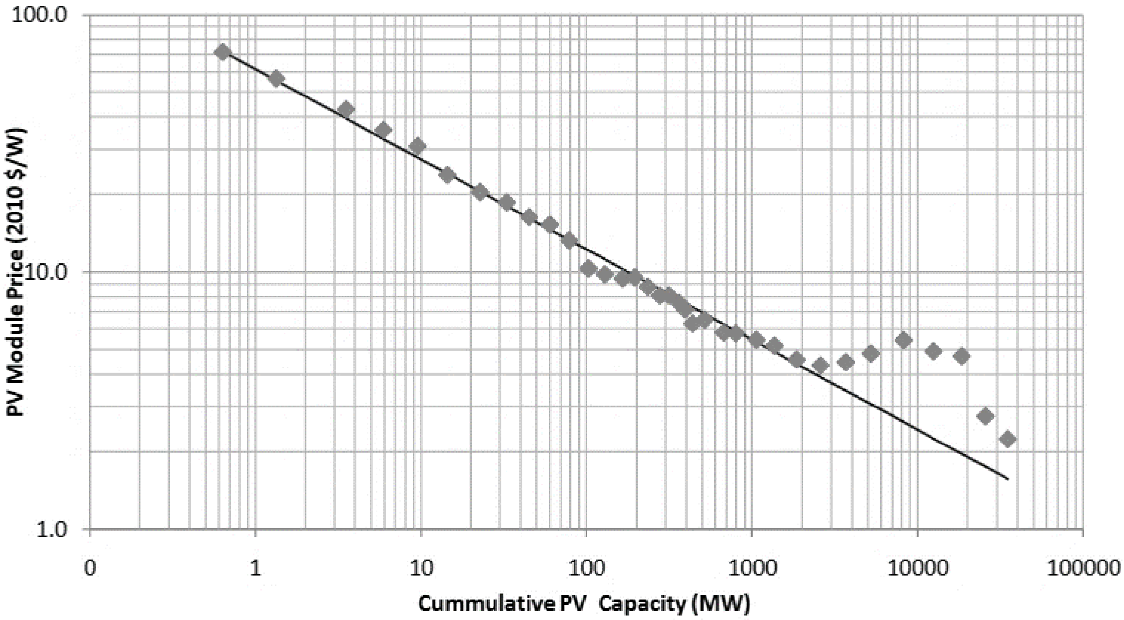

Figure 7 – Historical Experience curve for solar PV. Source: Hearps and McConell [50]

Figure 8 shows the reduction of cost per installed kw of onshore wind power capacity based on annual weighted averages from individual project data from 12 countries which shows that global weighted average installed cost per kw declined from USD 4 766/kW in 1983 to USD 1 623/kW in 2014 (prices in constant 2015 dollars).

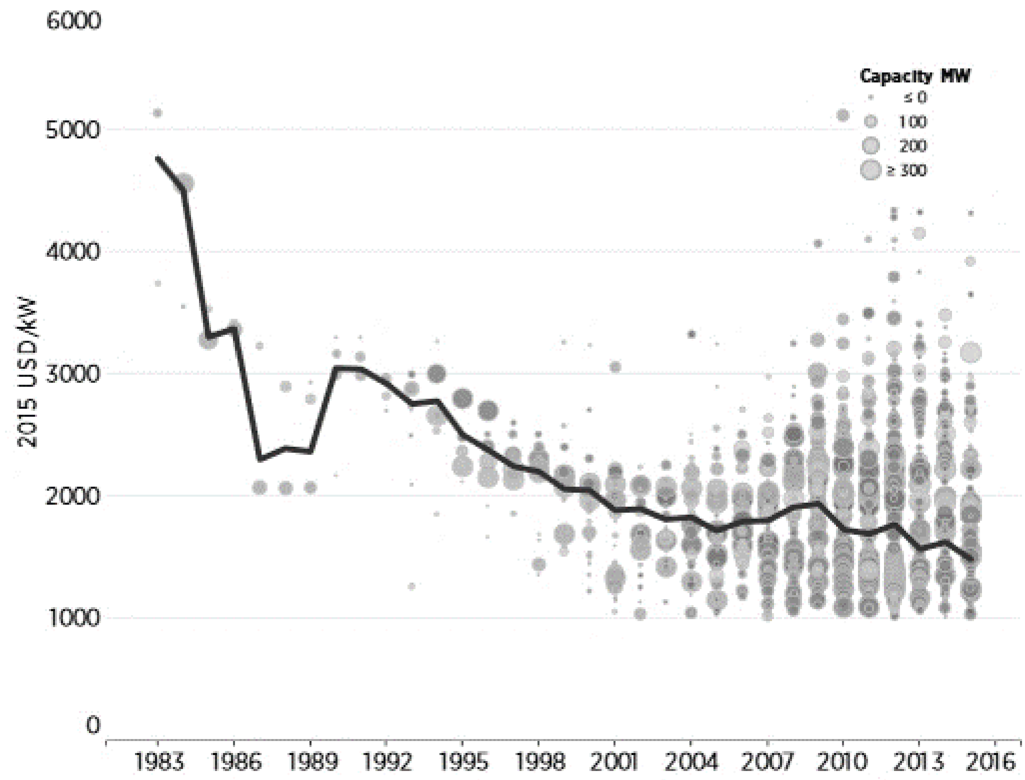

Figure 8 - Weighted Average Installation cost reductions of onshore wind, 1983 – 2016. Source: International Renewable Agency [51]

According to the above presented data, International Renewable Energy Agency reports that on average, a doubling of the cumulative installed capacity of onshore wind between 1983 and 2014 resulted in a 7% reduction in weighted average installed costs [51].

Rising load factor is also reported, which will further contribute to rising EROEI for onshore wind power (from 20% in 1983 to 27% in 2014). This is due to a higher hub heights and larger rotor diameters, which helped to rise the load factor even despite the fact that in some countries, lower quality wind sites were used for the development of new projects [51].

4.1.4 Energy end-use capital stock

Grubler emphasizes importance of energy end-use capital stock for energy transition. This capital stock is many times bigger than energy generating capital stock, so his role in energy transition is considerable, as it might be necessary to change its composition alongside the changing energy generating capital stock, which can multiply many times necessary investment resources. It means that the energy using equipment stock may create a lock-in for the energy supply. Grubler further presents figure for the total energy investment, which amounts to 0.3 – 3.5 Trillion US$ and surpass energy supply side investment of 0.7 to 1.0 Trillion US$ (annual figures in 2005 constant dollars) [52].

4.2 Analysis of the Feedback structure of current models

4.2.1 The Energy Transition and the Economy: A System Dynamics Approach

The purpose of John Sterman's dissertation was to develop an integrating framework to evaluate the effects of depletion of non-renewable energy resources and rising energy prices on economic growth, inflation and other key economic and energy indicators. For that purpose, he created the system dynamics model of the U.S. economy which provided a general disequilibrium representation of the major linkages between the energy sector and the economy. GNP, consumption, investment, wages and prices and other economic and energy variables were determined endogenously by the model [22].

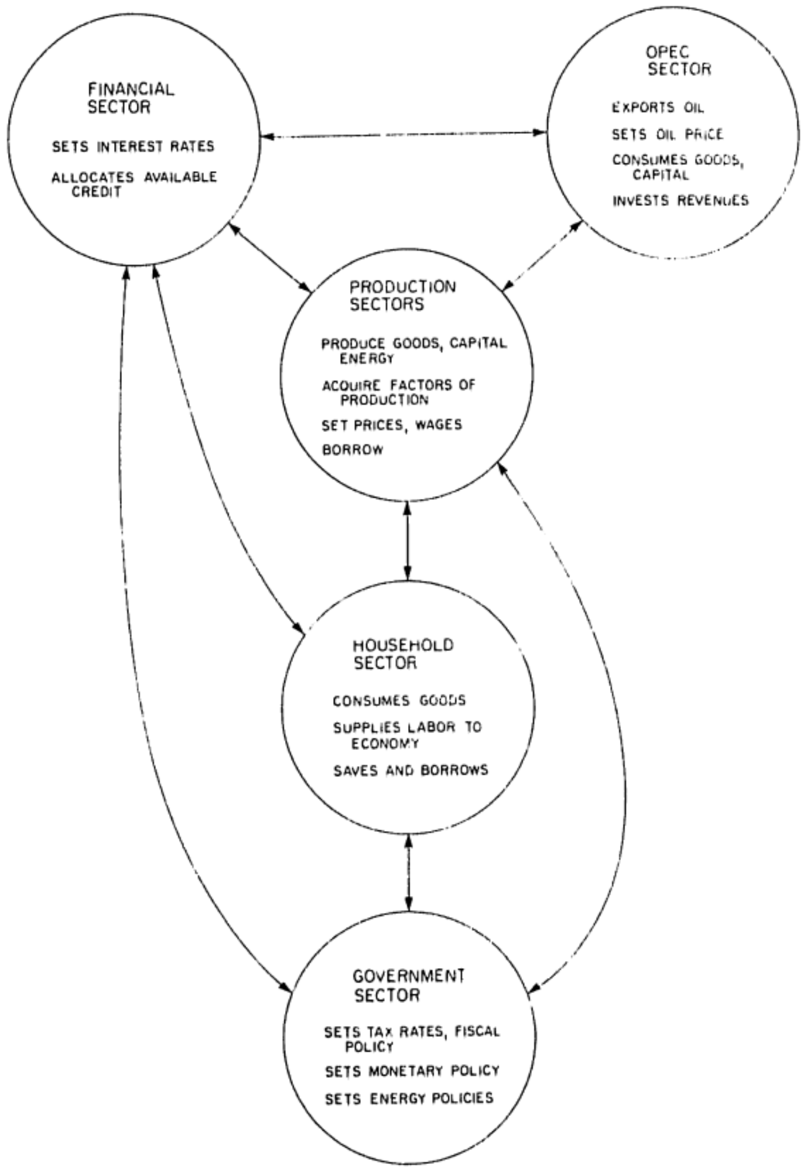

Figure 9 - General scheme of interactions between economic sectors in Sterman's model. Source: Sterman [22]

Analysing the model, Sterman concluded that depletion of energy resources will cause rise of real energy prices along with increased capital requirements in the energy sector and that these depletion effects will be amplified by feedback mechanisms in the economy, further worsening economic performance. Delays in substitution and the development of new energy sources were expected to further exacerbate the impact of depletion. The magnitude of the economic effects was found to be substantial, including reductions in economic growth and even reductions in the absolute value of GNP [22].

The model itself is indeed a case of seminal work, although it is not free of major drawbacks, as author himself pointed out. One recognized problem is the size of the model (over 250 state variables) which obstructs its deeper analysis and potentially hinders understanding of its behaviour in simulation and applied policy analysis. Another problem is connected to the assumed backstop energy technologies or unconventional energy sources. No depletion effects or resource constraints are assumed in their case and long run costs are stable, environmental constraints are also non-existent. None of these are true. Current understanding of the limits of unconventional energy sources like oil sands or renewable energy sources in general has advanced in the last decade.

4.2.2 Dynamic Integrated model of Climate and the Economy (DICE)

According to its author, William Nordhaus, DICE is [53]: "*… a simplified analytical and empirical model that represents the economics, policy, and scientific aspects of climate change*".

The DICE model views the economics of climate change from the perspective of neoclassical economic growth theory, adopting Solow-Swan growth model. That means that economic output is represented by a Cobb-Douglas production function which uses physical capital, technology factor and labour as inputs. Total global population is assumed to be available labour force and it grows exogenously over time. Technological factor, or technology level (otherwise known as total factor productivity) also increases exogenously over time. The DICE model includes the "natural capital" of the climate system, it views concentrations of greenhouse gases as negative natural capital, and emissions reductions as investments that raise the quantity of natural capital (or reduce the negative capital). In each simulated period a part of output is lost according to a climate change damage function, rest is then divided between consumption, investment (savings) and expenditures on emissions reductions. Expenditures used to limit harmful emissions reduce current consumption, but prevent economically harmful climate change in the future, enhancing consumption possibilities in later periods [53-54].

The DICE model is designed as policy optimization model. The approach is to maximize an economic objective function which represents the economic well-being associated with a certain path of consumption. The concrete objective to be maximized is the discounted sum of all future utilities from consumption. Total utility in each period is the product of the population present in the model and the utility derived from consumption of manufactured goods of a representative individual with average income in that period[53-54].

The model results indicate that even uncontrolled climate change is not highly problematic at all. In the base case scenario, which is equal to almost no policies aimed at reducing GHG`s and in which temperature rises to 4 °C above the year 1900 levels, global output is equal to 511 trillion U.S. dollars, while output in scenario limiting temperature rise to 2 °C is equal to 515 trillion U.S. dollars (both values for the year 2100), a negligible difference[53].

It is out of scope for this dissertation to evaluate model assumption, that even the huge temperature increase of 6 °C is judged to be relatively safe by the model (expressed as a modest decline in the world GDP). Model is a very important for proposed dissertation as it has a very aggregated, relatively simple economic basis. This basis is currently used for calibration of the author’s own system dynamics model. Main problems of DICE are non-existent representation of energy sector and the assumption of output as a result of optimization instead of explicit decision rules.

Model has been replicated in system dynamics form by Thomas Fidamman, fund flow structure of its economy module is depicted below.

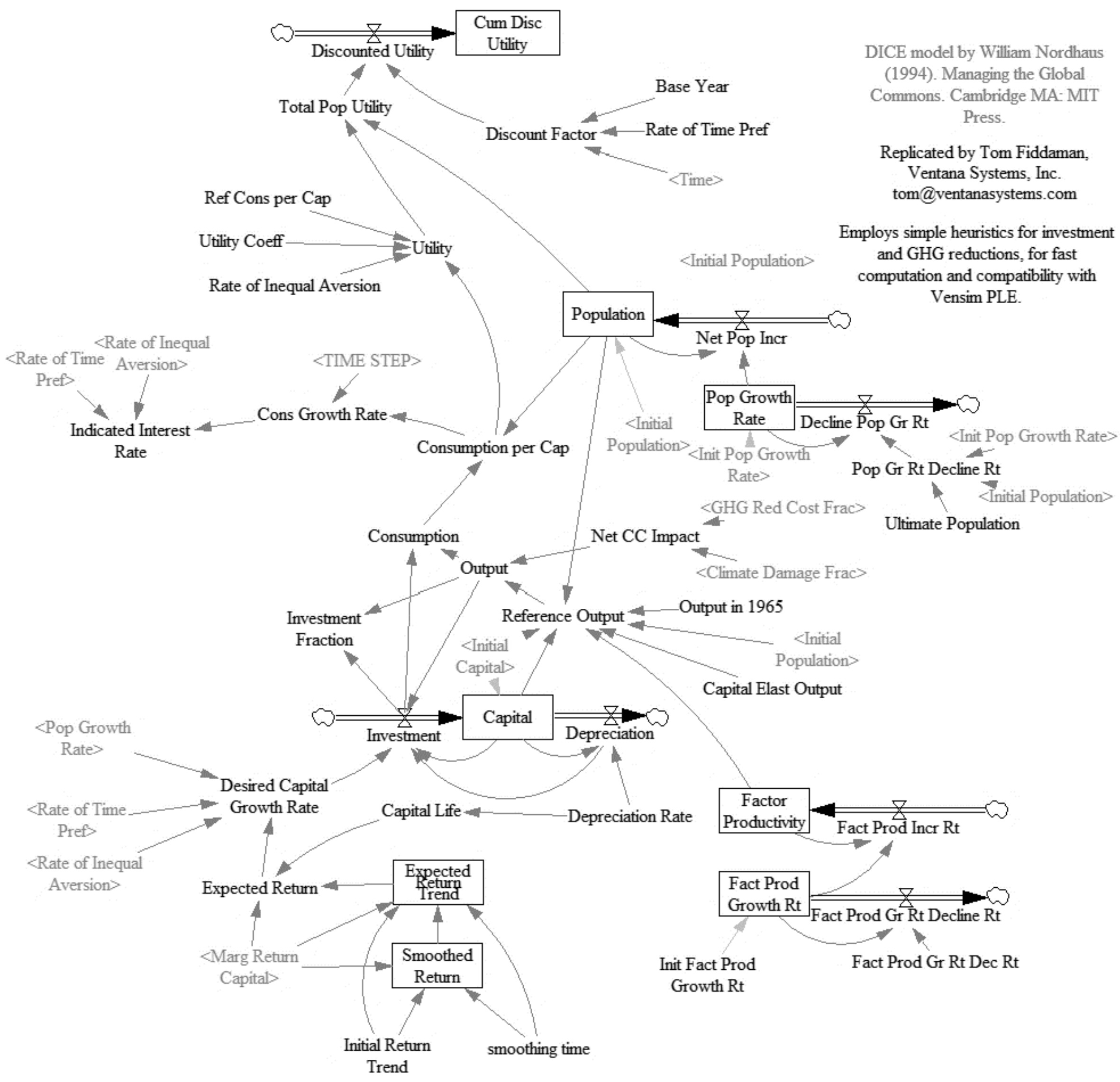

Figure 10 – Economy sector of DICE model replicated by Tom Fiddaman. Source: Fiddaman [55]

4.2.3 Feedback Rich Energy Economy model (FREE)

Fiddaman's research builds on earlier system dynamics models of energy economy interactions (e.g. previously introduced model developed by John Sterman, and DICE model), creating a model that tests the implications of a number of feedback processes that have not been previously explored in the climate change context. Among these were [23]:

- a disequilibrium energy-economy system, with adjustment and perception delays, embodiment of energy requirements in capital, and resource depletion,
- inclusion of endogenous technological change and other positive feedback effects which may lead to lock-in of the energy-economy system to particular supply

and end-use technologies, explicit behavioral rules, rather than myopic or intertemporal optimization, for decision making,

- separation of the search for optimal social policies from savings, factor allocation, and other decisions, and
- an equitable approach to the valuation of impacts across time.

The main purpose of the model was to identify the policy implications of the previously presented structures, so policy makers may become aware of blind spots in previous analyses [23].

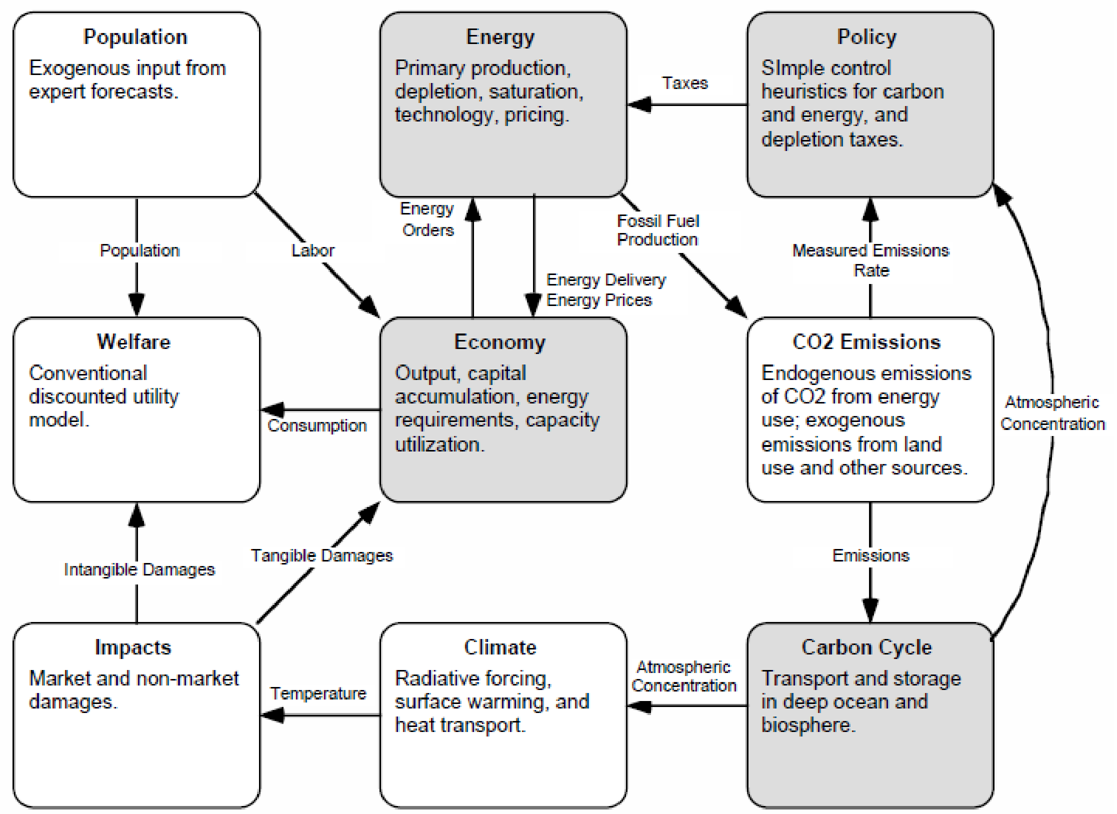

Figure 11 - FREE model sectors boundary and interactions diagram. Source: Fidamman [23]

The major feature that differentiates the production structure of the FREE model from others is that energy requirements are embodied in the capital stock itself. Once capital is constructed, it is not possible to improve its energy intensity significantly. This reflects the fact that, in the real world, energy consumption depends on the energy requirements of durable products like automobiles, machinery, and homes [23].

$$Y(t) = A\, \Omega_{(t)} K_{(t)}{}^{\gamma} (L_{(t)}{}^{d(t)} E_{(t)}{}^{(1-d(t))})^{(1-\gamma)}$$

Where Y is output, A is technology Ω represents climate effects, K capital, L labor, d labor rate, and γ stands for capital share.

The results from simple integrated models like DICE were that abatement efforts in the near term should be limited, with modest carbon taxes on the order of 10-50 $ per tonne of emitted carbon. Fiddaman's work showed that this conclusion rests on an assessment of the trade-offs between near-term abatement costs and long-term benefits from reduced climate damages. The FREE model facilitates exploration of a number of assumptions that influence the recommendation of limited abatement effort. In the Standard run of the FREE model, Scenario J, the optimal tax is 950 $/TonC (tonnes of emitted carbon), a very high tax with strong effects on the energy economy system. The difference in conclusions is dramatic. It arises from the interactions of a number of assumptions about discounting, economic growth, energy technology, the flexibility of the economy, depletion, and decision making [23].

One of the problems of the model is insufficient representation of resource depletion process, as author himself noted [23]: "At the time of model conceptualization, the depletion issue was not expected to be as dramatic as it later proved to be. The depletion issue needs to be re-examined. A central part of this effort should be the development of a resource valuation process founded on observations of real behavior rather than on principles of optimal control".

4.2.4 Resource Exergy Services model (REXS)

The REXS model simulates economic growth of the U.S. through the 20th century and extrapolates the simulation for several decades into the next century. The REXS model differs from previous energy–economy models such as DICE by eliminating the assumption of exogenously driven exponential growth. Instead, authors suggest a simple model representing the dynamics of technological change in terms of decreasing energy (exergy) intensity of GDP and endogenously increasing efficiency of conversion of raw material and fuel inputs (exergy) to primary exergy services ('useful work'). Traditional assumption of exogenous technological progress increasing at a constant rate is replaced by two learning processes based on cumulative economic output and cumulative energy (exergy) service (useful work) production experience [24].

The authors adopt an alternative view of technological progress which grows according to a different covering law, namely the law of constrained growth. Authors agree that knowledge creation is endogenous, but they also argue that knowledge, as applied to production processes, is not homogeneous or fungible, nor does it grow without limit. In particular, they conceive technical progress as the increasing time trend of value added to raw materials, which is the sum total of process-chains, aggregated over the whole economy. They then focus solely on the impact of accumulating knowledge as applied specifically to aggregated materials conversion processes in the economy. They suggest that exergy conversion efficiency is a plausible and quantifiable surrogate for knowledge accumulation [24].

The REXSF model consists of four distinct linked modules, namely (1) capital accumulation, (2) population growth, (3) resource consumption and (4) technological change dynamics, all of which are linked together by the production function called LINEX.

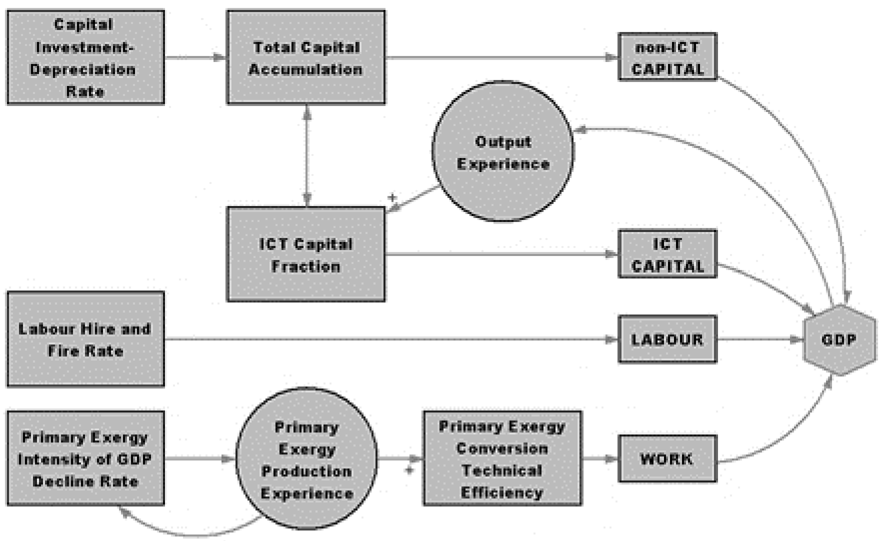

Figure 12 - REXS model overview. Source: Ayers and Warr [56]

The generic form of the production function is Y = f (K, L, U), where Y, output; K, industry capital; L, labour; U, exergy services (Exa Joules).

$$y = \mathrm{u}\exp[a\left(\left(2-\left(\frac{l-u}{k}\right)\right)\right)+ab(\frac{l}{u}-1)]$$

Where the previously unmentioned variables are parameters a, b are constant parameters. Authors developed two forecasts using this model. The first one involved varying the future rate of decline of the energy intensity of output from 1.2% (business-as-usual) to 1.5% (significant efforts to dematerialize) over the period 2000–2050. The corresponding forecasts of GDP are following: In the business-as-usual case (intensity decline rate of 1.2%), output doubles from the 1998 level. The corresponding flows of natural resource exergy are forecast to increase by 50% over 1998 levels. For the more rapid rates of energy intensity decline of 1.4 and 1.5% economic slowdown and even shrinkage are forecasted.

In the second set of forecasts, the exogenously given rate of energy intensity decline was fixed at the historically observed rate of 1.2%. This time the rate of improvement of technical efficiency was varied with cumulative primary energy production along three possible trajectories. The technical efficiency growth rate varied from a low of 0.16% and economic decline (GDP growth rate −2.97%) to a high of 1.23% and a corresponding economic growth rate of approximately 2.6%. This latter scenario corresponds to the classical forecasts of continuous exponential growth. The REXSF model forecasts suggest that to maintain this level of output growth, the efficiency with which exergy services must be supplied should increase over the first half of the century by as much threefold. The REXSF model suggests that if the growth of technical efficiency does not exceed 1%, we can expect to see economic slowdown towards 2025 and even possible shrinkage by 2050.

The first implication of the REXSF model is that exergy services derived from natural resources are an essential factor of production and driver of growth, as opposed to the only exergy flux per se. The second implication is that if objectives to dematerialize are not to slow output growth, the technical efficiency with which natural resource flows are used must increase. The authors conclude with observation that the role of labour in the US economy has changed over the past century, becoming increasingly only supervisory in nature. Through investments in automated capital and consumption of exergy services output growth has boomed and the output intensity of labour has fallen dramatically [24].

The revolutionary approach of the model to the economic growth is spoiled because it ignores of the resource stocks, violating the paradigm of good system dynamics modelling practices. The model unrealistically assumes that there are always enough readily available energy resources at hand to be used in the economic process. The second problem is that authors claim that the model is better because it does not explain economic growth on the basis of exponentially growing technological factors, yet the rate of energy intensity decline of the output is also exogenously driven, so the advancement consists only from the factor identification.

4.2.5 Energy Sector for the Integrated System Dynamics Model for Analyzing Behavior of the Social-Economic-Climatic Model

This is how Simonovic and Davies describe their model: "Five interconnected components constitute the full energy sector: demand, resources, economics, production, and emissions. The energy demand component calculates changes over time in heat energy and electric-energy demand as a result of economic activity, price-induced efficiency measures, and technological change. Energy resources models change in the amounts of three non-renewable energy resources -- coal, oil, and natural gas -- as a result of depletion and new discoveries. Energy economics, the largest of the energy sector components, models investment into the maximum production capacities for primary energy and electricity, based on market forces or the prescriptions of policy makers. Energy production represents the supply portion of the energy sector by producing primary (heat) and secondary (electrical) energy to meet energy demands; six electricity production technologies are included, and other options can be added relatively easily. Finally, energy emissions calculates the carbon emissions resulting from the combustion of fossil fuels to meet energy demands, and includes important non-energy processes such as cement production and natural gas flaring."[57]

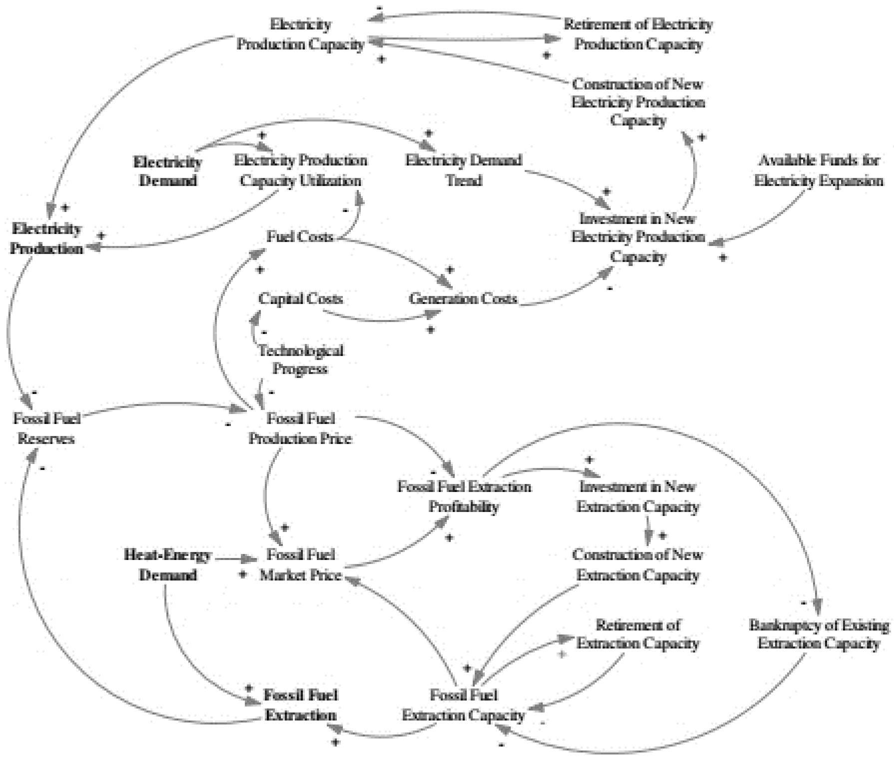

Figure 13 - Casual loop diagram for energy production/supply in the model, Source: Davies and Simonovic [57]

Resource stocks are well represented for each fossil fuel source, and extraction prices rise with declining reserves according to this equation:

$$FC_i = fc_i(0) * (\frac{R_i}{R_{i(0)}})^p$$

where $fc_i(0)$ is initial resource price, R_i and $R_i(0)$ are current and initial resource reserve, p is resource coefficient set to -0,4 [57]. Energy demand in the model is defined in a following way:

$$ED(t) = r_{ED:GDP_{1990}} * Q(t) * SMOOTH([\frac{AEP}{AEP_{1990}}]^p, 10)$$

where ED is energy demand, $r_{ED:GDP_{1990}}$ is the ratio of energy use to GDP, Q is macroeconomic product SMOOTH() is Vensim function that averages left hand argument over specified period, AEP is the average energy price and AEP_{1990} is the starting energy price [57].

Q is a result of unmodified Cobb-Douglas production function and necessary energy investment is prescribed, thus always satisfied. The problem with this approach is that there is no feedback from the energy sector to the economic sector. In other words, Q can rise indefinitely, regardless of what happens with energy sector output. This is utterly unrealistic, according to previous section, reviewing current empirical literature focused on the problem.

The model also lacks more elaborated representation of the renewable energy sources. There is only hydropower and other renewable energy sources, without further specifications of their parameters (other renewables). In this form, the model cannot meaningfully model energy transition. The authors probably intended to use this model to improve their previous model encompassing climate and water sub models and their development till the year 2100. Unfortunately, while the model in this form might meaningfully represent past system behavior as authors note, it cannot realistically provide future possible scenarios of development, moreover in such a long period. We were not able to verify that authors actually used (horizontally integrated it into bigger model, which authors call ANEMI: a new model for integrated assessment of global change) this model in their later modelling as they did not mentioned energy sector explicitly [58-59].

4.2.6 World Limits Model (WOLIM)

WOLIM is described as Economy-Energy-Environment model based on System Dynamics which integrates following aspects: the physical restrictions (with peak estimations for oil, gas, coal and uranium), the technosustainable potential of renewable energy estimated by a novel top-down methodology, the socio-economic energy demands, the development of alternative technologies and the net CO2 emissions [60].

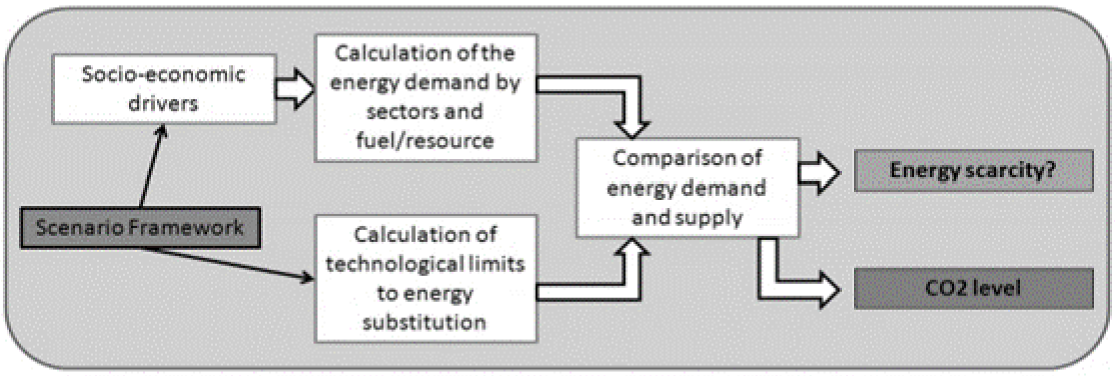

Figure 14 - Basic logic functioning of the WOLIM model. Source: Capellán-Pérez et. al. [60]

The authors themselves note, that the model is not as feedback-rich as SD models tend to be, e.g. it does not incorporate feedback from the energy sector to the economy – increased energy scarcity, lack of fuels for capital goods, does not reduce economic growth. Among exogenous variables of the model we can find GDP growth, non-renewable resources extraction curves and renewable energy sources installations [60].

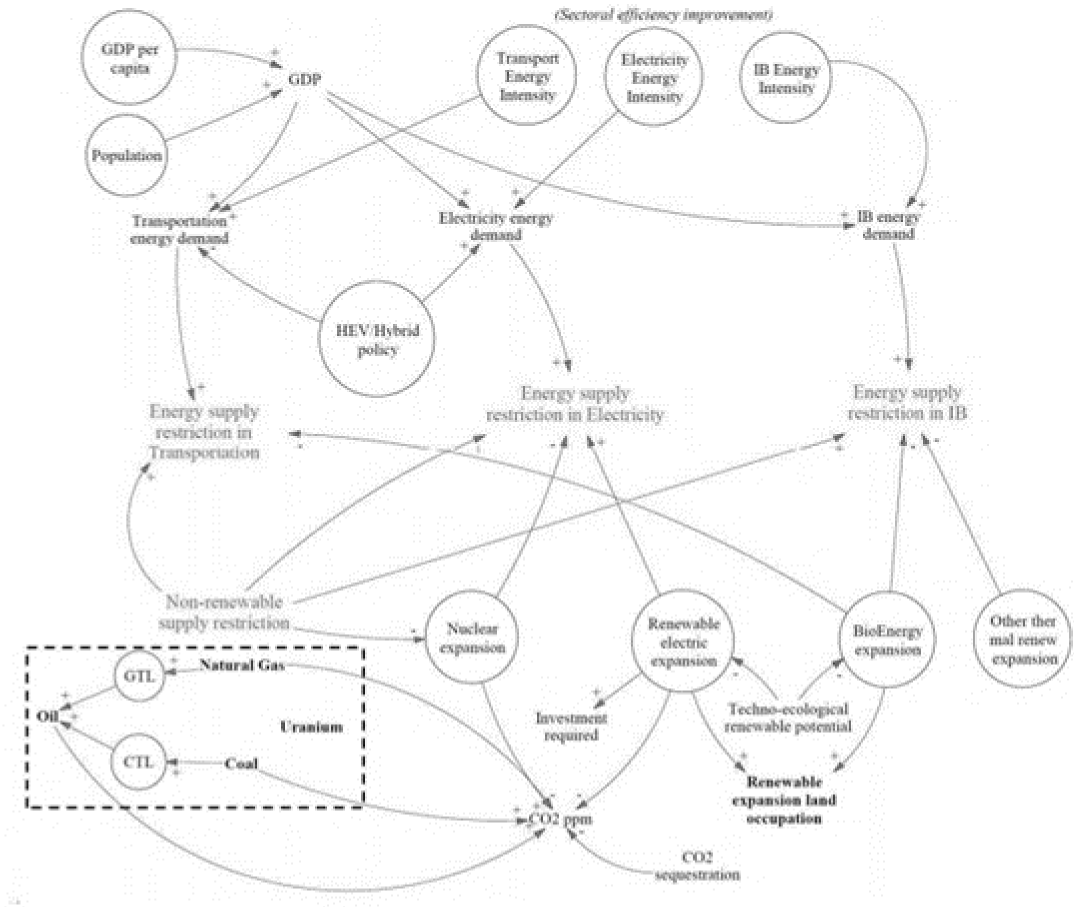

Figure 15 – Casual loop diagram of the model with its basic elements, Source: Capellán-Pérez et. al. [60]

Energy demand E_i calculation is simple:

$$E_i = GDP * I_i$$

where GDP is exogenously generated time series and I_i is energy intensity of a given sector (model considers three sectors, transport, electric, and industrial buildings sector). Energy intensities are exogenously decreasing, based on past trends and differences between various scenarios, according to the assumptions considered for them by the authors [60].

Exogenous variables are grouped into scenarios, according to different sets of assumptions. During the model simulation, feasibility of any given scenario is determined by difference between energy demand and energy supplied. If there is a gap bigger than 5% of energy demand, than scenario is considered to be unrealistic. Energy shortages appear in the model soonest in the transportation sector (in all scenarios before 2020) and before 2030 for total primary energy production [60].

4.2.7 Sustainable Energy Transition Model (SET)

Sgouridis et. al. developed this model as a tool to assist planning towards a sustainable energy transition. It is a net-energy based model that quantifies the energy transition trajectory, i.e. the rates at which society should install renewable energy in purely physical terms. Renewable energy installation rate is in their model fully determined by four factors: the net energy demand over time, the carbon emissions limits, the profile of the fossil fuel phase-out, and the renewable energy technology characteristics—especially it's EROEI. Using this model, a range of possible transition trajectories is mapped and their relative desirability is assessed. The trajectory selected as desirable can then serve as a clear mechanism for setting renewable energy policy targets [45].

SET model is unique in its consideration of EROEI for fossil fuels. The net primary power ($PF_{net}(t)$) of the resource has a declining average EROEI $R_f(t)$ through a combination of the increase in technological efficiency and the decrease in the quality of the remaining resource. Net primary power can be written in relation to EROEI as [61]:

$$PF_{net}(t) = PF(t)\frac{R_f(t) - 1}{R_f(t)}$$

Another unique feature of the model is its detailed representation of renewable energy resources. Authors assume an increasing EROEI due to a learning curve effect, determined by total cumulative installed capacity [61].

Energy economy subsystem is different than in other models, there is no Cobb-Douglas production function nor its variant used in the mode. Authors adopt different approach. The energy is provided by the renewable and non-renewable resource subsystems. This energy is not fully available to society as a portion must be reinvested in building renewable and non-renewable energy (I) generation infrastructure, with the remainder being available for societal needs—e.g., agriculture, non-energy manufacturing, and services (net social surplus—PS_{net}).

$$PS_{net}(t) = PF_{net}(t) + PR(t) - I(t)$$

Authors then form three constrains which has to be fulfilled in order for energy transition to be successful[45]:

- the impacts from energy use during SET should not exceed the long-run ecosystem carrying and assimilation capacity
- per capita net available energy should remain above a level that satisfies societal needs at any point during SET and without disruptive discontinuities in its rate of change
- the rate of investment in building renewable energy harvesting and utilization capital stock should be sufficient to create a sustainable energy supply basis without exhausting the non-renewable safely recoverable resources.

Results indicate that the easiest pathway requires installation of renewable energy plants to accelerate from its level in the year 2013 by roughly a factor of 79 (when compared to the level in the late 2030s) for an early or a late fossil-fuel phase-out respectively in order for emissions to stay within the recommended CO2 budget [45].

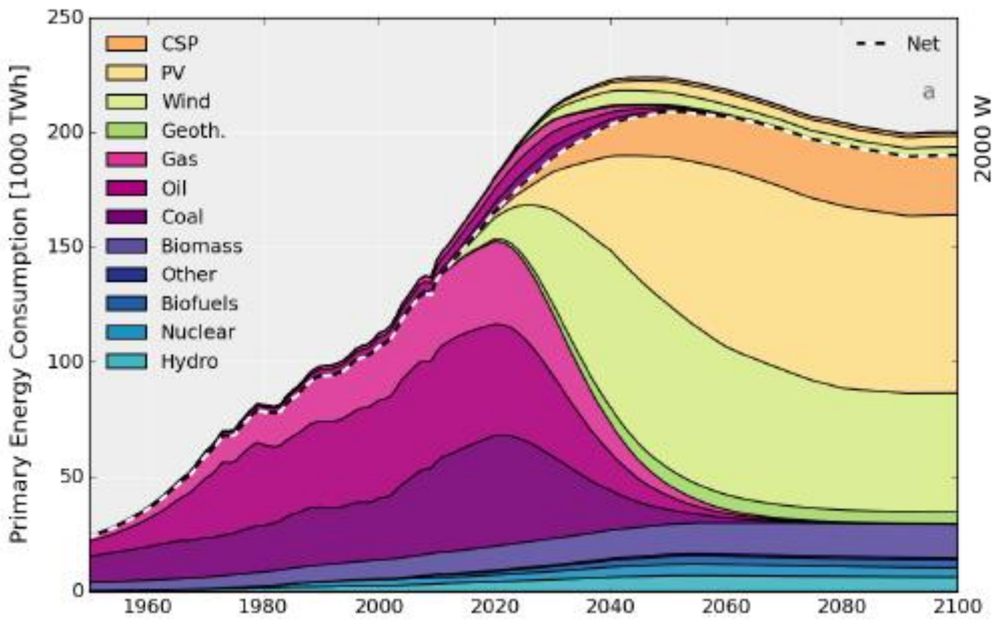

Figure 16 - primary energy supply evolution (in PWh) for providing 2000 W average net power per capita by 2100 to a population of 10.8 billion. Fossil fuel emissions comply with a 990 Gt CO2 cap peaking in 2020 and phased-out by 2075. Source: Bardi et. al. [45]

4.2.8 Comparison of the feedback structures present in the models with the main feedbacks of the energy-economy nexus identified from the empirical literature

Following table sums up feedback structures present in the reviewed models and compares them with the dominant feedbacks which drive ongoing energy transition. It is clearly visible that there is no model which covers all the critical aspects of energy transition. FREE comes closest, but it omits finer details of resource exhaustion process and is also one of older, no longer updated models.

Model	Energy and GDP relation	Resource stocks exhaustion	EROEI	Energy end use capital stock	Atmosphere
The Energy Transition and the Economy: A System Dynamics Approach	X	X			
DICE					X
FREE	X	X		X	X
REXS	X				
Energy Sector for the Integrated System Dynamics Model for Analyzing Behaviour of the Social-Economic-Climatic Model		X			X
WOLIM		X	X		X
SET		X	X		

Table 2 – Comparison of the dominant feedbacks which drive ongoing energy transition with feedback structure of existing models. Source: own work.

5 Model Description

This chapter describes the Solow-Swan Growth model translated into System Dynamics format. There are also some elements added to it, e.g. capital already needs energy to be useful in production (trait shared amongst many previously presented models). This model was implemented in the software ISEE systems Stella, version 9.1.3.

5.1 General overview of the model

The model is comprised of a few basic components, or sectors. Typical and not very different from mainstream economic models (Solow-Swan etc.) are population sector, general purpose capital goods sector and the technology sector. The production process sector is highly modified and includes effects of energy availability on capital usability in production and endogenous savings rate, which reacts on total capital amount and availability of energy resources for its operation. The energy Sector is composed of a renewable energy source and non-renewable energy source. At the start of the simulation, the non-renewable energy source is cheap and plentiful, however, with the decline of its limited reserves, its price grows. The renewable energy source starts with high price which declines with its cumulative installed capacity. Energy capital investment redistribution mechanism (which divides investment between two aforementioned energy sources) is also part of the energy sector.

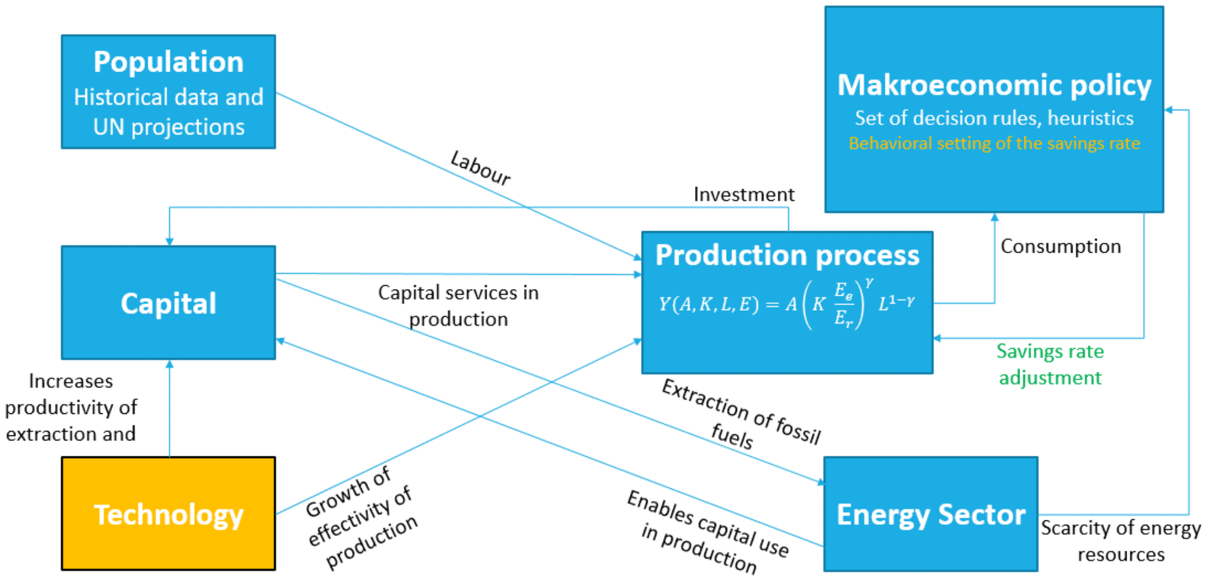

Figure 17 – Overview of the basic model blocks. Source: own work.

The following table sums up the main variables of the model plus some omitted variables, which are important. It is important to understand the limitations of the model which results from these omissions.

Endogenous variables	Exogenous variables	Omitted elements
Macroeconomic product	Population	Atmosphere
Consumption	Factor productivity	Emissions of CO_2
Savings/Investment	Technology	Natural resources of nonenergy nature
Capital		
Role of energy in creation of macroeconomic product		
Extraction and depletion of fossil fuels		
Renewable energy sources		
Demand for energy sources		
Representation of EROEI		

Table 3 - Model variables. Source: own work.

Simulation period for the model are the years 1965 – 2065. The model recreates historical behavior for 50 years and then forecasts the next 50. This forecast is the main topic of this dissertation.

5.2 Model user interface in SW Stella

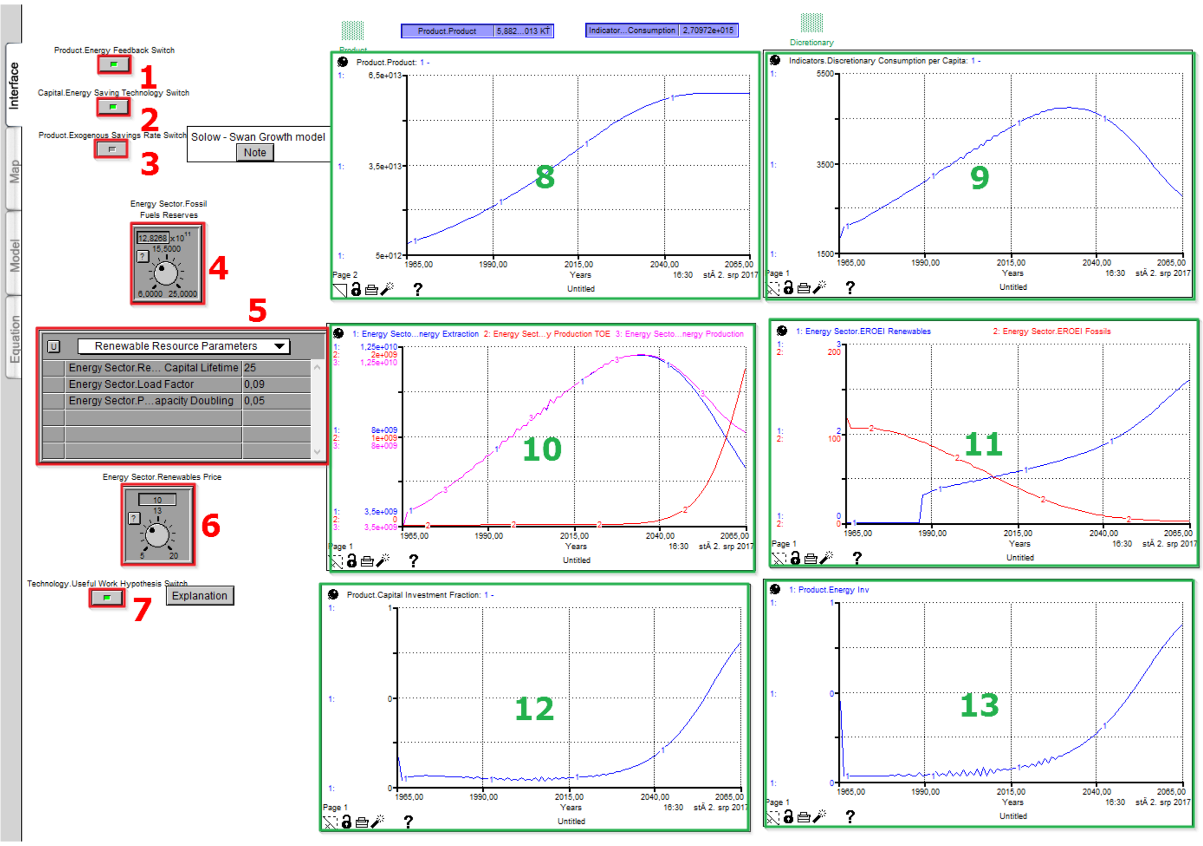

Figure 18 - Model graphic user interface in SW Stella. Source: own work.

- **Model assumptions setting**

1. Energy as a necessary production factor – maximal product potential can be verified in this switch *off* state.
2. Energy Saving Technological progress – the model is calibrated in such a way that it reproduces energy consumption data till the year 2015. By activating this assumption, the growth of the technological factor (technology level) will be reflected also in the reduction of the energy consumption by capital goods.
3. Exogenous/Endogenous savings rate – if this condition is activated, the savings rate in the model is exogenous, fixed. When it is switched off, the savings rate becomes endogenous and the system can respond to the increased need for investment in the energy sector (formally, it then becomes the Cass-Koopmans-Ramsey growth model).
4. Starting quantity of the non-renewable source, calibrated to represent the fossil fuels and the uranium ore reserves at the same time (TOE).
5. Parameters settings for the renewable energy source. The lifetime of the capital used for its generation, the load factor (the percentage of amount of time when the

energy source operates on the level of its maximum performance), and the fall in the cost of capital used for the renewable energy generation by doubling its installed capacity (so called learning curve).

6. Initial cost of the Renewable energy source (1989$).
7. Ayres - Warr's hypothesis. When explaining economic growth, the part which cannot be explained by a change in the amount of labor or capital employed in production is automatically attributed to the technological progress, but in fact it is a residual error caused by exclusion of other variables in the statistical model. The aforementioned authors show that it was a failure to factor in the useful work, which in other words, means the increased efficiency of capital in the transformation of energy resources into useful work. By activating this assumption, the exogenous growth of the technological factor is limited in the model. This corresponds to an observation that in a number of processes we are already approaching thermodynamic limits (e.g. combustion engine efficiency).

- **Graphs**

8. Product (1989$)
9. Per capita discretionary consumption (1989$)
10. Energy acquired by fossil fuels extraction, renewable energy source generation and total energy production/consumption (TOE)
11. EROEI of non-renewable and renewable energy source (dmnl)
12. Fraction of the product dedicated to investment (the graph is confusing – table with numeric values can be find in the module *Product*)
13. Fraction of total investment directed into the energy sector (the graph is confusing – table with numeric values can be find in the module *Product*)

5.3 Standard modules

Standard modules are based on the elements already present in the Solow-Swan growth model. The economic module is based and calibrated according to the DICE model made by William Nordhaus which also uses Solow-Swan growth model in its core [53].

5.3.1 Population

Population is treated exogenously in the model. Variables are calibrated such that the model closely recreates World Bank historical data in the base case [62]. Starting in the year 2015, model incorporates United Nations population predictions [63].

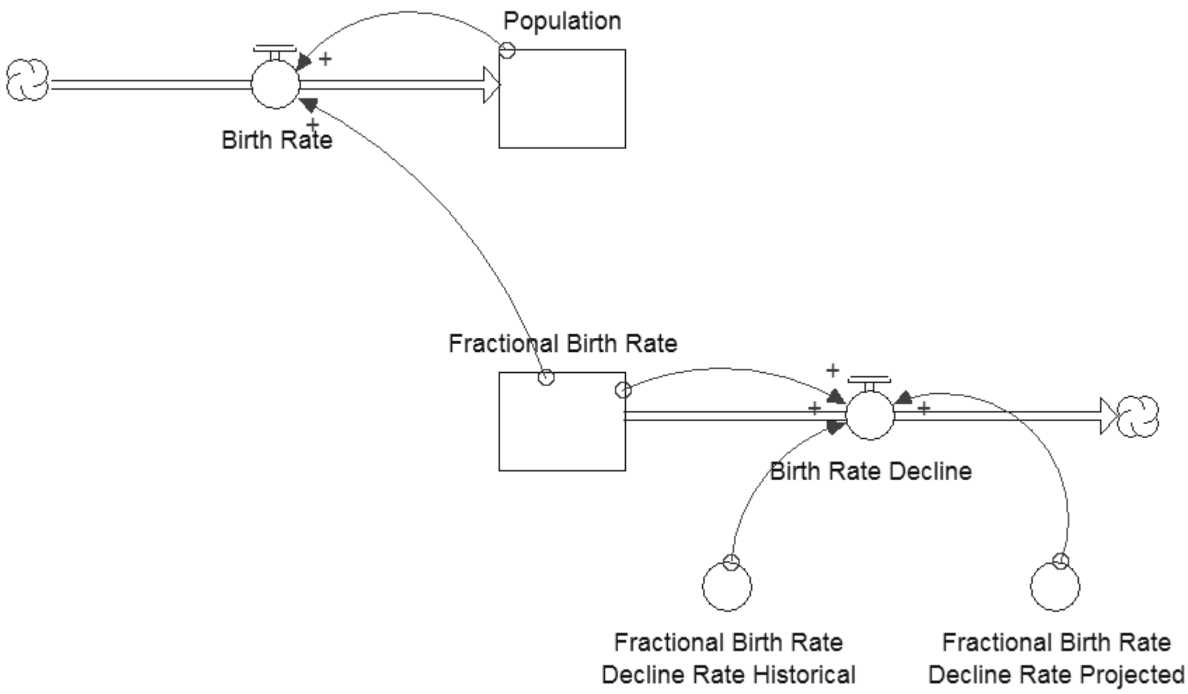

Figure 19 - Population sector structure. Source: own work.

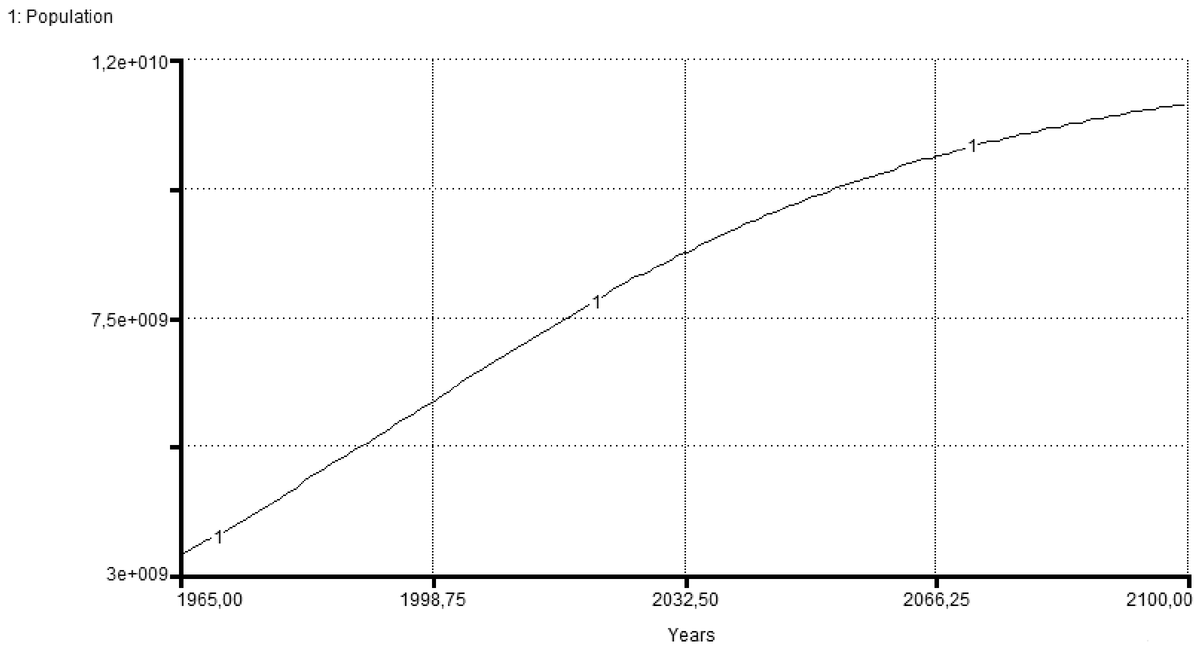

Figure 20 - Model population, number of people in any given year. Source: own work.

Population parameters

Parameter	Value	Units	Notes
Initial Population	3.326e9	people	Nordhaus, DICE 1992-1994 model[53]
Initial Fractional Birth Rate	0.0222		Calibrated to World Bank data [62]
Fractional Birth Rate Decline Historical	0.0143		Calibrated to World Bank data [62]
Fractional Birth Rate Decline Rate Projected	0.02139		Calibrated to United Nations projections [63]

Table 4 - Population module parameters. Source: own work.

5.3.2 Capital

Parameters for capital mechanics are adopted from the oldest version of DICE model, so the model can start in the year 1965.

$$K\ (t+1) = (1-\delta)\ K(t) + I\ (t)$$

Where K is stock of capital in time t, δ stands for capital depreciation and I represent investment.

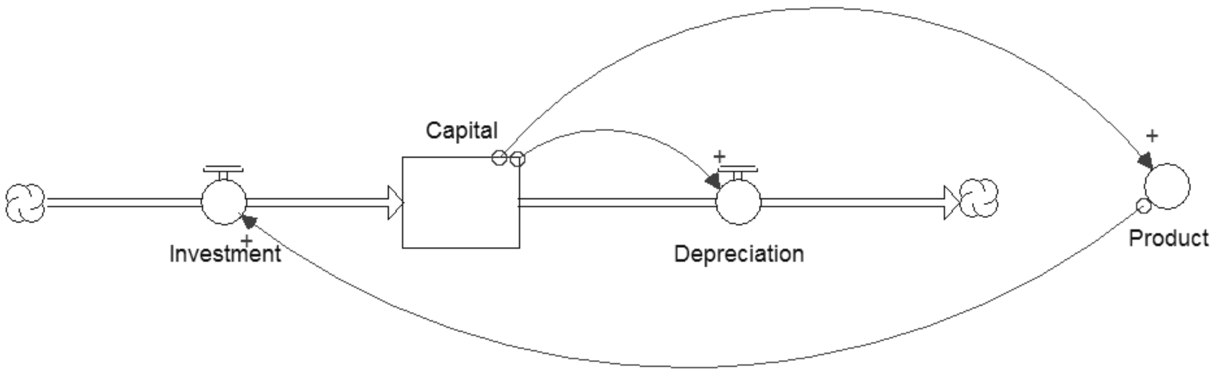

Figure 21 - Capital sector structure, Source: own work.

Capital parameters

Parameter	Value	Units	Notes
Initial Capital	16.03e12	1989 US Dollars	Nordhaus, DICE 1992-1994 model [53]
Depreciation	0.1		Nordhaus, DICE 1992-1994 model [53]
Investment	Endogenously determined		Nordhaus, DICE 1992-1994 model [53]

Table 5 - Capital module parameters, Source: own work.

5.3.3 Capital Energy Consumption

Capital stock creates energy demand. Variable Capital energy requirement constant is calibrated in a way that $Capital\ (1965)/Total\ Energy\ production(1965)$ which equals to 2.33e-04 TOE/1989 Constant $. *Energy saving technological progress* has to be activated before the model simulation and it reduces capital energy consumption by the ratio of *INIT(Technology.Technology)/Technology.Technology*. *Energy Capacity Orders* variable is based on the estimated future capital energy requirement plus total capacity depreciation of energy generating capital minus total energy production.

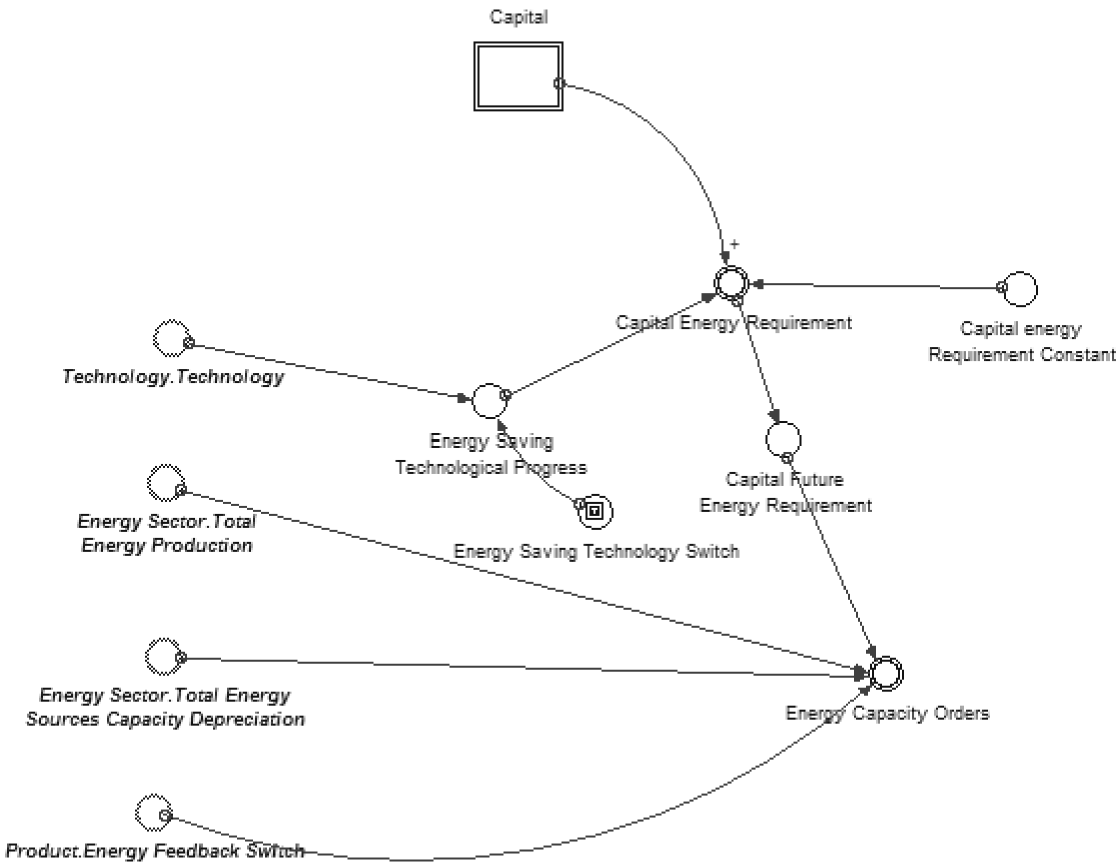

Figure 22 - Capital energy demand sector structure. Source: own work.

Capital Energy consumption parameters

Parameter	Value	Units	Notes
Capital Energy Requirement Constant	2.33e-04	TOE/1989 Constant $	Result of model calibration

Capital Energy Requirement	(Capital*Capital_energy_Requirement_Constant) *Energy_Saving_Technological_Progress	TOE	
Energy Saving Technological Progress	IF Energy_Saving_Technology_Switch=1 THEN INIT(Technology.Technology)/Technology.Technology ELSE (IF TIME<=2015 THEN INIT(Technology.Technology)/Technology.Technology ELSE INIT(Technology.Technology)/HISTORY(Technology.Technology, 2015))	dmnl	
Energy Saving Technology Switch	0/1	dmnl	User control
Capital Future Energy Requirement	Capital_Energy_Requirement*1.03	TOE	Matches historically observed rate of economic growth
Energy Capacity Orders	IF Product.Energy_Feedback_Switch = 1 THEN MAX (0, (Capital_Future_Energy_Requirement+Energy_Sector.Total_Energy_Sources_Capacity_Depreciation)-Energy_Sector.Total_Energy_Production) ELSE 0	TOE	

Table 6 - Capital Energy demand module parameters. Source: own work.

5.3.4 Technology

Exogenous variable of the model, increases production. It grows at an increasingly slower pace, see the parameters in the table 7.

It is possible to slow down a future growth considerably in the model with the use of a switch parameter described in the table below. This corresponds to a hypothesis presented in the book The Economic Growth Engine[34], in which the growth of technological progress is nothing other than growth in material productivity, namely the effectiveness of the energy conversion to useful work. This kind of progress is limited by thermodynamics and cannot continue unbounded. With the activation of the switch, technological progress stops growing at around the year 2030.

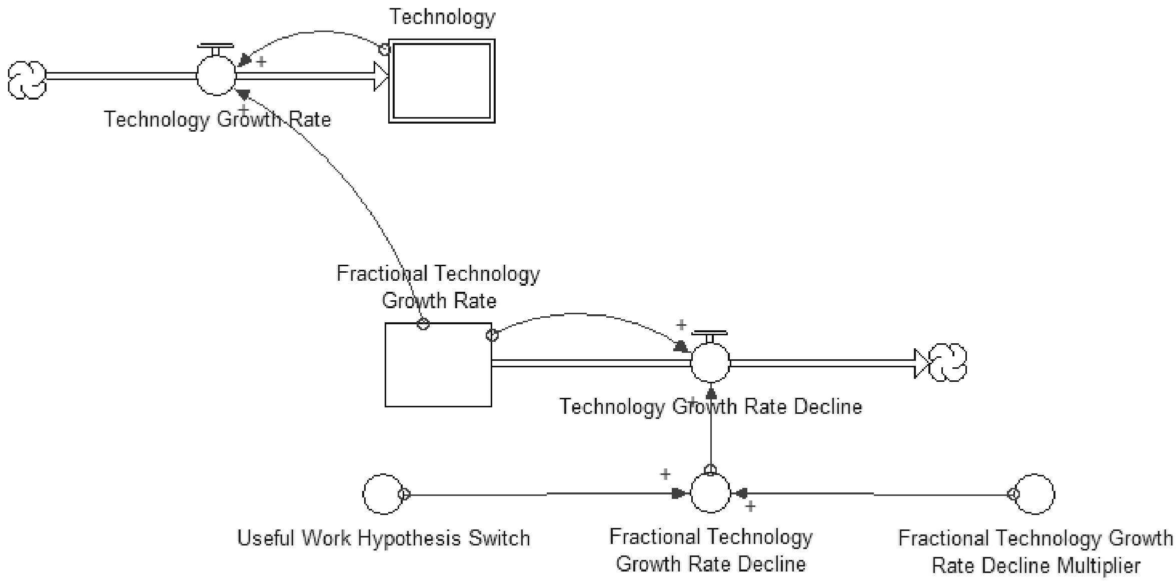

Figure 23 - Technology sector structure. Source: own work.

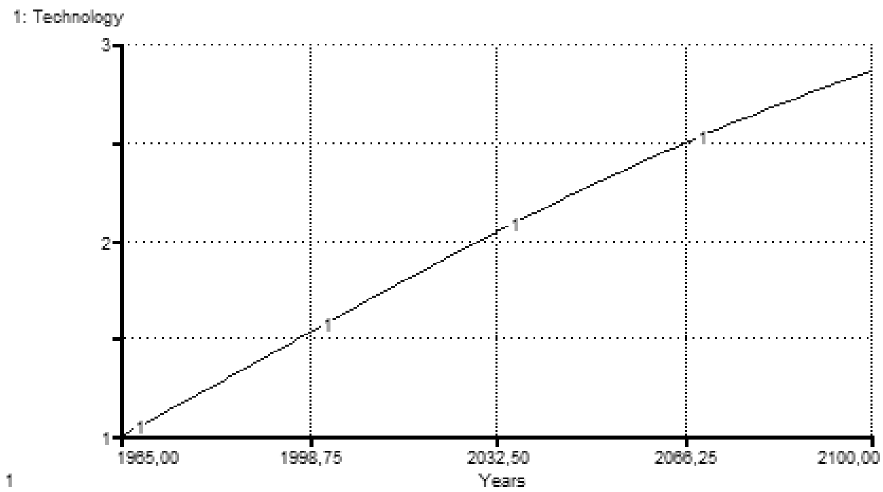

Figure 24 - Technology growth corresponding to Usefull Hypothesis Switch=0, unit: dimensionless. Source: own work

Technology parameters

Parameter	Value	Units	Notes
Initial technology level	1	dmnl	
Fractional Technology growth Rate	0.015		Nordhaus, DICE 1992-1994 model [53]

Fractional Technology growth Rate Decline	IF Usefull_Work_Hypothesis_Switch=0 THEN 0.011 ELSE IF TIME>2015 THEN 0.011*Fractional_Technology_Growth_Rate_Decline_Multiplier ELSE 0.011		Nordhaus, DICE 1992-1994 model [53]
Fractional_Technology_Growth_Rate_Decline_Multiplier	5	dmnl	Results in lower total technology level, 2.1 compared to 2.5 with Usefull Work Hypothesis Switch = 0
Usefull Work Hypothesis Switch	0/1		Corresponds to hypothesis of Ayres and Warr about slower growth of technology level

Table 7 - Technology module parameters. Source: own work.

5.3.5 Output

Cobb-Douglas, with added energy as a production factor. Its lack causes capital underutilization in production.

$$Y(A,K,L,E) = A\left(K\ \frac{E_e}{E_r}\right)^{\gamma} L^{1-\gamma}$$

Where *A* is stock of technology, *K* is stock of capital, E_e is extracted amount of energy and E_r (maximal value of $\frac{E_e}{E_r}$ is limited to 1) is energy required by given stock of capital. Labour force is for simplicity assumed to be equal to model population. When the *Energy Feedback Switch* is activated, the production function uses *Operational Capital* instead of a *Capital stock*. The amount of *Operational Capital* is given by a ratio of *Energy production/Capital Energy Requirement*.

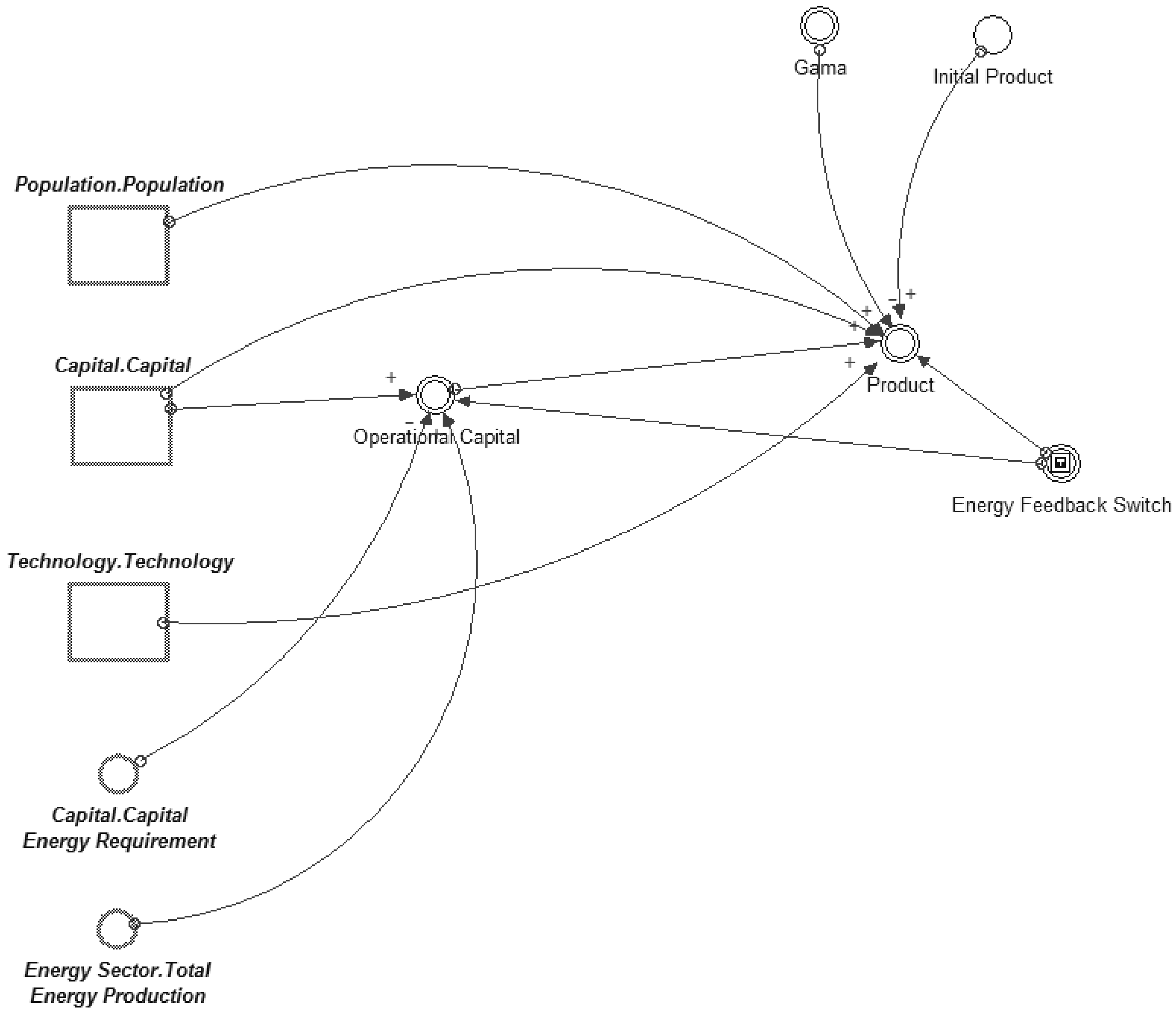

Figure 25 - Simplified model output structure. Source: own work.

Output parameters

Parameter	Value	Units	Notes
Initial product	8.519e12	1989 US Dollars	Nordhaus, DICE 1992-1994 model [53]
Gama (Capital share in output)	0.3		Nordhaus, DICE 1999 onward [53]
Energy Feedback Switch	0/1		
Operational Capital	IF Energy_Feedback_Switch=1 THEN Capital.Capital*(MIN(1,Energy_Sector.Total_Energy_Production/Capital.Capital_Energy_Requirement)) ELSE Capital.Capital		

Table 8 - Output module parameters. Source: own work.

5.3.6 Investment

There are two types of investment – into general, energy using capital and into an energy sector capital.

$$I = I_c + I_e$$

Where *Ic* corresponds to Capital Investment in the scheme below and *Ie* to *Energy Sector Available Investment*. The total investment fraction I_f is given by

$$I_f = I_{f0} + MRC/NRC$$

Where I_{f0} corresponds to *Initial Capital Investment Fraction*, MRC to *Marginal Return on Capital* and NRC to Normal Return on Capital. Calibration in the table below corresponds to a third Kaldor's fact, that the capital/output ratio is roughly constant (around two in this case, which corresponds to also to the value reached in DICE model).

Investment is then separated into energy and general-purpose capital investment, determined by the *Energy Capital Investment Fraction* variable. It is the transition function based on the ratio of the $Operational\ Capital/Capital$.

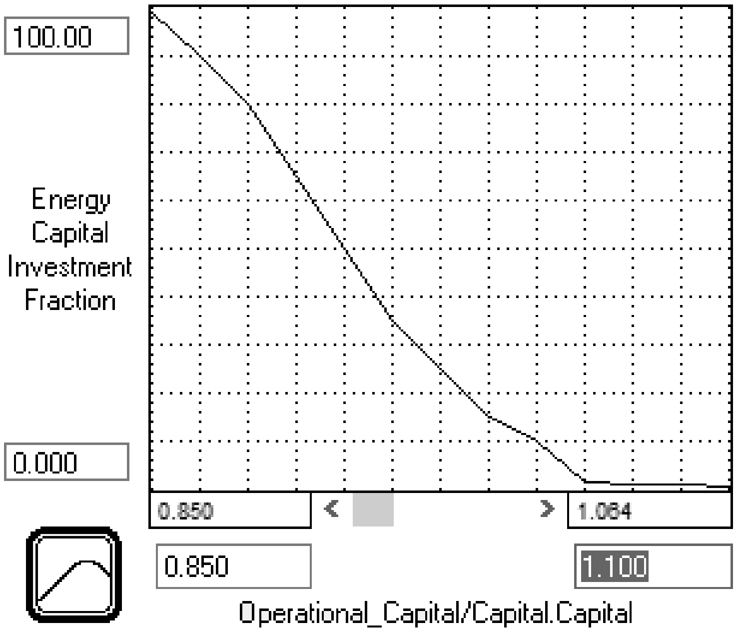

Figure 26 – Energy sector investment transition function. Source: own work.

This corresponds to the total investment dedicated to energy sector, thus it is clear that when there is less than 85% of total capital operated, all investment assets are redirected to energy sector alone.

Investment

Parameter	Value	Units	Notes
Energy Inv Needed	Energy_Sector.Total_Necessary_Energy _Investment/Product	dmnl	
Exogenous Savings Rate Switch	0/1		Switches investment to a constant value
Operational Capital	IF Energy_Feedback_Switch=1 THEN Capital.Capital*(MIN(1,Energy_Sector.T otal_Energy_Production/Capital.Capital		

	_Energy_Requirement)) ELSE Capital.Capital		
Initial Capital Investment Fraction	0.22	dmnl	Nordhaus, DICE 1992-1994 model [53]
Normal Return On Capital	0.06	dmnl	
Capital Investment Fraction	IF Exogenous_Savings_Rate_Switch = 0 THEN MIN(1,Initial_Capital_Investment_Fraction*Indicators.Marginal_Return_on_Capital/Normal_Return_On_Capital) ELSE Initial_Capital_Investment_Fraction	dmnl	
Energy Inv	Capital_Investment_Fraction*(Energy_Capital_Investment_Fraction/100)	dmnl	
Energy Inv Final	MIN(Energy_Inv,Energy_Inv_Needed)	dmnl	
Production Capital Investment	Capital_Investment_Fraction-Energy_Inv_Final	dmnl	
Capital Investment	Production_Capital_Investment*Product	1989 US Dollars	
Energy Sector Available Investment	Energy_Inv_Final*Product	1989 US Dollars	

Table 9 - Investment parameters. Source: own work.

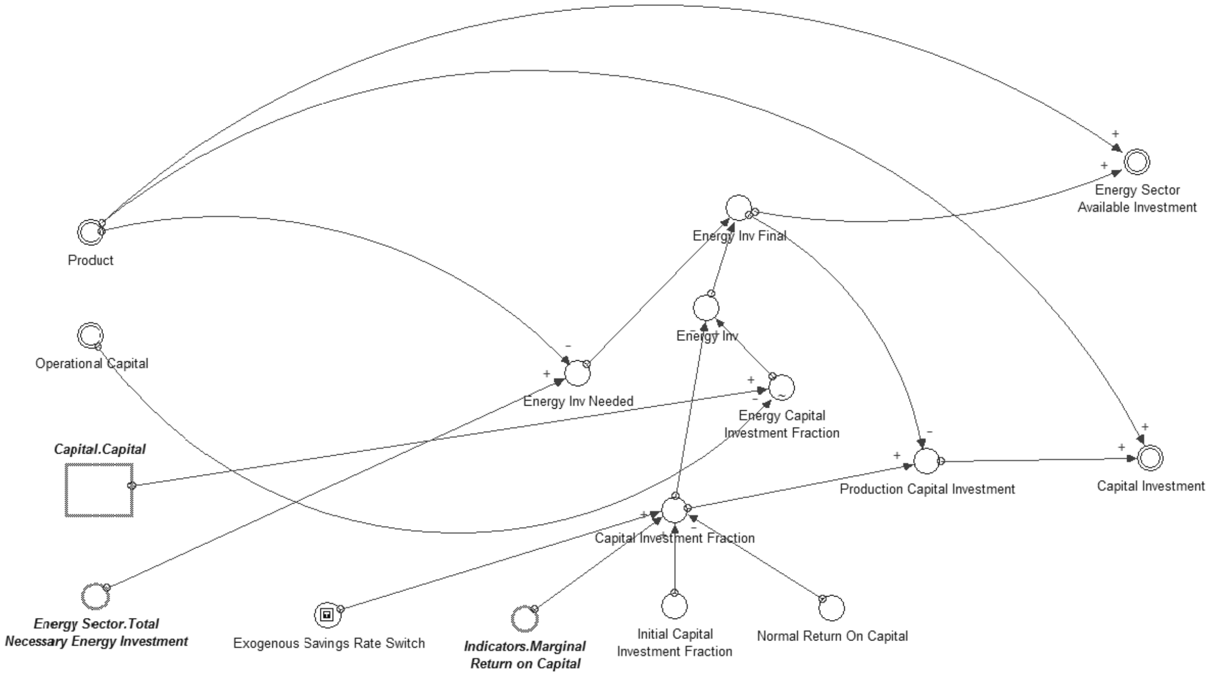

Figure 27 – Model investment structure. Source: own work.

5.4 Added modules

Parts of the model which add the role of the energy in the economic process.

5.4.1 Fossil Fuels sector

This represents the stock of fossil fuels, from which is energy extracted necessary for production to operate capital stock. *Fossil Fuels Extraction Capital* represents capacity, amount of resources which can be extracted from available stocks of fossil fuels in one year and it depreciates with a constant rate. The price of fossil fuels, *Added TOE capacity price* grows with declining amount of *Fossil Fuels Reserves*. The model uses the following version of the equation[57]:

$$FC_i = f_{ci}(0) * (\frac{R_i}{R_i(0)})^{\rho}$$

Where FC_i is a resource price, $R_i(0)$ is the initial resource stock, R_i stands for current reserves and ρ is a resource coefficient. Model uses value of -0,78 which corresponds to a six time higher price than initial (this roughly corresponds to historical oil price movements, see graph below). Douglas Reynolds in his research also concluded that the resource price during the exhaustion phase slowly grows to the levels seen during the start of the extraction [64]. There is also the second variant for the price function which is used for the EROEI sensitivity analysis in the scenario D.

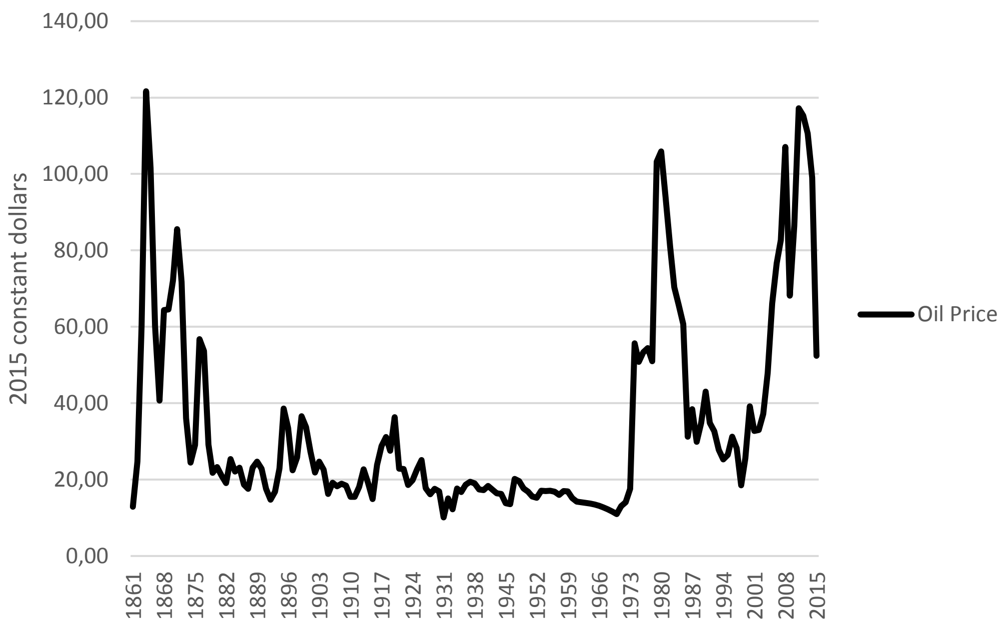

Figure 28 - Historical oil prices. Source: own work, data provided by British Petroleum [65].

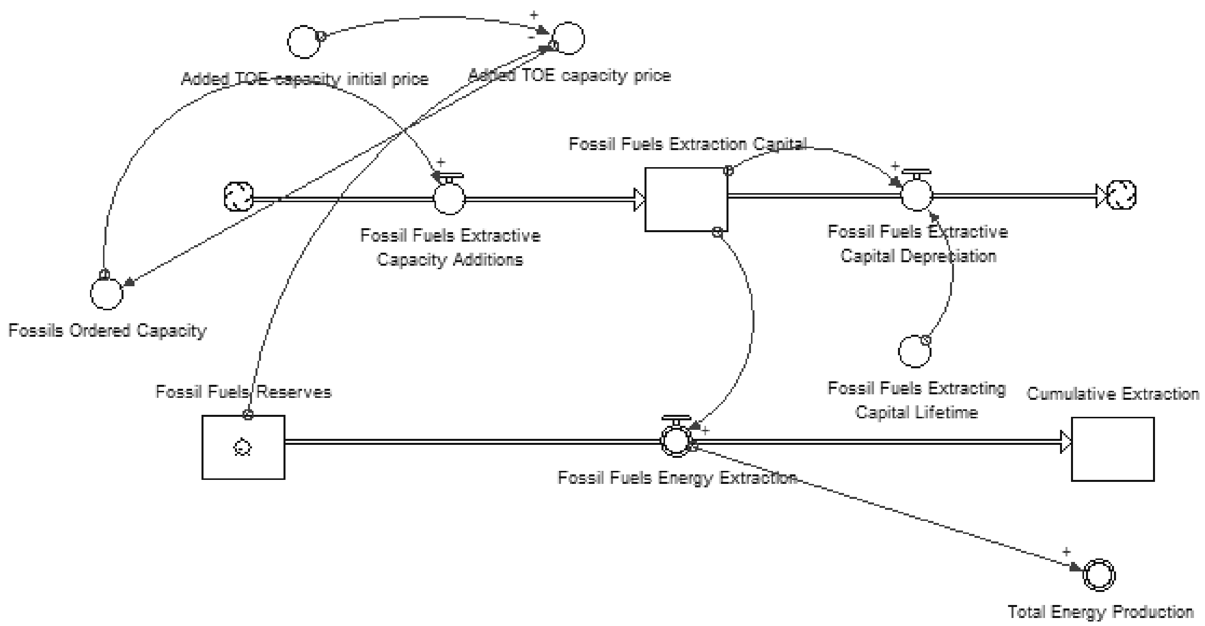

Figure 29 - Energy sector structure. Source: own work.

Fossil Fuels Sector parameters

Parameter	Value	Units	Notes
Energy Resources	8.519e9	TOE (Tonnes of Oil equivalent)	Shafiee, Topal *"An overview of fossil fuel reserve depletion time"* [66]
Capital Effectiveness in Extraction	1.89155e-016	TOE/$ 1989 US Dollar	Calibrated such that in 1965, primary energy extraction is 3,7302 Billion tonnes of Oil Equivalent (GTOE).
Added TOE capacity initial price	403.0640431	1989 US Dollar	Result of calibration

Added TOE capacity price	IF (Fossil_Fuels_Reserves>0) THEN MIN(6*Added_TOE_capacity_initial_price, (Added_TOE_capacity_initial_price *((Fossil_Fuels_Reserves/INIT(Fossil_Fuels_Reserves))^(-0.78)))) ELSE 0
	Alternatively
	IF (Fossil_Fuels_Reserves> 0) THEN (Added_TOE_capacity_initial_price *(1/((Fossil_Fuels_Reserves/INIT(Fossil_Fuels_Reserves))^5))) ELSE 0
		1989 US dollar	

Fossil Fuels Extractive Capacity Additions	Fossils Ordered Capacity	TOE
Fossil Fuels Extractive Capital Depreciation	1/Fossil_Fuels_Extracting_Capital_Lifetime*Fossil_Fuels_Extraction_Capital	TOE
Fossil Fuels Extracting Capital Lifetime	20	Years
Fossil Fuels Energy Extraction	Fossil_Fuels_Extraction_Capital	TOE/Year

Table 10 - Energy sector parameters. Source: own work.

5.4.2 Renewable energies sector

Production of energy from renewable energy sources depends only on their actual amount, which depreciates and needs to be renewed by new investment. *Renewable Energy Installed Capacity* is enumerated in Watts, but for the compatibility with the model it needs to be converted to tonnes of oil equivalent. *Renewables Cumulative Capacity* is a critical variable which drives down the price of renewable energy source and you will find description of this mechanic in the next section.

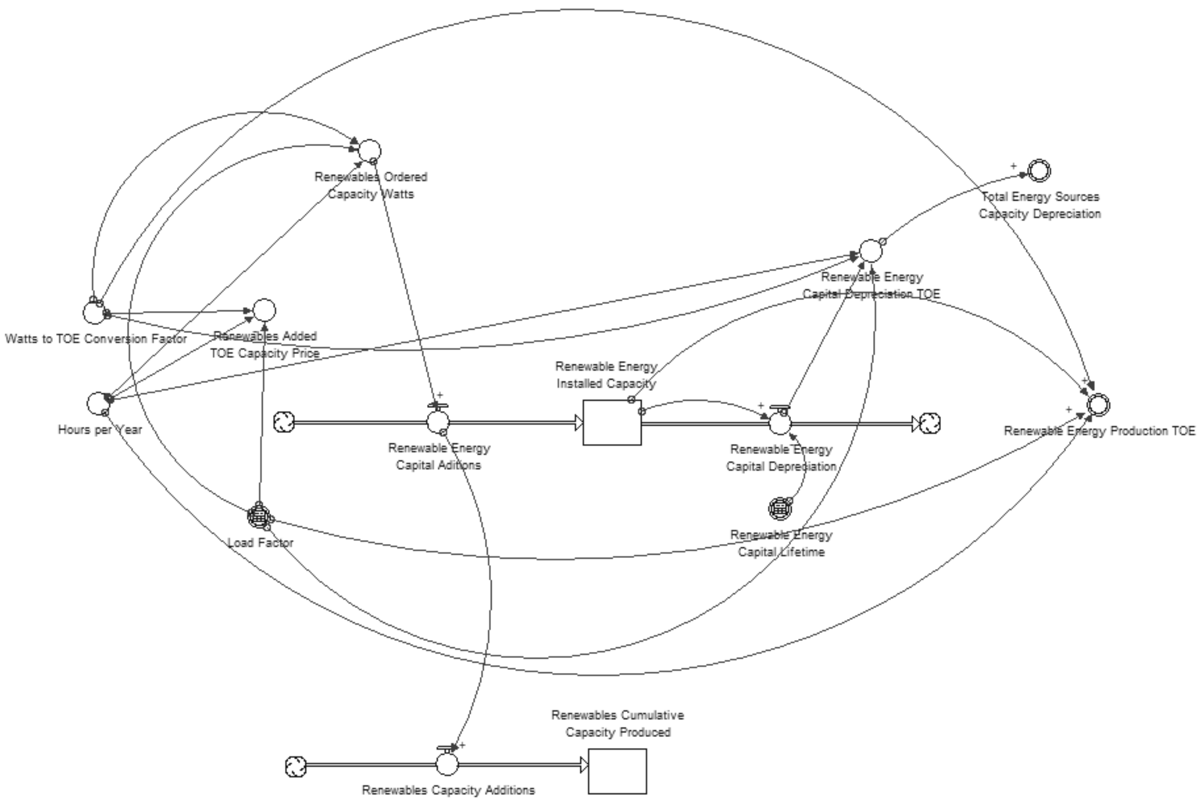

Figure 30 – Renewable energies sector structure. Source: own work.

Renewable Energies Sector

Parameter	Value	Units	Notes
Renewable Energy Installed Capacity [Stock]	0 [Initial]	Watt	
Watts to TOE conversion factor	11630000	dmnl	
Hours per Year	8760	hours	
Renewables Added TOE Capacity Price	Renewables_Price*((Watts_to_TOE_Conversion_Factor/(Load_Factor*Hours_per_Year)))	1989 US Dollar/TOE	
Renewables Ordered Capacity Watts	(Renewables_Ordered_Capacity_TOE*Watts_to_TOE_Conversion_Factor)/(Load_Factor*Hours_per_Year)	Watt	

Load Factor	0.20	Percent of time for which is given renewable energy source operated on its maximum capacity.
Renewable Energy Capital Lifetime	20	Years
Renewable Energy Capital Depreciation	(1/Renewable_Energy_Capital_Lifetime) *Renewable_Energy_Installed_Capacity	Watts
Renewable Energy Capital Depreciation TOE	(Renewable_Energy_Capital_Depreciation*Load_Factor*Hours_per_Year)/Watts_to_TOE_Conversion_Factor	TOE
Renewable Energy Production TOE	(Renewable_Energy_Installed_Capacity*Load_Factor*Hours_per_Year)/Watts_to_TOE_Conversion_Factor	TOE

Table 11 – Renewable energies sector parameters. Source: own work.

5.4.3 Renewable energy sources learning curve

This part of the model corresponds to the mechanics described on the pages 16-18. The price of the renewable energy source declines by certain percentage (*Price Reduction Per Total Capacity Doubling*) for every doubling of its produced capacity (*Renewables Cumulative Capacity Produced*).

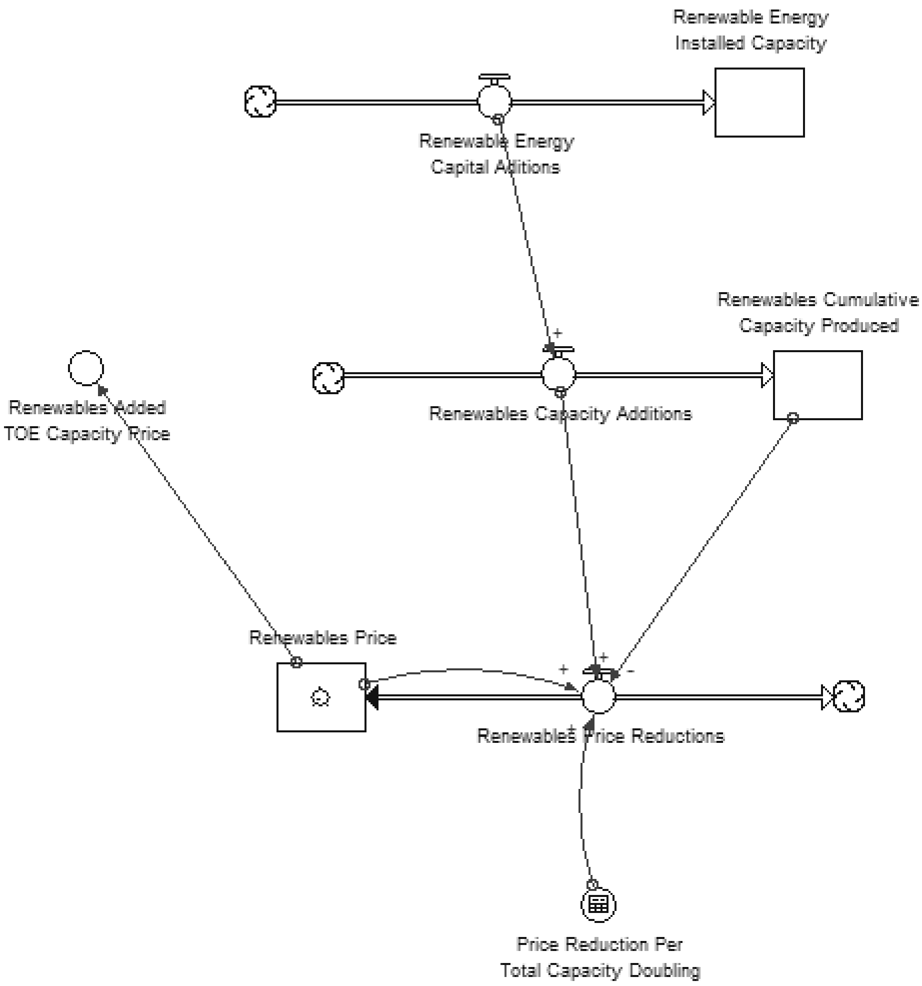

Figure 31 – Renewable energy sources learning process structure. Source: own work.

Renewable Energies Learning Curve

Parameter	Value	Units	Notes
Renewables Capacity Additions	Renewable_Energy_Capital_Aditions	Watts	
Price Reduction Per Total Capacity Doubling	0.20	dmnl	
Renewables Price Reductions	IF TIME>Renewable_Energy_Investment_Start_Year THEN Renewables_Price*(Price_Reduction_Per	1989 US Dollar	

	_Total_Capacity_Doubling*(Renewables _Capacity_Additions/Renewables_Cumul ative_Capacity_Produced)) ELSE 0	
Renewables Price [Stock]	13	1989 US Dollar/Wa tt

Table 12 - Renewable energies learning process parameters. Source: own work.

5.4.4 EROEI

This part of the model corresponds to the mechanics described on the pages 14-17, where you can find the details. EROEI is computed using the assumption that the investment into renewable energy and fossil fuels has the same energy intensity – average energy intensity computed as

$$\frac{Y}{E}$$

Where *Y* is total product and *E* energy consumption. EROEI itself is then a computation

$$EROEI = \frac{E_{output}}{E_{input}}.$$

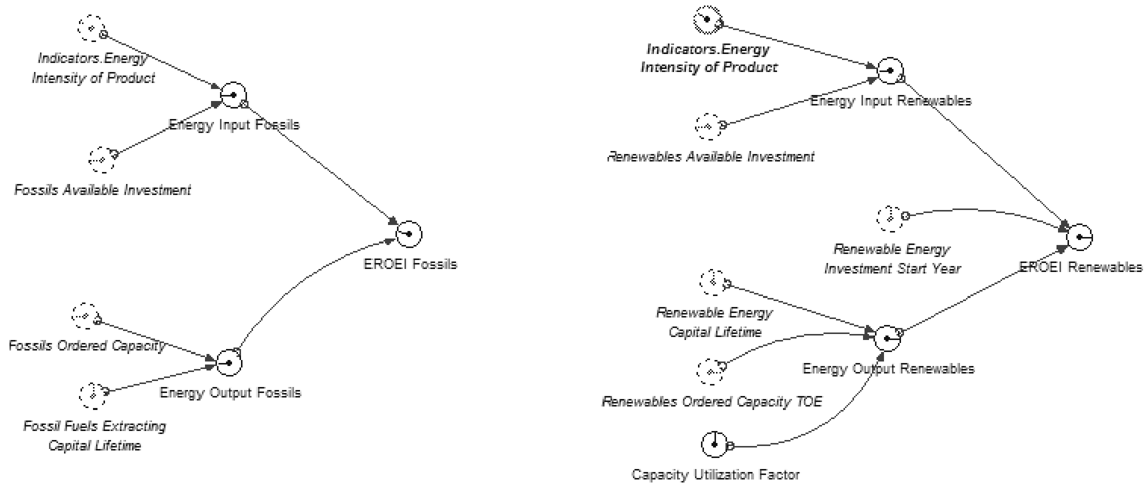

Figure 32 – Sector of the model dedicated EROEI computation. Source: own work.

EROEI

Parameter	Value	Units	Notes
Energy Input Fossils	Fossils_Available_Investment*Indicators.Energy_Intensity_of_Product	TOE	
Energy Output Fossils	Fossil_Fuels_Extracting_Capital_Lifetime*Fossils_Ordered_Capacity	TOE	
EROEI Fossils	IF Energy_Input_Fossils>0 THEN Energy_Output_Fossils/Energy_Input_Fossils ELSE 0	dmnl	
Energy Input Renewables	Indicators.Energy_Intensity_of_Product*Renewables_Available_Investment	TOE	
Energy Output Renewables	Renewables_Ordered_Capacity_TOE*Renewable_Energy_Capital_Lifetime*Capacity_Utilization_Factor	TOE	
EROEI Renewables	IF TIME>=Renewable_Energy_Investment_Start_Year AND Energy_Input_Renewables>0 THEN Energy_Output_Renewables/Energy_Input_Renewables ELSE 0	dmnl	

Table 13 – EROEI parameters. Source: own work.

5.4.5 Energy Demand and Supply

Energy supply and demand works as follows: Capital creates energy demand (*Capital.Energy Capacity Orders*), Capacity is then allocated inversely proportional to energy source costs (*Added TOE capacity price, Renewables Added TOE Capacity Price*), recalculated to available investment, which is based on actual product and investment share (*Fossils Available Investment, Renewables Available Investment*) and then transformed into capacities (*Fossils Ordered Capacity, Renewables Ordered Capacity*).

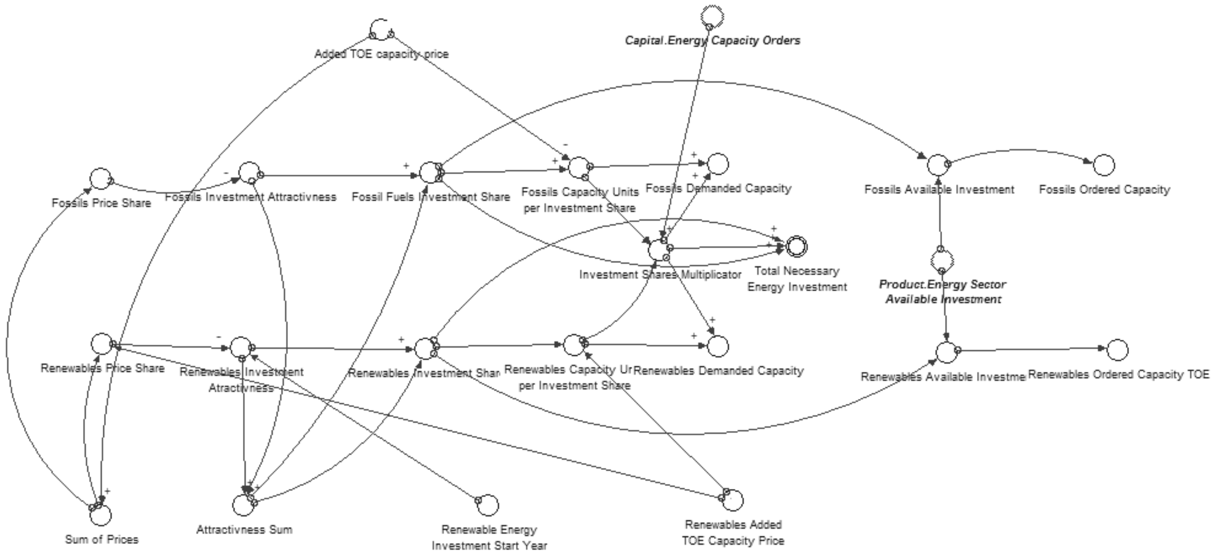

Figure 33 – Energy demand and supply structure. Source: own work.

Energy Supply and Demand

Parameter	Value	Units	Notes
Fossils Price Share	Added_TOE_capacity_price/Sum_of_Prices	dmnl	
Renewables Price Share	Renewables_Added_TOE_Capacity_Price /Sum_of_Prices	dmnl	
Sum of Prices	Added_TOE_capacity_price+Renewables _Added_TOE_Capacity_Price	Constant 1989 dollar	
Fossils Investment Atractivness	1/Fossils_Price_Share	dmnl	
Renewables Investment Atractivness	IF TIME<Renewable_Energy_Investment_Start_Year THEN 0 ELSE 1/Renewables_Price_Share	dmnl	
Atractivness Sum	Renewables_Investment_Atractivness+Fossils_Investment_Attractivness	dmnl	
Renewables Investment Share	Renewable_Investment_Attractivness/Attractivness_Sum	dmnl	

Fossil Fuels Investment Share	Fossils_Investment_Attractivness/Attractivness_Sum	dmnl
Fossils Capacity Units per Investment Share	Fossil_Fuels_Investment_Share/Added_TOE_capacity_price	TOE/share
Renewables Capacity Units per Investment Share	IF Renewables_Investment_Share>0 THEN Renewables_Investment_Share/Renewables_Added_TOE_Capacity_Price ELSE 0	TOE/Share
Investment Shares Multiplicator	Capital.Energy_Capacity_Orders/(Fossils_Capacity_Units_per_Investment_Share +Renewables_Capacity_Units_per_Investment_Share)	dmnl
Fossils Demanded Capacity	Fossils_Capacity_Units_per_Investment_Share*Investment_Shares_Multiplicator	TOE
Renewables Demanded Capacity	Renewables_Capacity_Units_per_Investment_Share*Investment_Shares_Multiplicator	TOE
Total Necessary Energy Investment	(Fossil_Fuels_Investment_Share+Renewables_Investment_Share)*Investment_Shares_Multiplicator	TOE
Fossils Available Investment	Product.Energy_Sector_Available_Investment*Fossil_Fuels_Investment_Share	Constant 1989 dollar
Renewables Available Investment	Product.Energy_Sector_Available_Investment*Renewables_Investment_Share	Constant 1989 dollar
Fossils Ordered Capacity	Fossils_Available_Investment/Added_TOE_capacity_price	TOE
Renewables Ordered Capacity	Renewables_Available_Investment/Renewables_Added_TOE_Capacity_Price	TOE

Table 14 - Energy demand and supply parameters. Source: own work.

6 Model dynamics

First, different simulation scenarios are defined and their assumptions are revealed. Analysis of the results follows.

Variable	Scenario A	Scenario B	Scenario C	Scenario D
Energy-Product Feedback		X	X	X
Endogenous Savings Rate			X	X
Technology useful work Hypothesis				X

Table 15 – Model scenarios with list of activated assumptions. Source: own work.

6.1 Scenario A, "Business as usual"

This is basically a case of an unrestricted economic growth (without the dependence of capital on energy consumption), unconstrained Solow-Swan growth model. That is the reason why for this scenario, only the GDP growth and discretionary spending per capita are reported. Investment rate is constant at 22% and there is no energy consumption, resource stocks exhaustion and other constraining factors.

6.1.1 Economic Growth

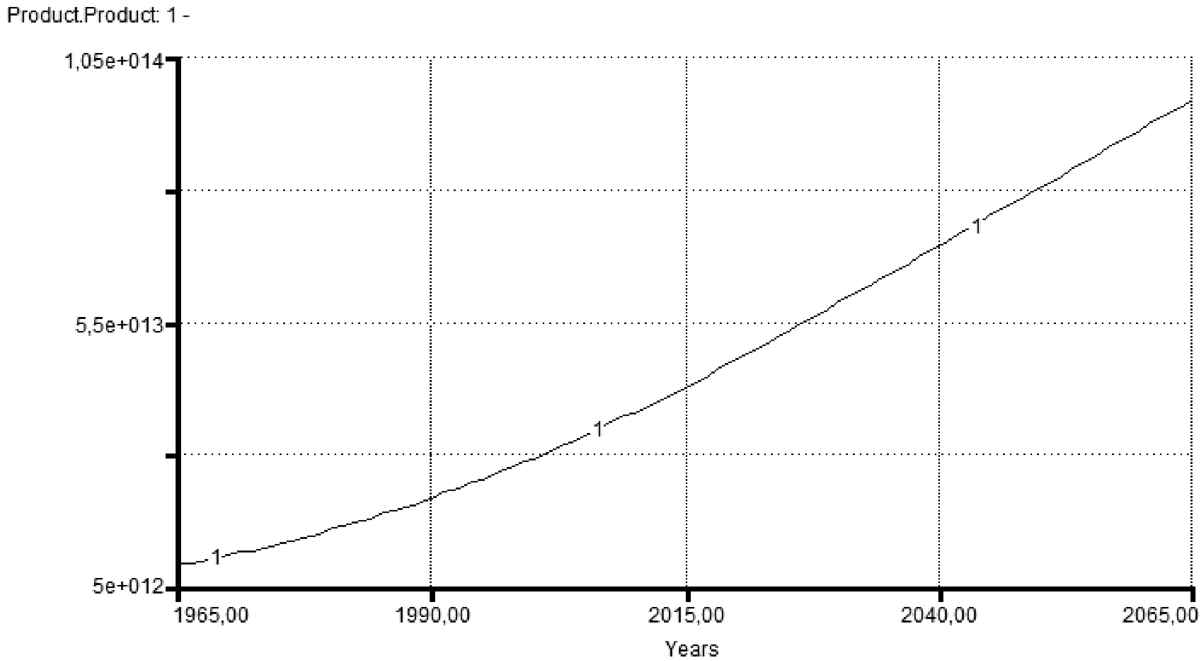

Figure 34 – GDP Growth in the scenario A, Y axis – 1989$. Source: own work.

In the scenario A, Economic growth continues smoothly in the second 50 years of simulation. It is slowed down only by declining growth rates of technology and population. Product reaches the value of 9,65e+013 of 1989$.

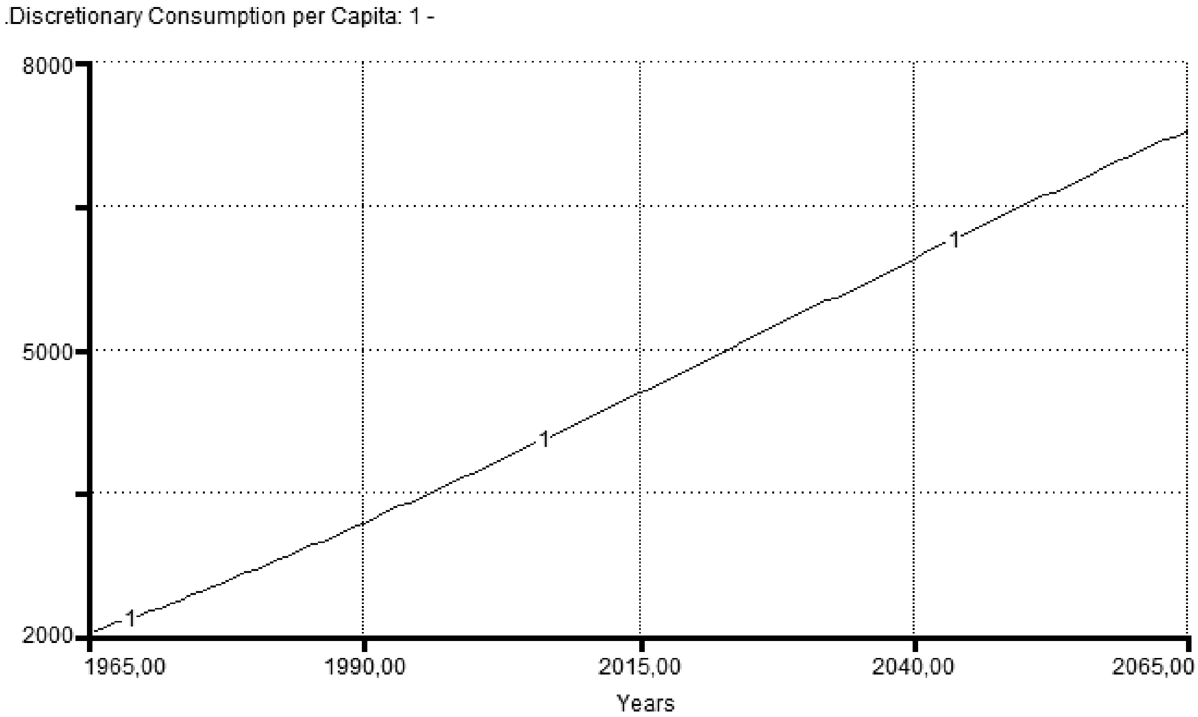

Figure 35 – Per capita GDP growth in the scenario A, Y axis – Constant 1989 dollars. Source: own work.

Aforementioned declining GDP growth rate is translated into almost linear growth of discretionary consumption per capita, which reaches a value of 7278 of 1989$, which represent almost double the consumption reached in the year 2015. This value corresponds to total cumulative consumption of 3,55e+015 1989$.

6.2 Scenario B

In this scenario, capital needs energy to be usable in production process. Since the energy is important in production process now, it is necessary to mention energy sector parameters chosen for the simulation. Reserves of fossil fuels correspond precisely to value presented on the page 54, for the renewable energy source parameters are presented on the pages 56 and 58. Implications of the activated Product-Energy feedback are explored below.

6.2.1 Economic Growth

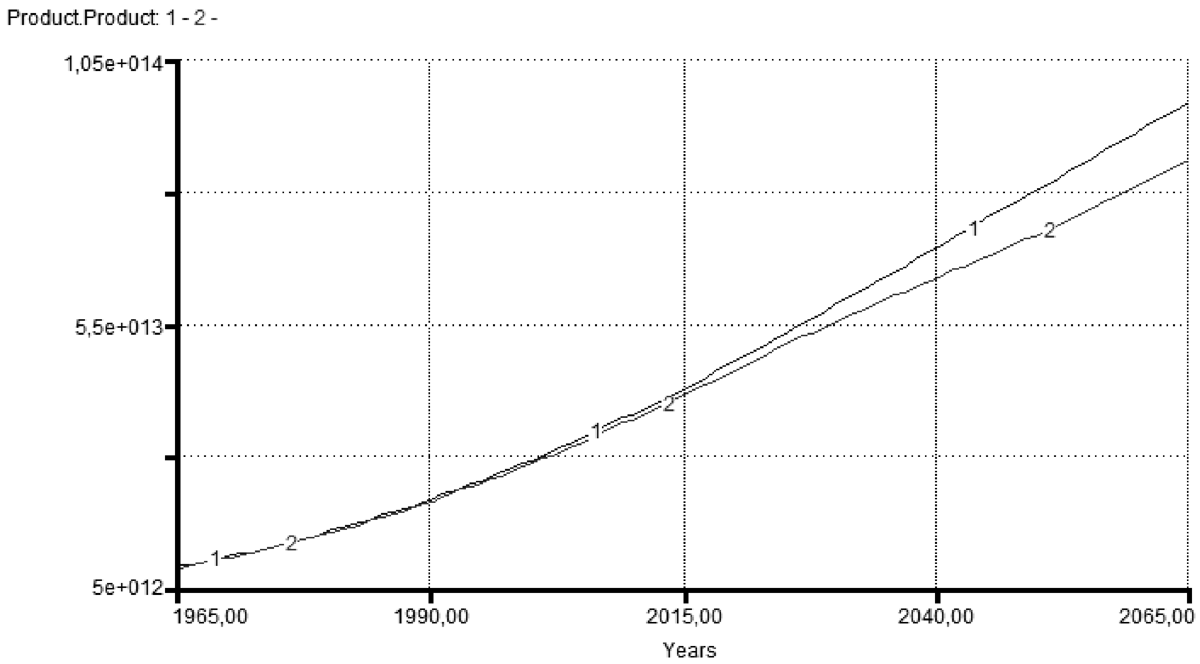

Figure 36 - GDP Growth in the scenario A and B, Y axis – 1989$. Source: own work.

It is clear that activation of the feedback between energy and production sectors leads to a lower GDP growth. In the previous scenario, product reaches the value of 9,65e+013 of 1989$, but in this one, it is only 8,569e+013 1989$, or roughly 12% lower.

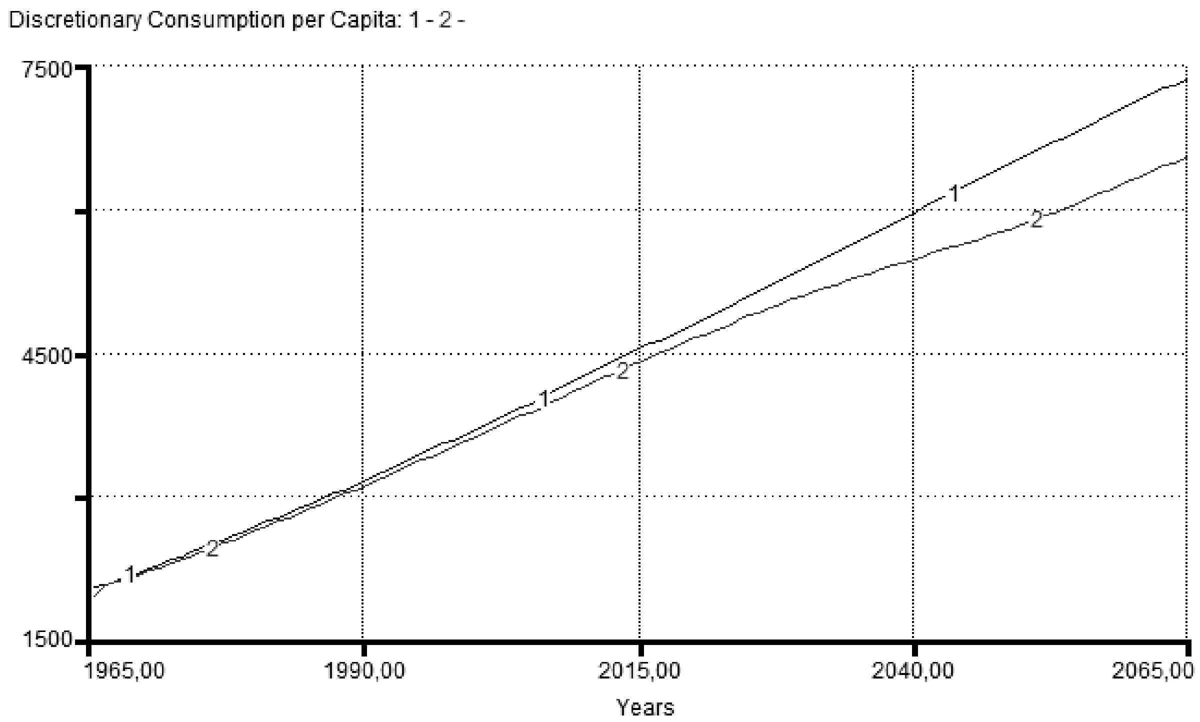

Figure 37 – Per capita GDP growth in the scenario A and B, Y axis – 1989$. Source: own work.

Discretionary consumption per capita reaches a value of only 6538 from the previous 7278 of 1989$. Cumulative discretionary consumption declines to 3,3e+015 1989$.

6.2.2 Energy Sector

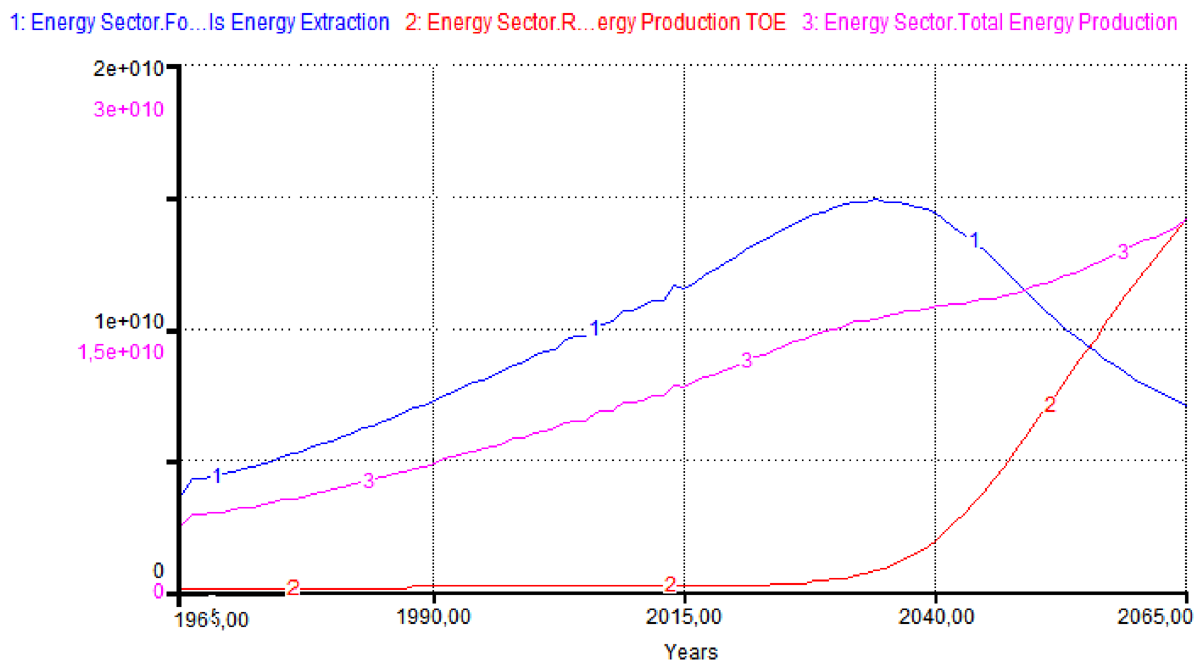

Figure 38 – Energy sector situation in the scenario B, Y axis – Energy production/consumption in Tonnes of oil equivalent, Lines identification: 1 – Fossil fuels energy extraction, 2 – Renewables energy production, 3 – Total energy sector energy production. Source: own work.

First, energy production is dominated by fossil fuels energy source, thanks to its low price. But with the exhaustion of most accessible and highest quality deposits, extraction moves to more distant, lower quality deposits. Good example can be movement of oil extraction from the onshore fields to offshore fields, which require costly drilling platforms. This process is thus accompanied by rising capital costs.

As the cost of the nonrenewable energy source rises, renewables investment is more attractive. On top of that, renewable energy source cost declines with its cumulative installed capacity.

Fossil fuels extraction curve has the predicted bell-shape, and it peaks in the year 2034 at 14,81e+09 TOE. Renewables take on from this point forward and replace the fossil fuels decline. There is only a small dip in the total energy sector energy production.

6.2.3 Investment

In this scenario, investment rate is exogenous, fixed at the 22% of product. But the investment available to energy sector is a proportion from the total investment and it varies in this scenario. It starts at around 6% of the total investment and slowly rises to 31% in the year 2045 (that means roughly 7% of GDP in the energy expenses).

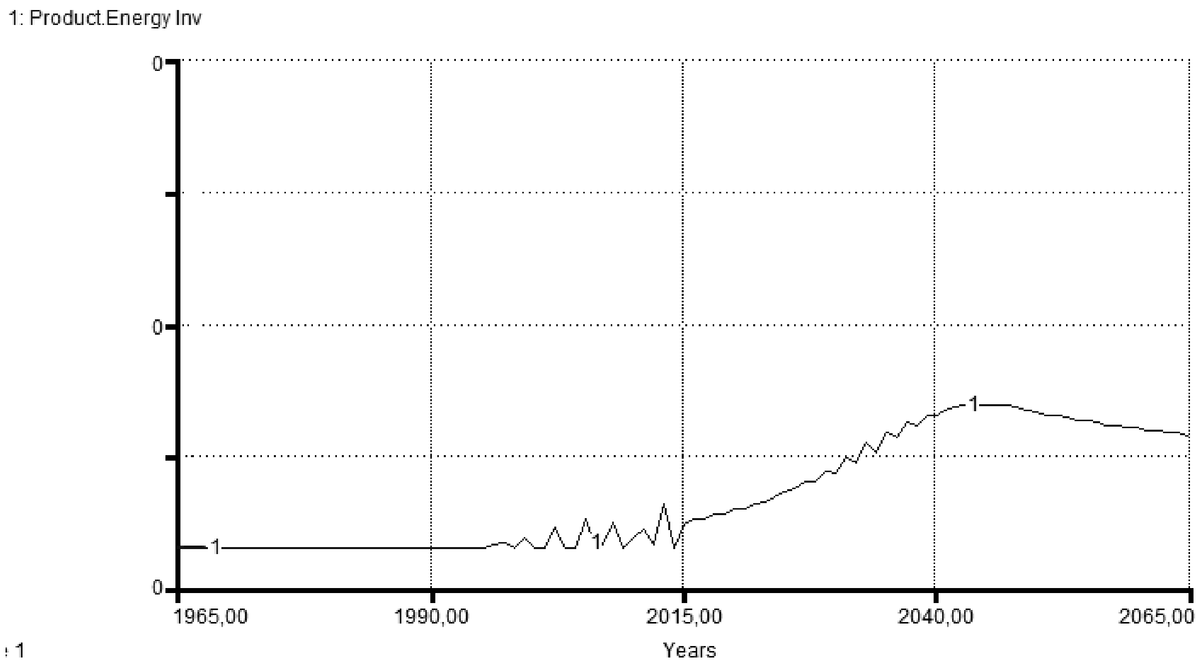

Figure 39 – Energy sector investment in the scenario B, Y axis – percentage of the total capital investment. Source: own work.

6.3 Scenario C

In the third scenario, capital investment rate is endogenous, dependent on the total amount of capital in production and the energy availability for capital utilization in production process.

6.3.1 Economic Growth

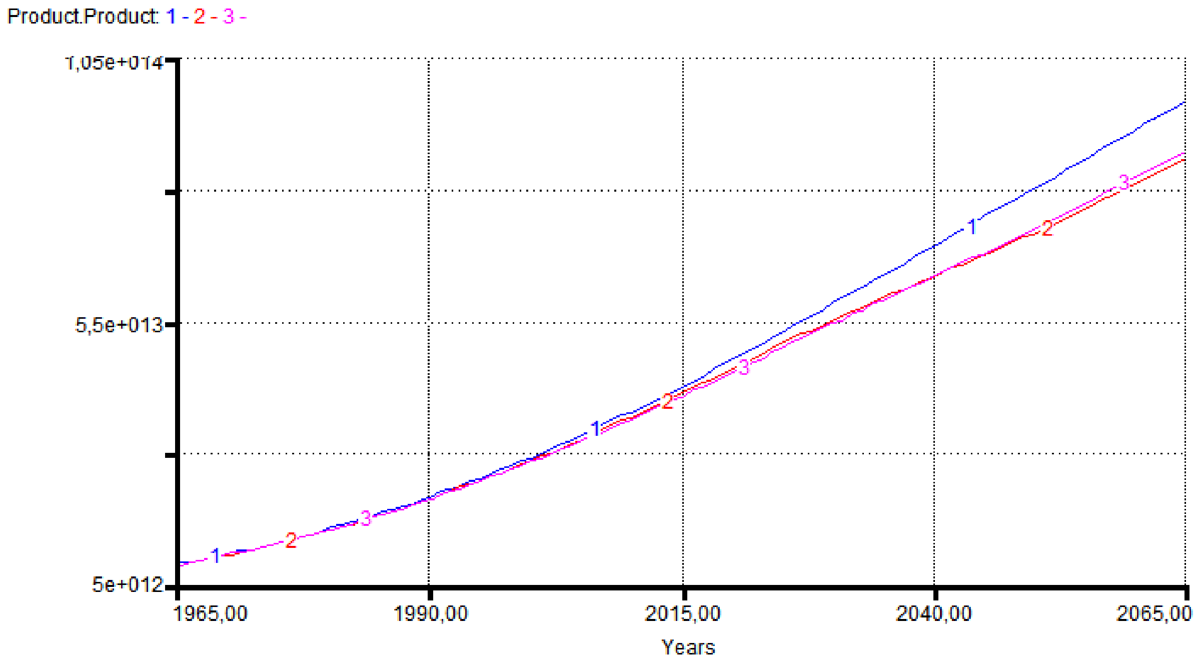

Figure 40 - Per capita GDP growth in the scenario A, B and C, Y axis – 1989$. Source: own work.

Economic performance is only negligible better than in the scenario B. Differences in discretionary consumption are also negligible, thus graph showing them is omitted.

6.3.2 Energy Sector

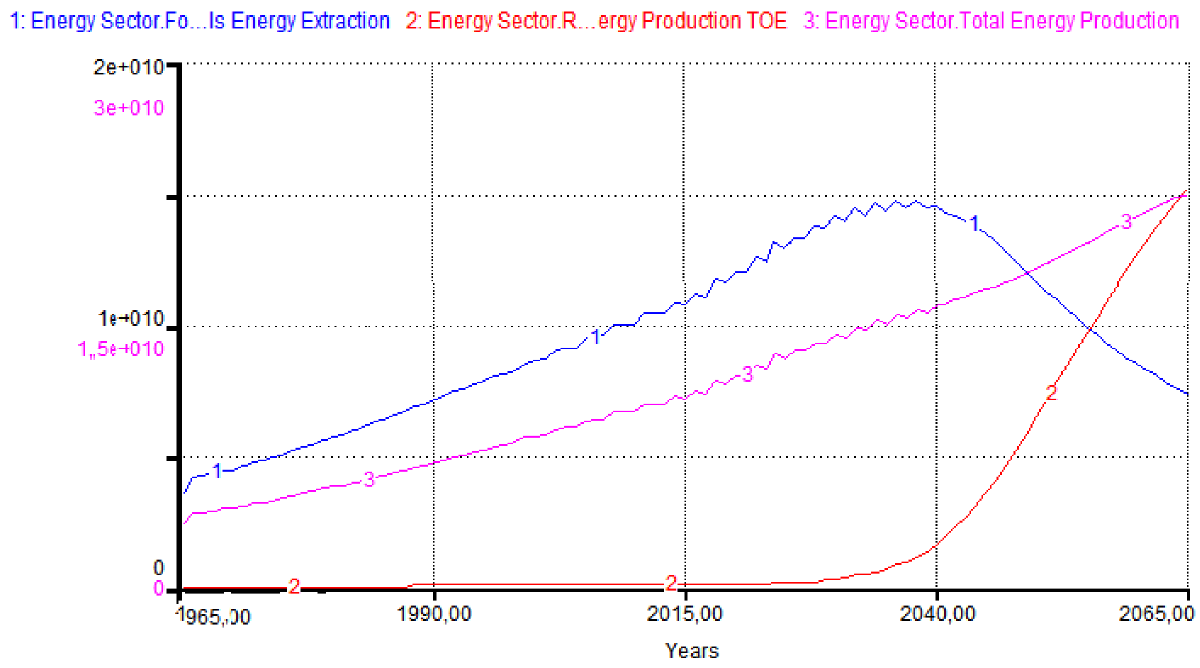

Figure 41 – Energy sector situation in the scenario C, Y axis – Energy production/consumption in Tonnes of oil equivalent, Lines identification: 1 – Fossil fuels energy extraction, 2 – Renewables energy production, 3 – Total energy sector energy production. Source: own work.

In the third scenario, there is almost no dip in the total energy production thanks to the variable investment rate, which helps to allocate investment into the energy sector as needed. Total energy production is also slightly higher, which helps to reach a higher GDP in this scenario.

6.3.3 Investment

Third scenario presents endogenously adjusted investment rate, which reacts to the energy availability for capital and on total amount of capital used in production.

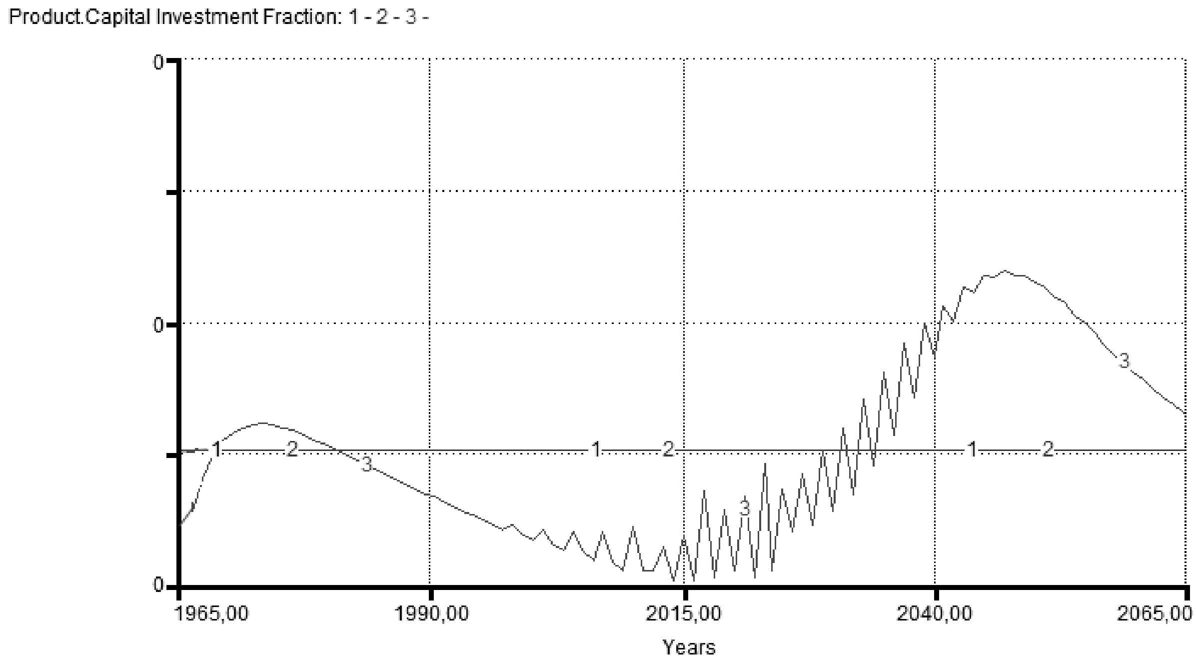

Figure 42 – Total investment in the scenario A, B and C, Y axis – percentage of the total product. Source: own work.

In the third scenario, total capital investment varies between the 22% of the total product around the year 1975, and then it declines to around 20% in year 2016 and climbs up to 24% in reaction to energy crisis created by the exhaustion of fossil fuels.

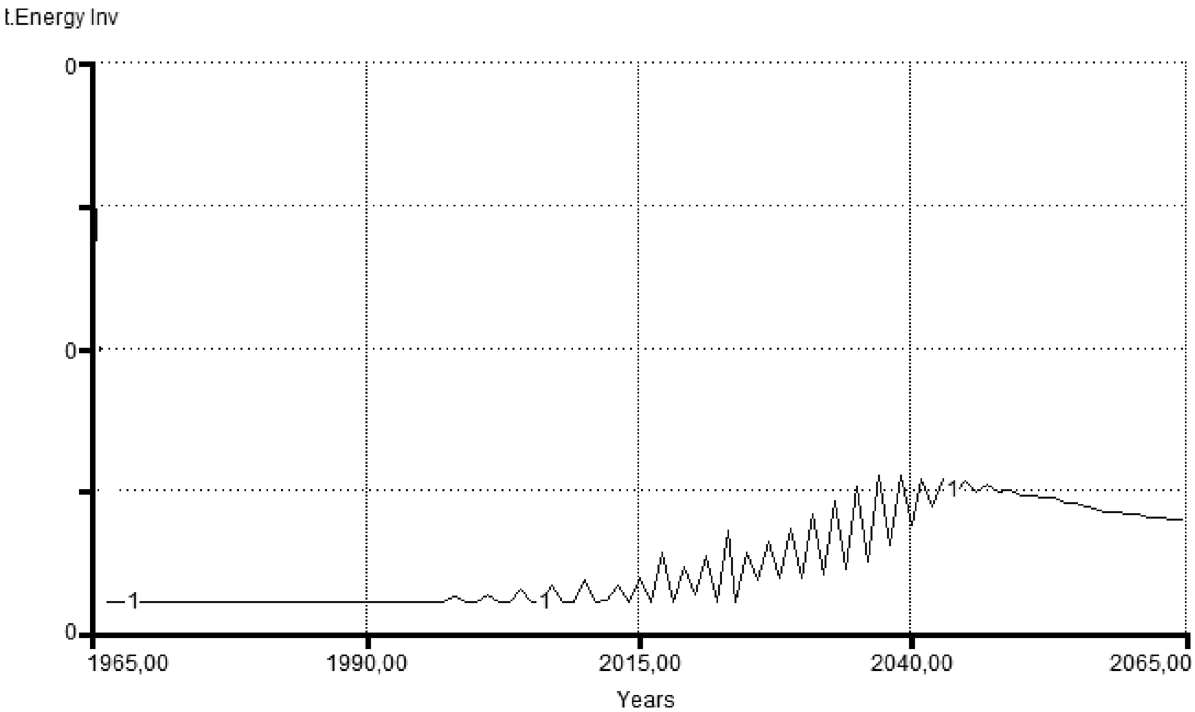

Figure 43 – Energy sector investment in the scenario C, Y axis – percentage of the total capital investment. Source: own work.

Investment into the energy sector peaks in the year 2039 with the value of 8% of total capital investment allocated for the energy sector, which is enough to keep more than 95% of capital usable in the production process most of the time.

6.4 Scenario D

In the fourth and last scenario, there is one more assumption activated – the assumption of the end of growth of the Technology factor. This assumption is based on the work of Ayress and Warr, who associated it with the growing efficiency of transformation of energy inputs into useful work. This also means that this increasing efficiency is limited by the laws of thermodynamics, which we are currently approaching in many energy conversion processes [34]. Below is depicted difference between growth of the Technology factor with and without activation of this assumption.

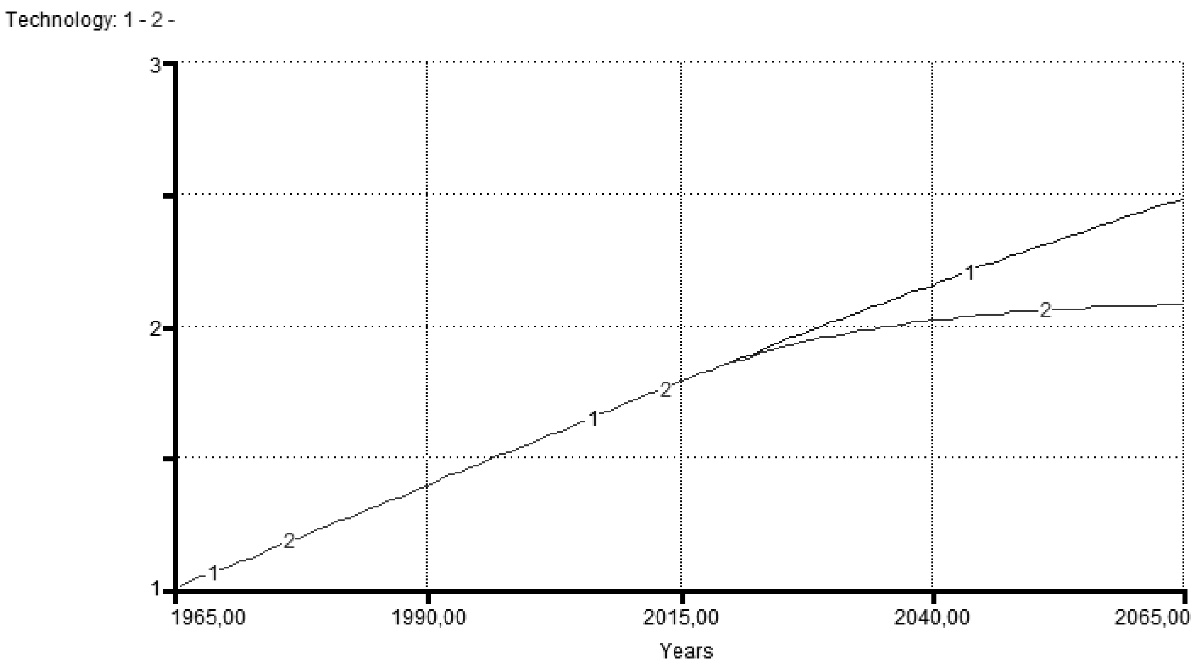

Figure 44 – Different Technology growth rates without (1) and with (2) useful work assumption activated. Y axis – dimensionless. Source: own work.

With the activation of this assumption, growth of the technological factor almost completely stops after the year 2040 and it can be no longer a main driver of economic growth.

6.4.1 Economic Growth

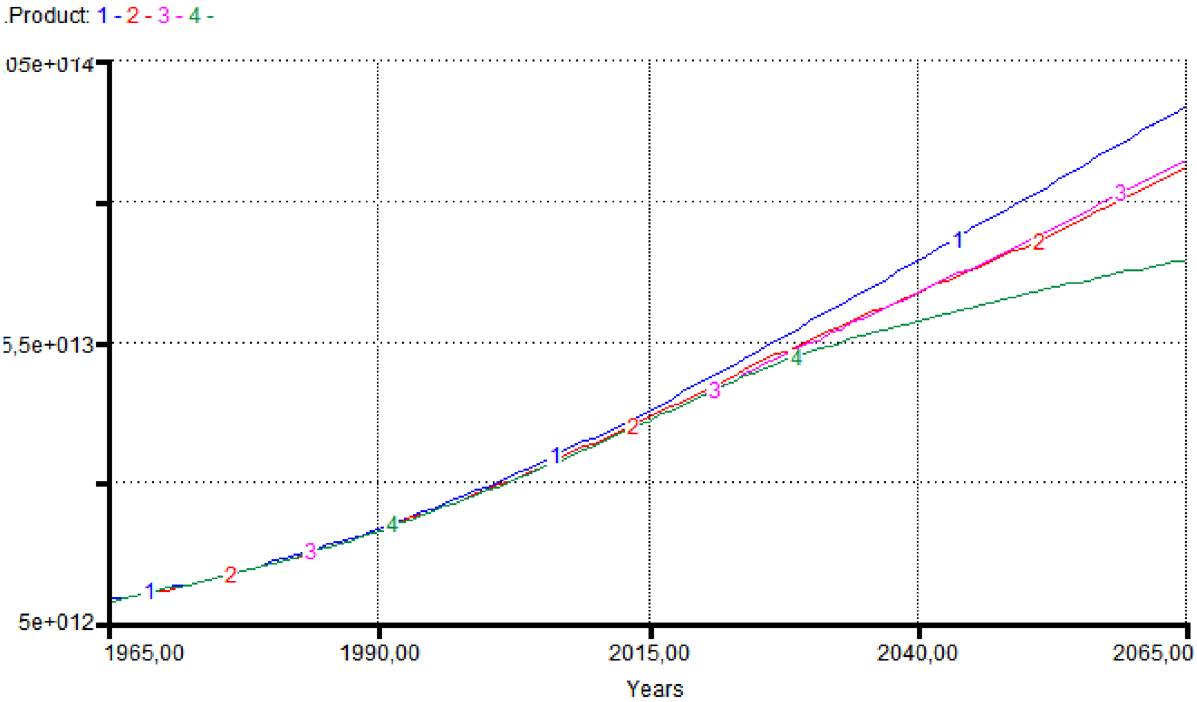

Figure 45 - GDP Growth in the scenario A, B, C and D. Y axis – 1989$. Source: own work.

Product in this case reaches only value of 6,878e+013 1989$, which is only 71% compared to the product in the first scenario with unconstrained economic growth.

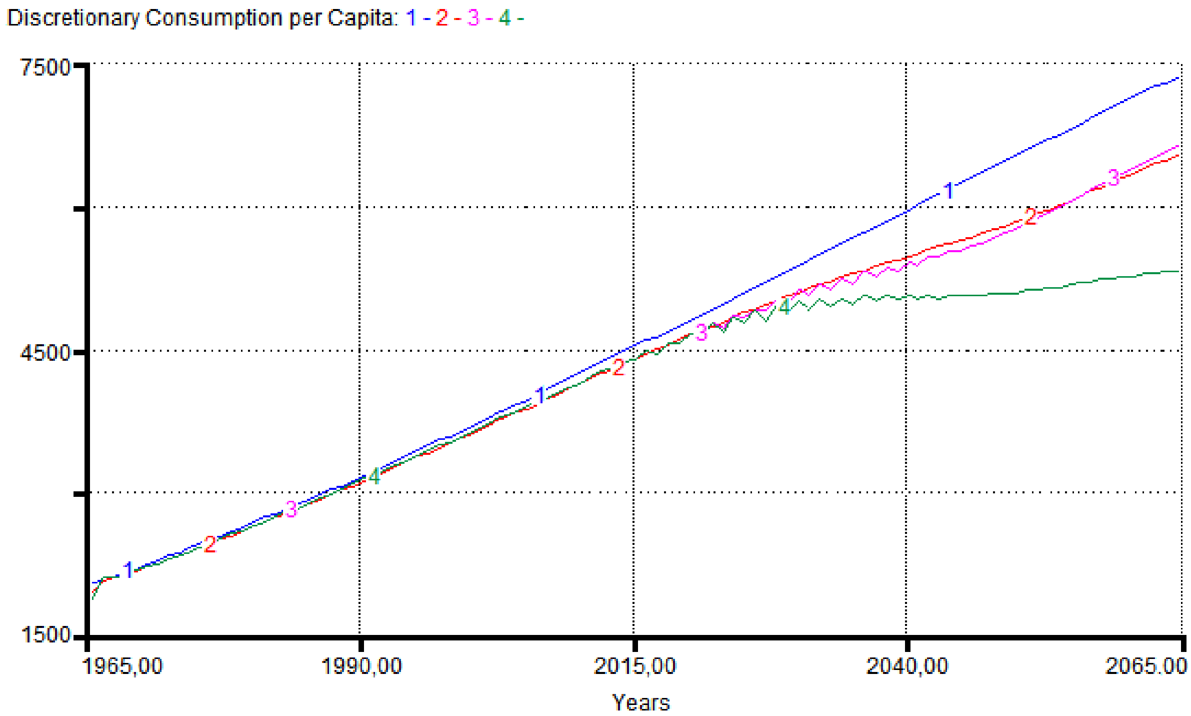

Figure 46 - GDP Growth in the scenario A and B, Y axis – 1989$. Source: own work.

Per capita GDP growth stops and stagnates around the level reached in the year 2030. This corresponds to the total cumulative discretionary consumption of 2,98e+015 1989$, significantly lower than in the previous scenarios.

6.4.2 Energy Sector

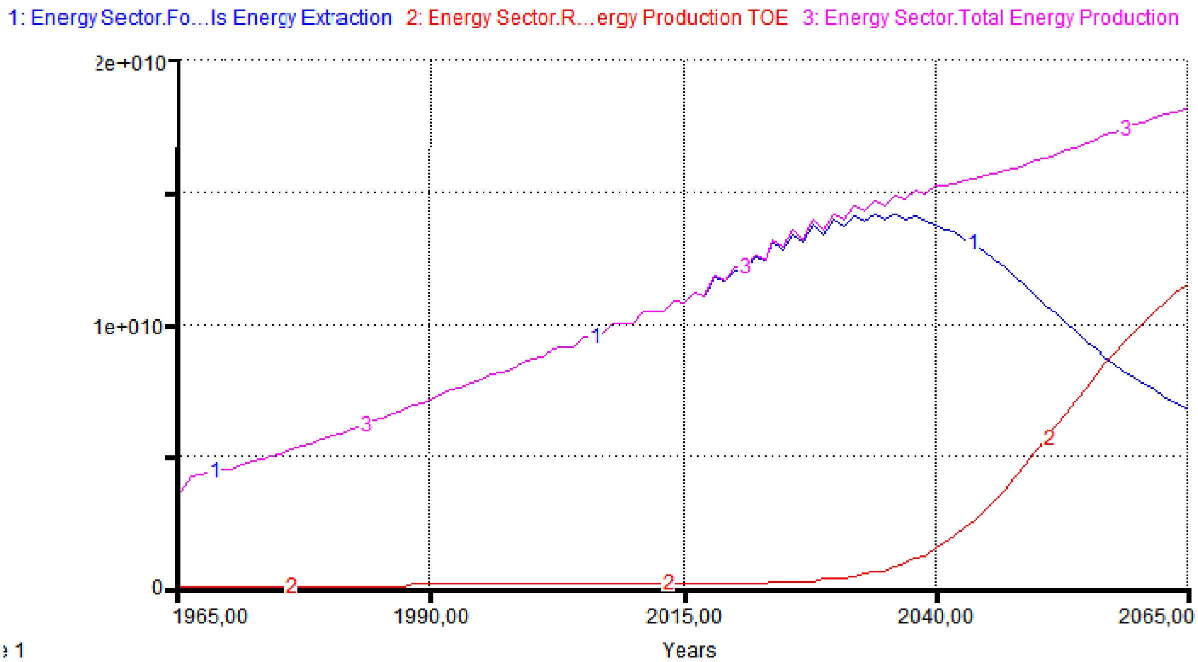

Figure 47 – Energy sector situation in the scenario B, Y axis – Energy production/consumption in Tonnes of oil equivalent, Lines identification: 1 – Fossil fuels energy extraction, 2 – Renewables energy production, 3 – Total energy sector energy production. Source: own work.

Since the Technology factor fails to contribute meaningfully to economic growth after the year 2040, it leads to lower GDP, lower investment and thanks to that smaller stock of capital goods, which needs lower amount of energy than in previous scenarios. In the first scenario, capital stock reaches a level of 2.4e+014 1989$, but in this scenario, it is only 1,33e+014 1989$. Thanks to this, peak extraction of the fossil fuels is postponed by a few years in this scenario.

6.4.3 Investment

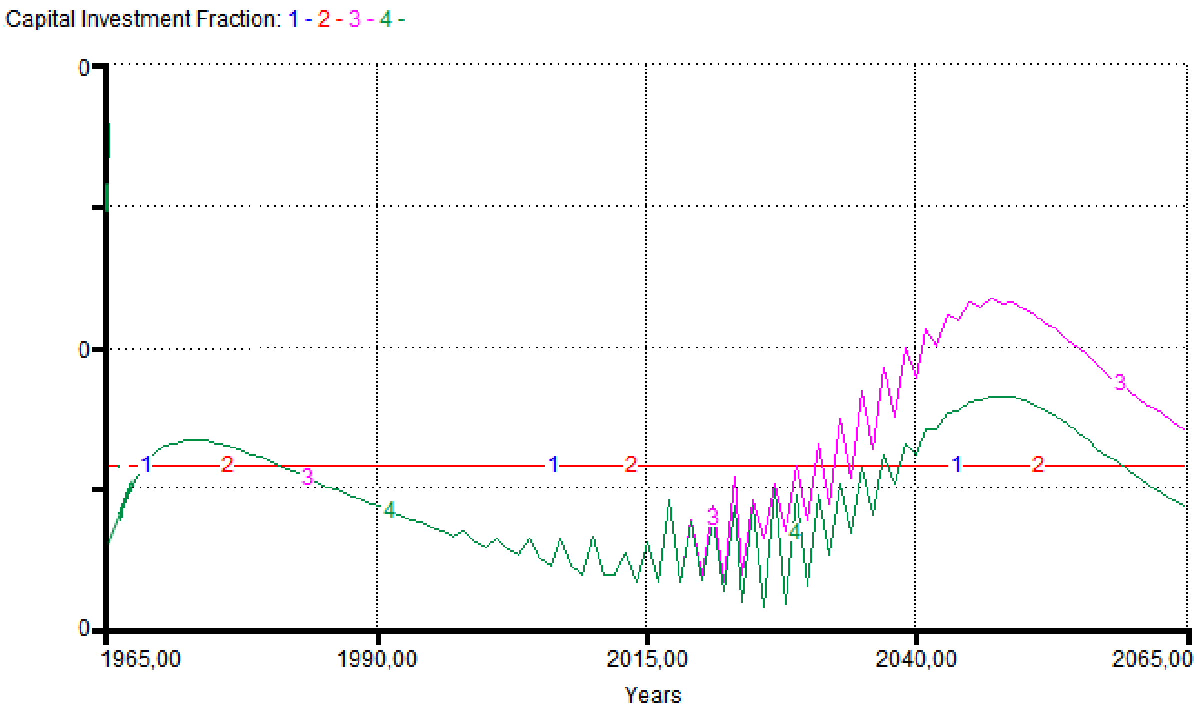

Figure 48 - Total investment in the scenario A, B, C and D. Y axis – percentage of the total product. Source: own work.

Total capital investment is not much different compared to the third scenario till the year 2020, when the total capital investment starts to be about 1 or 2% lower. Amount of total investment going straight into the energy sector is not much higher than in the previous scenario and it reaches value of 10% of the total capital investment in the year 2040.

6.5 Sensitivity analysis for the scenario D

The sensitivity analysis has been performed on the scenario D. Varied were following parameters: *Renewable Energy Capital Lifetime*, *Load Factor*, *Price Reduction Per Total Capacity Doubling*, and *Renewables Price*. All these variables have one in common – they all influence EROEI of renewable energy source. Chapter dealing with EROEI demonstrated uncertainty about its true value in the cases of many renewable energy sources, above all solar PV. This sensitivity analysis thus explores influence of the varied EROEI on the model.

Run number	Renewable Energy Capital Lifetime	Load Factor	Price Reduction Per Total Capacity Doubling	Renewables Price
1	30	0,3	0,15	10
2	27	0,25	0,125	12
3	24	0,2	0,1	15
4	20	0,15	0,1	17
5	18	0,1	0,1	20

Table 16 – Parameter values in the sensitivity analysis of the scenario D, Source: own work.

6.5.1 Economic Growth

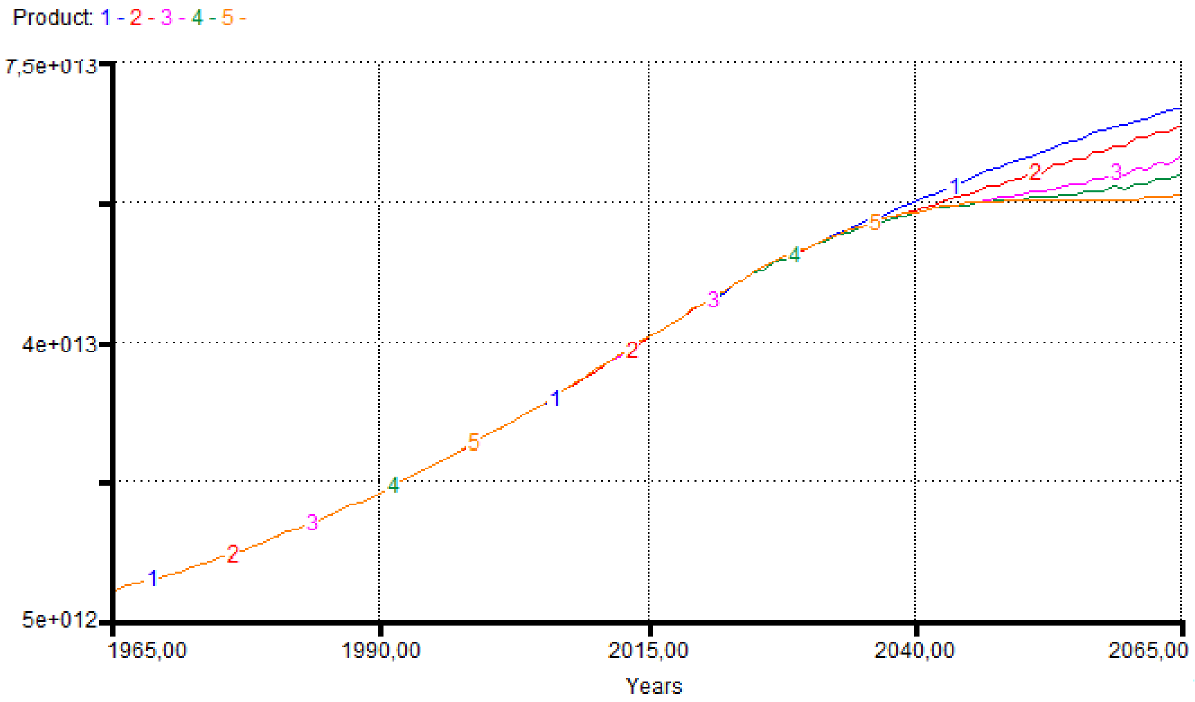

Figure 49 - GDP Growth in the scenario with varied EROEI in scenario D. Y axis – 1989$. Source: own work.

Economic growth is somewhat influenced by varied renewable energy resource parameters, but maybe less than expected. With the best renewable energy source (1) product reaches a value of 6,91e+13 1989$, with the worst in run number 5 it is 5,82e+13 1989$.

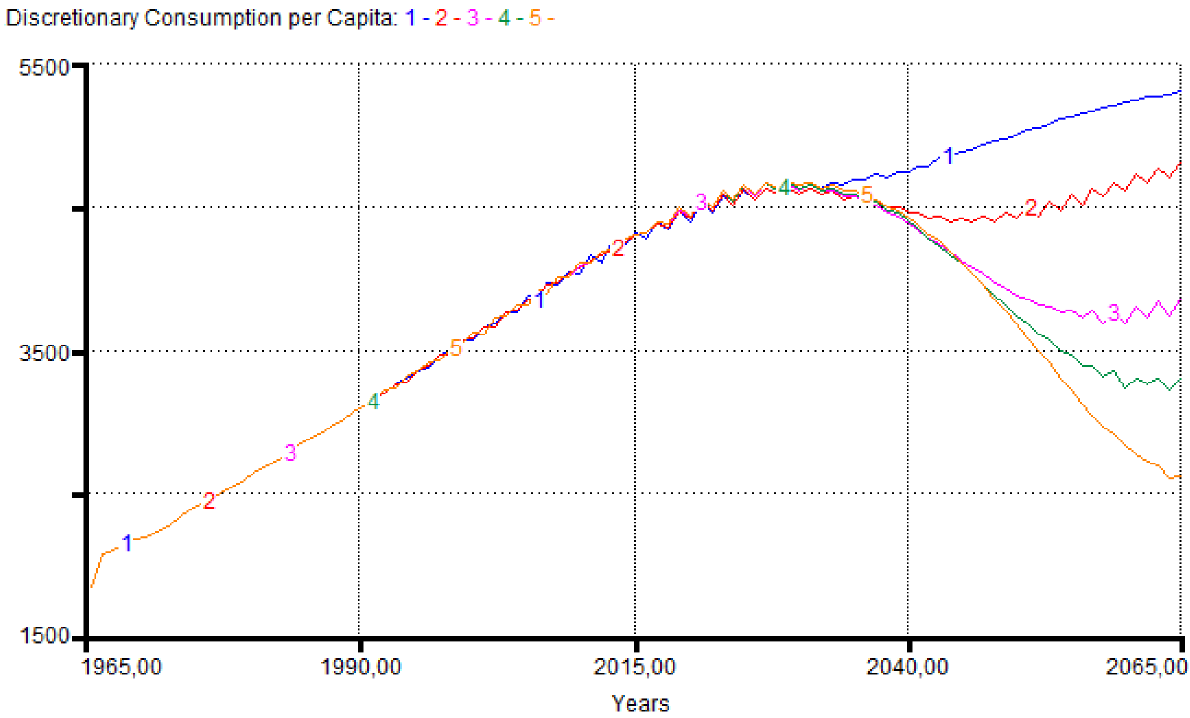

Figure 50 – Discretionary consumption development with varied renewable energy resource EROEI in the scenario D, Y axis – 1989$ per capita. Source: own work.

Influence on discretionary consumption is on the other hand decisive. This is given by drastically higher investment demands in different runs. In run number 1, discretionary consumption per capita still grows and reaches a total cumulative value of 3e+15 1989$, but in the fifth run it is only 2,62e+15 1989$, or a discretionary consumption roughly corresponding to the year 1975.

6.5.2 Energy Sector

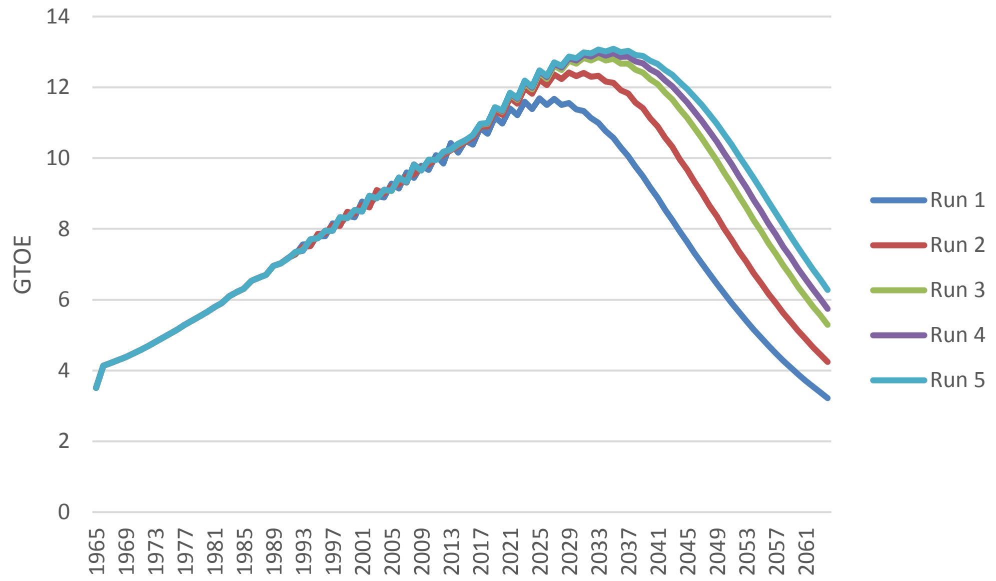

Figure 51 – Influence of varied EROEI rate on timing of the peak of fossil fuels energy extraction in scenario D. Source: own work.

Influence of varied EROEI on the timing of the peak of fossils energy extraction is straightforward – the worse is the renewable energy resource, the longer and in higher amounts are fossil fuels extracted.

6.5.3 Investment

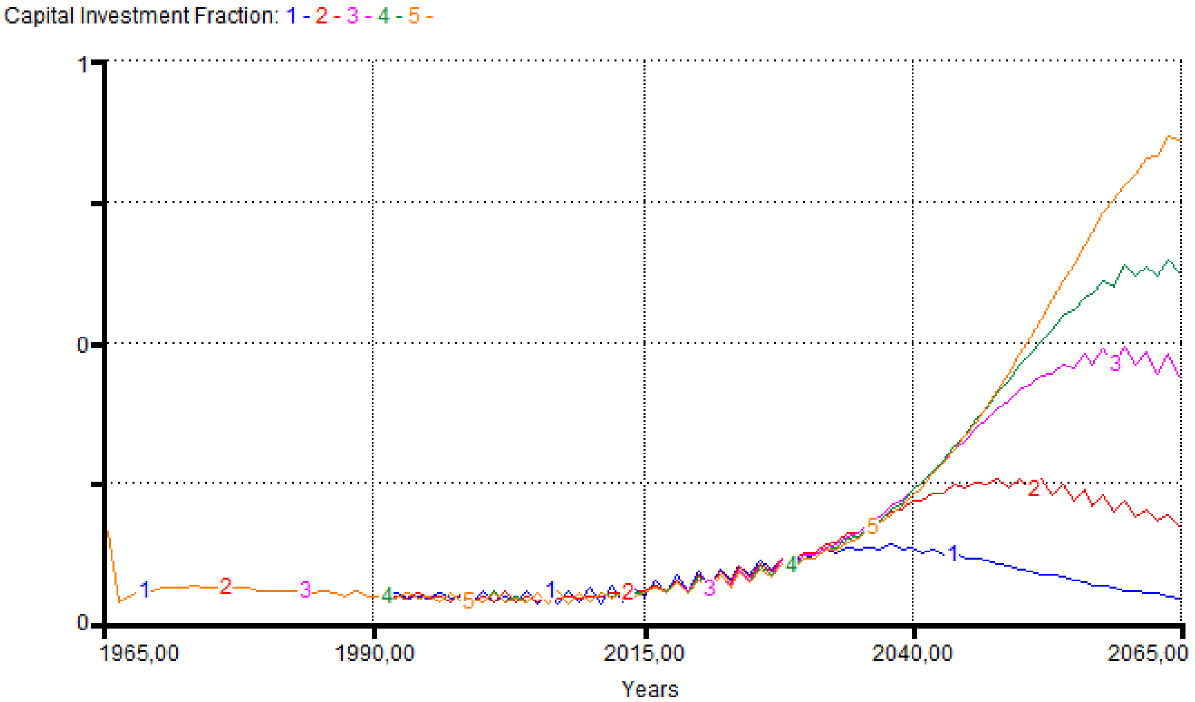

Figure 52 – Influence of varied EROEI rate on Total Capital Investment in scenario D, Y axis – Investment as percentage of total product. Source: own work.

Investment varies wildly with renewable resource quality, in first run it is only a bit higher than in preceding period with abundance of cheap fossil fuels, at around 26% of product, to the last scenario, when whopping 54% of product needs to be reinvested, and almost totally into the energy sector, as Figure 53 shows.

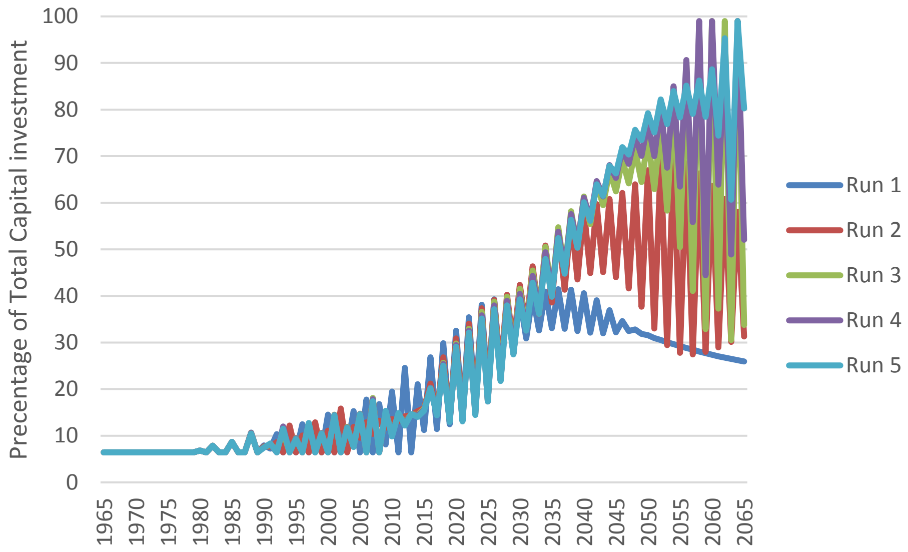

Figure 53 - Influence of varied EROEI rates on Energy sector investment in scenario D. Source: own work.

It is clear that the quality of the renewable energy source is a strong predictor of future wellbeing. In run 5, its EROEI is just around two, which corresponds to around 50% investment straight into energy sector, clearly unrealistic value. Even run 3 does not look realistic with investment rate oscillating around 75% of total product and at around 60% of that invested straight into the energy sector.

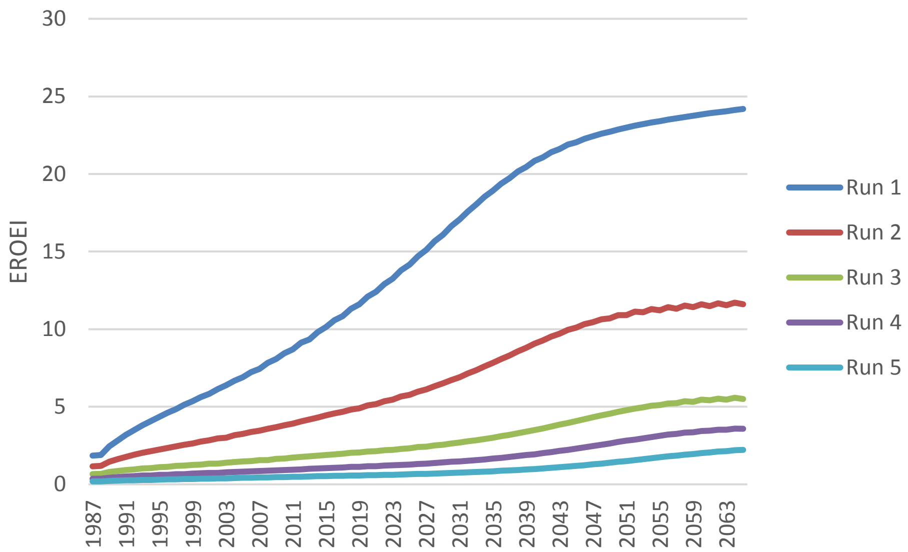

Figure 54 – EROEI of renewable energy source with its varied parameters in scenario D. Source: own work.

7 Discussion

Chapter about EROEI showed large uncertainty regarding their true values for various renewable sources. Probably most extreme case is the EROEI of solar PV, when two studies evaluated its EROEI below 2,45:1, which is according to the model results hopelessly low value. On the other hand, mean value for solar PV is around 10, which is associated with certain problems during energy transition, but still feasible in economic terms.

In reality, there is not one non-renewable energy source, as it is in the model. It is nothing more than a simplistic assumption. Attempts to implement a renewable energy mix into the model were defeated by the fact that in the real world, investment into renewable energy resources is not driven just by their prices. There are many other factors at play. In the case of Hydropower, main factor is usually a political decision about the dam placement [57]. Decisions about investment into the windpower can be influenced by esthetical concerns regarding damage of natural scenery. Model could not simulate all the various concerns considered during the decision process and from that reason there is only one abstract renewable energy source. This of course limits model significance, as the total EROEI of the whole renewable energy mix will be influenced by its composition. Hydropower has a high EROEI values, but it is seriously limited by its total scalability. Windpower has a higher EROEI than Solar, but a flattening price learning curve at the same time. There are currently doubts about true solar PV. All these factors could change the model results and elaborate on the true scale of economic burden which energy transition constitutes.

Another problem of the model are the omissions of a few well-known feedbacks. There is no representation of the CO_2 emissions and the atmosphere capability of storing that carbon and consecutive global warming. This would probably create a need to phase off fossil fuels energy resources faster and create bigger pressure on the amount of investment necessary for the renewable energy source. Another omitted feedback is the omission of the need to replace energy end use capital stock, responsible for the production of the economic goods. This capital stock is much bigger than energy generating capital stock so it will raise the costs of the energy transition considerably. The need to replace this capital stock faster than it would otherwise been arise from the speed of energy transition and the new composition of the energy mix. Inclusion of this feedback could influence model results very negatively as the amount of investment needed in various scenarios could raise many times, thus making those scenarios unfeasible.

Comparison with other models is not straightforward, as they usually employ different set of assumptions. Compared to the standard run of the legendary Limits to Growth, model results are a bit more optimistic. LTG's industrial output and services per capita peaked and declined shortly before the year 2020 [67]. Current model does not predict decline in per capita discretionary consumption before the year 2027 and not in all scenarios, some of them permit even further growth. But then again, LTG considered more comprehensive set of the environmental feedbacks. In the WOLIM model, energy shortages in terms of Total Primary Energy Extraction occurred in all scenarios around the year 2020 with the transport sector being hardest hitted (with the assumption of exponential GDP growth of various growth speeds). This is relatively similar to the results of this model in a sense that exponential growth continues only to the year 2027 in scenario D and slows considerably after that (see the sensitivity analysis). Interesting is also the comparison with the SET model. One of its conclusions is that in order for the energy transition to be sustainable, fossil fuels has to be phased out completely around the year 2065. Best model case leads to fossil fuels consumption previously reached around the year 1965, which is still far from the complete phase out. This need would increase necessary investment ratio for the energy transition even more.

Further research should focus mainly on the model extensions by previously identified omitted feedbacks and their consequences for model dynamics. Energy resources should be disaggregated to individual fuels – e.g. coal, oil, natural gas in a case of fossil fuels and a hydropower, windpower and solar in a case of renewables. Second step should follow – make the energy end-use capital dependent on certain composition of energy mix. With rapidly changing energy mix, energy end-use capital has to be also replaced faster to be able to use new energy mix composition. Since every energy source has different CO_2 emissions profile, model should be also extended by the module containing various atmospheric stocks and flows to represent CO_2 accumulation and consecutive temperature and weather changes.

8 Conclusion

To reiterate, the purpose of this dissertation is to bridge the gap between mainstream models of economic development and system dynamics models incorporating environmental feedbacks to economic process. This need has been demonstrated in the literature review, which demonstrated deep fragmentation of the presented models (e.g. the majority of models do not incorporate solid representation of economic growth models, while others usually do not incorporate the energy sector, with the exception of the FREE model). This fragmentation can lead to incorrect conclusions, for example baseline emission scenarios commonly projected in the models assessing climate damages with levels of coal combustion many times higher than is estimated by models focused on fossil fuels depletion [68].

The representative model of economic development has been selected and translated into system dynamics format; its extension by the complete energy sector containing stock of fossil fuels, renewable energy source and demand for energy sources has been demonstrated. Another improvement is the energy dependent production function, in which capital usability depends on the energy available for its operation.

Extension of the model resulted in a new behaviour in which shortage of energy leads to lower amount of capital available for production. This increases savings rate and investment available for the energy sector. However, smaller general-purpose capital stock leads to lower GDP growth, and higher savings rate limits discretionary consumption.

Main contribution of the model is the association of renewable resource quality, expressed as EROEI with certain levels of future economic performance and investment requirements. The final sensitivity analysis showed that for the renewable energy sources with EROEI of 20 and higher, economic growth can continue with the same momentum. For EROEI of 10, investment path seems feasible and investment rate does not displace too much of discretionary spending. But for renewable energy sources with lower EROEI, there is a significant drop in discretionary spending per capita signalling economic hardship not just during the energy transition, but also after it, because discretionary spending does not seem to recover after it in the last years of simulation. The model shows the critical importance of the renewable resource quality for future economic development.

9 Student publications related to the topic of dissertation

[1] REŽNÝ, Lukáš and James Buchanan WHITE. Economic Growth and Hubbert Curve. Hradec Economic Days 2013. Conference proceedings no. 3., p. 473–484. ISBN 978-80-7435-251-5.

[2] REŽNÝ, Lukáš and James Buchanan WHITE. Knowledge Economy: Key to sustainable development? Degrowth conference 2014, Leipzig, Germany.

[3] HÁJEK, Ladislav and Lukáš REŽNÝ. 20 Years of Czech economy development, comparison with Slovakia. E+M. 2014, no. 1, pp. 19-31. Available: http://www.ekonomie-management.cz/archiv/detail/1020-20-let-vyvoje-ceske-ekonomiky-srovnani-se-slovenskem/

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11 Annex

11.1 Model Equations (Model version 0.954)

Capital:

Capital(t) = Capital(t - dt) + (Behavioral_Investment_Rule - Depreciation) * dt

INIT Capital = 16.03e+012

INFLOWS:

Behavioral_Investment_Rule = Product.Capital_Investment

OUTFLOWS:

Depreciation = Capital_Depreciation_Rate*Capital

Capital_Depreciation_Rate = 0.075

Capital_Energy_Requirement = (Capital*Capital_energy_Requirement_Constant)*Energy_Saving_Technological_Progress

Capital_energy_Requirement_Constant = 2.5e-04

Capital_Future_Energy_Requirement = Capital_Energy_Requirement*1.03

Energy_Capacity_Orders = IF Product.Energy_Feedback_Switch = 1 THEN MAX(0,(Capital_Future_Energy_Requirement+Energy_Sector.Total_Energy_Sources_Capacity_Depreciation)-Energy_Sector.Total_Energy_Production) ELSE 0

Energy_Saving_Technological_Progress = IF Energy_Saving_Technology_Switch=1 THEN INIT(Technology.Technology)/Technology.Technology ELSE (IF TIME<=2015 THEN INIT(Technology.Technology)/Technology.Technology ELSE INIT(Technology.Technology)/HISTORY(Technology.Technology, 2015))

Energy_Saving_Technology_Switch = 1

Energy Sector:

Cumulative_Extraction(t) = Cumulative_Extraction(t - dt) + (Fossil_Fuels_Energy_Extraction) * dt

INIT Cumulative_Extraction = 0

INFLOWS:

Fossil_Fuels_Energy_Extraction = Fossil_Fuels_Extraction_Capital

Fossil_Fuels_Extraction_Capital(t) = Fossil_Fuels_Extraction_Capital(t - dt) + (Fossil_Fuels_Extractive_Capacity_Additions - Fossil_Fuels_Extractive_Capital_Depreciation) * dt

INIT Fossil_Fuels_Extraction_Capital = 3514e+006

INFLOWS:

Fossil_Fuels_Extractive_Capacity_Additions = Fossils_Ordered_Capacity

OUTFLOWS:

Fossil_Fuels_Extractive_Capital_Depreciation = 1/Fossil_Fuels_Extracting_Capital_Lifetime*Fossil_Fuels_Extraction_Capital

Fossil_Fuels_Reserves(t) = Fossil_Fuels_Reserves(t - dt) + (- Fossil_Fuels_Energy_Extraction) * dt

INIT Fossil_Fuels_Reserves = 1282.682e+009

OUTFLOWS:

Fossil_Fuels_Energy_Extraction = Fossil_Fuels_Extraction_Capital

Renewables_Cumulative_Capacity_Produced(t) = Renewables_Cumulative_Capacity_Produced(t - dt) + (Renewables_Capacity_Additions) * dt

INIT Renewables_Cumulative_Capacity_Produced = 0.1

INFLOWS:

Renewables_Capacity_Additions = Renewable_Energy_Capital_Aditions

Renewables_Price(t) = Renewables_Price(t - dt) + (- Renewables_Price_Reductions) * dt

INIT Renewables_Price = 10

OUTFLOWS:

Renewables_Price_Reductions = IF TIME>Renewable_Energy_Investment_Start_Year THEN Renewables_Price*(Price_Reduction_Per_Total_Capacity_Doubling*(Renewables_Capacity_Additions/Renewables_Cumulative_Capacity_Produced)) ELSE 0

Renewable_Energy_Installed_Capacity(t) = Renewable_Energy_Installed_Capacity(t - dt) + (Renewable_Energy_Capital_Aditions - Renewable_Energy_Capital_Depreciation) * dt

INIT Renewable_Energy_Installed_Capacity = 0

INFLOWS:

Renewable_Energy_Capital_Aditions = Renewables_Ordered_Capacity_Watts

OUTFLOWS:

Renewable_Energy_Capital_Depreciation = (1/Renewable_Energy_Capital_Lifetime)*Renewable_Energy_Installed_Capacity

Added_TOE_capacity_initial_price = 403.0640431

Added_TOE_capacity_price = IF (Fossil_Fuels_Reserves> 0) THEN (Added_TOE_capacity_initial_price*(1/((Fossil_Fuels_Reserves/INIT(Fossil_Fuels_Reserves))^5))) ELSE 0

Attractivness_Sum = Renewables_Investment_Atractivness+Fossils_Investment_Attractivness

Capacity_Utilization_Factor = 0.95

Energy_Input_Fossils =
Fossils_Available_Investment*Indicators.Energy_Intensity_of_Product

Energy_Input_Renewables =
Indicators.Energy_Intensity_of_Product*Renewables_Available_Investment

Energy_Output_Fossils = Fossil_Fuels_Extracting_Capital_Lifetime*Fossils_Ordered_Capacity

Energy_Output_Renewables =
Renewables_Ordered_Capacity_TOE*Renewable_Energy_Capital_Lifetime*Capacity_Utilization_Factor

EROEI_Fossils = IF Energy_Input_Fossils>0 THEN
Energy_Output_Fossils/Energy_Input_Fossils ELSE 0

EROEI_Renewables = IF TIME>=Renewable_Energy_Investment_Start_Year AND
Energy_Input_Renewables>0 THEN Energy_Output_Renewables/Energy_Input_Renewables
ELSE 0

Fossils_Available_Investment =
Product.Energy_Sector_Available_Investment*Fossil_Fuels_Investment_Share

Fossils_Capacity_Units_per_Investment_Share =
Fossil_Fuels_Investment_Share/Added_TOE_capacity_price

Fossils_Demanded_Capacity =
Fossils_Capacity_Units_per_Investment_Share*Investment_Shares_Multiplicator

Fossils_Investment_Attractivness = 1/Fossils_Price_Share

Fossils_Ordered_Capacity = Fossils_Available_Investment/Added_TOE_capacity_price

Fossils_Price_Share = Added_TOE_capacity_price/Sum_of_Prices

Fossil_Fuels_Extracting_Capital_Lifetime = 20

Fossil_Fuels_Investment_Share = Fossils_Investment_Attractivness/Attractivness_Sum

Hours_per_Year = 8760

Investment_Shares_Multiplicator =
Capital.Energy_Capacity_Orders/(Fossils_Capacity_Units_per_Investment_Share+Renewables_Capacity_Units_per_Investment_Share)

Load_Factor = 0.22

Price_Reduction_Per_Total_Capacity_Doubling = 0.25

Renewables_Added_TOE_Capacity_Price =
Renewables_Price*((Watts_to_TOE_Conversion_Factor/(Load_Factor*Hours_per_Year)))

Renewables_Available_Investment =
Product.Energy_Sector_Available_Investment*Renewables_Investment_Share

Renewables_Capacity_Units_per_Investment_Share = IF Renewables_Investment_Share>0 THEN Renewables_Investment_Share/Renewables_Added_TOE_Capacity_Price ELSE 0

Renewables_Demanded_Capacity =
Renewables_Capacity_Units_per_Investment_Share*Investment_Shares_Multiplicator

Renewables_Investment_Atractivness = IF TIME<Renewable_Energy_Investment_Start_Year THEN 0 ELSE 1/Renewables_Price_Share

Renewables_Investment_Share = Renewables_Investment_Atractivness/Attractivness_Sum

Renewables_Ordered_Capacity_TOE =
Renewables_Available_Investment/Renewables_Added_TOE_Capacity_Price

Renewables_Ordered_Capacity_Watts =
(Renewables_Ordered_Capacity_TOE*Watts_to_TOE_Conversion_Factor)/(Load_Factor*Hours_per_Year)

Renewables_Price_Share = Renewables_Added_TOE_Capacity_Price/Sum_of_Prices

Renewables_Subsidies = 0

Renewable_Energy_Capital_Depreciation_TOE =
(Renewable_Energy_Capital_Depreciation*Load_Factor*Hours_per_Year)/Watts_to_TOE_Conversion_Factor

Renewable_Energy_Capital_Lifetime = 30

Renewable_Energy_Investment_Start_Year = 1987

Renewable_Energy_Production_TOE =
(Renewable_Energy_Installed_Capacity*Load_Factor*Hours_per_Year)/Watts_to_TOE_Conversion_Factor

Sum_of_Prices = Added_TOE_capacity_price+Renewables_Added_TOE_Capacity_Price

Total_Energy_Production =
Fossil_Fuels_Energy_Extraction+Renewable_Energy_Production_TOE

Total_Energy_Sources_Capacity_Depreciation =
Fossil_Fuels_Extractive_Capital_Depreciation+Renewable_Energy_Capital_Depreciation_TOE

Total_Necessary_Energy_Investment =
(Fossil_Fuels_Investment_Share+Renewables_Investment_Share)*Investment_Shares_Multiplicator

Watts_to_TOE_Conversion_Factor = 11630000

Indicators:

Cumulative_Utility_Derived_From_Consumption(t) =
Cumulative_Utility_Derived_From_Consumption(t - dt) + (Utility_Increase) * dt

INIT Cumulative_Utility_Derived_From_Consumption = 0

INFLOWS:

Utility_Increase = Discretionary_Consumption_per_Capita*Population.Population

Capital_Product_Ratio = Capital.Capital/Product.Product

Discount_Factor = 0.015

Discretionary_Consumption_per_Capita = (Product.Product*Product.Discretionary_Spending_Fraction)/Population.Population

Energy_Intensity_of_Product = (Energy_Sector.Total_Energy_Production)/Product.Product

EROEI = (Energy_Sector.Total_Energy_Production)/(Energy_Intensity_of_Product*MAX(1,Product.Energy_Sector_Available_Investment))

Marginal_Productivity_of_Capital = Product.Gama*Product.Product/Usable_Capital

Marginal_Return_on_Capital = Marginal_Productivity_of_Capital-Capital.Capital_Depreciation_Rate

Per_Capita_Energy_Use = Energy_Sector.Total_Energy_Production/Population.Population

Usable_Capital = IF Product.Energy_Feedback_Switch=0 THEN Capital.Capital ELSE Product.Operational_Capital

Population:

Fractional_Birth_Rate(t) = Fractional_Birth_Rate(t - dt) + (- Birth_Rate_Decline) * dt

INIT Fractional_Birth_Rate = 0.0222

OUTFLOWS:

Birth_Rate_Decline = IF (TIME<2015) THEN (Fractional_Birth_Rate_Decline_Rate_Historical*Fractional_Birth_Rate) ELSE (Fractional_Birth_Rate_Decline_Rate_Projected*Fractional_Birth_Rate)

Population(t) = Population(t - dt) + (Birth_Rate) * dt

INIT Population = 3.326e+009

INFLOWS:

Birth_Rate = Fractional_Birth_Rate*Population

Fractional_Birth_Rate_Decline_Rate_Historical = 0.0143

Fractional_Birth_Rate_Decline_Rate_Projected = 0.02139

Product:

Capital_Investment = Production_Capital_Investment*Product

Capital_Investment_Fraction = IF Exogenous_Savings_Rate_Switch = 0 THEN MIN(1,Initial_Capital_Investment_Fraction*Indicators.Marginal_Return_on_Capital/Normal_Return_On_Capital) ELSE Initial_Capital_Investment_Fraction

Capital_Utilization = Energy_Sector.Total_Energy_Production/Capital.Capital_Energy_Requirement

Discretionary_Spending_Fraction = (Product-Capital_Investment_Fraction*Product)/Product

Energy_Feedback_Switch = 1

Energy_Inv = Capital_Investment_Fraction*(Energy_Capital_Investment_Fraction/100)

Energy_Inv_Final = MIN(Energy_Inv,Energy_Inv_Needed)

Energy_Inv_Needed = Energy_Sector.Total_Necessary_Energy_Investment/Product

Energy_Sector_Available_Investment = Energy_Inv_Final*Product

Exogenous_Savings_Rate_Switch = 1

Gama = 0.25

Initial_Capital_Investment_Fraction = 0.22

Initial_Product = 8.519e+012

Normal_Return_On_Capital = 0.06

Operational_Capital = IF Energy_Feedback_Switch=1 THEN Capital.Capital*(MIN(1,Energy_Sector.Total_Energy_Production/Capital.Capital_Energy_Requirement)) ELSE Capital.Capital

Product = Initial_Product*((Population.Population/INIT(Population.Population))^(1-Gama))*(IF Energy_Feedback_Switch=0 THEN ((Capital.Capital/INIT(Capital.Capital))^Gama) ELSE (Operational_Capital/INIT(Capital.Capital))^Gama)*(Technology.Technology/INIT(Technology.Technology))

Production_Capital_Investment = Capital_Investment_Fraction-Energy_Inv_Final

Energy_Capital_Investment_Fraction = GRAPH(Operational_Capital/Capital.Capital)

(0.85, 99.0), (0.868, 90.0), (0.886, 80.0), (0.904, 65.0), (0.921, 50.0), (0.939, 35.0), (0.957, 25.0), (0.975, 15.0), (0.993, 10.0), (1.01, 1.10), (1.03, 1.00), (1.05, 0.8), (1.06, 0.4), (1.08, 0.2), (1.10, 0.00)

Technology:

Fractional_Technology_Growth_Rate(t) = Fractional_Technology_Growth_Rate(t - dt) + (-Technology_Growth_Rate_Decline) * dt

INIT Fractional_Technology_Growth_Rate = 0.015

OUTFLOWS:

Technology_Growth_Rate_Decline = Fractional_Technology_Growth_Rate*Fractional_Technology_Growth_Rate_Decline

Technology(t) = Technology(t - dt) + (Technology_Growth_Rate) * dt

INIT Technology = 1

INFLOWS:

Technology_Growth_Rate = Fractional_Technology_Growth_Rate*Technology

Fractional_Technology_Growth_Rate_Decline = IF Useful_Work_Hypothesis_Switch=0 THEN 0.011 ELSE IF TIME>2015 THEN 0.011*Fractional_Technology_Growth_Rate_Decline_Multiplier ELSE 0.011

Fractional_Technology_Growth_Rate_Decline_Multiplier = 5

Useful_Work_Hypothesis_Switch = 1

11.2 Model Calibration

Short overview of the model calibration for the few basic variables. Model is able to recreate historical development of the selected variables reasonably well. Explanation of the short term fluctuations (eg. oil embargoes) cannot be reasonably expected.

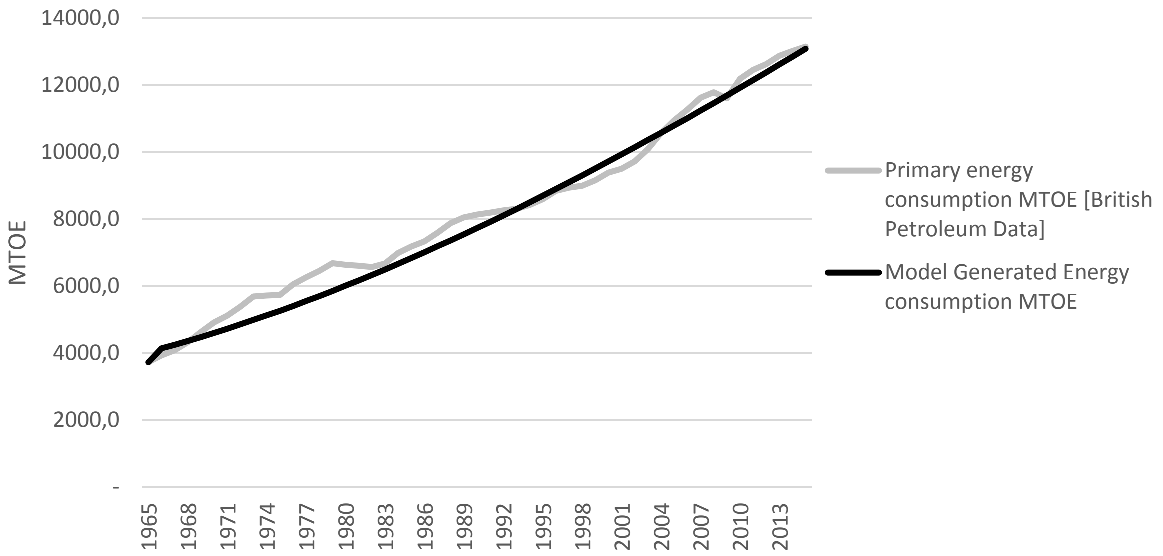

Figure 55 – Primary energy consumption, real world vs. model generated. Source: own work.

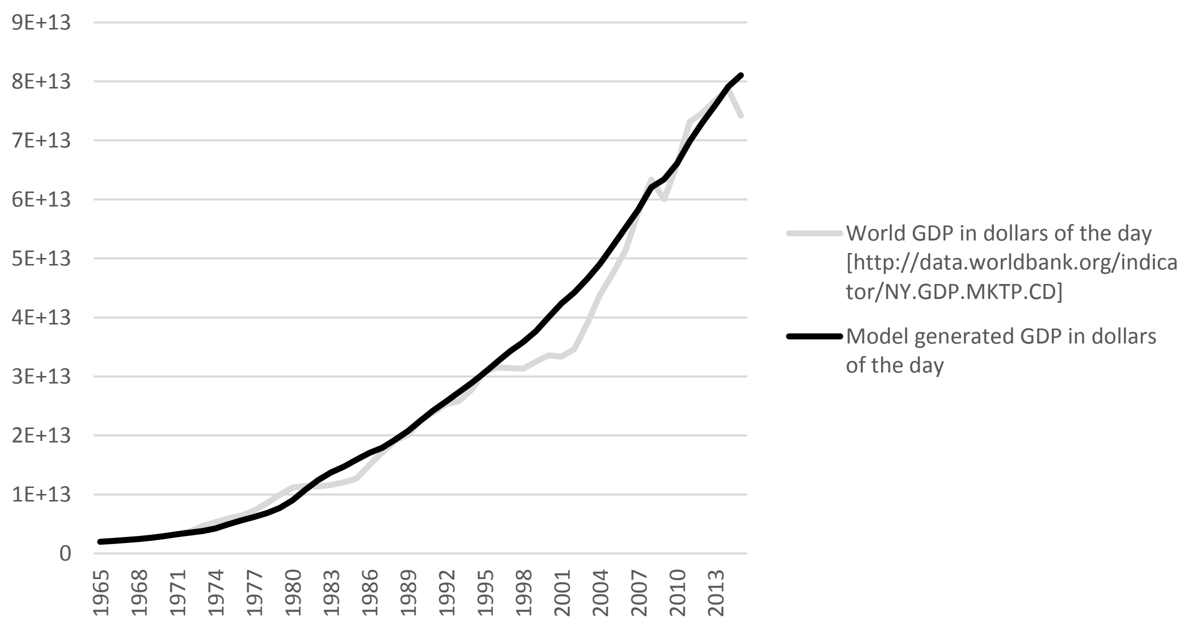

Figure 56 – World GDP, real world vs. model generated. Y axis – dollar of the day, Source: own work.

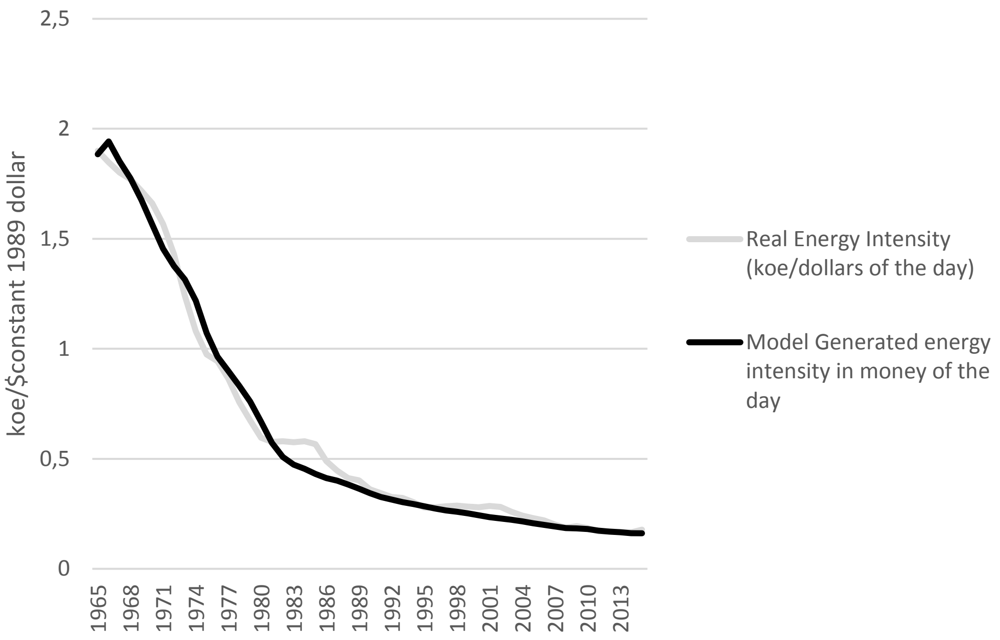

Figure 57 - Energy intensity of product, real world vs. model generated. Source: own work.