The SUSCLIME model
Exploring adjustment of behaviour to climate change and resource depletion

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Master's thesis Energy Science

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Master's thesis project *The SUSCLIME model - Exploring adjustment of behaviour to climate change and resource depletion* by Chris Roorda. This thesis project is conducted in partial fulfilment of the Master of Science programme *Energy Science* at the Utrecht University, Utrecht, the Netherlands.

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Abstract

In this thesis, a highly stylized population-economy-energy-climate system dynamics model is constructed: the SUSCLIME model. The model is applied to illustrate the process of climate change, resource depletion and transition towards non-fossil energy sources by varying the initial settings for archetypical regions.

SUSCLIME describes the dynamics of a population, economy, energy and climate system and their mutual interaction. Central elements of the energy system are the depletion effect for fossil energy and learning-by-doing for renewable energy. The market share of the supply options is determined by their relative prices and therefore the price development causes a transition from fossil to renewable energy. The climate system describes temperature change caused by fossil fuel use and the resulting impact on the economy. The economic system deals with the balance between short-term benefits of expenditures for consumption and long-term benefits of investments for production.

The model-world consists of a limited number of regions (in this thesis 1 or 2). Two archetypical region settings, representing a "poor" and a "rich" region are used for exploration of the process of resource depletion and climate change. The model behaviour is analysed under varying parameter settings.

SUSCLIME is further extended with forward-looking agents to explore the process of adjustment of behaviour when the effects of depletion and climate change are foreseen. The agents try to maximize the welfare level of a region by applying carbon taxes or subsidies for renewable energy.

The agents can be successful in reducing the impact of sudden depletion and climate change. They have to balance short term intervention costs and long-term impacts. Agents with short time-horizon are less successful then agents with long foresight. Poor regions have to deal with relatively higher intervention costs and therefore postpone intervention. In such cases, investments by rich regions in poor regions might be advantageous.

Despite its high level of abstraction, SUSCLIME is a useful tool for the illustration of the process of climate change and resource depletion. The implementation of agents in this model is a valuable example of inclusion of human response to changing circumstances in a global model. Both SUSCLIME and the implementation of agents can be easily extended for specific purposes in further research.

Contents

1 Introduction

1.1 Background

1.1.1 Climate change

The issue of climate change has gained wide public attention during the last four years. Scientists and a selected group of policy makers were already dealing with this problem for decennia, but it only recently gained momentum among the general public. Climate change is put in the spotlights by the alarming reports from the Intergovernmental Panel on Climate Change (IPCC), the movie *An inconvenient truth* by Al Gore and the supposed relation with remarkable hot summers and the hurricane Katrina.

One of the most influential reports next to the IPCC reports is the *Stern Review on the Economics of Climate Change.* The report estimates investments necessary to avoid the worst effects of climate change and the magnitude of the impact that climate change can have on economic development. The main conclusion is that costs of wait-and-see policies are high and strong climate policies are profitable.

Climate change is a global problem and needs a global effort to come to a solution. The Kyoto protocol was a first attempt for international cooperation in prevention of climate change. Subsequent climate conferences try to set more ambitious targets for a new agreement in 2009. The allocations of costs and efforts is subject to a heavy debate. An interesting aspect in this discussion is the contrast between low-income and high-income regions. The carbon emissions of the high-income regions contribute most to the problem, while in general the highest impact is expected in the low-income regions.

1.1.2 Resource depletion

Fossil fuels (oil, gas and coal) are essential in a modern society. Fossil energy fuels the transport sector needed for the global economy and increases productivity of the industry by enabling a high level of mechanization. Also in daily life people profit from the availability of fossil fuels: they use it to drive their cars, heat their houses, cook their food and need it indirectly for the production of all goods they consume.

People are used to the situation that fossil energy is abundantly available at low costs. However, fossil resources are limited. The demand for fossil energy keeps increasing, while the rate of discovery of new fossil resources decreases and the existing production sites become depleted. This will lead to scarcity and the rise of energy prices and increasing dependency on a few production regions.

On the other hand, alternative energy sources such as wind and solar energy go through a face of rapid development. The production costs decrease due to learning and their market shares multiply quickly – although their absolute shares remain marginal. The price development can lead to a energy transition from fossil to non-fossil energy carriers.

The speed of this process is subject to discussion. Will fossil energy prices gradually increase and alternative energy sources replace fossils as their prices become competitive? Or will the world face rapid energy price increases and suffer from impacts on its economy, as the peak-oil movement predicts?

1.1.3 Response

The insights about climate change and resource depletion not only lead to debate about the cause and severity of the issues, but also to development of strategies to avoid the problems.

Policy makers can for example apply subsidies and taxes to influence the energy market and stimulate the use of non-fossil energy and efficiency measures, or invest in technology development of alternative energy sources.

Despite the evidence of the costly impact of climate change and resource depletion, policy makers do not show the leadership that is needed to promote an energy transition. The 'wait and see' policies might be supported by erroneous insights in the underlying dynamics of the problems.

This thesis constructs a tool to gain insight in these system dynamics. This tool, the SUSCLIME model, illustrates the process of climate change, resource depletion and transition towards non-fossil energy sources. SUSCLIME is further used to explore the process of adjustment of behaviour when the effects of depletion and climate change are foreseen.

1.2 Modelling

1.2.1 Poor understanding of system dynamics

Central elements of energy and climate models are basic stock-flow dynamics and feedback loops. Most people have a poor level of understanding of these dynamics, even though they are confronted daily with them. Common examples include bathtubs that accumulate the inflow of water through the tap less the outflow through the sink and bank accounts that accumulate deposits less withdrawals.

A research of Sterman and Booth Sweeney points out that high-educated people with essentially no prior exposure to system dynamics concepts have a poor level of understanding of stock and flow relationships and time delays ([Sterman, J.D. and Booth Sweeney, L., 2000]).

In this research, students at the MIT Sloan School of Management are asked to draw the time path for the quantity in the stock, given a flow. The task is given in a very concrete way, the stock is represented by either a bathtub or a cash account.

The results were very poor: one fifth of the students did not correctly show the stock rising when the inflow was greater than the outflow. More than a fifth failed to show the stock rising and falling linearly during each segment, though the net rate was constant. Nearly two fifths failed to relate the net flow over each interval to the change in the stock.

The authors extended their research to the understanding of the central principles behind climate change ([Booth Sweeney, L. and Sterman, J.D., 2007]). They gave 212 graduate students at MIT a description of the relationships among greenhouse gas (GHG) emissions, atmospheric concentrations, and global mean temperature. Participants were then asked to sketch the emissions trajectory required to stabilize atmospheric CO2.

Nearly two-thirds of the participants asserted that atmospheric GHGs can stabilize even though emissions continuously exceed removal—analogous to arguing a bathtub continuously filled faster than it drains will never overflow. Most believe that stopping the growth of emissions stops the growth of GHG concentrations.

The subjects of this research were high-educated students, a large share even in the field of technology and mathematics. This feeds the expectation that the general public does in majority not understand the basic dynamics between emissions, concentrations and temperature. Wait-and-see policies are supported by the erroneous belief that stabilizing emissions would quickly stabilize the climate.

Models can be used as a gaming tool to make people familiar with the long-term dynamics and feedbacks in the economic, energy and climate systems. For this reason, the SUSCLIME model is originally constructed.

1.2.2 Modelling: Stylised relations to represent dynamics

The use of models in science has become popular due to the rapid development of the personal computer during the last decennia – which made high speed computing available to every researcher. Instead of expensive or dangerous experiments in real life, a scientist can now run model experiments.

A model can basically be designed by first formalizing the objects of the system under consideration and the relations between them, then formulating the system dynamics in a computer or modelling language and finally calibrating the model constants to collected data. The model can be used for experiments by varying relevant variables in the model.

Models are used for various purposes, ranging from prediction to explanation. Models used for prediction are models that should produce (quantitatively correct) predictions depending on its input values, like weather forecasting models. Models designed for explanation and exploration provide qualitatively significant results that are sufficient for understanding the reaction of the system to input values. The SUSCLIME-model that is the subject of this thesis is an example of this type.

Simulation – the use of models for experimentation - is often preferred over regular experiments. Simulation makes it possible to experiment with systems of which the time scale or spatial scale is too large for observation, like the climate system or the formation of the solar system. It also gives the unique opportunity to experiment with systems that should not be disturbed or even harmed by experiments, for example the spread of an epidemic or the risk assessment of a nuclear power plant.

Models can also be a valuable tool in communication of scientific knowledge. With an appropriate interface, users can visualize the outcome of a model and get a feeling for the system dynamics by experiencing direct feedback of the adjustment of input variables.

Just like with statistics, a thread related to simulation is that models can be falsely applied to "proof" everything a researcher wants to. It is therefore important to realize that the value of a model is dependent on the reliability of the underlying theories and data. A model can be an important element in a scientific approach, but is never a final objective on its own.

1.2.3 The use of agents

This research is set up to contribute to the inclusion of individual-based elements in energy-climate models. The interaction between the energy/climate system and mankind must not be presented only one way, mankind influencing its environment, but also include adjustment of behaviour according to (incomplete) information and expectations about the environment and the actions of others.

Agents sense, decide and act. An agent gets information about the state of the environment, the macro-model which is in this case SUSCLIME. A set of decision rules using this input determines the agents' behaviour, which in turn influences the environment.

Agents commonly work with the principle of maximum expected utility [Vidal, 2007]. The agent's preferences are captured by a utility function, not necessarily in monetary terms. This function provides a map from the states of the environment to a real number. The bigger the number the more the agent likes that particular state. The agent uses a range of possible actions or policies to test to which expected state each choice would lead. The agent's goal becomes that of finding its optimal policy which is the one that maximizes its expected utility.

Agent models have a wide range of purposes: from speech recognition to directing enemies in computer games, from the use in information systems to logistical planning.

A term associated with agent models is self organization. A system with a large number of agents using simple algorithms for behaviour on micro-level can produce patterns at macro-level. Examples are flocking of birds (see e.g. [LaLena, 2008]) and the emergence of vegetation patterns [Rietkerk *et al*., 2004].

The use of agents in this thesis is different: it is about the interaction between the macro-model and the agents. The number of agents is limited, in this report to only one or two. The agents are implemented in a simple population-economy-energy-climate model to represent governments that can adjust their behaviour to information and expectations about the environment. The use of agents also makes it possible to implement differences in attitude and expectations.

1.3 SUSCLIME

1.3.1 Basic model description

This thesis introduces the SUSCLIME model. This is a system dynamics model that describes, in highly-stylized form, dynamics of population, economy, energy and climate and their mutual interaction.

The model-world consists of a limited number of regions (in this thesis 1 or 2). Two archetypical region settings, representing a "poor" and a "rich" region are used for exploration of the process of resource depletion and climate change. The model behaviour is analysed under varying parameter settings.

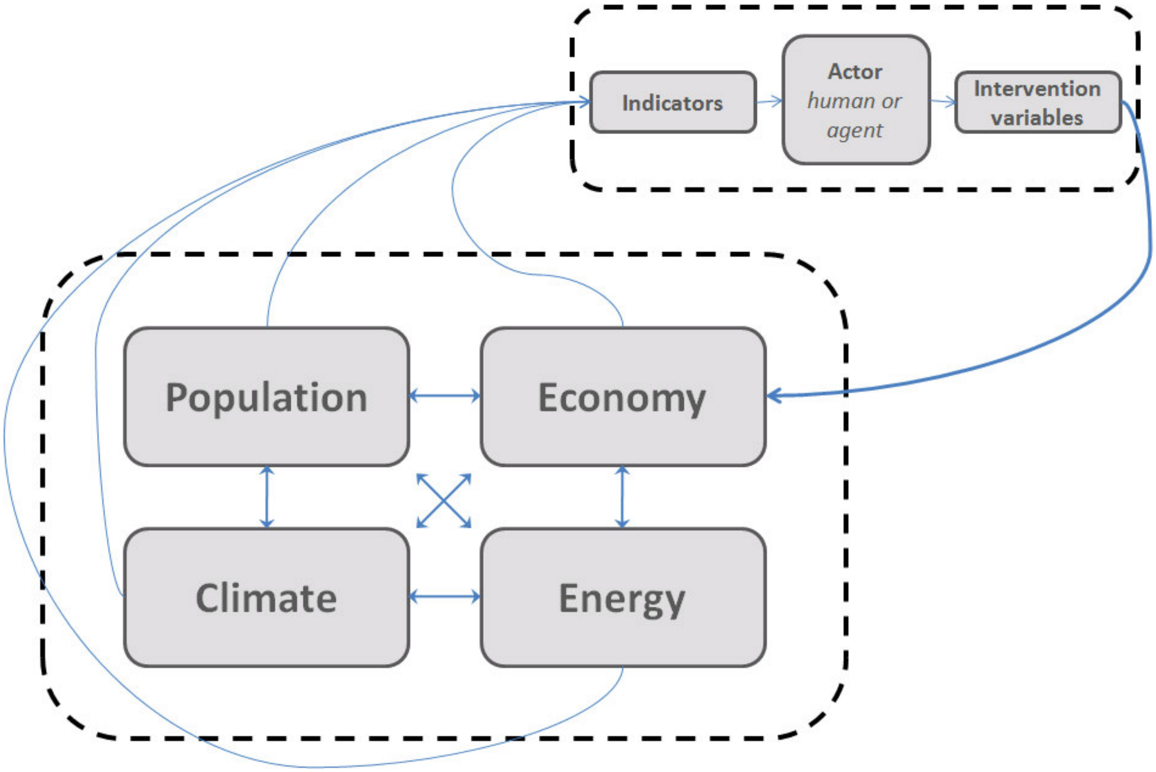

figure 1 Overview of the modules in SUSCLIME

Figure 1 sketches a basic overview of the "building blocks" of SUSCLIME, as briefly explained below.

The process of demographic development for a region is represented in SUSCLIME by a population system. An economy system describes the dynamics of production and consumption.

Economic activities require energy. Energy is supplied by producing fossil energy or by a non-carbon form of energy from a renewable source like wind or sun.

The use of fossil energy is associated with depletion, which leads to increasing energy costs and sudden energy shortage. The use of renewable sources is initially more expensive, but due to learning the costs reduce as the production increases. Because of the development of the relative costs, an energy transition towards renewable energy takes place.

The use of fossil energy furthermore causes CO_2 emissions, which contribute to the enhanced greenhouse effect and lead to climate change. Climate change in turn has a negative impact on the economic system.

The model functions as stand-alone model, but can also be used in a game setting. In that case, human players administrate a region. They get information about the state of the model via indicator and use the information to decide upon the use of interaction variables, such as subsidies and taxes.

In this report, the regions in the model are not governed by human players, but by automated agents. The agents replace the human players by making decisions upon the interaction variables for their region, based on expectations for the development of the indicators. In this way, the process of adjustment of behaviour is explored when the effects of depletion and climate change are foreseen.

When constructing the model and especially choosing the settings for constants and archetypical regions, this use with external decision makers played a central role. The model is set up such that it gives clear response to changes in policy within a limited time period.

This thesis does not consider interaction between regions – the model is only run for one region at the time. An exception is made in case of trade (paragraph 3.3). By default, the model is run for the period 1990-2050.

SUSCLIME is implemented in M, a programming language developed by the Netherlands Environmental Assessment Agency ([van Wijk, 1997]). The agents are implemented using the MatLab software package ([MathWorks, 2004]).

1.3.2 Use in the past

The SUSCLIME model [de Vries, 1998] was originally constructed to educate students and policy-makers on the dynamics of resource depletion and climate change and to explore the options for policy in a multi-region world with differences in resource base and climate impacts. SUSCLIME simulates development of population, economy and energy systems of a set of (hypothetical) regions. These regions are linked via energy trade, feedbacks from climate change and transfer of knowledge on non-carbon energy technologies.

The model was developed as a game, in which human players represent the governments of the regions and allocate every five year investments among different parts of the economy and the energy system.

The original game-version of SUSCLIME is used as starting point for the development of the current model. For this thesis SUSCLIME is re-modelled from scratch, using - but often adjusting - the ideas from the game-version. This thesis analyses the behaviour of the model step by step. Two major changes have been made to the original model structure.

First, the allocation of investments is based on several *decision rules* that can be influenced by *intervention variables* (policy options). The decision rules make that SUSCLIME can run independently, without the need for players or agents needed to make decisions. The use of intervention variables, such as subsidies and taxes has a clear parallel to the real world.

The second major change is the introduction of automated agents. These agents each control a region and can apply several policy measures and look forward to assess the consequences of their intervention with respect to depleting resources and climate change. The agents replace the human players in the game.

The former version of SUSCLIME was implemented in the STELLA model. Many model relations like depletion and learning were defined by sketching the graphs of the functions. In this new version, these relations are stated in a mathematical formulations that comply wiith other models.

1.4 Research question

The research goal is to *create a population-economy-energy-climate system dynamics model that illustrates the process of climate change, resource depletion and transition towards non-fossil energy sources, and to implement forward-looking agents in this model to explore the process of adjustment of behaviour.*

The following sub-goals are elaborated during the research:

- Reconsider the system dynamics of the current SUSCLIME model. Changes that will be considered are implementing aspects of other models available in literature, simplifying the model dynamics and re-aligning the constants.
- Step-by-step describe and illustrate the dynamic relations of the model in detail.
- Design and implement automated agents that can influence the model runs.
- Analyse the effect of using agents for model runs with climate change, resource depletion, or both.
- Analyse the differences between regions with different initial income level, regarding the impact of resource depletion and climate change as well as strategies to avoid this impact.

1.5 Outline of the report

The SUSCLIME model is described up step by step. The behaviour of the model is analysed with each newly introduced model feature. For the intermediate model results, text boxes are used between the paragraphs.

The most basic version of the model includes only a population and economic system (chapter 2). Then an energy demand function is added, and the possibility to produce energy from fossil fuels (paragraph 3.1).

Paragraph 3.2 introduces alternative energy options. The productivity development of fossil energy (with depletion effect) and renewable energy (with dominant learning effect) is compared and the SUSCLIME model is extended with transition dynamics. Also the option of energy efficiency investments is introduced.

In chapter 4, the model is further extended with the effect of climate change and the possibility of trade between regions.

Chapter 5 finally introduces and analyses agents that decide on the use of intervention variables like subsidies and taxes for a region. The agents adjust their behaviour to the circumstances and base their decisions on incomplete information.

The discussion (chapter 6) and summary and conclusions (chapter 7) complete the report.

2 SUSCLIME model – economic system

2.1 General description

The process of demographic and economic development is represented in SUSCLIME by a population stock (*Population*) and the capital stocks of goods producing capital (K_P) and consumption capital (K_C). K_P represents factories, machines, tractors etc. –capital that is used for production. K_C symbolises all capital that is used to provide welfare services, e.g. televisions, cars and houses. Depreciation of all capital stocks is an exponential decline function. Population growth (δPop) decreases with increasing welfare.

In SUSCLIME, per capita consumption C is a derivative of K_C. Goods production (Q) is determined by the per capita values of K_C and K_P. Goods production is invested in the capital stocks according to an allocation that can be set by an agent, a human player or a set of decision rules.

To operate the economic capital stocks, energy (*E)* is required. Demand for energy to run the economic capital stocks K_C and K_P evolves as a function of C in the form of an average energy-intensity ε, which can be decreased by investing in energy efficiency (E_{Eff}).

Energy is supplied by a capital stock producing fossil energy (K_{Fos}) - for practical purposes limited to one source: oil. Alternatively, energy can be supplied by non-carbon form of energy from a renewable source like wind or sun (K_{Ren}). In a multi-region world, trade (import *M* and export *X*) in fossil fuels is another option for energy supply.

The use of fossil energy causes CO_2 emissions, which contribute to the enhanced greenhouse effect and lead to climate change (*CC*). This influences the life time of all capital stocks and the productivity of the goods production and consumption capital producing stocks. Figure 1 shows the most important dynamic relations in the SUSCLIME model.

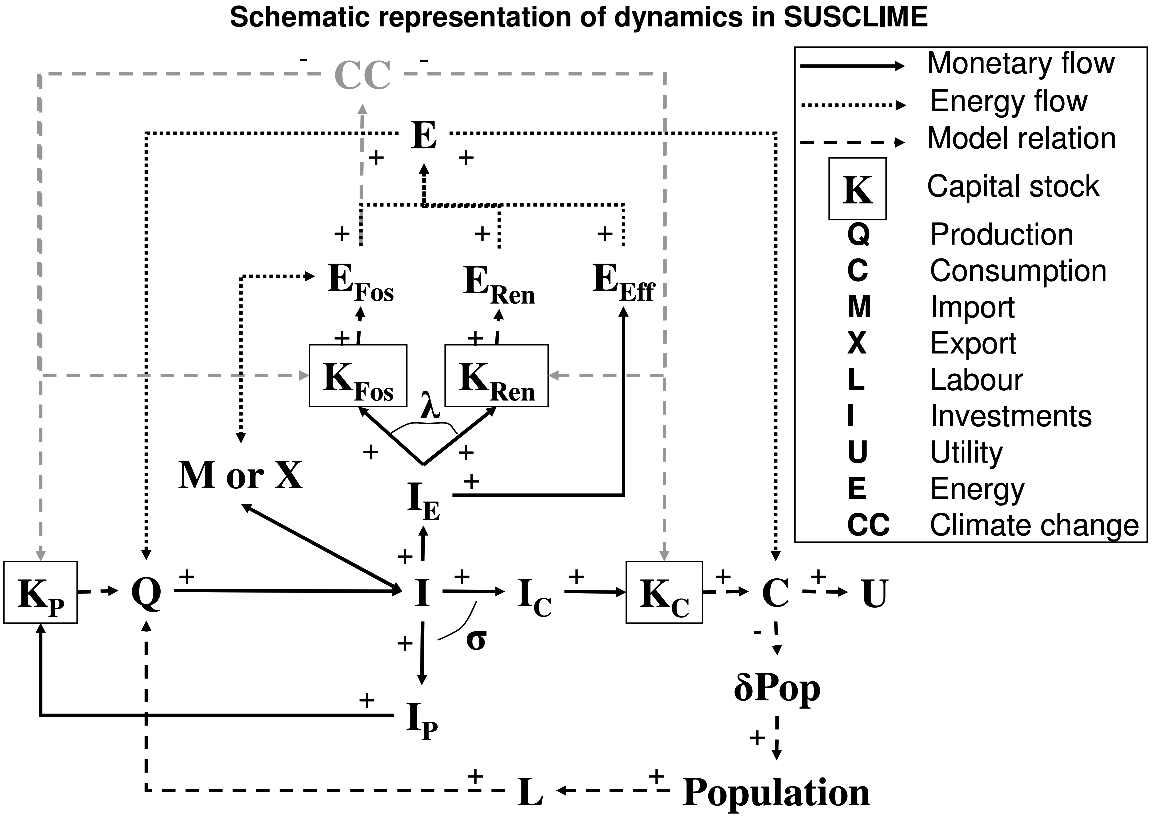

figure 2 Dynamic relations within a region in the SUSCLIME model

To use such a simple model to represent a region's population and economy system does not permit any form of meaningful quantitative validation with real-world events. SUSCLIME is meant for explanation and exploration purposes, for a qualitative understanding of systems dynamics.

Therefore, model relationships are introduced which at least represent some of the aggregate meta-relations, or 'stylized facts', which can be established from a time-series cross-country data base as provided by the World Bank (WDI) [1]. As explained in the respective paragraphs, the dynamics for climate change and demand and supply of energy are also based on existing models and data-series, simplified and converted to fit the SUSCLIME model.

2.2 Capital stocks

Stocks and flows are used for all types of capital investments in SUSCLIME. The stocks represent the amount of installed capital, the flows investment and depreciation.

All capital stocks in the model are modelled identically: each time-step, the existing capital stock is updated by adding investments (*I*) and subtracting depreciation (*D*):

i. $$K_{(t)} = K_{(t-1)} + I_{(t)} - D_{(t)}$$

---

[1] See for instance the IFs model [Hughes, 1999] for a similar use of aggregate relationships based on correlations.

The investment (*I*) is a fraction of last year's goods production *Q* (paragraph 2.3.3). The allocation of the goods production is determined by decision rules as introduced further on in this thesis. Depreciation of capital is represented as an exponential decay function of capital lifetime (*LT*). The lifetime for all capital stocks is by default set at 10 years, but can be affected by climate change (see paragraph 4.1.2).

$$D_{(t)} = \frac{K_{(t-1)}}{LT_{(t)}} \tag{ii.}$$

If the investments are constant, the capital stock stabilises at a value of $K = I * LT$. The use of stocks and flows leads to a delay in the model. For example, if no investments are made, the stock will lose half of its value every seven years[2]. Figure 3 shows the development of the stock size and investments over time for three example investment paths.

In all three examples, the initial stock size is 1000 goods. The first 10 years the stock size is kept stable by keeping investments at 100 goods per year but then the investments change. Two investment paths represent a sudden halving or doubling: the investment is constant 50 or 200 goods per year. The third example lets the investment growth linearly from 100 to 200 goods per year in 25 years.

These examples illustrate the inherent delay due to the use of stocks and flows.

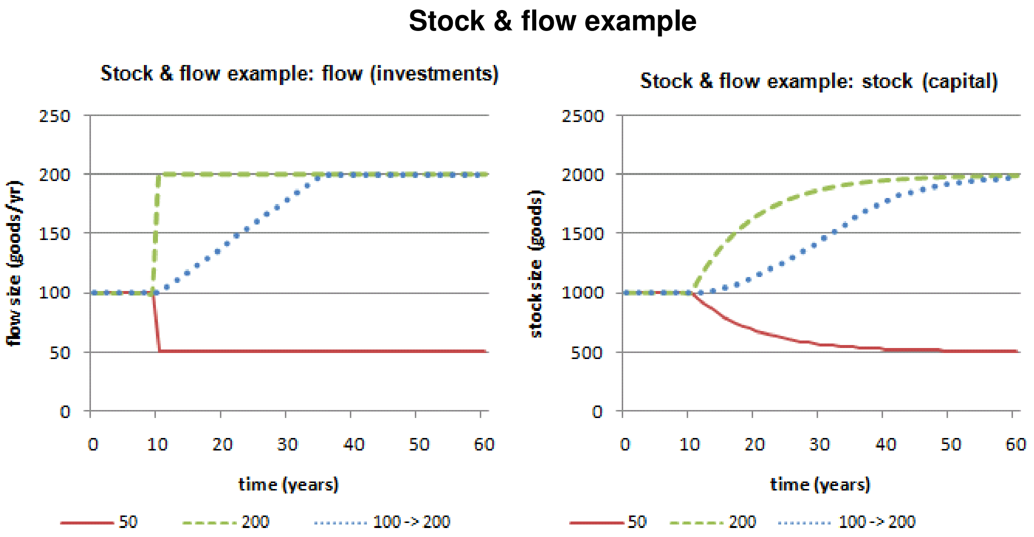

figure 3 Stock size and investments over time for the three example investments paths.

2.3 Population and economy

2.3.1 Population

In SUSCLIME, population growth is assumed to be a function of consumption level: poor regions have a higher population growth than rich regions.

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[2] Without investments, $dK/dt = -1/10\ K$, thus $K_t = K_0\ e^{-1/10\ t}$. K has lost half its value at a t for which $e^{=1/10\ t} = 1/2$, thus $-1/10\ t = \ln(1/2)$. Then $t = \ln(1/2)/(-1/10) = (\ln(1)-\ln(2))/(-1/10) = 10\ \ln(2) \approx 7$.

The function for population growth in SUSCLIME is derived from historic data available in the World Development Indicators reports (WDI) of the World Bank [World Bank, 2007]. Figure 4 plots the yearly population growth (in %) countries against the Gross Domestic Product per capita (GDP/cap, ppp-corrected, in thousands constant 2000 international $). Only countries with more than 5 million inhabitants in 1990 are taken into account, in total 92 countries.

The data suggest that a power-law decline in population growth as a function of income is a reasonable assumption. In SUSCLIME, the following formulation is used:

iii. $$Population_{(t)} = Population_{(t-1)} \cdot (1 + \delta Pop_{(t)})$$

iv. $$\delta Pop_{(t)} = 0.03 \cdot C_{(t)}^{-0.6}$$

in which *C* represents per capita consumption (goods per capita per year). This relation is plotted in figure 4, using a parallel between the income *C* in the model and the GDP per capita from the WDI-data by making 1 good correspond to 1000 US$.[3]

Dynamically, this part of the model contains the positive feedback loop that an increase in income leads to lower population growth, which will further increase the available income per capita. This corresponds to the demographic transition – as the welfare in a country increases, the death rates and, with a delay, birth rates will drop.

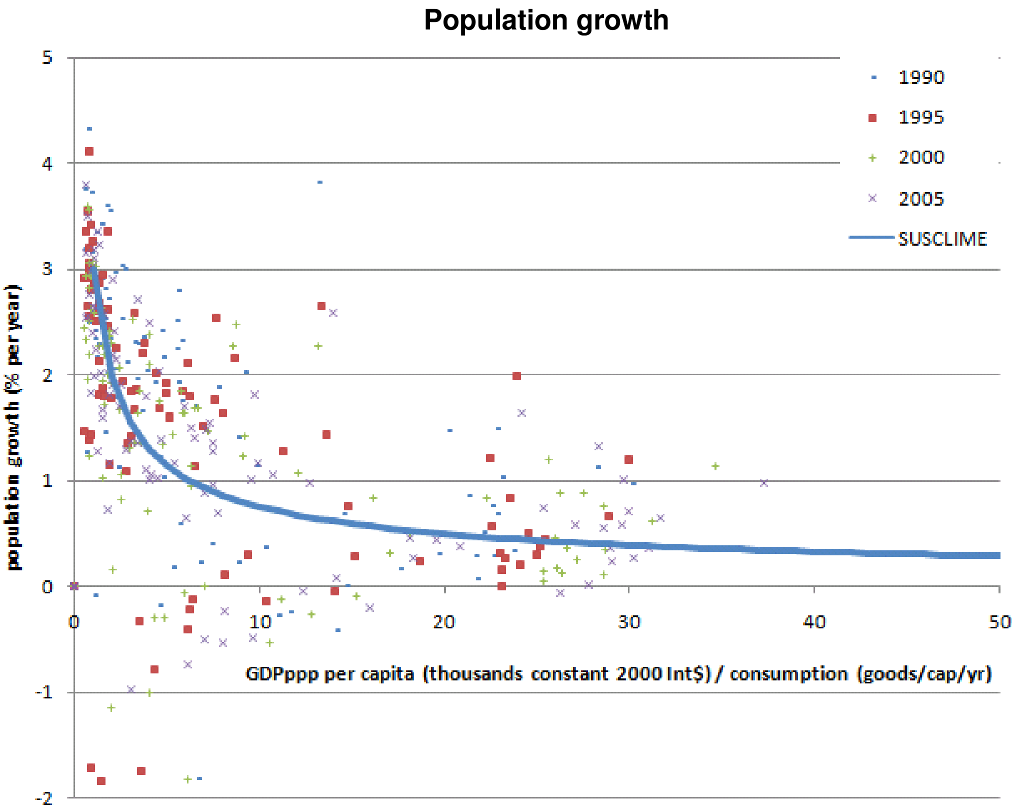

figure 4 The relation between population growth and GDP per capita (ppp corrected, in thousands constant 2000 international $) or, in SUSCLIME, consumption (goods/capita/yr). The dots represent statistical data for 92 countries in the years 1990, 1995, 2000 and 2005.

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[3] The example runs later in this chapter show *C* ranges from 0 to 70 in SUSCLIME. The WDI-data indicate the maximum GDPppp per capita is 54,000 US$ (Luxembourg in 2005).

2.3.2 Consumption capital

Consumption in SUSCLIME is not directly taken from production or income – as in most other macro-economic models – but indirectly via the investments in consumption capital that produces consumption of goods and services.

Consumption capital (K_C) represents all goods that provide welfare. It includes the aggregate of all the goods which are used for consumption, such as cars and televisions.

The capital stock K_C is associated with the delivery of consumption: each effective capital unit produces one consumption good per year. Consumption C equals the amount of consumption goods per capita per year.

v. $$C_{(t)} = \frac{K_{C(t)} \cdot f\left(E_{S(t)} / E_{D(t)}\right) \cdot g\left(CC_{(t)}\right)}{Population_{(t)}}$$

The effectiveness of consumption capital K_C can be affected by two factors. First, energy is needed to operate it. If energy demand is not met, productivity decreases. Secondly productivity as well as the lifetime of the capital can decrease due to climate change. These two features are discussed in more detail in paragraph 3.1.4 and paragraph 4.1.2.

To account for the effect that consumption growth at higher consumption levels has less effect on the perceived welfare, the output variable utility (U) is used. Utility is defined as the natural logarithm of consumption (plus one, to make utility never negative):

vi. $$Utility_{(t)} = \ln(C_{(t)} + 1)$$

The relation between utility and consumption is illustrated in figure 5. Utility is only used as an indicator for objective functions (paragraph 5.3) and has no relation to other variables.

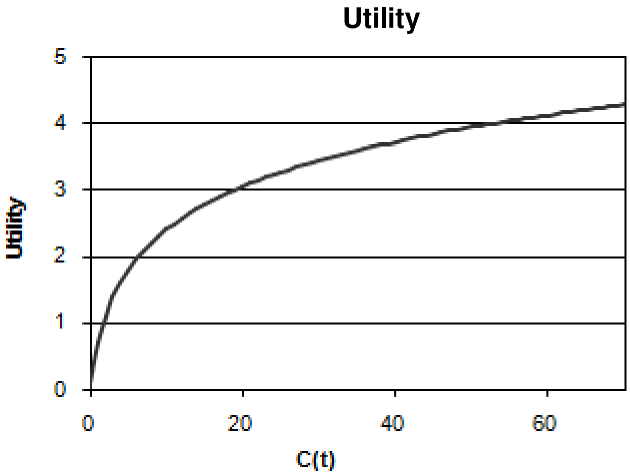

figure 5 Utility as function of consumption capital per capita.

2.3.3 Goods producing capital and goods production

Goods producing capital (K_P) represents all industrial capital that produces goods to be used for investment. It includes all the raw material exploitation (except for energy) and the processing and manufacturing of goods. Basically, it is the machinery and factories in an economy: tractors, food processing plants, car factories etc.

The size of K_P is not the only factor that determines production. Goods production (Q) is calculated as the product of labour productivity and the labour force. The labour force (L) is a fraction of the population, fixed at 25%. Labour productivity (Λ, in goods per labourer per year) is a function of goods producing capital (K_P), consumption capital (K_C), labour force, energy (E) and climate change impacts (CC), with a maximum value of Λ_{max}.

The factor that strongest influences labour productivity is the ratio between goods production capital and labour force, the K_P/L ratio. Figure 6a shows the productivity multiplier $\psi(K_P/L)$ as used in SUSCLIME. An increase in goods production capital per labourer will increase labour productivity but at a declining marginal rate.

This formalism of productivity as function of the K_P/L ratio is similar to the Cobb-Douglas two-factor production function in a conventional neoclassical growth model ([Cobb and Douglas, 1928])[4]. Many economic models also include a "technology factor", representing increasing economic opportunities and improving efficiency. This factor makes the overall productivity grow exponentially in time, and thus leads to unbounded economic growth. In SUSCLIME, such a factor is not included. As a result, goods production and income stabilise at a maximum level.

Another multiplier is introduced to reflect that a relatively poor labour force is not fully productive. This multiplier ξ is a function of the ratio between consumption capital and goods production capital, as plotted in figure 6b.

Similar to capital stock K_C, the effectiveness of K_P can be affected by two other factors: energy shortages and climate change. These two features are discussed in more detail in paragraph 3.1.4 and paragraph 4.1.2.

The factors influencing goods production are summarized in the following two formulas. The maximum labour productivity (Λ_{max}) is set at 40 goods per labourer per year.

vii. $$Q_{(t)} = L_{(t)} \cdot \Lambda_{(t)}$$

viii. $$\Lambda_{(t)} = \Lambda_{max} \cdot \psi_{(t)}(K_{P(t)} / L_{(t)}) \cdot \xi(K_{C(t)} / K_{P(t)}) \cdot f(E_{D(t)} / E_{S(t)}) \cdot g(CC_{(t)})$$

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[4] The Cobb-Douglas function states that $Q = A*K^{\alpha}L^{\beta}$, with A, α and β constants. Under the assumption of constant returns to scale, β equals $1-\alpha$, thus $Q = A*K^{\alpha}L^{1-\alpha}$. Since $\Lambda = Q/L$ this can be rewritten as $\Lambda = (A*K^{\alpha}L^{1-\alpha})/L = A*K^{\alpha}*L^{-\alpha} = A*(K/L)^{\alpha}$. Taking $A = \Lambda_0*120^{\alpha-1}$ and $(K/L)^{\alpha} = \psi(K_P/L)$, this gives the basic formulation structure in SUSCLIME. Note that $(K/L)^{\alpha}$ differs only slightly from figure 6a for $\alpha=0.8$.

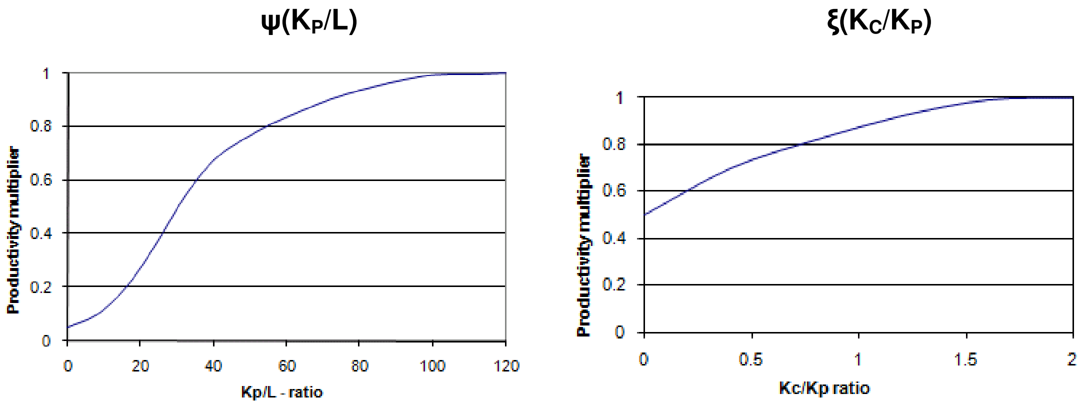

figure 6 *Productivity multipliers to express the influence of a) the K_P/L-ratio and b) the K_c/K_P-ratio on the labour productivity.*

All produced goods are invested during the next time step. Up to now, only two investment options have been introduced: investments in goods production capital and consumption capital:

ix. $$Q_{(t-1)} = I_{(t)} = I_{P(t)} + I_{C(t)}$$

In the course of this thesis, expenditures for energy production (I_{Fos} and I_{Ren}), efficiency (I_{Eff}) and energy import *(M)* will be added to the right-hand side of the equation. The left-hand side will be extended with revenues from energy export (*X*).

The demographic and economic dynamics alone make up a basic model. All relations in this basic model are illustrated in figure 7. In following chapters, energy use and production, trade and climate change will be incorporated in the model.

In this basic model the only decision variable is the savings rate σ, the share of I_P in the total economic capital investments I_C+I_P. Box 1 explores the model behaviour if the savings rate is fixed during the whole model run. Paragraph 2.3.4 introduces a decision rule for σ. The behaviour of the basic model with this decision rule is analysed in box 2.

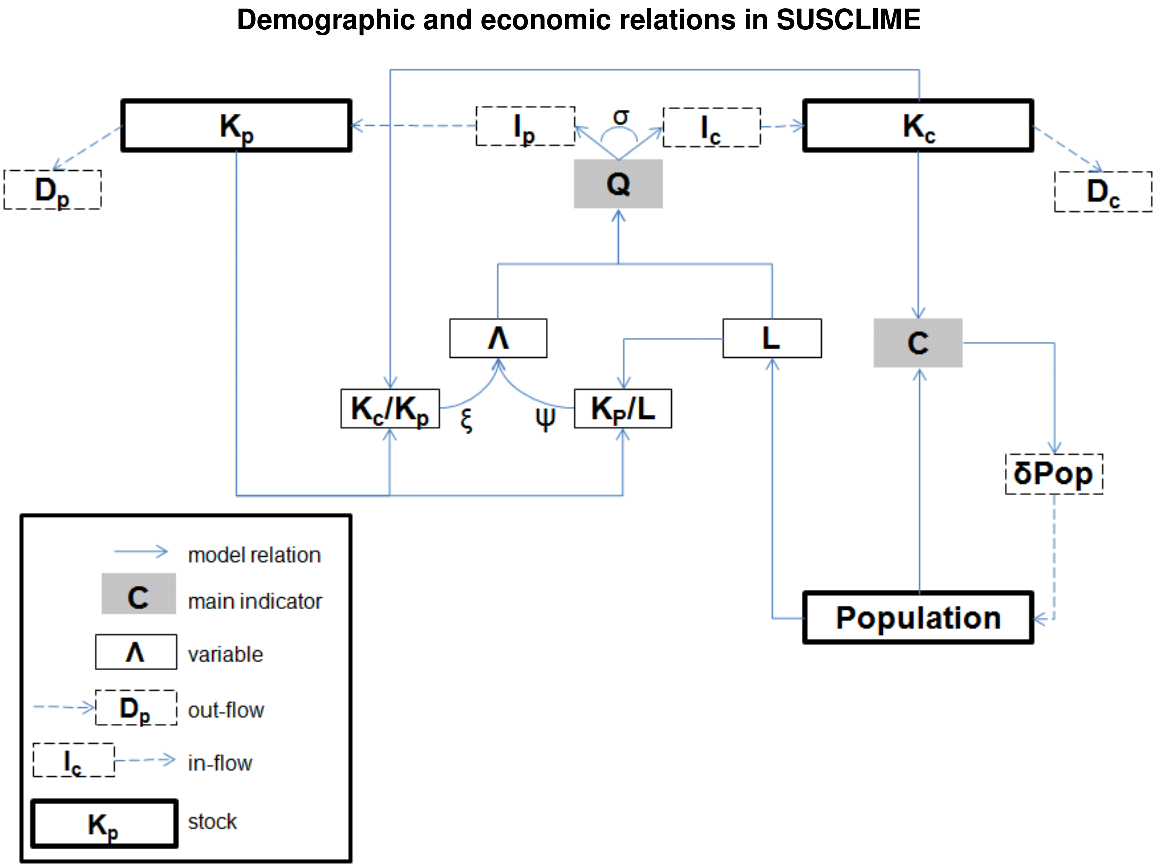

figure 7 Demographic and economic relations in SUSCLIME. The dotted lines and boxes represent flows, the large boxes the stocks. Production Q and consumption C are the main development indicators.

Box 1: Economic model with fixed savings rate

The description in the previous paragraphs makes up a basic model, including demographic and economic dynamics (see figure 7). The only decision variable in this model is the savings rate σ, the ratio between I_P and $(I_P + I_C)$.

The course of a model run depends on choice of σ and the initial setting of the stocks *Population*, K_P and K_C. To illustrate the influence of these variables, the model is run for several values of σ in the period 1990-2050. Each run, the value of σ is kept constant over the whole time period.

The initial per capita value for the total of the capital stocks is varied to represent regions with different levels of development. The ratio between the initial values of K_P and K_C is set at 1:1. Figure 8 shows the influence of the fixed value of σ on the consumption and labour productivity in the end year.

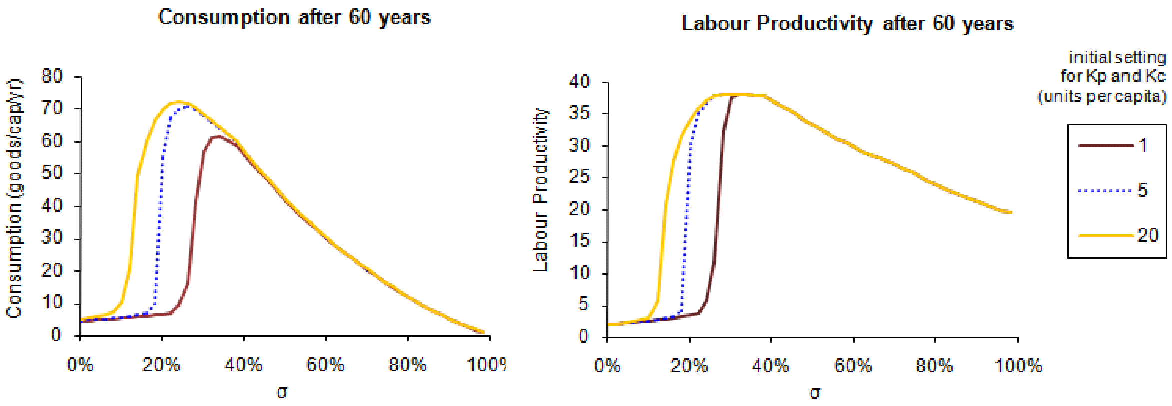

figure 8 Dependency of consumption (in 2050) and labour productivity (in 2050) on the choice of the savings rate σ, for several settings for the initial capital stocks.

For richer regions, the consumption in the end year is highest for a savings rate between 20% and 30%. The poorer a region starts, the more it needs to invest in goods capital in order to increase the labour productivity. Therefore the optimal savings rate is higher, up to about 40%.

The left figure shows the effect of σ on the consumption. When σ approaches 100%, no investment is made in consumption capital thus the consumption approaches zero. On the other side of the spectrum, σ approaching 0%, the lack of investment in goods capital will make the labour productivity drop to a minimum. But since this minimum is not zero (producing without capital is possible but highly inefficient), goods production will continue, enabling investments in consumption capital. The size of the capital stocks will decrease until the depreciation and investments balance.

Box 1: Economic model with fixed savings rate - continued

For a closer look on the labour productivity, the effect of σ at the multipliers ξ and ψ is indicated separately. As figure 9 shows, ξ has no effect when $\sigma < 40\%$ (Because then $K_c/K_p \approx (1-\sigma)/\sigma > 2$ –the labour force is satisfied with their share of the wealth). For increasing $\sigma > 40\%$, ξ makes the labour productivity decline gradually.

Multiplier ψ shows a strong dependency on σ near a critical value. Above this value, ψ will grow towards the maximum during the model run, below it will stabilize at very low rates. The critical value is dependent on both the initial settings and the duration of the model run: the poorer a region and the shorter the model run, the higher the critical value of σ for which labour productivity reaches its maximum. Poorer regions thus need a higher savings rate. In time a region gets richer and thus the optimal value for σ decreases. Since σ is now chosen to be fixed during the model run, the optimum after 60 years is a trade-off between a higher optimum value in the beginning and a lower optimum value in the end.

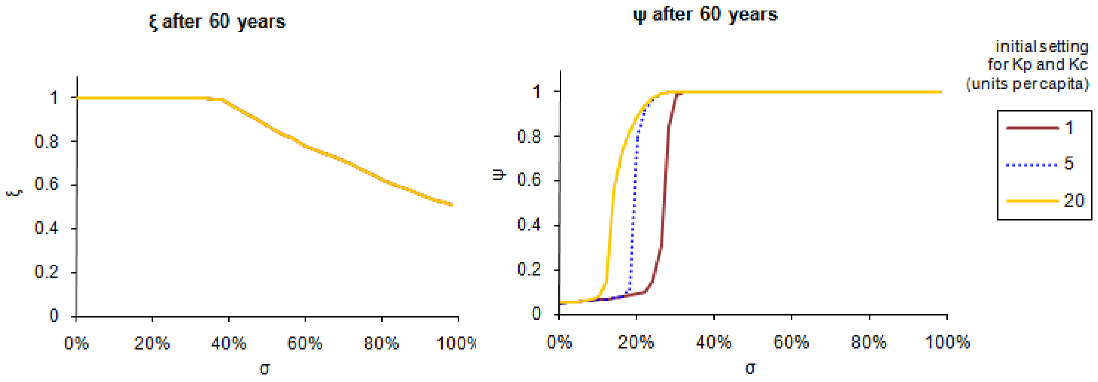

figure 9 Dependency of the multipliers ξ and ψ on the choice of the savings rate σ, for several settings for the initial capital stocks.

The figures below (figure 10) indicate the development of consumption and labour productivity in time for four model runs: σ is set at either 10% (low) or 40% (medium) and the initial capital stocks per capita is set at either 16 to represent a rich region or to 1.6 to represent a poor region. These figures illustrate that a low σ value first leads to higher consumption, but also leads to decreasing labour productivity which decreases production and – with a delay - consumption.

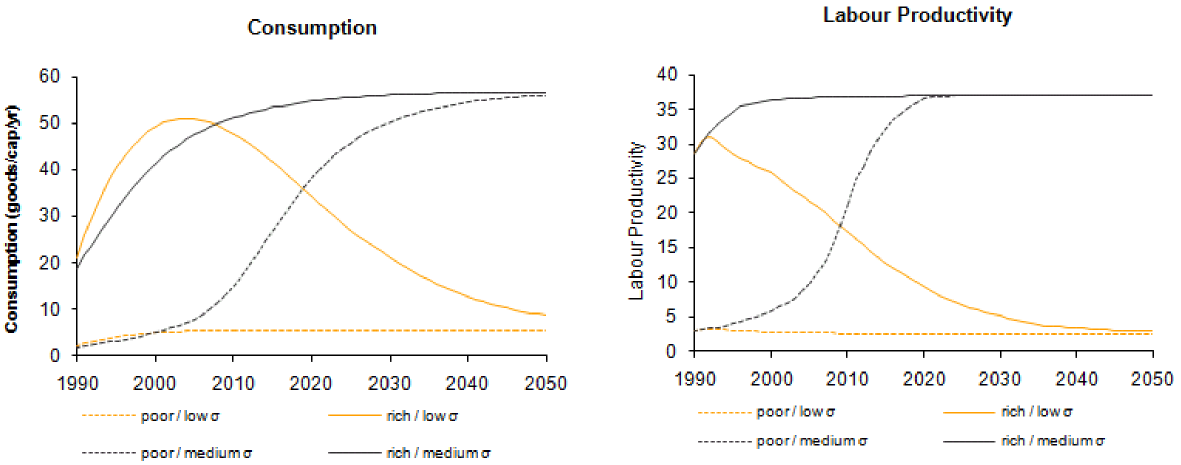

figure 10 Development of consumption and labour productivity in time for model runs with initial capital stocks of 1.6 (poor) resp. 16 (rich) units/capita for sigma set at 10% (low) and 40% (medium).

2.3.4 Automatic adjustment of savings rate

The savings rate *σ* is briefly introduced in the last paragraph as the share of I_P in the total economic capital investments I_C+I_P. This paragraph investigates ranges for *σ* and introduces a decision rule to adjust this variable to the development phase of a region.

A comparable (real world) indicator to *σ* is the Gross Capital Formation (GCF)[5] as fraction of the GDP, for which statistics are provided by the World Bank [World Bank, 2007]. Figure 11 shows the GCF-fraction for 90 countries[6].

On average, the GCF-fraction is around 20%. For countries that are in a stage of rapid development, like China and India, the GCF-fraction is generally higher (resp. 40% and 27% in 1995). In SUSCLIME, the savings rate *σ* typically ranges from 25% to 40%. Note that the parallel between the GCF-fraction and the savings rate holds only at a very stylized, conceptual level and the ranges for *σ* highly depend on the choices for the multipliers ξ and ψ.

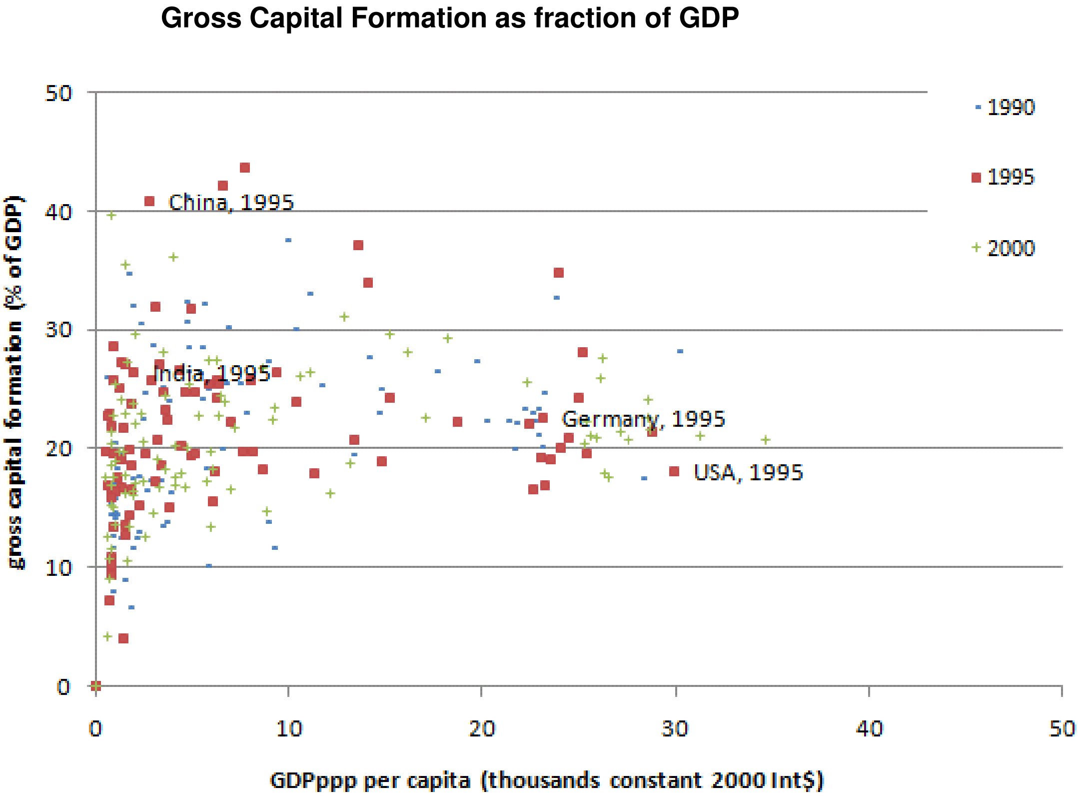

figure 11 The relation between Gross Capital Formation (% of GDP) and GDP per capita (ppp corrected, in thousands constant 2000 international $). The dots represent statistical data for 90 countries in the years 1990, 1995 and 2000.

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[5] Gross Capital Formation equals
acquisitions less disposals of new or second-hand tangible fixed assets (Machinery and equipment, dwellings, cultivated assets)
plus major improvements to existing fixed or natural assets, including land
plus acquisitions less disposals of intangible fixed assets (e.g., computer software)
plus changes in inventories (acquisitions less disposals of stocks held by producers)
plus acquisitions less disposals of valuables (precious metals or stones, expensive jewels, works of art, etc. held as investments)

[6] A country is taken into account if it has more than 1 million inhabitants, providing the GCF-data is available for that country.

The examples in box 1 keep σ fixed at a constant value during the whole model run. For a poor region, a higher value for σ is needed for the development of the region than for a rich region. Because wealth develops in time, σ should also develop in time.

To construct a time path for σ automatically, a decision rule is introduced. This decision rule is not meant to provide the unique optimal value, but to adjust the value of σ to the development phase of a region.

This rule is based on diminishing the difference between the productivity multipliers. As discussed in paragraph 2.3.3, labour productivity is influenced by both the K_P/L ratio via multiplier ψ and the K_C/K_P ratio via multiplier ξ.

Both multipliers have a maximum value of 1. Increasing σ leads to an increase of ψ and a decrease of ξ. Decreasing σ leads to the opposite. The procedure to automatically determine a value for σ is based on diminishing the difference between both multipliers:

x. **Decision rule 1:** $\sigma_{(t)} = \sigma_{(t-1)} + (\psi_{(t)} - \xi_{(t)}) / c_{speed}$

The value of σ will thus increase when $\xi > \psi$ and decrease when $\xi < \psi$. Ultimately, σ stabilizes at a value where both ξ and ψ approach 1 and labour productivity reaches its maximum. Several settings for the factor c_{speed} are tested below (figure 13), the default setting is 5. σ_0 is set at 0.4; the value of σ is furthermore limited between 0.1 and 0.6 to exclude extreme, unrealistic values.

This procedure regards labour productivity, but not the other main indicator in this economic model: consumption. As long as labour productivity is not affected, deceasing σ leads to increasing K_C and thus C. Therefore, a small adjustment to the procedure is made: when labour productivity almost reaches its maximum, σ is lowered by a fraction of a percent to start a process of finding a new equilibrium. [7]

The development of the savings rate σ as well as the indicators consumption and labour productivity is shown in figure 12. Two default regions are used: representing a "poor" and a "rich" region (see box 2).

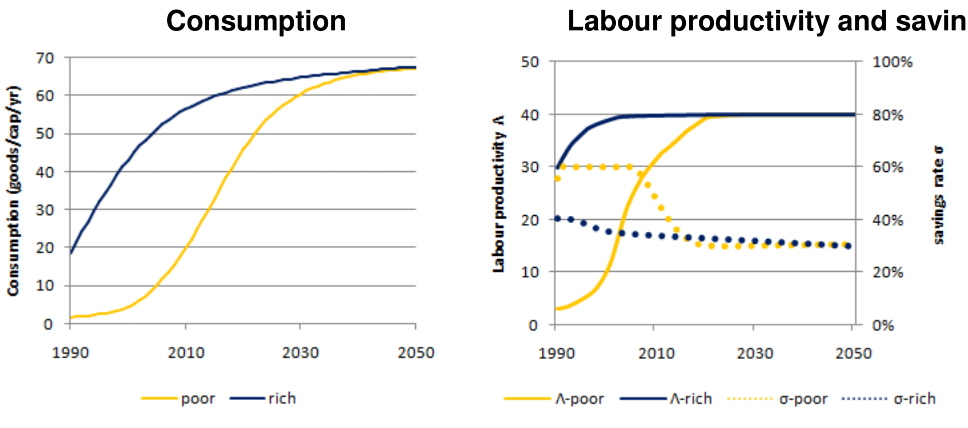

figure 12 Development of consumption, labour productivity and savings rate σ in time for model runs with initial capital stocks of 1.6 (poor) resp. 16 (rich) units/capita.

---

[7] When ξ>=1 and ψ>0.9995, σ is lowered by 0.001. A similar result would be achieved by adjusting the function for ξ, such that it always increases for increasing KC (now it reaches its maximum when KC/KP=2)

The initial settings of the capital stocks make the multipliers for the poor region start as $\psi=0.09$; $\xi=0.87$. First, σ rapidly rises to its upper bound of 0.6, until K_P has increased so much that $\psi>\xi$. Then σ drops, so that K_C/K_P and thus ξ can start to increase. At this point, the labour productivity is so high that K_P/L and thus ψ also keeps rising so that ψ remains higher than ξ. When both multipliers reach 1, σ stabilizes at 30%.

The rich region already starts at more developed stage. The initial values of the multipliers are $\psi=0.86$; $\xi=0.87$, but ψ rises quicker than ξ in the first years. Therefore σ is adjusted downwards in the first years. After ten years, both ψ and ξ have reached their maximum and σ is yearly decreased by 0.001. In this way, consumption is increased while the labour productivity is still at its maximum - until, in 2050, ψ drops below the value of 0.9995 and σ would again starts rising very slowly. Just as in the poor region, σ has (almost) stabilized at a value of 30% in 2050.

In comparison to the runs with a fixed σ of 40% (box 1), both regions have higher consumption in the end year because the investments in consumption capital are being increased when the labour productivity has reached its maximum. The poor region reaches the maximum productivity a few years earlier than with fixed σ, because σ is set higher in the beginning of the model run.

The factor c_{speed} is rather arbitrary set at 5. A higher setting for c_{speed} would make σ adjust more slowly; with a lower setting σ would adjust so fast that a temporally correcting oscillating behaviour would easily occur. Figure 13 shows the effect of variation of c_{speed} for a poor region – for which adjustment of the σ during the development of the region is most important.

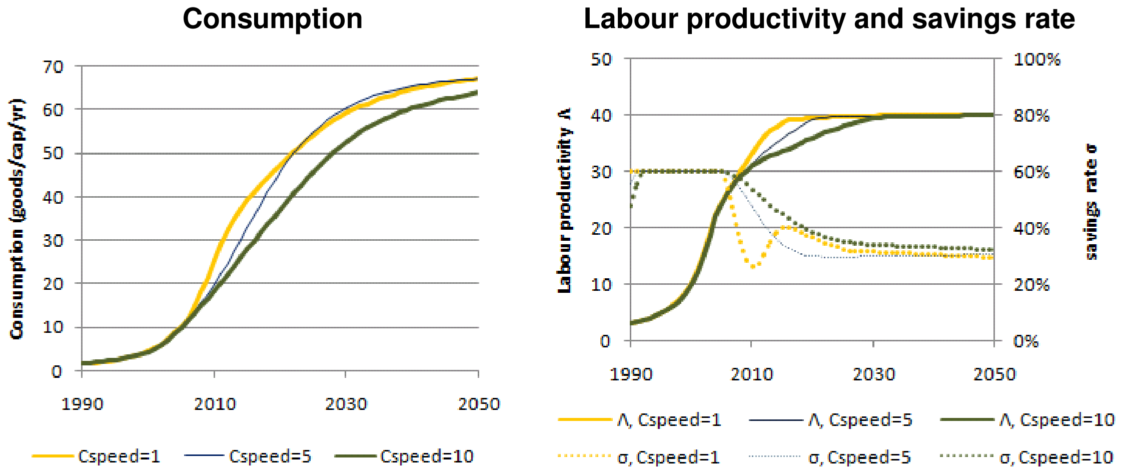

figure 13 The effect of varying the factor c_{speed} on the development of consumption, labour productivity and savings rate σ. The initial capital stocks are set at 1.6 to represent a poor region.

This paragraph shows that the decision rule (formula x) is useful for adjusting for σ to the development phase of a region. In chapter 3 will also be demonstrated the decision rule is useful to adjust σ in case part of the goods production is allocated to investments in energy supply.

Box 2: Economic model and default regions

After the introduction of the decision rule for the savings rate σ, the course of a model run of the basic model - with only economic and demographic dynamics - now solely depends on the initial conditions.

The figures below show the development of consumption, labour productivity, population size and savings rate for four settings of the initial size of the economic capital stocks. The initial size of both K_P and K_C is ranged between 1.6 and 64 units per capita. The model is invariant for the initial size of the population, which is set at 1000.

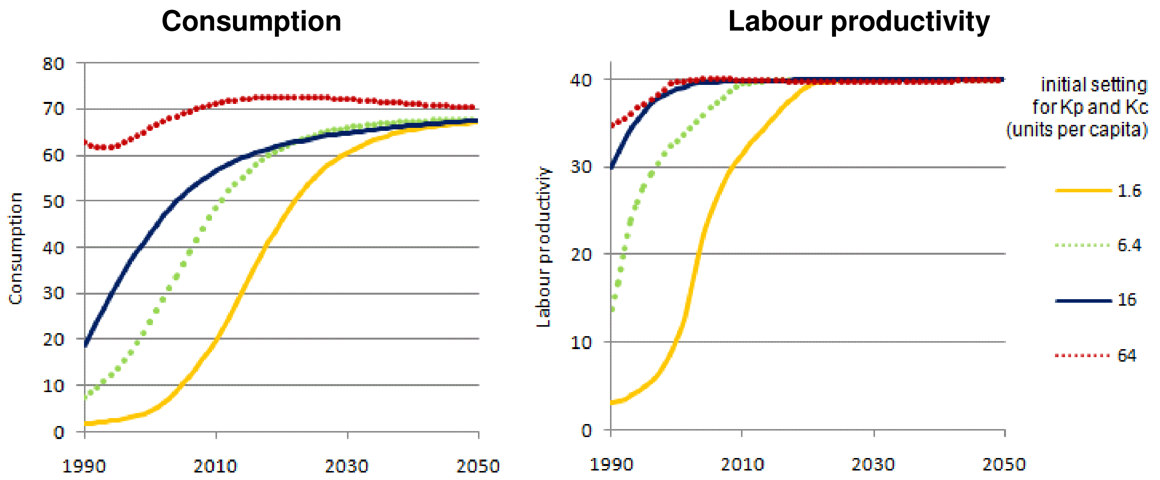

figure 14 Development of a) consumption and b) labour productivity over time for model runs with several settings for the initial size of the economic capital stocks.

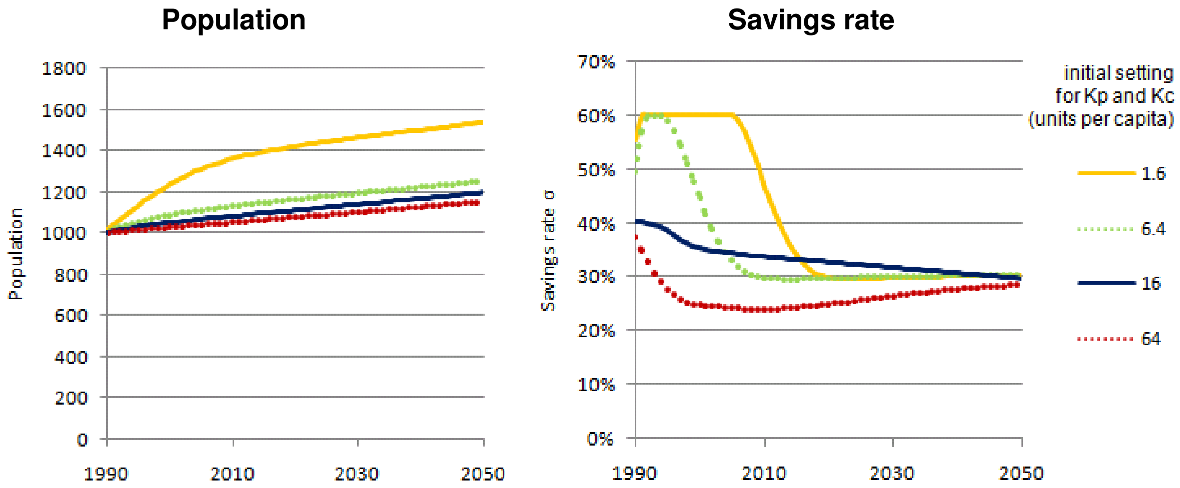

figure 15 Development of a) population and b) savings rate over time for model runs with several settings for the initial size of the economic capital stocks.

In the run representing the poorest region of these examples ($K_{P(0)}/Population_{(0)} = K_{C(0)}/Population_{(0)} = 1.6$), the savings rate is at its maximum during the first 20 years. Labour productivity rises quickly in that period, with a delay followed by the consumption. For even lower initial settings, the behaviour is similar, though it takes a longer investment period before the development of the consumption takes off.

Box 2: Economic model and default regions - continued

Remarkable is the higher population growth for the poorest region, which will have an impact when climate change or scarcity of resources is taken into consideration. Except for the population size, the difference in the initial size of the economic capital stocks does not lead to a difference for the indicators in the end year 2050.

The consumption of the richest region under consideration ($K_{P(0)}/Population_{(0)} = K_{C(0)}/Population_{(0)} = 64$) fluctuates. First the region does not produce enough to compensate for the depreciation of K_C. In reaction, σ is adjusted downwards leading to higher consumption. This level of consumption cannot be sustained, because K_P per capita declines so that multiplier ψ would drop below 1. The savings rate growths towards the lowest possible value which is still high enough to keep multiplier ψ at its maximum.

The example run with K_P and K_C initially set at 16 units per capita shows the most stable development. With the region starting with economic capital stocks of 6.4 units per capita, the savings rate peaks in the first period just like with the poorest region, but population growth is limited.

These examples all use an initial K_C:K_L ratio of 1:1. Figure 16 shows the effect of a significant variation of this ratio. For the rich region, the model behaviour for the default setting $K_P=K_C=16$ (thin blue line) is compared to that of initial settings $K_C=8;K_P=24$ (dark green line) and $K_C=24;K_P=8$ (yellow line). Clearly, the consumption in the region with low K_P is higher for a short period, but it takes a longer time to invest enough in K_P for an optimal labour productivity – partly because of the low productivity decreases the investments.

For a poorer region, the initial difference in stock size has almost no influence, because the region will set its savings rate to the maximum anyway and, secondly, because the absolute initial difference in stock size is small compared to the stock size after a few years.

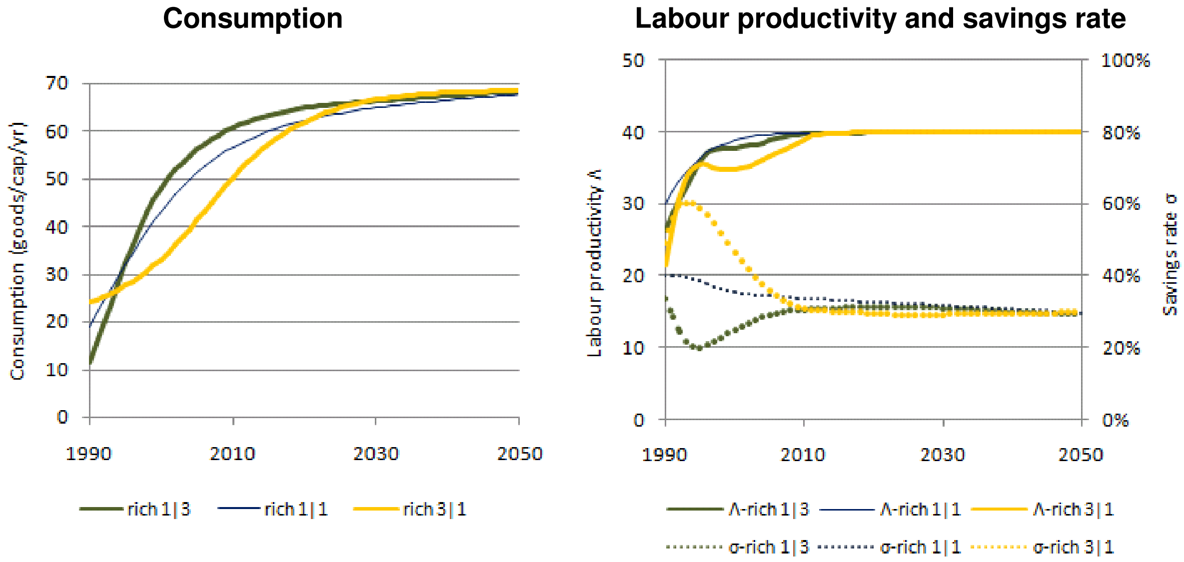

figure 16 Development of a) consumption and b) labour productivity and savings rate over time for model runs with several settings for the ratio between the initial size of the economic capital stocks – where the average of the stocks is always set at 16 units per capita.

In this report, two default regions are used: one representing a "rich", one a "poor" region. The initial population size for both regions is set at 1000, the initial stock size for the two economic capital stocks to 16000 units (16 units/capita) for the rich region and 1600 units (1.6 units/capita) for the poor region.

3 SUSCLIME model – energy system

3.1 Basic energy system

3.1.1 Introduction

Energy plays an important role in the SUSCLIME model, especially the dynamics of depletion of fossil fuel resources and the transition to a non-carbon economy. This chapter elaborates the energy demand function and the options for energy supply.

Energy is needed to operate the economic capital stocks K_C and K_P. Total energy demand (E_D) is the product of the size of the economic capital stocks ($K_C + K_P$) and the energy intensity (ε), measured in energy units per capital unit. The energy intensity is assumed to be a function of consumption C, which is in turn proportional to K_C. This function represents the change in energy intensity due to a transition from a pre-industrial to an industrial society, followed by a transition to an economy based on services. The energy demand is discussed in detail in paragraph 3.1.2.

In order to meet total energy demand, investments in energy supply (I_E) are needed. These investments can be allocated over three options: oil producing capital (I_{Fos}, paragraph 3.1.5) and renewable producing capital (I_{Ren}, paragraph 3.2.1) for domestic energy production and energy efficiency (I_{Eff}, paragraph 3.2.3) to reduce the energy demand. Furthermore, fossil energy can be imported (M_E, paragraph 3.3) from other regions, if available.

SUSCLIME uses a procedure to allocate the investments in energy supply such that the energy demand is fully met, see paragraph 3.1.2. One exception is made: the investments in energy supply are limited to 25% of the total investments – although this situation only occurs in model runs with exceptional initial settings. If the supply at that level does not meet the demand, energy shortage will occur. This will decrease the effectiveness of the economic capital stocks, as further discussed in paragraph 3.1.4.

Due to the depletion effect, the productivity (i.e. annual fossil energy production per unit capital) of the fossil producing capital (φ_{Fos}) will decrease with increasing cumulative production. In contrast, there is positive feedback between cumulative production and productivity of the renewable energy capital because of the dominant learning effect. Therefore, an energy transition from a fossil to a non-fossil energy supply is expected, which is elaborated in paragraph 3.2.2.

The relations of the energy system are summarized in figure 17.

SUSCLIME energy system overview

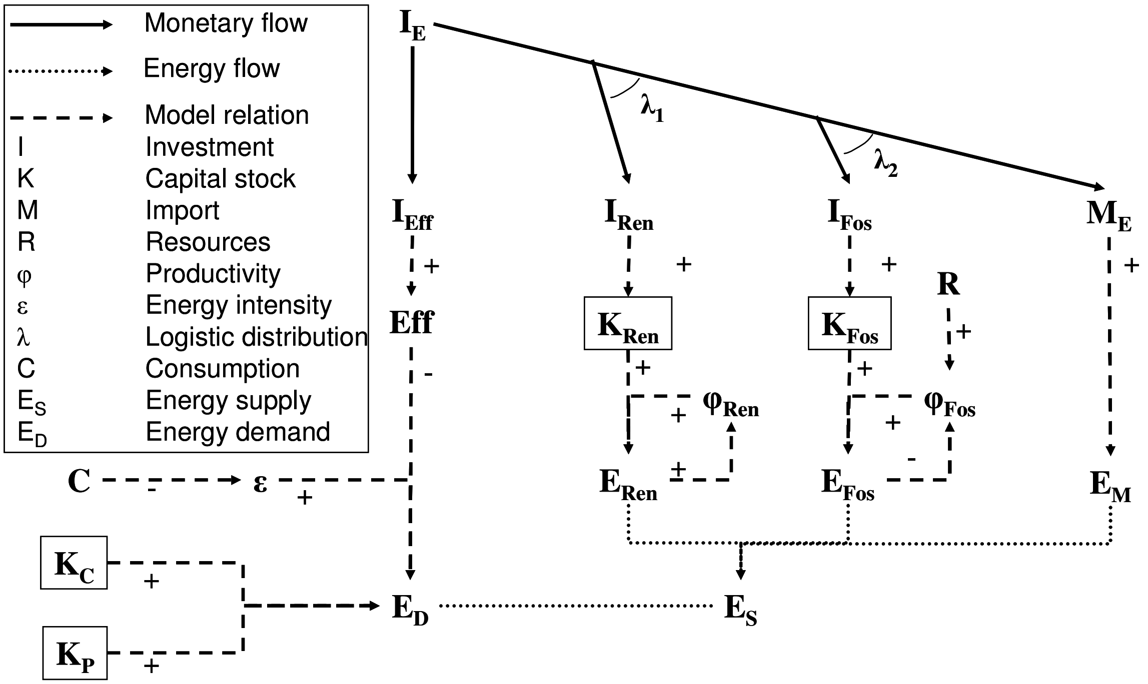

figure 17 Schematic overview of the relations of the energy system of the SUSCLIME model

3.1.2 Energy demand

The energy demand *(E_D)* consists of energy demand from the economic capital stocks, K_C and K_P. E_D is the product of $K_C + K_P$ and the energy intensity *(ε)*, measured in energy units per capital unit.

Energy-intensity can be reduced by investments in energy efficiency, as described in section 3.2.3.

xi. $$E_{D(t)} = (K_{P(t)} + K_{C(t)}) \cdot \varepsilon_{(t)} \cdot (1 - Eff_{(t)})$$

The energy intensity is furthermore affected by the nature of economic activities, which changes with increasing income levels (see e.g. [van Ruijven *et al.*, 2008a]). In a low-income region, the energy intensity is very low because traditional agriculture makes out most of the economic activity.[8] A middle-income region, economic activity is generally dominated by very energy-intensive industry. Finally, the service sector, with lower energy-intensity, is dominant in a high-income region.

To account for these structural changes in the process of economic development, the energy-intensity changes with consumption using a function from the TIMER model ([de Vries *et al.*, 2001], [van Vuuren *et al.*, 2006]):

xii. $$\varepsilon_{(t)} = \varepsilon_0 + \frac{1}{\beta \cdot C_{(t)} + \gamma \cdot C_{(t)}{}^{\delta}}$$

---

[8] This holds for commercial energy sources. SUSCLIME only takes into account fossil and renewable energy supply, not traditional, non-commercial energy sources.

with β, γ and δ as shape-parameters and ε_0 the minimum energy intensity[9]. The function is parameterised such that ε increases initially with rising consumption levels and then, after a top, decreases slowly towards a constant value equal to ε_0. This function is illustrated in figure 18.

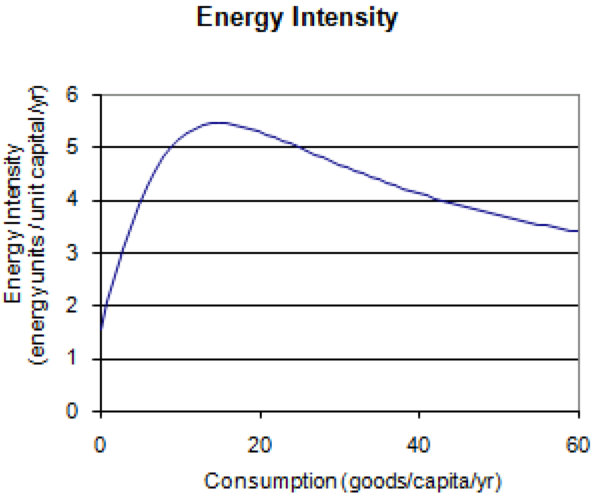

figure 18 Energy intensity as function of consumption

3.1.3 Energy supply

The total investments in energy supply I_E are set such that domestic energy production plus imports meet total energy demand. I_E cannot simply be a function of installed capital, because both energy supply and energy demand are affected by the investment allocation. The procedure below projects the additional energy supply needed to meet the demand and allocates the investments among the supply options.

First, a projection is made for the amount of energy that is supplied by the capital already installed. This baseline supply ($E_{S,baseline}$) is calculated under the assumption that no investments will be allocated to energy supply options. $E_{S,baseline}$ equals the production of the last time step minus the depreciation of the production capacity (in energy units). This is elaborated in the respective paragraphs of the supply options.

xiii. $$E_{S,baseline(t)} = (\Pi_{Fos(t-1)} - D_{\Pi,Fos(t)}) - (\Pi_{Ren(t-1)} - D_{\Pi,Ren(t)}) - (\Pi_{Import(t-1)} - D_{\Pi,Import(t)})$$

The energy demand is projected as the demand of last time step times a factor *(1+c)* to account for an increase in demand because of economic growth. The factor *c* is fixed at 3%. Generally the actual increase in demand is slightly higher at the beginning of a model run, and lower at the end. Therefore an energy shortage or surplus of a few percent can occur, but the economic impact of this is low (paragraph 3.1.4).

---

[9] The values of the parameters are: β=0.009, γ=1.991, δ=-1, and ε_0=1.5. The derivation of parameters and behaviour of this function is more elaborately discussed in [van Ruijven, 2008b].

Now additional energy demand E_{AddD} is calculated as the expected energy demand minus the baseline supply:

xiv. $$E_{AddD(t)} = (1+c)E_{D(t-1)} - E_{S,baseline(t)}$$

The demand for extra energy is distributed among the energy options according to their market shares *(MS)*. The market shares of renewable energy, fossil energy and import are determined by a function of their relative market prices, as elaborated in the respective paragraphs introducing the energy options.

The investments for each supply option equal the additional energy demand allocated to that supply option divided by its marginal productivity *φ*.

xv. $$I_{Fos(t)} = \frac{MS_{Fos(t)} \cdot E_{AddD(t)}}{\varphi_{Fos(t)}}$$

xvi. $$I_{Ren(t)} = \frac{MS_{Ren(t)} \cdot E_{AddD(t)}}{\varphi_{Ren(t)}}$$

xvii. $$M_{E(t)} = \frac{MS_{Import(t)} \cdot E_{AddD(t)}}{\varphi_{Import(t)}}$$

The investment fraction for energy efficiency is determined such that the marginal costs for energy efficiency equal the average energy price (~1/*φ,* see paragraph 3.2.3)

xviii. $$I_{Eff(t)} = f(P_{Ren(t)}, P_{Fos(t)}, P_{Import(t)})$$

Total investments in energy supply are limited to 25% of all total investments, to stay within reasonable ranges. If this maximum is reached and energy demand exceeds supply, energy shortage occurs. The energy shortage influences the productivity of the economic capital stocks, see paragraph 3.1.4.

If investments in energy supply would exceed 25% of total investments, all investments in energy are adjusted while maintaining the ratio between the investments in energy supply options. More precisely, when $I_E = I_{Fos} + I_{Ren} + I_{Eff} + M_E = \alpha Q > 0.25\ Q$, all investments in energy supply (I_{Fos} ,I_{Ren} ,I_{Eff} , M_E) are adjusted by multiplication with the factor $0.25/\alpha$.

By default, the initial oil capital is set at the value for which the initial energy demand is met.

3.1.4 Energy shortage

In the SUSCLIME model, the energy supply does not a-priori balance the energy demand. The investments in energy supply are limited to 25 percent of the total investments. When energy demand exceeds supply and thus shortage occurs, the productivity of the economic capital stocks K_P and K_C decreases. The productivity multiplier is a function of the fraction of energy demand which is met, which equals E_S/E_D. This function is illustrated in figure 19.

In case of energy shortage, the loss of productivity of K_C directly influences consumption, the loss of productivity of K_P leads to a decrease of production *Q* and thus investments *I*.

When on the other hand supply exceeds demand, this overcapacity of energy producing capital leads to opportunity cost – the investments could have been used for economic capital stocks. This is the case when energy production capital is installed and the energy demand drops faster than the depreciation of the energy production capital.

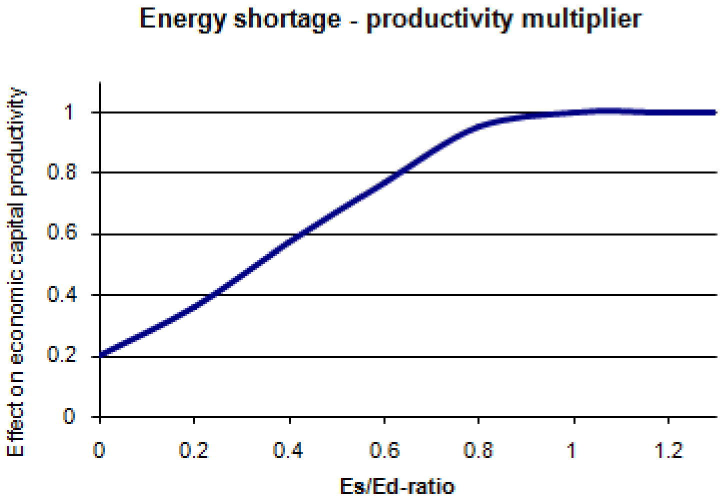

figure 19 Influence of energy shortage on the productivity of the economic capital stocks

3.1.5 Fossil fuels

The default energy source in the SUSCLIME model is oil, representing all types of fossil fuels. Fossil energy is produced by the fossil energy producing capital stock (K_{Fos}). The capital stock K_{Fos} is build up by investments I_{Fos} and faces depreciation D_{Fos} just as all other capital stocks (paragraph 2.2). The lifetime (*LT*) is initially set at 10 years, but can be affected by climate change (chapter 4).

xix. $$K_{Fos(t)} = K_{Fos(t-1)} + I_{Fos(t)} - D_{Fos(t)}$$

xx. $$D_{Fos(t)} = \frac{K_{Fos(t-1)}}{LT_{(t)}}$$

The energy production of the capital stock K_{Fos} equals the product of the size of the stock and the average productivity:

xxi. $$E_{Fos(t)} = K_{Fos(t)} \cdot \overline{\varphi}_{Fos}$$

The productivity develops in time due to depletion, as elaborated below. To deal with changing productivity a new stock is introduced, representing total fossil energy production. In this way, just as in a vintage model, the changing productivity only affects newly installed capital, not the capital that has been installed before. Retrofit to increase productivity of energy production capital is not taken into account, which amplifies the need for early action.

This fossil energy production stock Π_{Fos} is build up by adding each year the newly installed capacity, which equals the product of investments ($I_{Fos(t)}$, in capital units) and marginal productivity (φ_{Fos}, in energy units per capital unit per year) of that year. Depreciation is modelled similar to the other stocks[10].

xxii. $$\Pi_{Fos(t)} = \Pi_{Fos(t-1)} + I_{Fos(t)} \cdot \varphi_{Fos(t)} - D_{\Pi,Fos(t)}$$

xxiii. $$D_{\Pi,Fos(t)} = \frac{\Pi_{Fos(t-1)}}{LT_{(t)}}$$

In this way, Π_{Fos} approaches the product of K_{Fos} and the weighted average of the productivity of the installed production capital. The size of Π_{Fos} equals the amount of energy units that are annually produced by the capital stock K_{Fos}.

xxiv. $$E_{Fos(t)} = \Pi_{Fos(t)} \approx K_{Fos(t)} \cdot \overline{\varphi}_{Fos(t)}$$

The productivity of oil producing capital (φ_{Fos}) decreases with increasing cumulative production due to the depletion effect. The resources that are easiest to exploit are generally utilized first. The less fossil energy resources remain the harder and thus more expensive it is to exploit the leftover resources. A long term supply cost curve can be constructed by arranging the resources according to their estimated production cost. Many estimations of such curves exist (see e.g. [Rogner, 1997]).

---

[10] In case of depletion (productivity decreasing in time), this choice (deprecation of average capital) leads to lower depreciation than the use of a vintage model (depreciation of the oldest capital).

In SUSCLIME, productivity plays a central role, not costs. These two are of course directly related: the cost of one unit of energy is proportional to the inverse of the productivity: $c \sim E/K$. The depletion process is modelled with the following expression for productivity (i.e. annual fossil energy production per capital unit):

xxv.

$$\varphi_{Fos(t)} = \varphi_{max} \cdot \sqrt[1,5]{\frac{R - \sum_{T=0}^{t} E_{Fos\,(T)}}{R}}$$

in which R is the size of the initial fossil resources, so the factor in the root equals the fraction of the resources that is not yet exploited. φ_{max} is the maximum (i.e. initial) productivity. A similar formulation is used in the DICE model ([Nordhaus and Boyer, 2000]).

The value of φ_{max} can vary per region and is by default set at 32 energy units per capital unit per year. In this way, the energy investments share is by default about 10% of the total investments (see also box 3). This share is comparable to for example the United States, that spends 8.4% of its GDP to energy ([EIA, 2007]).

Figure 20 shows the influence of depletion on productivity (φ_{Fos}) and price ($\sim 1/\varphi_{Fos}$) of fossil fuels. Mind the difference between the horizontal axis in the left and the right graph: the first shows the remaining resource fraction, the other the cumulative production as percentage of the initial resources which equals one minus the remaining resource fraction.

Using the function $\sqrt[1,5]{x}$, with x being the fraction of fossil resources remaining, means that the costs to produce fossil energy initially increase slowly. When the resources get depleted the increase accelerates. Alternative formulations of fossil energy productivity as function of remaining resources (e.g. square root or exponential) involve similar dynamics.

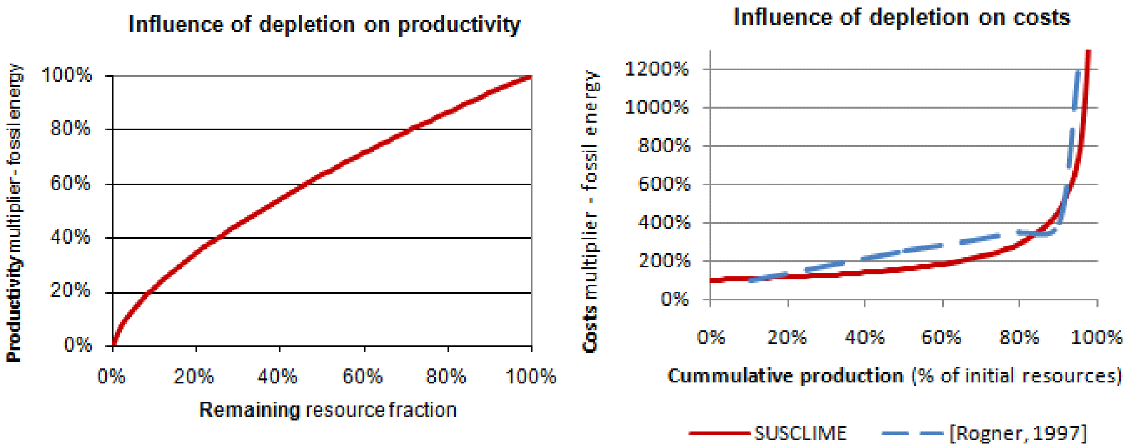

figure 20 Influence of depletion on productivity and price of fossil fuels

With the introduction of energy demand and energy supply by fossil fuels, the basic energy model in box 2 can be extended to explore the influence of the energy costs on the economy. This is done in box 3, using a situation with abundant fossil resources and thus without regarding depletion.

In chapter 3.2, the depletion effect is further analysed by comparing the productivity development of fossil fuels to that of renewable energy.

Box 3: Influence of the energy costs on the economy

The basic energy model in box 2 is extended to explore the influence of the energy costs on the economy. The economic capital stock leads to a demand for energy that must be met by energy investments. Investments in energy are made at the cost of investments in economy.

Energy is in these examples supplied by fossil fuels, under the assumption that the initial resources are abundant and thus productivity is not affected by the depletion effect.

The figures below show development of the consumption and investment fraction for (fossil) energy, for a poor and a rich region. Four settings for the energy capital productivity φ are used. The default setting is 32 energy units per capital unit, with $\varphi = 64$ the energy is twice as cheap. The runs with $\varphi = 16$ and $\varphi = 4$ represent cases where the energy costs are two respectively eight times as high. In comparison, the model runs in box 2 represent a case with freely available energy.

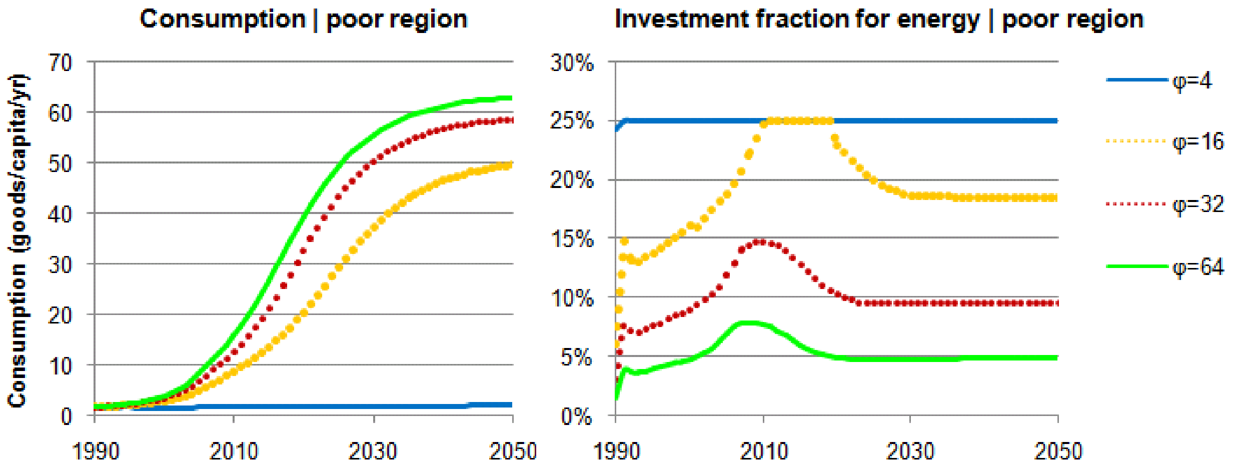

figure 21 Consumption and investment fraction for energy in time in a poor region. Several settings for the energy productivity are used.

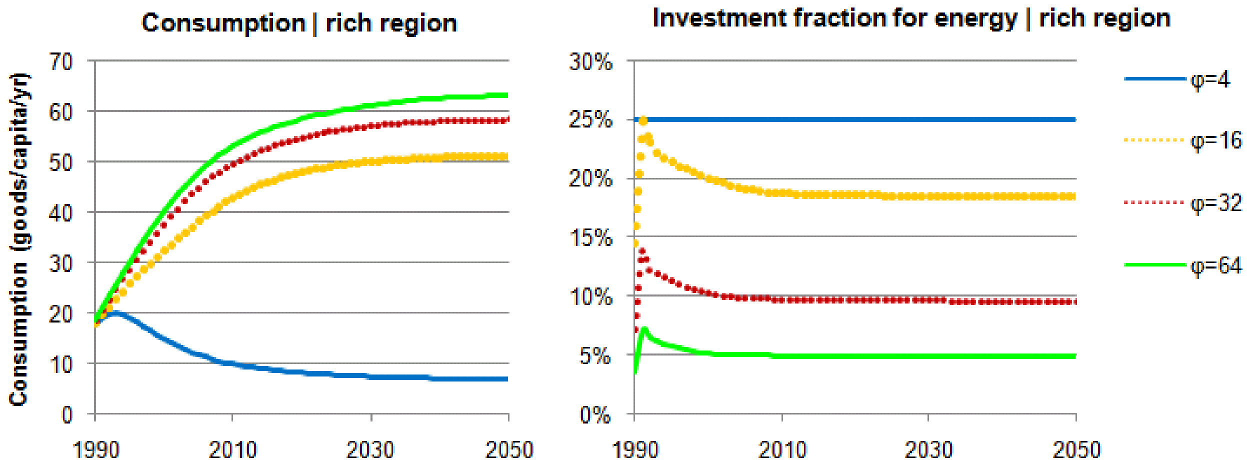

figure 22 Consumption and investment fraction for energy in time in a rich region. Several settings for the energy productivity are used.

The development of the investment fraction for energy (IF_E) for the poor region clearly follows the energy intensity, that changes with consumption (figure 18). For the rich region, this also explains the gradual decrease of IF_E in the first decade.

Box 3: Influence of the energy costs on the economy – continued

In the case with the most expensive energy (φ = 4), the high energy costs and the energy shortage hamper the development of the region. The energy demand is not fully met (E_S/E_D ratio of 56% resp. 30% for a poor and rich region) and thus the economic capital is not fully productive (poor 65%, rich 45%). The combination of little productive capital and limited resources for investment makes labour productivity bound to low ranges (resp. 5 or 22 goods/labourer/yr for a rich and a poor region).

In the other cases, the influence on the economy is more gradual: higher energy costs lead to lower investments in K_P and K_C. Only the poor region with φ = 16 reaches the maximum level of investments in energy supply, but the energy shortage is limited to a few percent.

Figure 23 shows the development of the investment allocation in time with the default productivity of 32 energy units per capital unit per year. For the poor region, the peak in energy investments correlates to a consumption level where the energy intensity is at its maximum. After that peak, both IF_P and IF_E decrease: IF_P because labour productivity reached its maximum and σ decreases, IF_E because the energy intensity decreases.

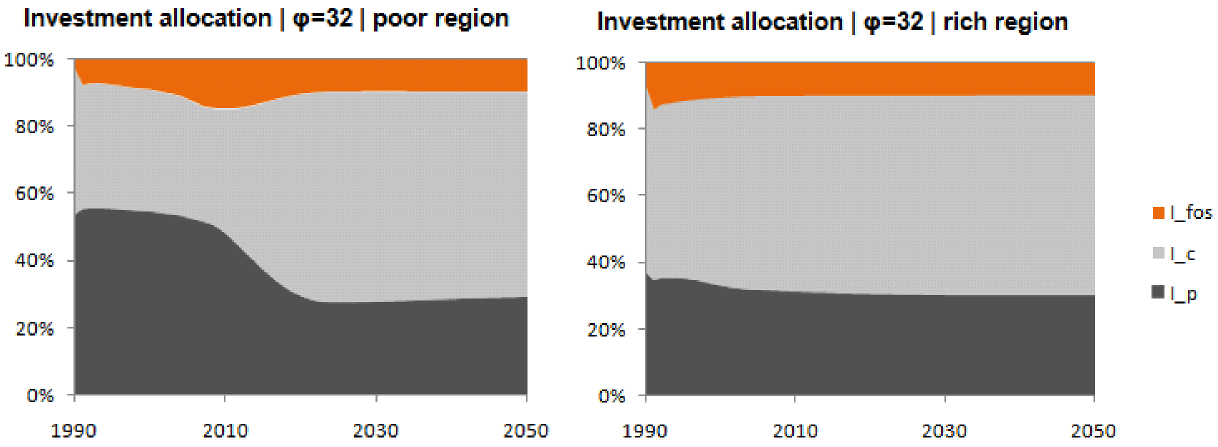

figure 23 Investment allocation in time with the default productivity.

To illustrate the effect of productivity φ on consumption and investment fraction IF_E, the values of these indicators are measured for varying settings. Figure 24 shows the resulting values for the end-year 2050 if φ is fixed in the period 1990-2050. For low ranges of φ, consumption is very reactive to changes in productivity and thus energy costs.

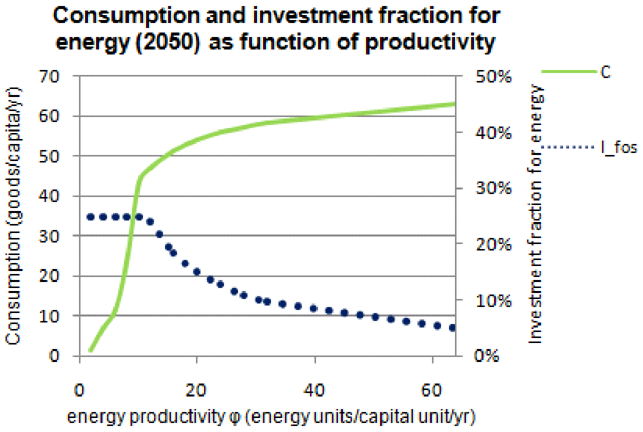

figure 24 Effect of varying productivity φ (fixed during the period 1990-2050) on both consumption and the investment fraction in the end year 2050. The relation is shown for a rich region, but is almost identical for a poor region.

3.2 Alternative energy policies

3.2.1 Renewable energy

Renewable energy production is introduced as an alternative to fossil energy production. Renewable energy refers to all renewable energy sources such as hydro-, solar- and wind power and bio-energy. Contrary to fossil energy, the use of renewable energy does not lead to problems of depletion and climate change. The drawback is that initially higher investments in energy supply are needed.

A dominant feature of renewable energy capital is the effect of learning. Learning-by-doing decreases the cost cq. increases the productivity with increasing cumulative production, representing the process of economies of scale and innovation. Renewable energy is introduced as a new technology, with high initial costs but where the learning effect strongly influences productivity.

The cost development of the renewable energy capital is thus assumed to be a function of cumulative production. In general, when such a cost development function applies to products or technologies, the logarithm of this function is a linear function of the logarithm of the cumulative production. In other words, when this function is plotted in a figure with double-logarithmic scale, the result is a linear curve: the experience curve (see e.g. [Junginger, 2005]).

A basic experience curve can be expressed as:

xxvi. $C_{Cum} = C_0 Cum^b$

xxvii. $\log(C_{Cum}) = \log(C_0) + b\log(Cum)$

xxviii. $PR = 2^b$

Where *Cum* denotes cumulative production (in units), C_{Cum} cost per unit after producing *Cum* units, C_0 cost of the first unit produced*, b* the experience index and *PR* the progress ratio.

The progress ratio (*PR*) expresses the rate at which costs decline for every doubling of cumulative production. For example, if the production of the 100th unit of a product costs €10,- and the progress ratio is 85%, the 200th product costs €8.50. The 400th costs again 15% less: €7.23. The lower the progress rate, the faster the costs decrease.

The estimation of progress rates for renewable energy technology range widely in literature. Junginger (2005) gives an overview of experience curves for wind energy, with *PR* values ranging from 68% to even 117%[11]. Three listed integrated assessment models use values between 85% and 90%. For solar energy often lower rates are found.

The progress ratio *(PR)* for renewable energy in the SUSCLIME model is set at 90%. Every doubling of cumulative energy production thus leads to a reduction of the costs per unit of 10%. Since cost per unit is inversely proportional to productivity, this equals an increase of the production per unit investment of 11%.

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[11] A progress rate above 100% indicates a price increasing with increasing production. This can for example be caused by a rapid increase in demand.

The productivity is thus a function of the cumulative energy production, which is illustrated in figure 25. The productivity increases with cumulative energy production, but at decreasing rate.

To prevent the productivity to increase already with minor investments and the model run to start with a rapidly increasing learning curve, it is assumed that a region already learned as if it produced a minimum amount of energy $E_{Minlearn}$. The energy production that is used an input for the learning curve is thus:

xxix. $$E_{Learn(t)} = \max(\sum_{T=0}^{t} E_{Ren\,(t)}, E_{Minlearn})$$

The learning curve itself has two parameters, the factor φ_C and the exponent γ. The latter is determined by the progress ratio. The constants φ_C and $E_{Minlearn}$ are set so that the initial productivity $\varphi_{Ren\,(0)}$ equals 12 units of renewable energy per unit capital per year.[12]

xxx. $$\varphi_{Ren(t)} = \varphi_C \cdot (E_{Learn(t)})^{-\gamma}$$

xxxi. $$\gamma = \log(PR)/\log(2)$$

By investment in renewable energy (I_{Ren}), the renewable energy production capital stock K_{Ren} is built up. The total renewable energy production is represented by the production stock Π_{Ren}, similar to Π_{Fos} (paragraph 3.1.5).

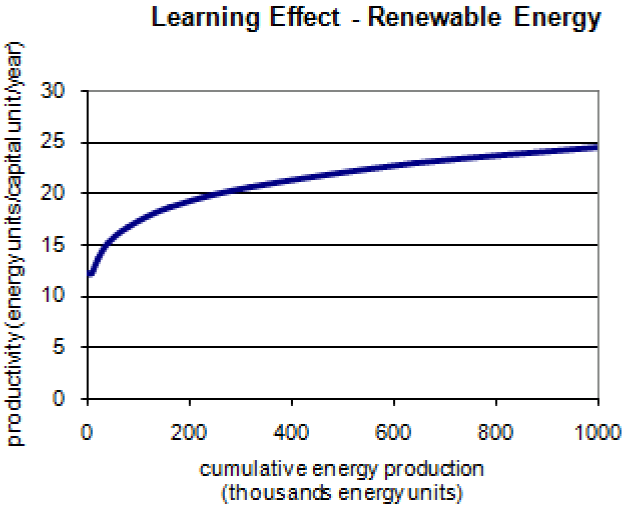

figure 25 Productivity $\varphi_{Ren\,(t)}$ (annual production of energy units per capital unit) as function of the cumulative energy production.

The development of the productivity of both oil and renewable capital during a model run is illustrated in box 4.

By default, the model is initiated with no renewable capital installed. Only when a case without fossil fuels is considered, the initial renewable capital is set at meet the initial energy demand.

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[12] $E_{Minlearn}$ is set at 10,000 energy units, approximately the initial yearly energy demand of a poor region. φ_C is set at 3. Now $\varphi_{Ren(0)} = 3 \cdot (10,000)^{-\gamma} = 12$

Box 4: Productivity of fossil and renewable capital stocks – without transition

This box investigates the development of the productivity of the fossil and renewable capital stocks separately. For both a rich and a poor region, four runs of the SUSCLIME model are performed: one with only renewable energy supply and no fossil energy option, the other three with only fossil energy supply and no renewable energy option. For the three runs with fossil energy, the initial fossil resources are set at respectively 2.5, 7.5 and 15 million energy units.

The graphs below show the development of the consumption, investment fraction for energy, energy capital productivity and economic capital productivity for the poor region. Each line represents a separate model run. The energy supply is limited to one option for each run; an energy transition is not possible.

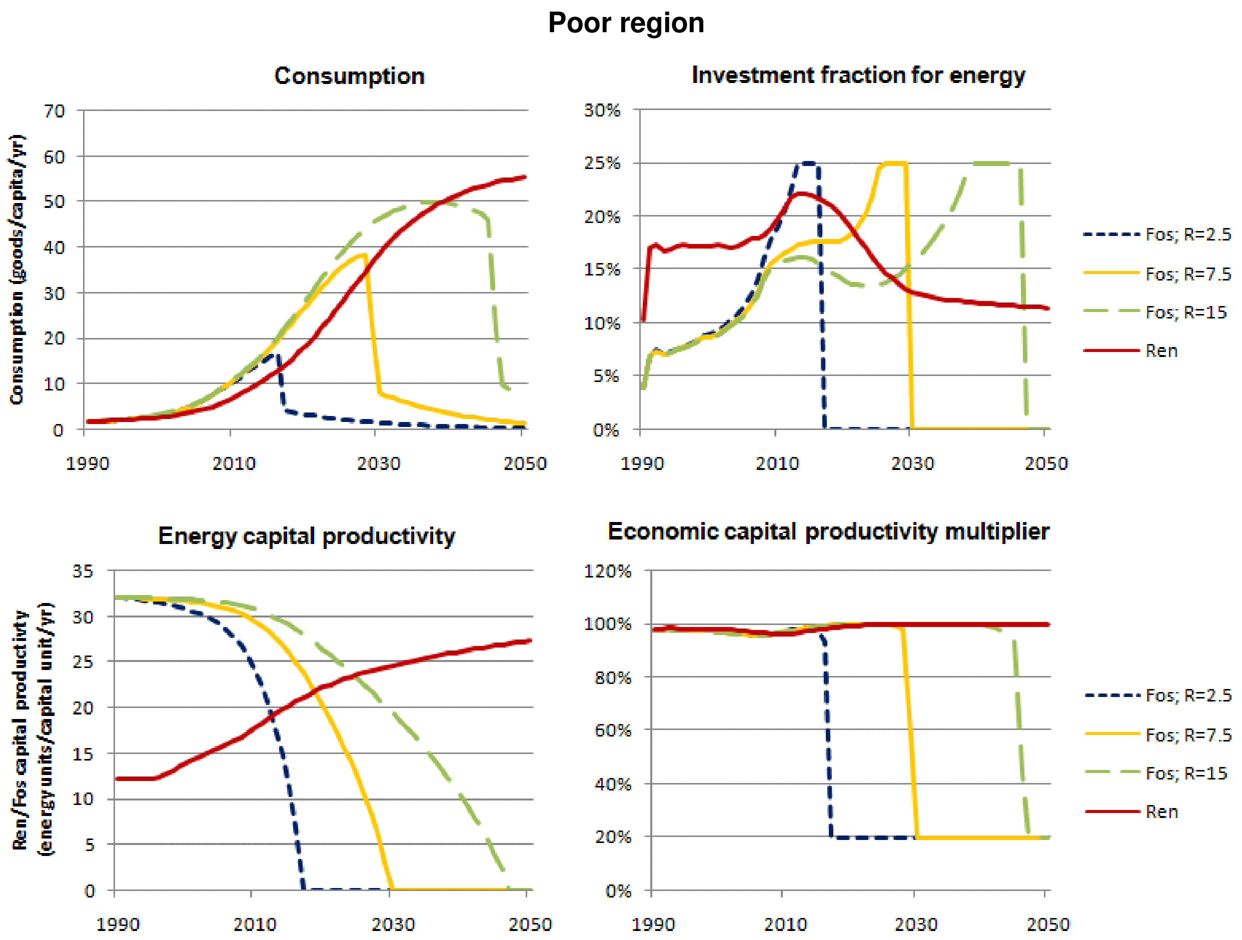

figure 26 Development of the consumption, investment fraction for energy, energy capital productivity and economic capital productivity for the poor region. Each line represents a separate run: either with renewable energy supply or with fossil energy supply with initial resources 2.5, 7.5 or 15 million energy units.

For the runs with fossil energy supply, the productivity of the newly installed capital decreases in time due to depletion. The costs of energy supply therefore increases, until the resources are fully depleted and no investments in energy supply are made no more. The installed fossil energy production capital still produces energy, but every year less because of depreciation. The energy shortage affects the productivity of the economic capital. This results in lower goods production and lower consumption.

Box 4: Productivity development of fossil and renewable capital stocks – without transition – continued

In the case of the renewable energy option, the productivity of the energy producing capital starts much lower than in the case of the fossil energy option. A larger fraction of the investments is allocated to energy, thus the development of the consumption lags behind.

Energy intensity is a function of consumption. Box 3 shows that with constant productivity, the investment fraction for energy (IF_E) is low for low consumption levels, peaks at moderate consumption levels and stabilizes for higher consumption levels. Now productivity changes because of learning or depletion, a combined effect occurs.

In case of the renewable option, this for example makes IF_E almost constant during the first two decades. The increase in productivity here compensates for the increase in energy intensity. In case of the fossil energy option with highest initial resources, this leads to an oscillation in IF_E: the increase in costs due to depletion is first accelerated by the increase in energy intensity, but later compensated by its decrease. When the resources are depleted, the consumption drops and thus the energy intensity peaks again.

The rich region shows similar behaviour, but the process of learning and depletion take place faster because the consumption level and thus the energy demand is higher from the start.

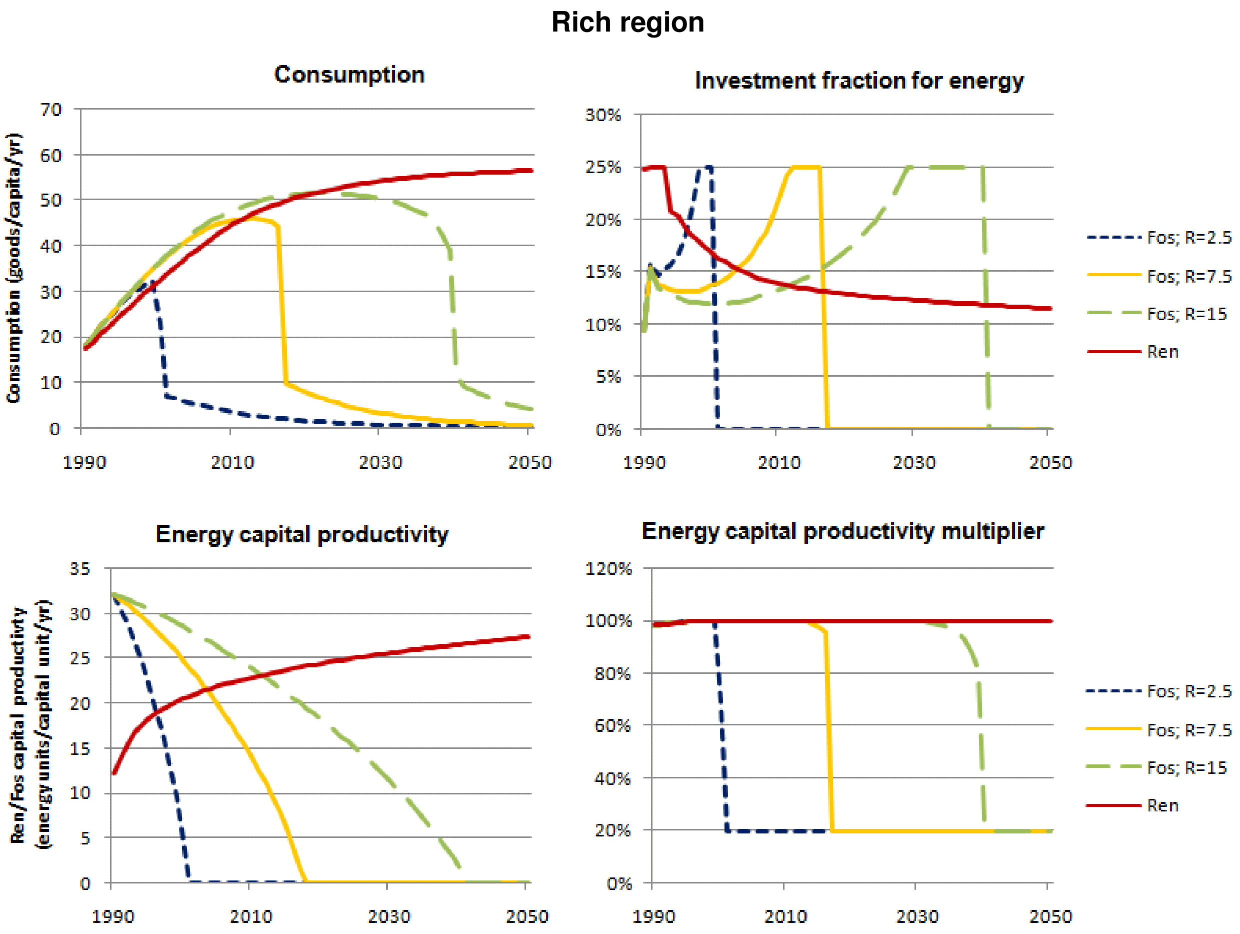

figure 27 Development of the consumption, investment fraction for energy, energy capital productivity and economic capital productivity for the rich region. Each line represents a separate run: either with renewable energy supply or with fossil energy supply with initial resources 2.5, 7.5 or 15 million energy units.

3.2.2 Energy transition

In the examples in box 4, the renewable and fossil energy options are analysed separately. In each model run, only one of the supply options is enabled. This section prepares for model runs with both energy supply options by introducing decision rules for the market share of both options. These rules determine the transition dynamics of the substitution of one energy option for the other.

The market share of an energy option is introduced as a logit function of its relative attractiveness, represented by the productivity. The most productive (i.e. cheapest) energy source will have the highest market share. The decision rule for market allocation between renewable energy and fossil energy is:

xxxii. **Decision rule 2:**

$$MS_{Ren(t)} = \frac{1}{1+\left(\frac{\varphi_{Ren(t)}}{\varphi_{Fos(t)}}\right)^{-\lambda}}$$

xxxiii.

$$MS_{Fos(t)} = 1 - MS_{Ren(t)}$$

in which λ is the logit parameter, determining the sensitivity for productivity differences, i.e. the price elasticity. The higher the value of λ, the more sensitive the allocation reacts to productivity differences and thus the more rapid the transition. The market share of renewable energy is plotted as function of relative attractiveness ($\varphi_{Ren}/\varphi_{Fos}$) for several values of λ in figure 28.

The allocation of market shares based on relative productivity leads to an energy transition when fossil resources are scarce. Then the productivity of fossil energy decreases, while on the other hand the productivity of renewable energy increases. Box 5 analyses the effect of varying λ on the energy transition.

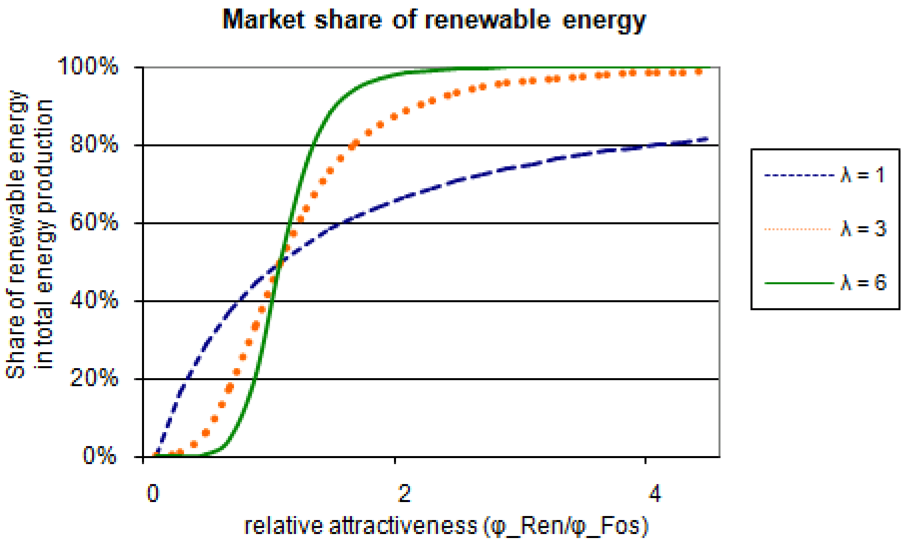

figure 28 Transition dynamics for several values of λ

Box 5 – Illustration of the energy transition

The graphs in figure 29 and figure 30 illustrate the energy transition and test the dependency of the transition on the value for *λ*. *λ* is set at either 1, 3 or 6. In these runs, a rich region with initial fossil fuel resources of 7.5 million energy units is used as example. The transition for a poor region is similar, but takes off later. The graphs for a poor region are omitted.

When *λ=1,* the market shares for renewable and fossil energy are little reactive to differences in the respective productivities. Relative to the other cases, the renewable investments are high in the first years, but the investment share hardly adjusts to development of productivity of the energy options. The investment shares for both options are almost equal until the fossil resources are fully depleted. The energy investments then peak and energy shortage occurs. Therefore, the level of consumption drops.

The runs with higher settings for *λ* show a more adequate reaction to the cost development. For *λ=6,* the investments for renewable energy starts up only late, but increase rapidly. Nonetheless, the peak in investments in energy supply due to the use of is much higher than for *λ=3*. This setting makes the transition smoother, because the renewable learning is equally spread over time. In this case, the transition comes in time to prevent full depletion.

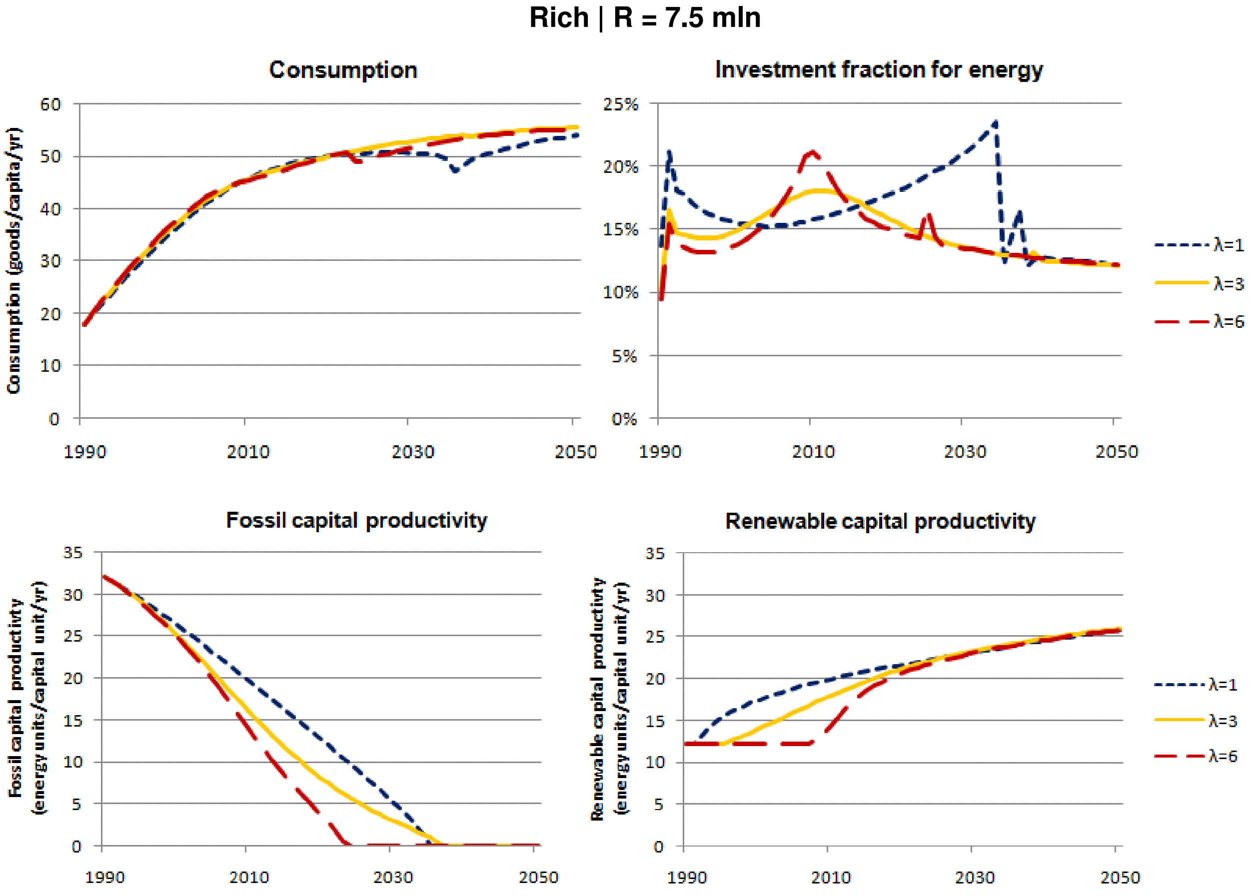

figure 29 The energy transition illustrated by four indicators as function of time. The run uses a rich region with initial fossil fuel resources of 7.5 million energy units. λ set at either 1, 3 or 6.

Box 5 – Illustration of the energy transition – continued

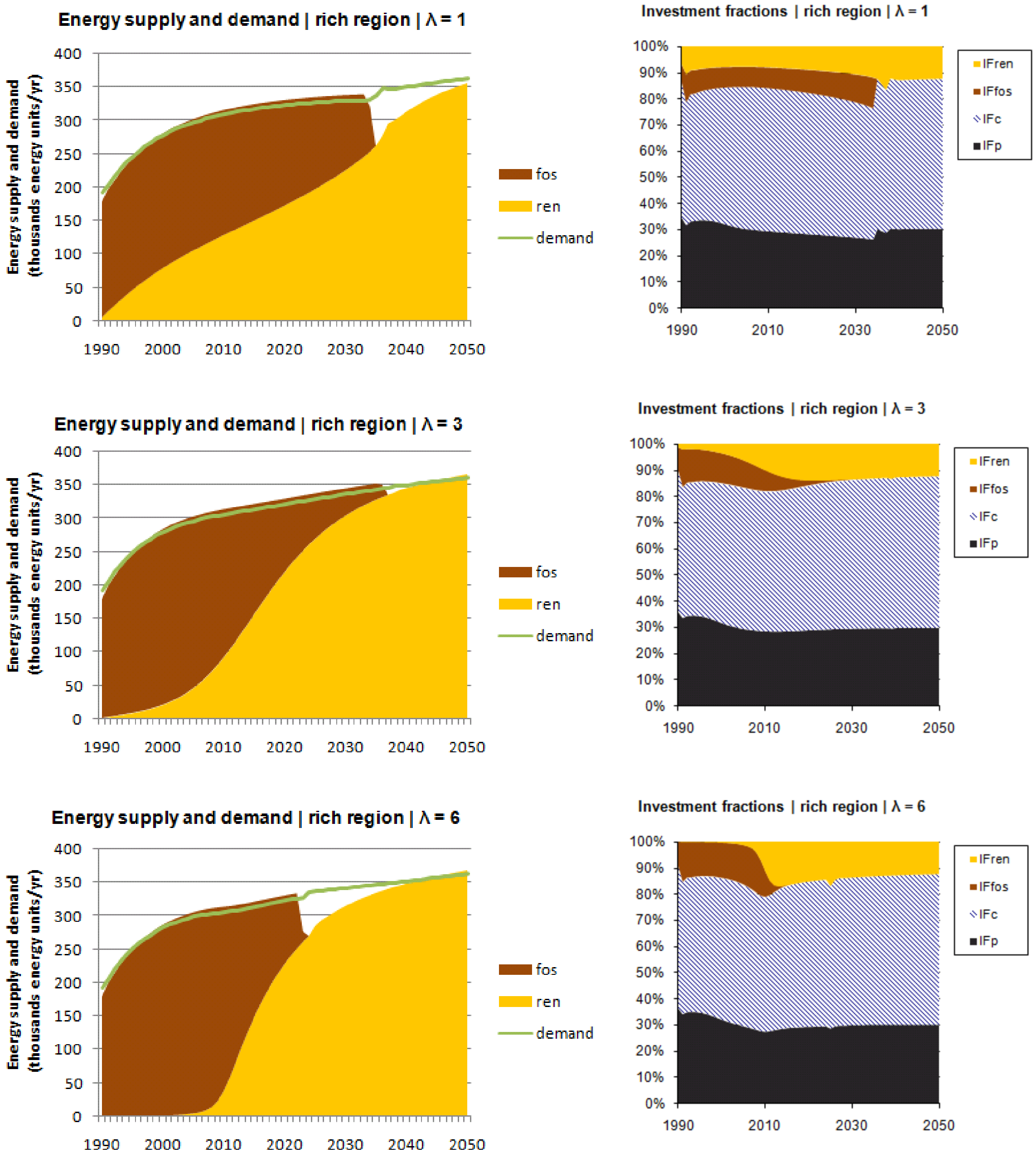

figure 30 Energy supply and demand and investment fractions over time for model runs illustrating the energy transition from fossil to renewable energy. λ set at either 1, 3 or 6.

By default *λ* is set at 3 in future runs, because this gives the smoothest transition. Use of lower settings for initial resources *R* leads to a more bumpy transition.

If a model run is meant to illustrate the effect of scarcity of resources, such a bumpy transition is desired. In that case, the initial fossil resources are set at 2.5 million energy units.

3.2.3 Energy efficiency

To balance energy demand and supply, an alternative to increasing the energy supply is decreasing the energy demand. For this, investments can be allocated to energy efficiency.

Energy efficiency investments (I_{Eff}) reduce the energy needed to operate the economic capital stocks (paragraph 3.1.2). The energy reduction not only depends on $I_{Eff,}$ but also on the size of the installed economic capital.

If the size of the installed economic capital stocks doubles, I_{Eff} should also double to reach the same efficiency gain. This would mean the efficiency gain is a function of $I_{Eff}/(K_C+K_P)$. This relationship is simplified by making the efficiency gain dependent on the investment fraction for efficiency: I_{Eff}/Q $(=IF_{Eff})$.[13]

The relation between the efficiency gain factor *Eff* (as fraction of total energy use) and the efficiency investments (as fraction of the total investments, I_{Eff}/Q) is given by*:*

$$\text{xxxiv.} \quad Eff_{(t)} = Eff_{max} - \frac{1}{f \cdot \frac{I_{eff(t)}}{Q_{(t)}} + \frac{1}{Eff_{max(t)}}}$$

in which Eff_{Max} is the maximum efficiency level and *f* is a scaling parameter[14]. This function is adapted from the price induced energy efficiency improvement function in the TIMER model [de Vries *et al*., 2001]. *Eff* is the efficiency gain factor, so the energy use is multiplied by the factor *1-Eff.*

Figure 31 illustrates the relation between the efficiency gain and the efficiency investments. The factor *f* determines the shape of the curve: a higher value means a steeper curve for x-values near 0 and later on a more rapid transition towards the maximum saving. This factor is set at 15. The maximum EE_{Max} is set at 90%, but this value is never reached in the model runs performed.

The efficiency gain affects all economic capital installed. In this way, it symbolizes the options of good housekeeping and retrofit investments for economic capital stocks.

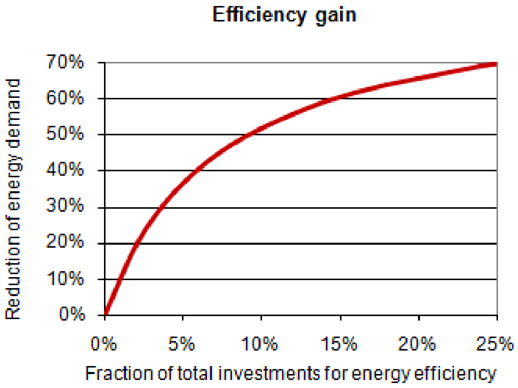

figure 31 Efficiency gain Eff *as function of the fraction of the total investments for energy efficiency (*I_{Eff}/Q*)*

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[13] In the long term, investments stabilize and $Q \approx c_1(I_c+I_P) \approx c_2(K_c+K_P)$

[14] Eff_{Max} is parameterised at 90%, *f* at 15. In this way, efficiency investments become attractive at cost levels above the default initial energy cost for fossil fuels, see also figure 32.

The energy efficiency investments are determined by a cost- benefit analysis comparing efficiency investments with investments in renewable energy and fossil fuel production.

First formula xxxiv is re-written to express the relation between investment fraction IF_{Eff} *(=* I_{Eff}/Q*)* and the efficiency gain factor *Eff*

xxxv. $$IF_{Eff\,(t)} = \frac{1}{f \cdot (Eff_{Max} - Eff_{(t)})} - \frac{1}{f * Eff_{Max}}$$

Now formula xxxv is differentiated to derive the marginal costs for energy efficiency (expressed as additional percentage of the total investments per percent additional energy savings) for any level of the total energy savings *Eff*.

xxxvi. $$MargIF_{Eff\,(t)} = \frac{1}{f \cdot (Eff_{Max} - Eff_{(t)})^2}$$

The function is illustrated by figure 32. This shows for example that at an efficiency gain level (*Eff*) of 40%, it costs 0.27% of the total investments *Q* to reach *Eff*=41%. Figure 31 indeed shows that the increase of *Eff* = 40% to *Eff* = 47% requires an increase of IF_{Eff} from 6% with approximately 7*0.27% ≈ 2% to 8%.

The marginal cost figure clearly shows the increasing marginal costs. This relates to the fact that the cheapest savings options are applied first.

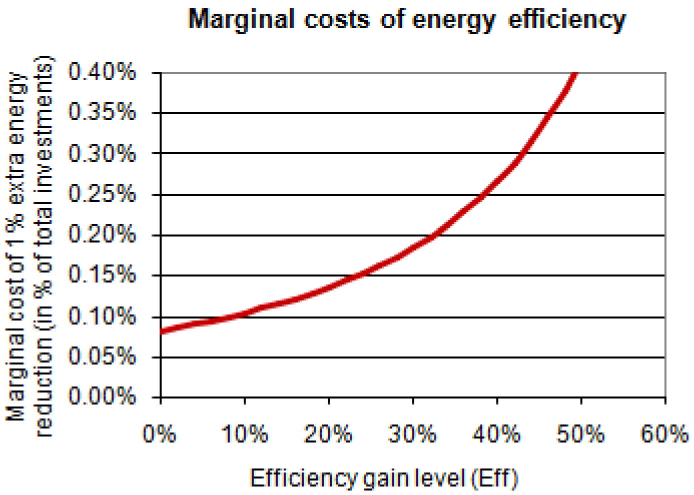

figure 32 Marginal cost of energy efficiency ($MargIF_{Eff}$*) as function of the efficiency gain level* Eff

Energy efficiency investments are set at the maximum level for which investing in energy efficiency is more beneficial than investing in energy supply.

The marginal costs of one percent reduction of energy demand are expressed in formula xxxvi. The costs of supplying one percent of the energy demand (*PE*) is calculated as the weighted average of the costs of renewable and fossil production, adjusted by the factor Q/E_D to express the costs as fraction of the total investments.[15]

xxxvii. $$PE_{(t)} = ((MS_{Ren(t)} \cdot P_{Ren(t)}) + (MS_{Fos(t)} \cdot P_{Fos(t)})) \cdot \frac{Q_{(t)}}{E_{D(t)}}$$

xxxviii. $$P_{Ren(t)} = \frac{1}{LT_{(t)} \cdot \varphi_{Ren(t)}} \; ; \; P_{Fos(t)} = \frac{1}{LT_{(t)} \cdot \varphi_{Fos(t)}}$$

The marginal costs of energy efficiency ($MargIF_{Eff}$) grow with increasing *Eff,* without upper bound, while the marginal costs of energy supply (*PE*) are invariant of *Eff.* Therefore, two cases can be distinguished:

- *PE* is lower than $MargIF_{Eff}$ for every level of *Eff* in the domain [0%,75%]. Then efficiency investments are not beneficial at all, thus the optimum Eff_{Opt} is 0%.
- *PE* equals $MargIF_{Eff}$ for one unique level of *Eff* in the domain [0%,75%]. Then this level is the optimum Eff_{Opt}

Eff_{Opt} can be found by solving $MargIF_{Eff} = PE$. Using formula xxxvi and xxxvii, this leads to

xxxix. $$Eff_{Opt(t)} = \max(0, Eff_{Max} - \frac{1}{\sqrt{f \cdot PE_{(t)}}})$$

Eff_{Opt} *is* inserted in formula xxxv to calculate the related optimum energy efficiency investments:

xl. $$IF_{Eff,Opt(t)} = \frac{1}{f \cdot (Eff_{Max} - Eff_{Opt(t)})} - \frac{1}{f * Eff_{Max}}$$

An illustration of the use of energy efficiency capital in the model is given in box 6.

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[15] *PE* typically ranges between 0.08% and 0.12%. The factor Q/E_D is derived in the following way:
Each unit energy costs $x = ((MS_{Ren(t)} \cdot P_{Ren(t)}) + (MS_{Fos(t)} \cdot P_{Fos(t)}))$ unit goods (see eq. xxxviii).
1% of the energy demand thus costs $x*E_D/100$ unit goods
Each unit good equals *100/Q* percent share of the total investments
1% of the energy demand thus costs $(x*E_D/100)*(100/Q) = x*Q/E_D = PE$ percent share of the total investments.

Box 6: The SUSCLIME model with completed energy and economy systems

With the introduction of energy efficiency, the energy system of the SUSCLIME model is completed. This box shows a baseline run of regions with abundant fossil resources *(R* set at 2500 million energy units*)* and not hindered by impact from climate change. The second part of this box treats regions with limited fossil resources.

Figure 33 combines the graphs of consumption and the total investment fraction for energy ($IF_E = IF_{Fos} + IF_{Ren} + IF_{Eff}$). As reference, also IF_E is included for the case no efficiency investments are allowed. Because fossil fuels are abundant, energy is cheap. Therefore the efficiency investments are limited and have little effect on the total energy costs. Consumption is in this case unaffected by the introduction of efficiency.

The peak in energy investments can be related to the peak in energy intensity for modest consumption levels (see figure 18). Before this peak is reached, the investment share for energy is so low that efficiency measures are not applied.

The energy graphs in figure 34 point out that even with cheap fossil fuels, the fossil fuel use stabilizes and the growth of energy demand – mainly caused by population growth – is accounted for by an increase in efficiency and renewable energy production. The market share function allocates (little) investments to renewable energy, even though this option is relatively expensive. The learning effect makes renewable energy production cheaper, so that the share of this option increases. At the same time, the more expensive renewable energy make the average costs of energy increase and thus more efficiency measures are applied.

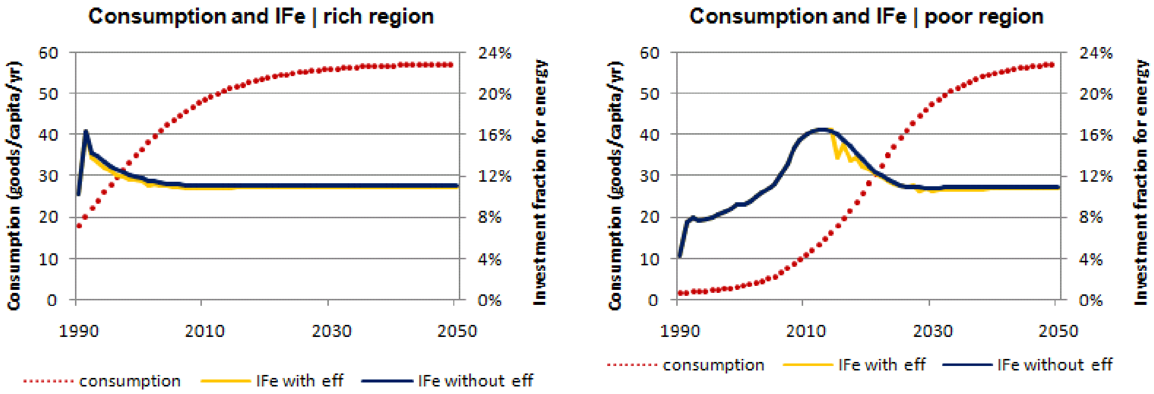

figure 33 Consumption and investment fraction for energy (IF_E) for a poor and rich region with initial fossil fuel resources of 2500 million units.

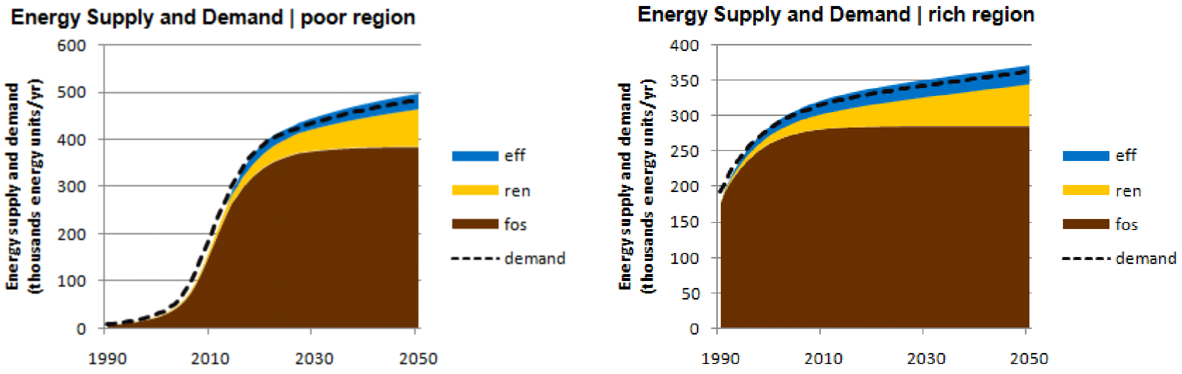

figure 34 Energy supply and demand for a poor and rich region with initial fossil fuel resources of 2500 million units

Box 6: The SUSCLIME model with completed energy and economy systems - continued

To analyse the dynamics of a transition to non-fossil energy in case of depletion, the model is run for a rich and a poor region, assuming scarce initial resources (initially set at 2.5 million energy units). Figure 35 and figure 36 show results of these model runs.

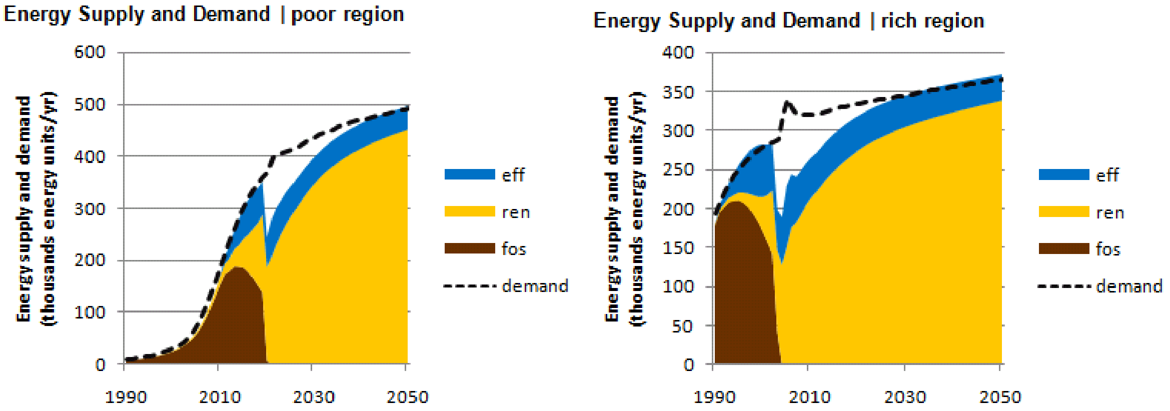

figure 35 Energy supply and demand for a poor and rich region with initial fossil fuel resources of 2.5 million units

The energy supply graphs in figure 35 show that fossil fuel resources are depleted after 30 years for the poor region. The rich region faces depletion in only 15 years, because of the higher level of consumption and thus higher energy use. The energy transition from fossil towards renewable energy and efficiency is too slow to be completed before the resources are depleted. Therefore a sudden energy shortage occurs. The energy shortage is further intensified because lower consumption caused by shortage in turn leads to higher energy intensity. This explains the peak in energy use.

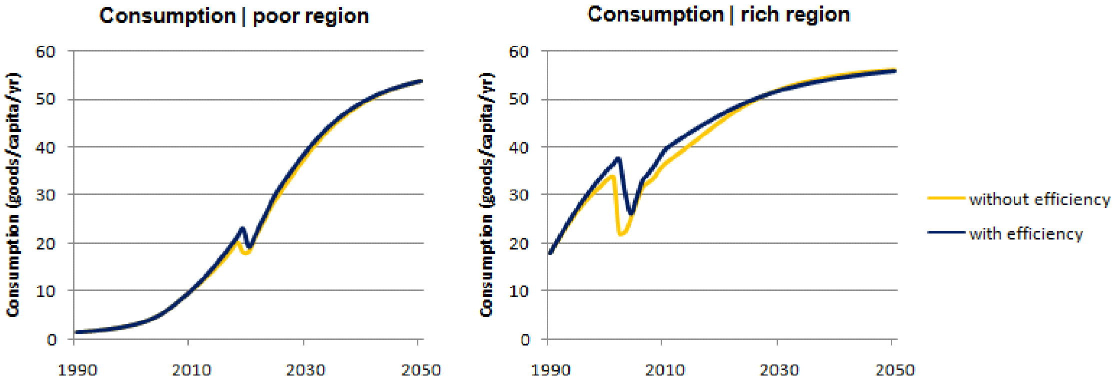

figure 36 Consumption for a poor and rich region with initial fossil fuel resources of 2.5 million energy units

Figure 36 plots consumption over time, with as reference the situation with the efficiency option disabled. In all cases, the energy shortage affects the consumption: directly because the population capital is less effective but also indirectly because the goods production capital is less effective and thus fewer goods are available for investment.

Comparing the runs with and without efficiency shows that energy efficiency option leads to a decrease of the investment fraction for energy, and therefore to a smaller increase in consumption. Interestingly, the efficiency option slows down the learning effect of renewable energy and thus the energy transition from fossil to renewable energy. On the other hand, the efficiency option also slows down the depletion effect of fossil fuels. It therefore decreases the speed of the transition.

The rich region has a higher loss of welfare when depletion occurs, but for both regions the consumption with and without efficiency converges to the same level.

3.3 Trade

If differences in fossil energy productivity exist, trade can be attractive. The option of trade is introduced in this paragraph, limited to trade between two regions. The trade option is not taken into account in the analysis in the other paragraphs.

Trade brings advantages for both the importing and exporting region: the importing region has access to the cheaper fossil energy and the exporting region gains extra goods to invest in its economy.

Suppose the fossil energy productivity of region 1 is higher than that of region 2 ($\varphi_{Fos,1} > \varphi_{Fos,2}$). Call region 1 the exporting region, region 2 the importing region. The world average fossil energy productivity $\varphi_{Fos,W}$ equals

xli. $$\varphi_{Fos,W(t)} = \frac{1}{2}(\varphi_{Fos,1(t)} + \varphi_{Fos,2(t)})$$

As an alternative to investments in domestic production, the importing region can choose to invest in trade contracts with the exporting region. The exporting region has to deliver fossil energy in return for this monetay flow. In this way, the importing region is actually investing in the production capital in the exporting region.

The payment for trade contracts is implemented similar to the investments in domestic production. If the importing region spends *M* goods to fossil energy import, it will receive $E_M = M^*\varphi_{Fos,W}$ energy units in the first year. Every subsequent year, the contract value and thus the delivery of energy units depreciates with a factor 1/LT. The contract cannot be broken, unless the fossil fuel resources in the exporting region are fully depleted.

Trade brings profit for the exporting region. Suppose the region receives *M* goods from the importing region. It must then extend its production capital stock ($\Pi_{Fos,1}$) with $E_M = M^*\varphi_{Fos,W}$. For this, it only needs to invest $(M^*\varphi_{Fos,W})/\varphi_{Fos,1}$. The exporting region therefore gains a profit of $M(1 - \frac{\varphi_{Fos,W(t)}}{\varphi_{Fos,1(t)}})$

A region will export if and only if its productivity is sufficiently higher than the productivity of the other region. A minimum level for this difference is set at 2%, to account for start-up barriers.

If trade is permitted in the model experiment, the actual amount of new trade contracts is determined by the importing region on the basis of a logit formulation. The importing region (region 2) can get new fossil energy supply either by new import contracts or by expansion of its domestic fossil production.

The share of new import contracts as fraction of total new fossil energy supply is determined as:

xlii. $$MS_{Fos,M(t)} = \frac{1}{1 + \left(\frac{\varphi_{Fos,W(t)}}{\varphi_{Fos,2(t)}}\right)^{-\lambda_2}}$$

The share of new domestic fossil production as fraction of the total new fossil energy supply equals $MS_{Fos,P} = 1 - MS_{Fos,M}$. Because import lowers the costs for fossil production, the function determining the market share of renewable energy (xxxii) is adjusted slightly:

xliii. $$MS_{Ren,M(t)} = \frac{1}{1 + \left(\frac{\varphi_{Ren(t)}}{MS_{Fos,M(t)}\varphi_{Fos,W(t)} + MS_{Fos,P(t)}\varphi_{Fos,2(t)}} \right)^{-\lambda}}$$

For the exporting region $MS_{Fos,M} = 0$, so this change only affects the importing region.

The trade option is not enabled in the model experiments in this thesis. A few model experiments with trade are analysed in [van Ruijven, 2008b].

4 SUSCLIME model – Climate change

4.1 Climate change

4.1.1 Climate system

When fossil energy is used, CO_2 is emitted into the atmosphere. This greenhouse-effect enhancing gas has an atmospheric lifetime of about 100 year and therefore the concentration in the atmosphere gradually builds up if sinks like forest do not take up enough to compensate for the emissions. This causes a rise in average global surface temperature and sea levels.

The impacts will not be evenly spread and the ways and means to cope with and gradually adapt to the impacts will differ across regions as well. The SUSCLIME model contains a simplified climate sub model as developed by [Janssen and de Vries, 1998]. This sub model calculates atmospheric carbon concentration directly from carbon emissions which are then converted to an estimated increase in temperature. The atmospheric carbon concentration (p_{CO2}) is based on carbon emissions (E), divided in 5 atmospheric lifetime classes with fractions $c_{1\text{-}5}$ and lifetime $a_{2\text{-}5}$ (the first class has an infinite lifetime), according to the formula (based on [Maier-Reimer and Hasselmann, 1987]):.

xliv.
$$p_{CO_{2(t)}} = p_{CO_{2(t0)}} + \int_{t0}^{t} 0.47 \cdot E_{(\tau)} \cdot \left\{ c_1 + \sum_{i=2}^{5} c_i \cdot e^{\frac{\tau - t}{a_i}} \right\} d\tau$$

The shares of the different lifetime classes are $c_{1\text{-}5}$ = 0.13, 0.2, 0.32, 0.25 and 0.1 and the atmospheric lifetimes are $a_{2\text{-}5}$ = 363, 74, 17 and 2 years. Based on these concentrations, the potential (equilibrium) change of global mean surface temperature is described by:

xlv.
$$\Delta Tp_{(t)} = \frac{\Delta T_{2XCO2}}{\ln(2)} \cdot \ln\left(\frac{p_{CO2(t)}}{p_{CO2(t=0)}} \right)$$

in which ΔT_{2XCO2} , the climate-sensitivity, is the global mean surface temperature change associated with a doubled CO_2 concentration. This climate-sensitivity is currently estimated to be most likely above 2℃ and below 4.5℃ with best estimate 3.0℃ ([IPCC, 2007]). Inertia in the system, for example the heat capacity of oceans that slows down the adaptation speed to a new climate equilibrium, implies that the actual temperature increase will lag behind the potential temperature increase, according to the formula:

xlvi.
$$\frac{d\Delta T}{dt} = \beta \cdot (\Delta Tp - \Delta T)$$

where β is assumed 0.05, causing a delay in reaching the equilibrium temperature that belongs to a given CO_2 concentration of about 20 years.

To illustrate the climate system isolated from the economic and energy systems, three pathways for CO_2 emissions are chosen. For each of these three pathways CO_2 emissions, atmospheric CO_2 concentration and surface temperature change are plotted in figure 37.

In all three cases, no new equilibrium is set in this period of 60 years. This would be possible if the emissions would be lower or the time period longer. Clearly, the surface temperature change lags behind on the atmospheric CO_2 concentration.

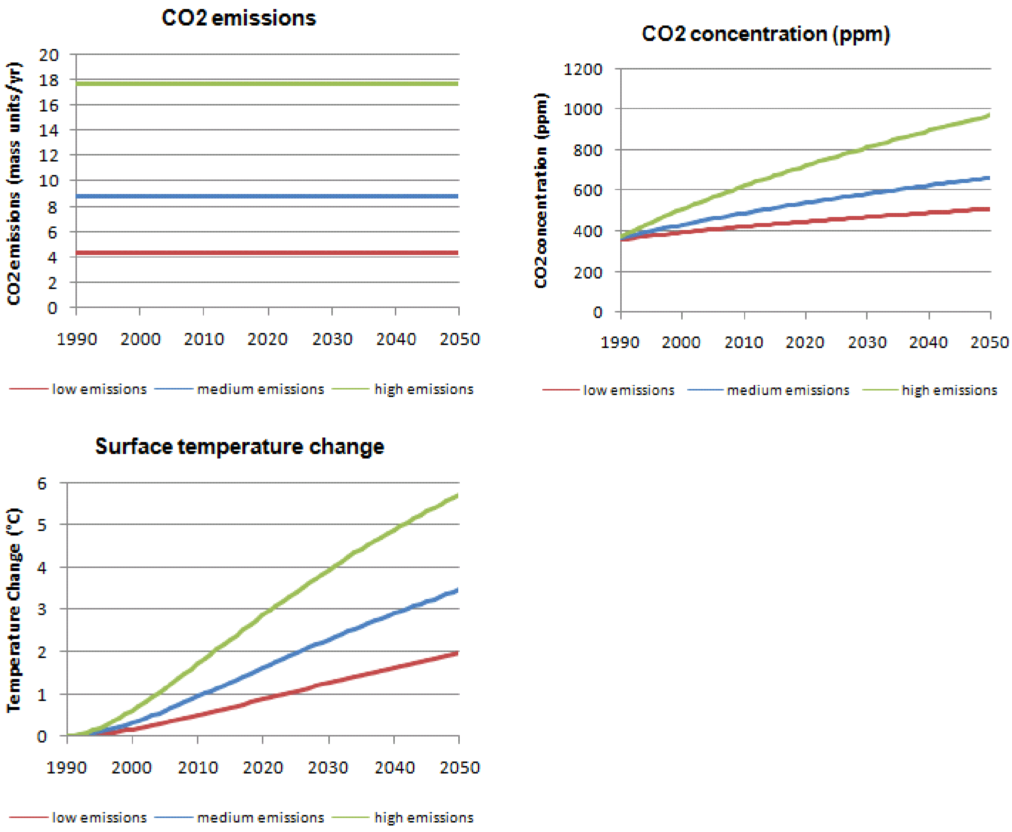

figure 37 CO_2 emissions, atmospheric CO_2 concentration and surface temperature change (relative to 1990) over time for three emission paths.

4.1.2 Feedback to economic system

A more uncertain aspect of climate change is the feedback to the economic system. The politically highly influential *Stern Review* ([Stern *et al.*, 2006) estimates that the world gross domestic product can decrease up to 20% due to climate change. This result is subject to discussion, see for example [Tol and Yohe, 2006] and [Nordhaus, 2007].

A commonly applied method is to use quadratic functions for market damages with increasing temperatures (e.g. the DICE and MERGE models: [Nordhaus, 1993], [Manne *et al.*, 1995]). An alternative approach is based on the – more optimistic - assumption that no 'optimal climate' exists as far as the economy is concerned - an implicit assumption in the quadratic function approach – and that society is able to adapt to climate change [Hallegate, 2005].

Only when the economic system is *not* in equilibrium with the climate, it faces impacts from climate change. In SUSCLIME, climate change then leads to a lower capital lifetime for all capital stocks and productivity loss for the economic capital. If the climate system stabilises for a longer period, the economic system has the ability to adapt to this new climate regime and the impacts will diminish or even disappear.

The process of adaptation is represented by an 'adaptation temperature' (T_a). This temperature equals the surface temperature (T_s) if the climate and economic systems are in equilibrium, but diverges from it when the climate changes faster than the socio-economic system can adapt. Adaptation takes place according to the equation:

xlvii.
$$\frac{dT_a}{dt} = \frac{1}{\mu} \cdot (T_s - T_a)$$

in which μ defines the pace of adaptation and is set at $3 \cdot LT$, three times the lifetime of the capital stocks. The economic system only faces impact from climate change when T_s and T_a differ. This implies that the economic system adapts asymptotically a new equilibrium.

If the economic system is not in equilibrium with the climate ($T_a \neq T_s$), the economic system faces two impacts: first productivity losses of the economic capital stocks K_P and K_C, representing for instance productivity losses in agriculture and infrastructure. Second the capital life time of all capital stocks decreases, caused for example by increased wear or destruction due to change in climate or early retirement for reasons of adaptation to climate change. Both impacts are represented by the climate impact multiplier (CC) and are assumed proportional to the maladjustment of T_a to T_s:

xlviii.
$$CC_{(t)} = 1 - \alpha \cdot (T_{s(t)} - T_{a(t)})$$

The parameter α represents the productivity loss and lifetime change due to 1 degree maladjustment of T_a to T_s. In this chapter, two settings are used for the climate impact: mild with $\alpha = 0.05$ and severe with $\alpha = 0.1$.

Figure 38 shows the development in time of adaptation temperature, the difference T_s - T_a and the climate impact (for $\alpha = 0.05$). The three emission paths are the same as used in figure 37.

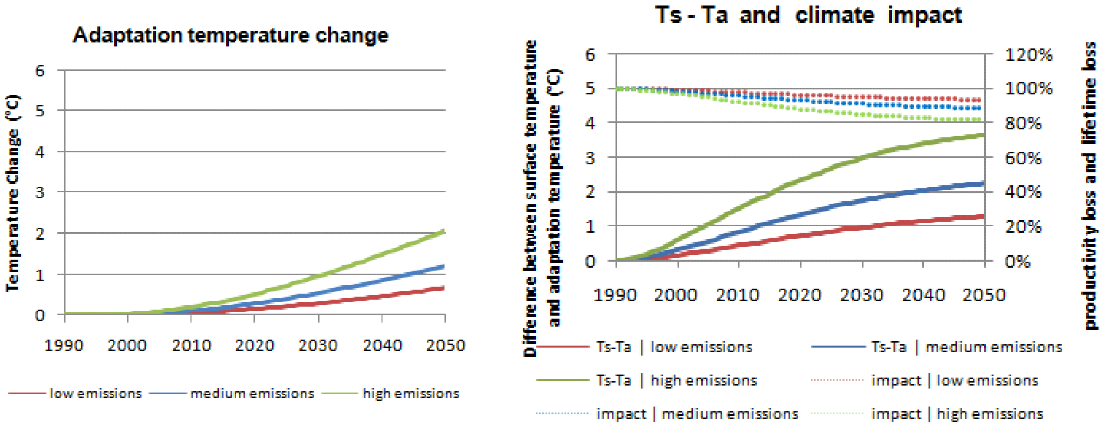

figure 38 Adaptation temperature change (relative to 1990), the difference T_s - T_a and climate impact multiplier (for $\alpha = 0.05$) over time for three emission paths.

The adaptation temperature lags behind on the surface temperature. The difference between the two first increases, but stabilizes at the end of the model run. If the model run would be extended, it would even start to decrease because the surface temperature change slows down. The climate impact multiplier reaches 90% in the end year for the time-path with medium emissions, which means both lifetime of all capital stocks and productivity of the economic capital stocks decrease with 10%.

With these emission paths, fossil fuels are continuously used and thus climate continues to change. On the other hand, when the initial fossil fuel resources are limited, the resources will deplete and the impact from climate change will decrease.

In the examples above the climate system is analysed separately from the rest of the model, using emission paths. Now the population, economy and energy systems are also taken into account. The model is run for rich region with a typical oil economy with abundant fossil fuel resources – the alternative energy options and the depletion effect are disabled. The development of a few important indicators is plotted in figure 39.

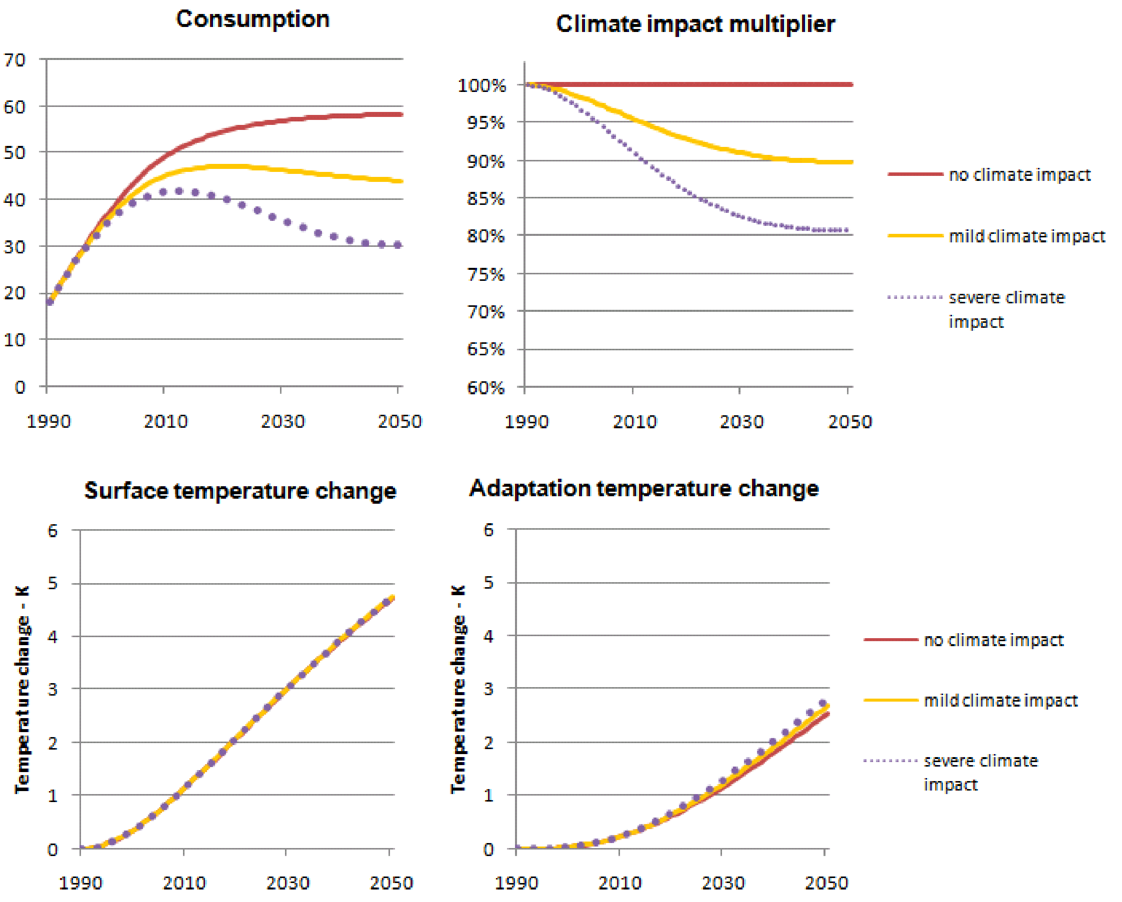

figure 39 Effect of climate change on main indicators, for a rich region using only fossil energy and several settings: no climate impact (α=0), *mild climate impact* (α=0.05) *and severe climate impact* (α=0.1)

In case of severe climate impact, the climate impact multiplier reaches the level of 80%, so both lifetime of all capital stocks and productivity of the economic capital stocks decrease

with 20%. This makes consumption decrease with 50%, relative to the case without climate impact. Mild climate impact leads to half the effect.
In this example the options of energy efficiency and renewable energy are not taken into account. If these alternatives are also considered, the fossil energy use and thus effect of climate change on consumption is less. It leads to a decrease of: about 15% in case of mild climate impact, 30% in case of severe climate impact. The mild climate impact is in line with for example the *Stern Review* mentioned above.

Climate change affects consumption not directly from the start, but only after a decade. This delay is partly because of the low emissions at the start of the time period and the delay in surface temperature. Another reason is that a decrease in investment in K_C does not directly decrease K_C at the same rate. The investments affect K_C and thus C with a delay.

For a poor region, the initial emissions are much lower. Therefore, the impact of climate change is also lower in the beginning. On the other hand, population growth is higher for a poor region and when per capita consumption increases to the same level as the rich region, emissions and thus climate impact will be higher.

Interestingly, the surface temperature change is the same for all three climate impacts. One might expect that the loss of economic activity would lead to a reduction in carbon emissions, but this is not the case, as elaborated below. The adaptation temperature does differ slightly, due to the difference in lifetime of capital stocks. A region facing higher climate impact can adapt a bit faster, because capital lifetime decreases and new technologies will be implemented more quickly.

The loss of economic activity does not lead to a reduction in carbon emissions, as figure 40 shows. The economic capital stock is less productive but still needs the same amount of energy to produce fewer goods.

The total installed economic capital stock will decrease because of the loss of production and investments, but this is compensated for by the increase of energy intensity. Energy intensity increases because of the lower level of consumption. K_P decreases less than K_C, because the savings rate increases for lower development levels.

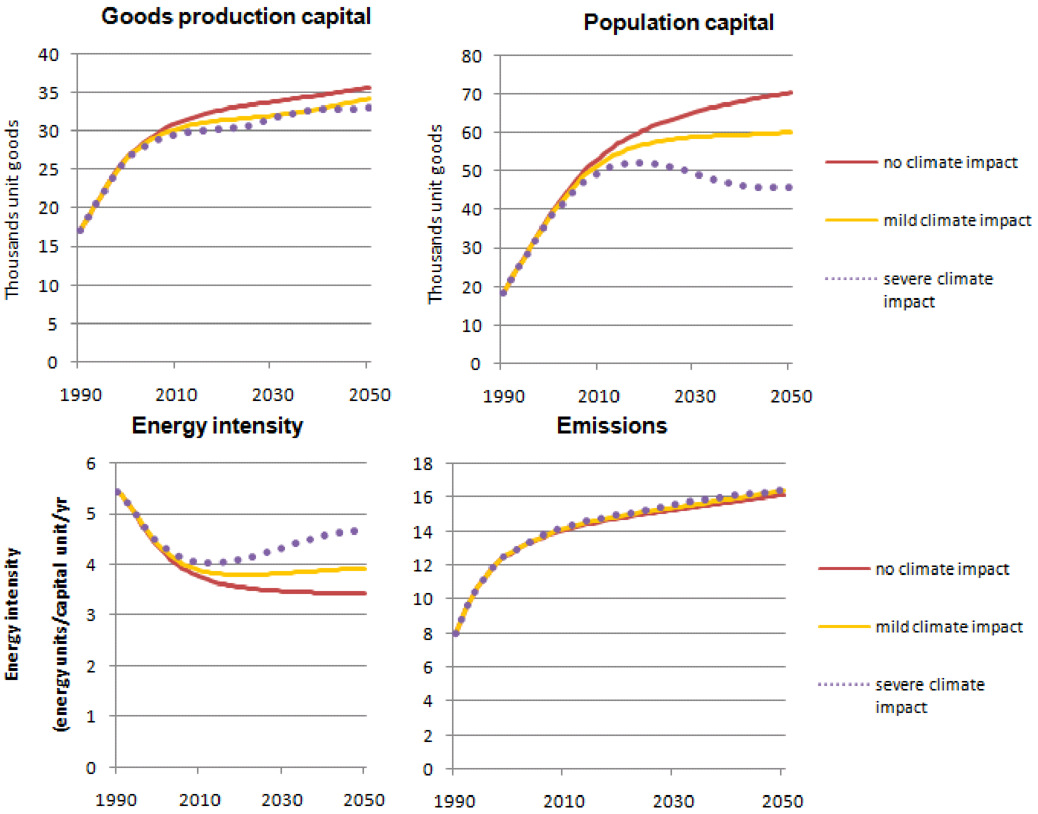

figure 40 *Effect of climate change on economic capital stocks, energy intensity and emissions, for several settings: no climate impact* (α=0), *mild climate impact* (α=0.05) *and severe climate impact* (α=0.1)

The effect of climate change on the economy can be compared to the effect of the fossil energy price in box 3. The figure below compares the effect on consumption of increasing climate impact and decreasing fossil productivity. The colour indicates the level of consumption. This graph shows for example that a region with φ_{Fos}=18 (energy units per capital unit per year) and a severe climate feedback (*α* set at 0.1) is just as wealthy as a region with φ_{Fos}=10 and no climate feedback (*α* set at 0).

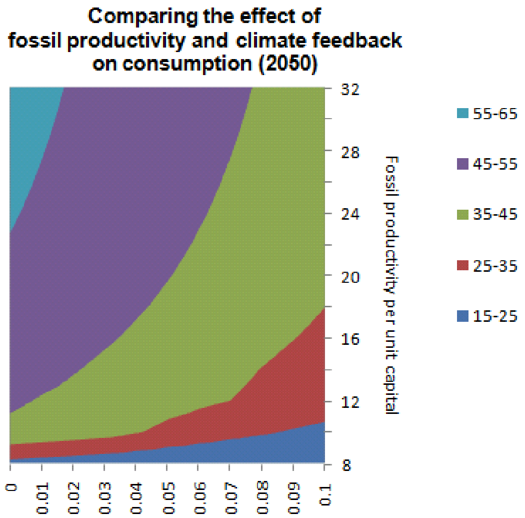

figure 41 *Comparing the effect on consumption of increasing climate impact (α) and decreasing fossil productivity (φ). The colour indicates the consumption level. The example uses a rich region with abundant fossil resources. No investments in renewable energy and energy efficiency are made.*

5 Agents and experiments

5.1 Agent approach

5.1.1 Decision structure

The model as introduced in chapters 2, 3 and 4 uses decision rules without taking into account expectations of future development. In several cases, regions face the effects of climate change and depletion. These impacts might be prevented by basing decisions on expectations of future development. In this chapter the model is therefore extended with forward-looking agents.

The behaviour of the agents represent human response to changing circumstances. An agent gets information about the state of the environment via indicators in the SUSCLIME model. A set of decision rules using this input determines the behaviour of the agents, which in turn influences the environment.

Each region is linked to an agent that represents a central planner. An agent can use policy options to optimize its objectives within a time window *T*. The agents can use information about the current state of the system and projections for the future.

An agent is implemented as an optimization procedure. Given a set of intervention variables, constraints, a time window and an objective function, this procedure finds settings for the intervention variables for which the objective function reaches its maximum at the end of the time window.

The intervention variables used are a climate tax C_{Tax} and renewable subsidies S_{Ren}. The use of these intervention variables is elaborated in paragraph 5.2. The objective function is taken to be the level of consumption after *T* years. This objective function and alternatives are explored in paragraph 5.3.

The intervention of the agent (*A)* can be characterised as a vector of its choices for the policy options (S_{Ren} and C_{Tax}), which are determined as function of its timeframe (*T*, set at 20 or 40 years) , the objective function (*D*) , the former choices for the policy options and the initial state of the model (Σ_{Tini}):

$$\text{xlix.} \qquad A_{(t)} = \begin{Bmatrix} S_{Ren(t)} \\ C_{Tax(t)} \end{Bmatrix} = f(T, D, \begin{Bmatrix} S_{Ren(t-1)}, \ldots, S_{Ren(T_{ini})} \\ C_{Tax(t-1)}, \ldots, C_{Tax(T_{ini})} \end{Bmatrix}, \Sigma_{(T_{ini})})$$

The optimization procedure works as follows: at time-step *t,* the agent tries an intervention $A=\{S_{Ren},C_{Tax}\}$. The SUSCLIME model is run for the time period [T_{ini}, $t+T$], with the intervention variables fixed at the chosen setting in the period [t, $t+T$]. The agent receives the value of the objective function *D* in the end year $t+T$. The agent keeps varying *A*, running the model and checking the value of the objective function until it cannot increase the objective function any further and thus found the optimal intervention $A_{(t)}$.

The intervention variables are fixed during T years only in the optimization procedure for year *t.* After $A_{(t)}$ is set, the time window moves on. When time elapses, projections for the future further ahead can lead to new insights. A future optimization procedure can still alter $A_{(u)}$ for $u>t$.

In total, the optimal intervention *A* is determined for 13 years: 1990,1995,...,2050. The value of the intervention variables between these years are calculated by linear interpolation. The moving time window, during which the agent evaluates its interventions, is schematically shown in figure 42.

As an example, suppose the time window is 40 years, a constraint sets C_{Tax} to zero and the agent is optimizing A_{2030}. The agent for example tries $S_{Ren,2030} = 10$. Then SRen is fixed at 10 during the period [2030,2070]. This setting also influences $S_{Ren,2026}$,..., $S_{Ren,2029}$ because these values are calculated by linear interpolation using the values $S_{Ren,2025}$ and $S_{Ren,2030}$. The model is run and the value of the objective function in 2070 is passed back to the agent. If this is found to be the optimum value, $S_{Ren,2030}$ is definitively set at 10 and the agent starts trying values for $S_{Ren,2035}$.

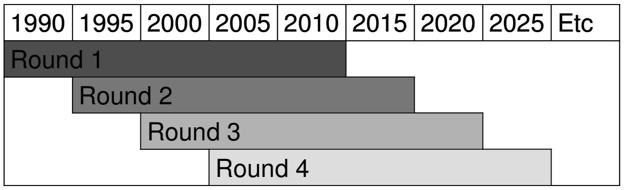

figure 42 Schematic representation of the moving time window with which the agents take their interventions. In this case the time window is 20 years.

Each region, high-income and low-income, has its own agent that only intervenes in its own region. Interaction is not considered, so the region experiences the world as if it is a one-region world.

5.2 Intervention variables

5.2.1 Introduction

In SUSCLIME, the allocation of investments in energy supply is determined by comparing the prices of fossil and renewable energy supply options and energy efficiency investments. This allocation does not take into account the external costs from climate change, nor does it take into account future events as depletion.

Agents can influence the allocation of the investments in energy supply in their region by using two intervention variables (policy options): a carbon tax C_{Tax} and subsidies for renewable energy production $S_{Ren.}$ The agents choose these variables by an optimizing procedure, using information about the system as a whole as well as projections for future development.

The carbon tax C_{Tax} increases the price of fossil fuel production in the decision process, which makes the alternatives renewable energy and efficiency improvement relatively more attractive.[16] This intervention variable is used in cases with climate change. The renewable subsidies S_{Ren} make the renewable energy production more attractive and are used in cases with depletion.

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[16] The tax C_{Tax} only influences the function determining the market share of the different energy options, but is not actually "paid". If the tax would generate a monetary flow, this would first be subtracted from the goods production *Q* as tax-payments, but directly be added to it as tax-income. The net result is zero. The same holds for the subsidy S_{Ren}.

The taxes and subsidies affect the energy capital productivity in the functions that determine the investment allocation: the market share (formula xxxii) and the average energy price used to optimize the energy efficiency investments (formula xxxvii). The actual energy productivity and cost remain unchanged, the taxes and subsidies only influence the decision process.

In this way, the agent can force its region to invest in more expensive energy options. This implies a trade-off between using the cheapest energy options in the short term and prevention of the damages from fossil energy depletion and climate change in the long-term.

Because the taxes and subsidies are used to influence productivity, they are measured in the units of productivity: energy units per capital unit per year. The maximum value for the taxes and subsidies is set equal to the initial difference in productivity between fossil energy and renewable energy: 20 energy units per capital unit per year. In all graphs, subsidies and taxes are expressed as percentage of this maximum.

When the subsidies or taxes are fully applied (100%), the initial difference in productivity thus diminishes. This percentage represents the same productivity gain and loss throughout the model runs. If for example $\varphi_{Ren}=15$ and $\varphi_{Fos}=30$, setting a renewable subsidy of 50% (=10 energy units/capita/yr) means that the market allocation reacts as if φ_{Ren} would equal 25.

In order to explore how the agents for high- and low income regions respond in this system to the challenges posed by climate change and depletion, a set of different experiments is performed. The effect of the policy options is first analysed without agents by keeping the intervention variables fixed during the model runs. This gives the effect of fixed time-paths for intervention. The results are then compared to runs where an agent decides on the interventions.

The settings for the experiments are summarized in the table below and elaborated in the following paragraphs. All settings are tested for both a high and a low income region.

Experiment (paragraph)	*S_{Ren}*	*C_{Tax}*	*Time horizon*	*Climate impact*	*Initial fossil resources*
1 - Baseline - no climate change, abundant resources					
1 No intervention (box 6)	-	-	-	-	2500 mln
2 - Depletion - no climate change, scarce resources					
2a No intervention (5.2.2)	-	-	-	-	2.5 mln
2b Sren = 50% (5.2.2)	50%	-	-	-	2.5 mln
2c Sren = 100% (5.2.2)	100%	-	-	-	2.5 mln
2d Agent, T = 20yr (5.4.1)	set by agent	-	20yr	-	2.5 mln
2e Agent, T = 40yr (5.4.1)	set by agent	-	40yr	-	2.5 mln
3 - Climate change – no/medium/high climate impact, abundant resources					
3a No intervention (5.2.3)	-	-	-	no/medium/high	2500 mln
3b Ctax = 50% (5.2.3)	-	50%	-	no/medium/high	2500 mln
3c Ctax = 100% (5.2.3)	-	100%	-	no/medium/high	2500 mln
3d Agent, T = 20yr (5.4.2)	-	set by agent	20yr	medium	2500 mln
3e Agent, T = 40yr (5.4.2)	-	set by agent	40yr	medium	2500 mln
4 - Combined effect - medium climate impact, scarce resources					
4a No intervention (5.2.4)	-	-	-	medium	2.5 mln
4b Sren = 100%, Ctax = 0% (5.2.4)	100%	-	-	medium	2.5 mln
4c Ctax = 100%, Sren =0% (5.2.4)	-	100%	-	medium	2.5 mln
4d Agent, T = 40yr, only Sren (5.4.3)	set by agent	-	40yr	medium	2.5 mln
4e Agent, T = 40yr, only Ctax (5.4.3)	-	set by agent	40yr	medium	2.5 mln

table 1 Overview of the model experiments with and without agents

5.2.2 Depletion and renewable subsidies

The graphs on the next page show consumption and energy supply and demand for a poor region (left) and a rich region (right). Subsidies for renewable energy are set at either no, medium (50% of initial difference) or high (100% of initial difference).

The energy graphs show that in case of no subsidies, the fossil fuel resources are depleted after 30 years for the poor region. The rich region faces depletion in only 15 years, because of the higher level of consumption, associated with higher energy use. The energy transition from fossil fuels towards renewable energy sources and efficiency too slow to be completed before the fossil resources are depleted. Therefore a sudden energy shortage occurs.

As can been seen from figure 43, the energy shortage affects the consumption: directly because the population capital is less effective but also indirectly because the goods production capital is less effective and thus less goods are available for investment. The energy shortage is further intensified because the lower consumption in turn leads to higher energy intensity. This explains the peak in energy use.

When the medium subsidy level is applied, the renewable energy option is promoted so that the annual production of fossil fuels decreases. Therefore depletion occurs later and the effect of energy shortage at that moment is less than without subsidies – but still an energy shortage occurs. When the subsidies are fully applied (last energy graphs) the transition is very smooth.

The subsidies help to make a smooth transition and not to face sudden depletion, but also have disadvantages. The subsidies influence the allocation of investments in energy supply towards the less productive renewable energy supply. Therefore, the investment fraction of energy must be higher in order to meet the energy demand. Fewer goods remain to be invested in the economic capital stocks, so that the development of the production and consumption slows down.

The graphs in figure 44 indeed show that until depletion occurs, the consumption of the model run without subsidy is higher than the runs with subsidies. After depletion, the opposite holds. An agent with short foresight will thus not from the beginning set subsidies, as paragraph 5.4.1 elaborates. At the end of the model run, the consumptions for all settings converge.

A side-effect of the renewable subsidies is that they hamper efficiency measures. Because the subsidies make energy from renewable resources appear cheaper, efficiency investments seem not to be cost-effective – while they actually are. The investment fraction for energy could therefore be decreased by replacing some renewable investments by efficiency investments.

Effect of subsidies for renewable energy for regions facing depletion (exp. 2abc)

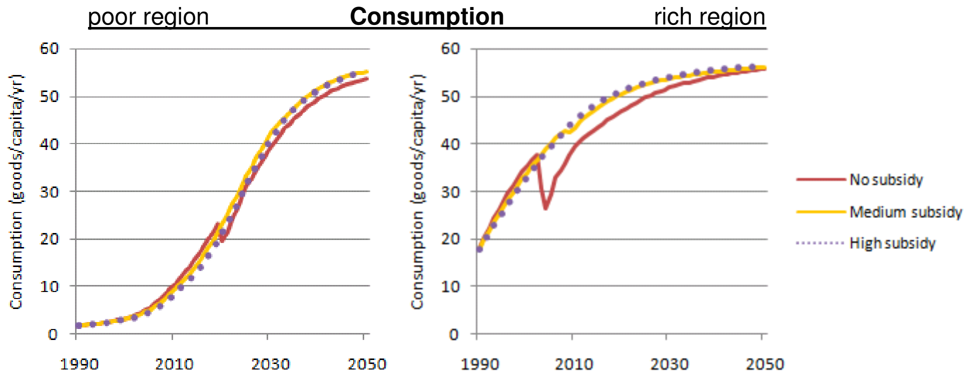


figure 43   Consumption for regions facing depletion with no, medium (10) and high (20) subsidy levels.

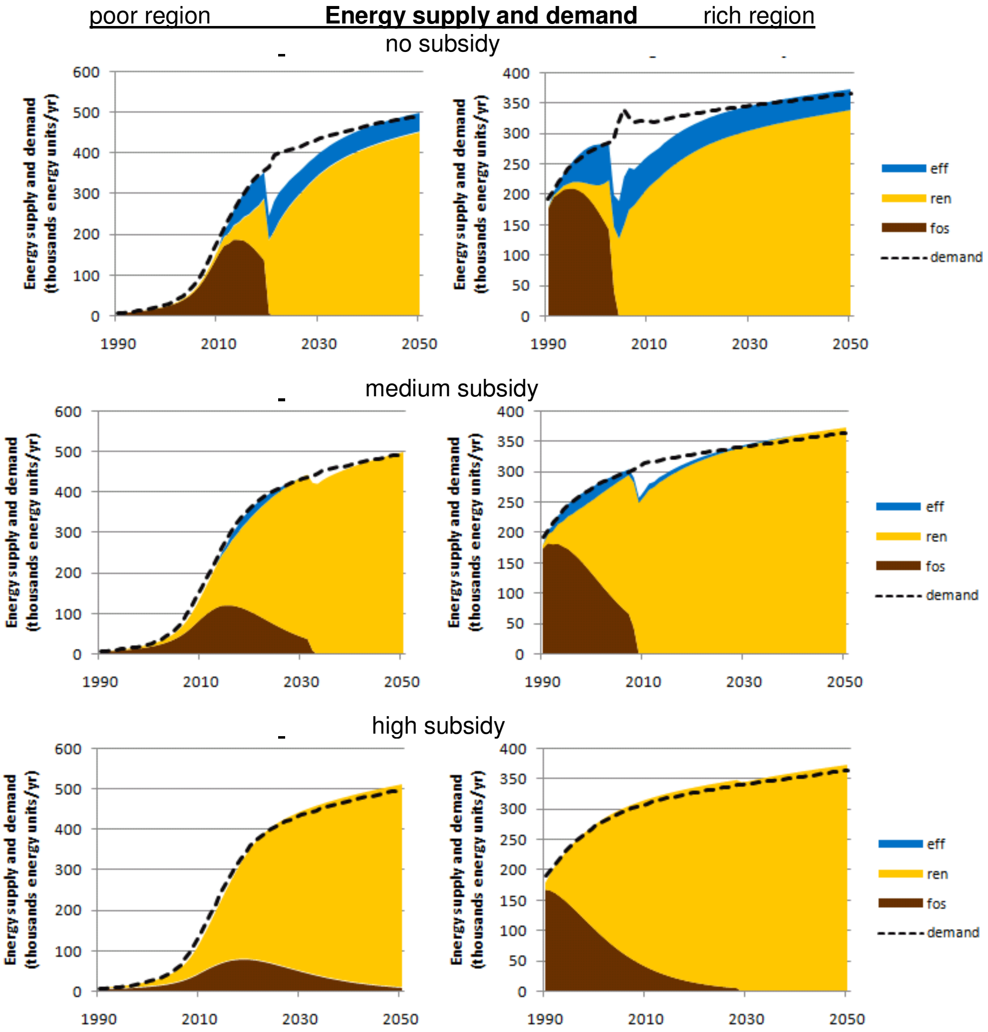


figure 44   Energy supply and demand for a poor and rich region facing depletion with no, medium (10) and high (20) subsidy levels.

5.2.3 Climate change and carbon tax

The previous paragraph explores the effect of the renewable subsidies S_{Ren} on model runs facing depletion, this paragraph the effect of the carbon tax (C_{Tax}) on model runs facing climate change. Again, this is done by fixing the intervention variable in time and analysing the effect on consumption and energy use and demand.

The model is run for a poor and a rich region facing either no, mild or severe impact from climate change (α set at 0, 0.05 or 0.1 respectively). The model is run for one region at the time, so the regions do not interact. To make sure depletion plays no role, the fossil fuel resources are abundant (2500 million).

The graphs on the next page show the development of consumption in time. The carbon tax is either not applied or set at medium (50% of the initial difference) or high (100% of the initial difference).

The run without impact from climate change (upper graphs) shows the effect of the introduction of the C_{Tax} on the economy. The taxes lead to a preference for more expensive energy options. The energy investments fraction IF_E therefore increases, making consumption decrease.

Comparing the runs with no C_{Tax} and high C_{Tax}, IF_E for the latter is 5% higher in the first year, but this difference decreases to 1% in 2050 as the learning effect proceeds. The negative effect of the taxes on consumption therefore also almost diminishes in the long term. In 2050, the level of consumption is 2% lower for the rich region and 3% lower for the poor region.

The consumption graphs for the cases with mild and severe climate impact indicate that when climate change occurs, the introduction of a C_{Tax} is beneficial. The positive effect of reducing the climate impact by decreasing CO_2-emissions is higher than the negative effect of the increased energy costs.

With mild impact from climate change, the introduction of a medium or high C_{Tax} leads to a 5% respectively 15% higher consumption level in 2050, relative to the situation without C_{Tax}. With severe impact, this difference is even higher: 16% respectively 46%.

Still, in the first years the consumption is higher without taxes. The break-even point is between 2010 and 2030. This makes it a challenge to implement agents that choose for early action, see paragraph 5.5.3.

Effect of carbon tax on consumption for several climate impact settings (exp. 3abc)

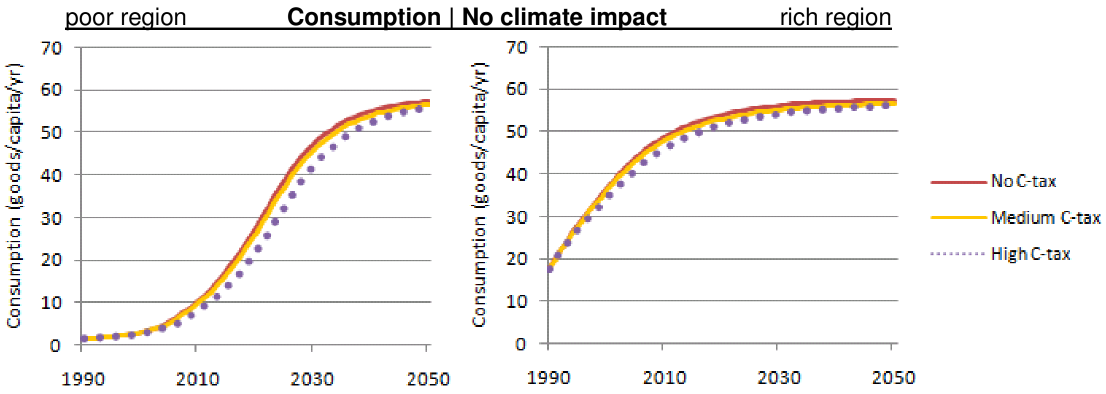


figure 45 Effect of carbon tax on consumption for regions facing no impact from climate change (α=0)

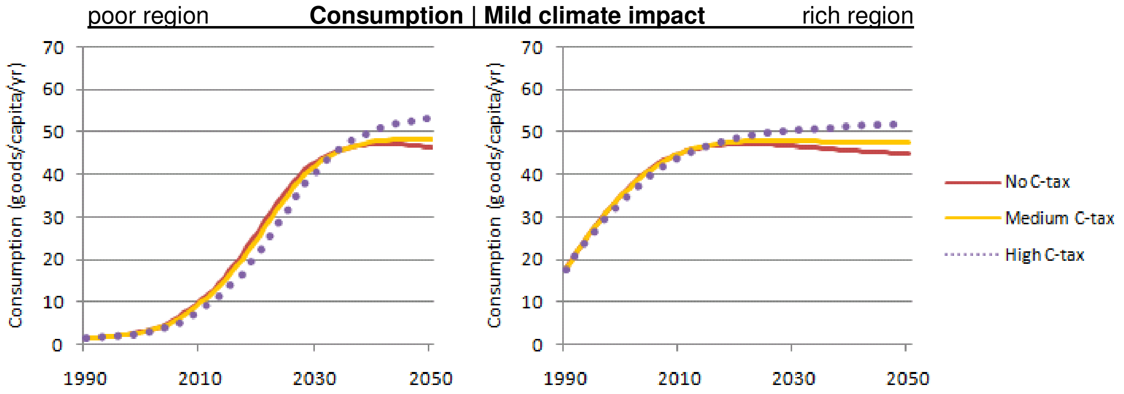


figure 46 Effect of carbon tax on consumption for regions facing mild impact from climate change (α=0.05)

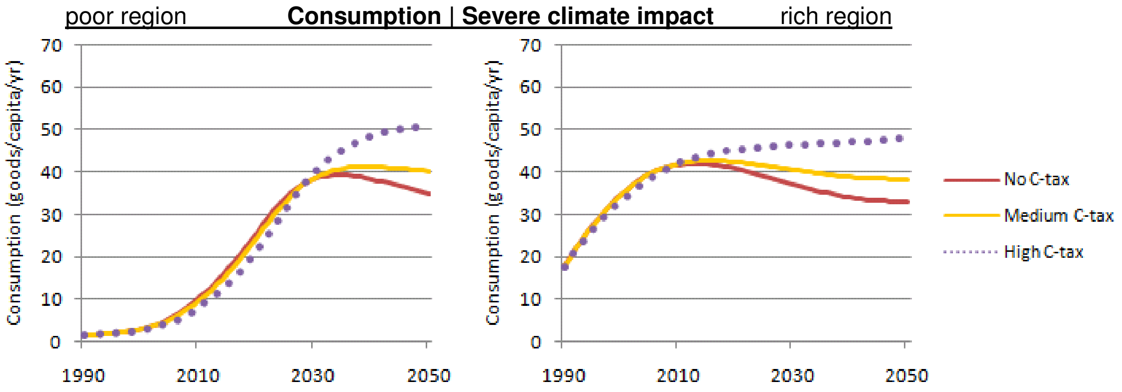


figure 47 Effect of carbon tax on consumption for regions facing severe impact from climate change (α=0.1)

The graphs on the next page show the development of some indicators that further illustrate the difference between the model runs. These indicators are the energy demand and supply, capital productivity loss (which equals the capital lifetime loss) and the main driver for climate change: the CO_2 emissions.

The graphs include only the case of a mild climate impact. In the other cases, with no or a severe climate impact, the energy use and thus CO_2 emissions are equal[17]. Only the graph of the productivity loss changes: without climate impact it always equals one, with a severe climate impact it is of the same shape, but the minimum reached is 84% instead of 91%.

Since the emissions per energy unit of fossil fuels are constant, the CO_2 emissions follow the fossil energy use. Without C_{Tax}, the emissions stabilize and the growth of energy demand – mainly caused by population growth – is accounted for by an increase in efficiency and renewable energy production.

The medium C_{Tax} makes the fossil fuel use drop by almost 50%. The high C_{Tax} is even more effective. The poor region uses hardly any fossil energy, the rich region has a higher initial production but the rapid decrease of this makes that the productivity loss stabilizes and even starts to improve. This is because the economic system adapts to the new climate equilibrium.

Just as the consumption graphs, these graphs indicate that the effects of climate change come with a delay. Reasons for this are that on the one hand, the initial fossil energy production is low; on the other hand the climate system has an inherent delay.

The main difference between the policy options S_{Ren}, and C_{Tax} is that the latter also stimulates efficiency investments. In the next paragraph, a comparison between the two is made.

---

[17] Climate change has an impact on the productivity of the economic capital stocks and the lifetime of all capital stocks. The energy use and thus the CO_2 emissions are hardly affected. On the one hand this is because the same amount of energy is needed to operate the – less effective – capital stocks. On the other hand, the decrease in production will lead to a decrease in installed economic capital, but this is compensated by a higher energy intensity due to the lower consumption. (see also paragraph 4.1.2)

Effect of carbon tax for regions facing a mild climate impact (exp. 3abc)

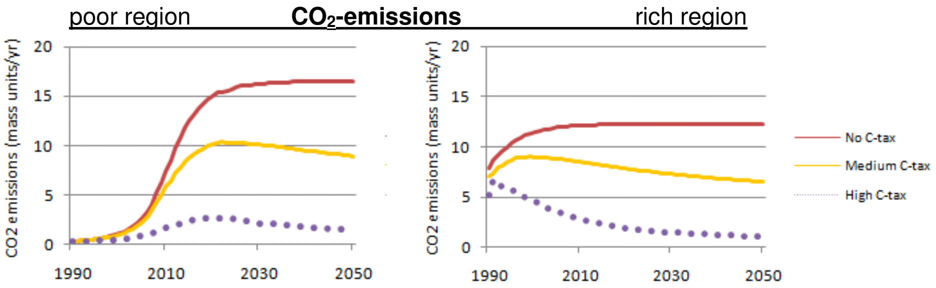


figure 48 Effect of carbon tax on CO_2-emissions for regions facing mild climate change impact

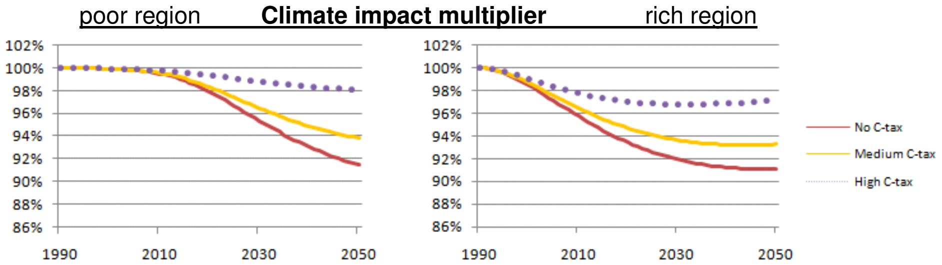


figure 49 Effect of carbon tax on climate impact multiplier for facing mild climate change impact

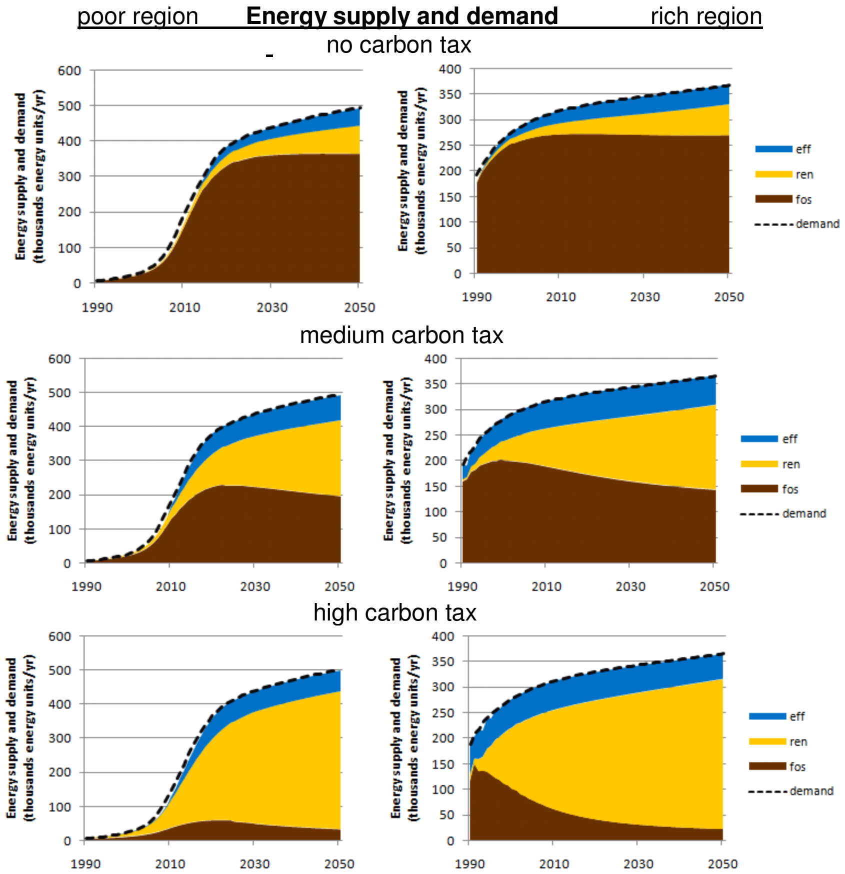


figure 50 Effect of carbon tax on energy supply and demand, for a poor and rich region facing mild climate change impact. From top to bottom, the graphs represent respectively the cases without intervention, with medium carbon tax and with high carbon tax.

5.2.4 Combination of climate impact and depletion

Now the combined effect of depletion and climate change is considered. Separate tests are performed for the two intervention variables. In each test, either taxes or subsidies are fully applied. The simultaneous use of these two is omitted, because they affect the same market share function (equation xxix).

The climate impact is mild ($\alpha = 0.05$), the initial fossil resources are set at 2.5 million energy units.

Both the use of C_{Tax} and the use of S_{Ren} prevent the sudden depletion effect on consumption*,* but C_{Tax} slightly more successful*.* The reason for this is two-fold.

First, because the market share function (equation xxix) takes into account relative differences in production, taxes – lowering the productivity of fossil energy – have a stronger effect on the market share then the same level of subsidies – that increase the productivity of renewable energy.[18]

Furthermore, subsidies have an additional negative side-effect on the energy costs: subsidies discourage investments in energy efficiency. Not all cost-effective energy efficiency measures are implemented and therefore energy supply becomes more costly.

The graphs also show that climate change impact reduces over time. This is because fossil fuels are quickly depleted and thus the cumulative CO_2 emissions are limited. The climate system reaches a new equilibrium, with a higher surface temperature, and the economic system adapts asymptotically to that new equilibrium.

---

[18] Suppose φ_{Ren}=15, φ_{Fos}=30. Normally, the market share for renewable energy (MS_{Ren}) would be 11%. With the maximum level of subsidies, φ_{Ren}=35, φ_{Fos}=30 and MS_{Ren}=61%. With the maximum level of taxes, φ_{Ren}=15, φ_{Fos}=10 and MS_{Ren}=77%

Effect of intervention for regions facing depletion and a mild climate impact (exp 4abc)

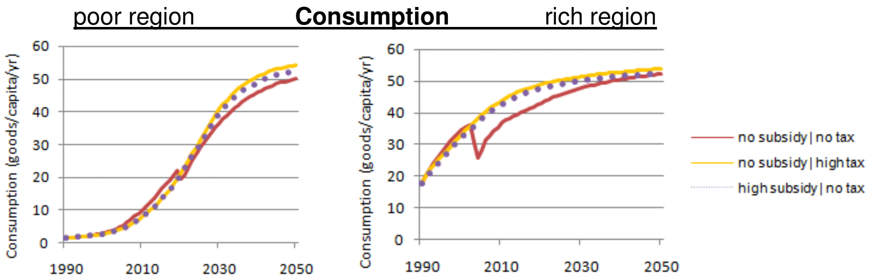


figure 51   Effect of intervention on consumption for regions facing depletion and a mild climate impact.

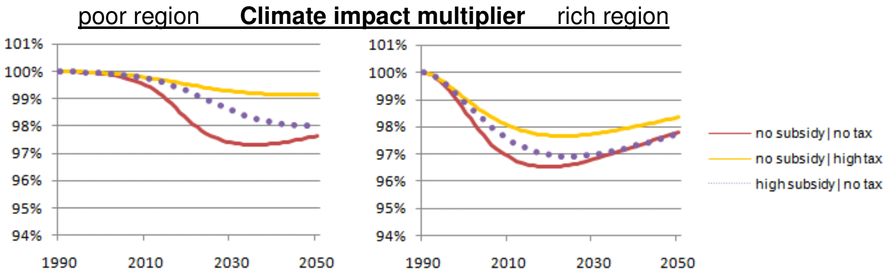


figure 52   Effect of intervention on the climate impact multiplier for regions facing depletion and a mild climate change impact.

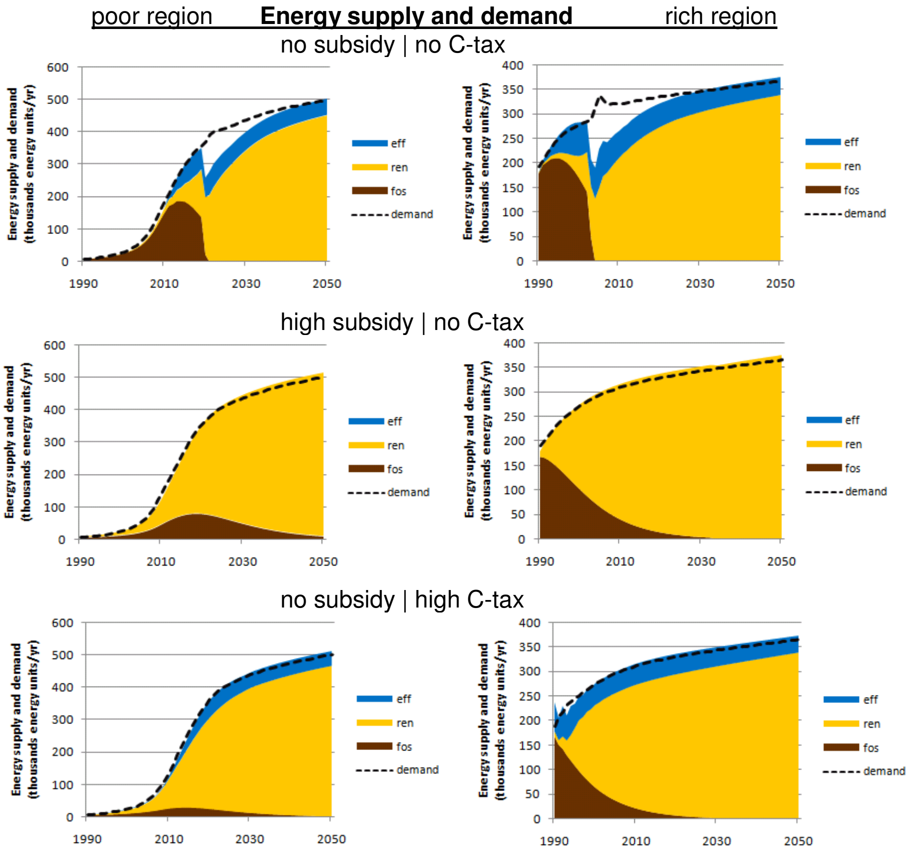


figure 53   Energy supply and demand in time for a poor and rich region facing depletion and a mild climate change impact. From top to bottom, the graphs represent respectively the cases without intervention, with full subsidies but no taxes and with full taxes but no subsidies.

5.3 Objective functions

5.3.1 Introduction

The agents choose the values for the intervention variables for which their objective function reaches a maximum. The objective function is evaluated over the time window *T* of the agent. Three objective functions are tested:

C	- the level of consumption in the end year of the time window (*C*);
AvgC	- the average level of consumption during the period [*t*, *t+T*];
Utility	- the level of utility (the logarithm of consumption) in the end year.

An objective function can be considered as function *Obj* of time *t,* time window *T* and intervention vector A_t. The functions are tested for a poor and a rich region in model runs concerning either depletion or climate change. The agents have a time window *T* of either 20 or 40 years.

The graphs in this paragraph show the dependency of the objective functions on the intervention variables. The indicator plotted is *Obj(t,T,A)/Obj(t,T,0),* or in words the value of the objective function relative to the value of the objective function in the reference case, when no policy options are applied at all. By looking at the behaviour of the objective functions, the choices of the agents can be explained.

During the optimisation procedure, at time *t*, the agents evaluate the effect of varying the intervention variable on the objective function over the period [*t, t+T*]. In the model runs in this paragraph, the intervention variables are always set at zero for the period before *t* ([1990, *t*]). In this way, the effect of varying the intervention variables at each time-step can be compared without an influence of former interventions.

Additional to the objective functions listed above, the objective function *AvgC* is also tested with discounting. The discount rate is then set at either 2% or 6%. The relevant indicator is again *Obj(t,T,A)/Obj(t,T,0).* The absolute values of the objective functions are lower because of the discounting, but the relative differences are similar to the use of the objective function without discounting. Only in periods of rapid growth or decline of the consumption, the indicator differs slightly. Because of the small differences, the graphs are not listed.

5.3.2 Experiment with depletion

The model is run for regions with scarce fossil fuel resources (initially 2.5 million energy units). Climate change is not considered. The renewable subsidies S_{Ren} are ranged between 0% and 100% of the initial difference in productivity of renewable and fossil.

The value of the objective function is plotted relative to the value of the objective function in the reference case, when no policy options are applied at all. The graphs at the next page show the result for a poor region.

Poor region
For the poor region, the situation in 2005 is similar to that of the rich region in 1990, and so is the development afterwards because the consumption levels are then in the same range. For this period, refer to the analysis of the rich region further on.

With the short time-window of 20 years, the effect of depletion (around 2019) is at first not accounted for in the objective function. The fewer subsidies, the higher the value of the objective function. This suddenly changes when the period 2000-2020 is evaluated. The objective function *C* peaks at a value of 128% for subsidies set at 10%. Later on, the optimum setting for subsidies only increase, but the relative difference in goal values decrease.

The objective function *Utility* shows similar behaviour, but with much smaller relative differences. This is because the logarithmic function levels out the differences. The objective function *AvgC* reacts much slower to the depletion, because the positive effect of lower subsidies on the short level out the negative effect on the long term. When the 'problematic' period after depletion takes up a higher share of the time window, the optimum subsidy level increases.

Influence of renewable subsidies on the objective functions - poor region


T=20

T=40

period 1990 – 2010

period 1990 - 2030

period 1995 – 2015

period 1995 - 2035

period 2000 – 2020

period 2000 – 2040

period 2005 – 2025

period 2000 – 2045

figure 54 Effect of subsidies on the objective functions for a poor region with scarce initial resources (R=2.5 million energy units).

When the time window is set at 40 years, the agent takes into account the depletion effect from the beginning. On the other hand, the relative differences are smaller because – for *C* and *Utility* – the end year of the time window is well after the depletion or - for *AvgC* – the average is taken over a longer period.

For renewable energy, the first investments are the least cost-effective. The graphs in this paragraph represent the situation that no renewable subsidies are set in the past. If they would be, renewable energy would be relatively cheaper and therefore subsidies might be more attractive. On the other hand this also means that stimulation of renewable investments is more rewarding over a period of 40 years than over a period of 20 years.

Rich region

For the rich region, the depletion and learning effects evolve faster because the initial levels of consumption and thus energy production are higher.

In this case, the depletion effect is also for the short time window already incorporated in the objective function in 1990.

In 2005 and afterwards, the differences in goal value quickly go towards zero. The goal values for $S_{Ren} > 0$ are slightly below 100%, so the case of no renewable subsidies will be preferred. This can be explained by the fact that the fossil fuels are depleted already, so the renewable subsidies only hamper the efficiency investments.

figure 55 *Effect of subsidies on the objective functions for a rich region with scarce initial resources (R=2.5 million energy units).*

5.3.3 Climate change and carbon tax

The model is now run for regions with abundant fossil fuel resources (initially 2500 million energy units), but facing a mild impact from climate change (α set at 0.05). The carbon tax C_{Tax} is ranged between 0% and 100% of the initial difference in productivity of renewable and fossil.

Contrary to the experiments with depletion, in this case no sudden effect occurs. The effect of climate change gradually builds up. Therefore, the graphs show no sudden shifts in the course of time.

For the poor region, the situation in 2005 is again similar to that of the rich region in 1990.

In case of the time window set at 20 years, taxes never become profitable within this time window. The same holds for the time window of 40 years and the objective function *AvgC.*

If the time window of 40 years is combined with the other objective functions, taxes become profitable if the CO_2 emission is sufficiently high – that is for the poor region after 5 years and for the rich region always.

In that case, the higher the taxes, the better. This predicts a duality: either taxes are totally not applied, or they are fully applied.

For the rich region, after 1995 the goal values converge to zero. The only objective functions taking positive values remain *Utility* and *C*, but only if the time window is set at 40. Contrary to the case of depletion, the use of C_{Tax} is in these cases still profitable after 2005, because there is no autonomous transition towards renewable energy.

The objective function *C* is preferable in both experiments: depletion as well as climate change.

The use of *Utility* levels out relative differences, the objective function *AvgC* values short-term development equally as long-term development and therefore levels out difference in future development.

figure 56   Effect of carbon tax on the objective functions for a poor region facing mild impact from climate change (α=0.05).

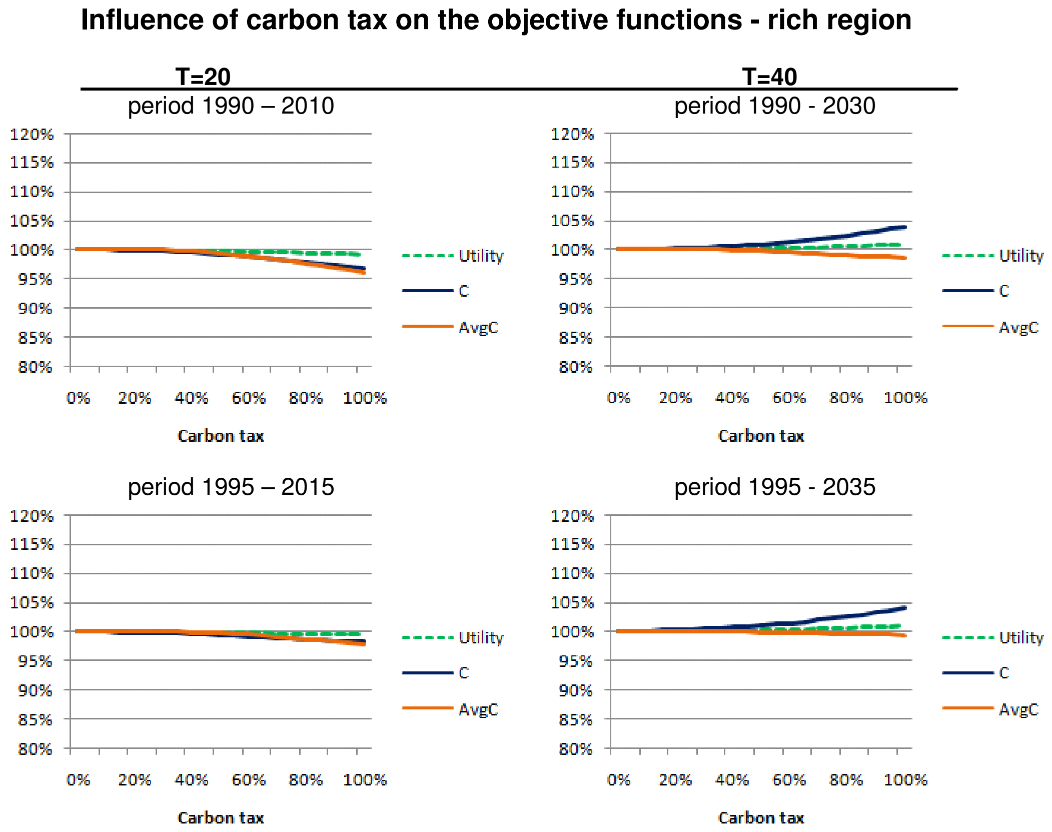


figure 57 Effect of carbon tax on the objective functions for a rich region facing mild impact from climate change (α=0.05).

5.4 Experiments with agents

5.4.1 Depletion and renewable subsidies

Now agents are implemented to set values for the intervention variables. In this case, the model is run for regions with scarce fossil fuel resources (initially 2.5 million energy units). Climate change is not considered. The agents can vary the renewable subsidies S_{Ren}. Each 5 years, the agents set a value for S_{Ren} between 0% and 100% of the initial difference in productivity of renewable and fossil.

For both a poor and a rich region, two agents are used: one with a time window (T) set at 20 years, the other to 40 years. The graphs on the next page also include a run without subsidies, that is equal the run in box 6.

In the poor region, the agent with T=40 first sets the subsidies to a medium level. In the period 2000-2020, the subsidies are fully applied. In 2020, the productivity of renewable – that increases by learning – becomes higher than the productivity of fossil fuels – that decreases due to depletion. Therefore, the region allocates more investments to renewable energy automatically and the subsidies are gradually lowered to zero.

The agent with T=20 start later with setting the subsidies, because the effect of depletion and energy shortage do not yet occur in the periods 1990-2010 and 1995-2015. Because the depletion effect is than already stronger, the subsidies are lowered to zero more quickly.

The rich region starts with higher subsidies, because the energy use is much higher and thus depletion occurs much faster than for the poor region. Although high subsidies can prevent the shock effect of depletion, a small energy shortage is accepted. The effects of energy shortage are low for small shortages (see paragraph 3.1.4). Apparently, in this case the negative effect of energy shortage is smaller than the negative effect of higher investments in energy supply.

In general, the subsidies prevent the shock of sudden depletion. In the long term, the consumption level of all runs converges.

When the subsidies are lowered, the energy efficiency investments increase. Because these investments are only made when they are economically beneficial, the agents perform slightly better with respect to consumption then in case of fixed settings for subsidies (paragraph 5.2.2).

Agents applying subsidies for regions facing depletion (exp. 2ade)

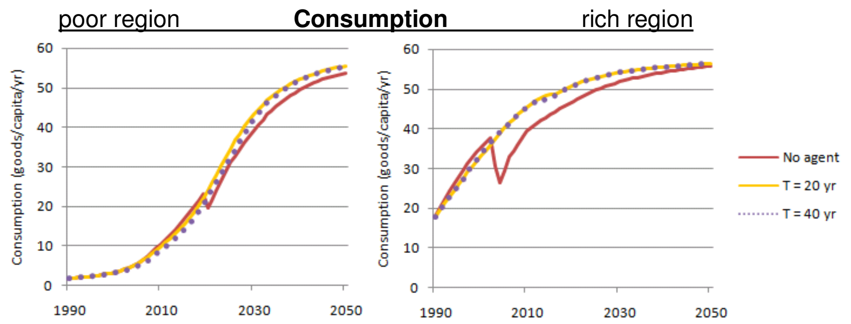

poor region **Consumption** rich region

figure 58 Consumption for regions facing depletion, with no agent or agent with time horizon 20 or 40 years

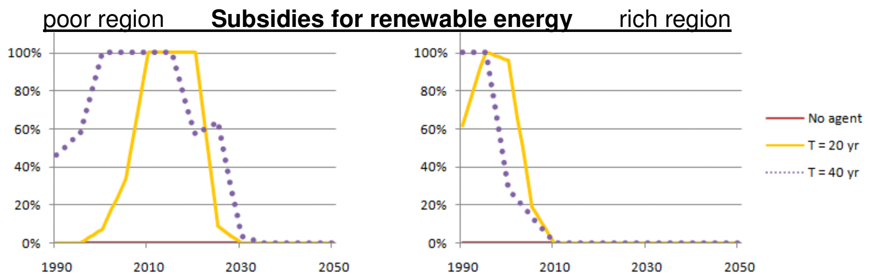
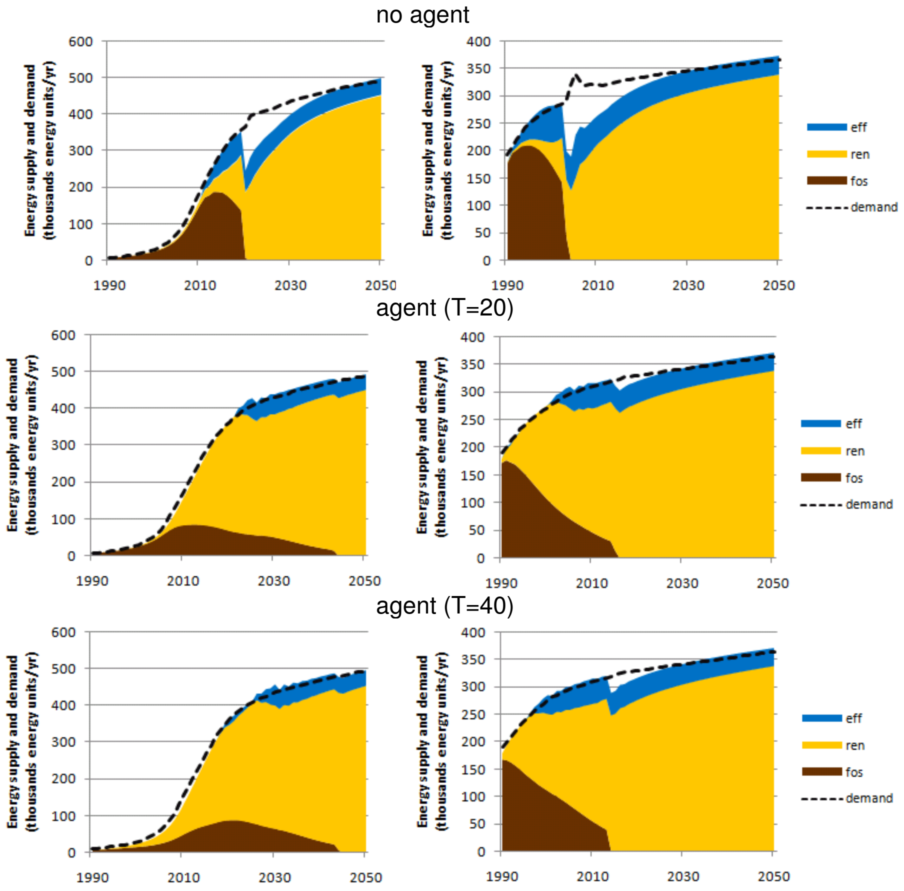

poor region **Subsidies for renewable energy** rich region

figure 59 Subsidy level for regions facing depletion, with no agent or agent with time horizon 20 or 40 years


poor region **Energy supply and demand** rich region

no agent

agent (T=20)

agent (T=40)

figure 60 Energy supply and demand for regions facing depletion, with no agent, an agent with time horizon of 20 years or an agent with time horizon of 40 years

5.4.2 Climate change and carbon tax

This paragraph explores the behaviour of agents in regions facing the impact of climate change. The agents can vary the carbon tax C_{Tax}. Each 5 years, the agents set a value for C_{Tax} between 0% and 100% of the initial difference in productivity of renewable and fossil.

For both a poor and a rich region, agents with a time window of 20 and 40 years are tested. The regions have abundant resources (initial oil resources set at 2500 million). The climate impact is medium (α=0.05).

The agents with time window of 20 years hardly apply the taxes. The taxes that are set are too little and too late. Therefore, the model runs are almost identical as the model runs without agents.

When the time window is set at 40 years, the agents fully apply the taxes. The agent in the poor region starts 10 years later, because the initial emissions are lower and the impact of applying more costly energy sources is higher for a poor region.

This duality of either applying no or full taxes is further explained in paragraph 5.3.3, treating the objective functions.

The runs without agents as well as with agents with T=20 are (almost) identical to the runs without taxes in paragraph 5.2.3, the runs with T=40 are (almost) identical to the runs with high taxes. For further analysis of the consumption and energy graphs, therefore, see paragraph 5.2.3.

Agents applying carbon tax for regions facing climate change (exp. 3ade)

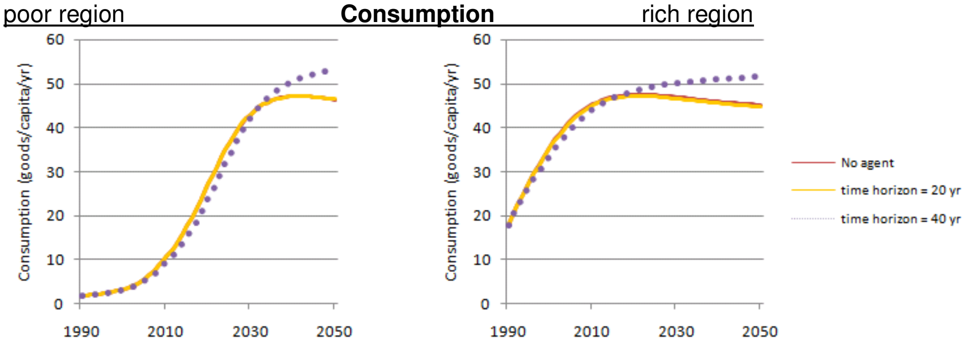

poor region **Consumption** rich region

figure 61 Consumption for regions facing climate change, with no agent, an agent with time horizon of 20 years or an agent with time horizon of 40 years

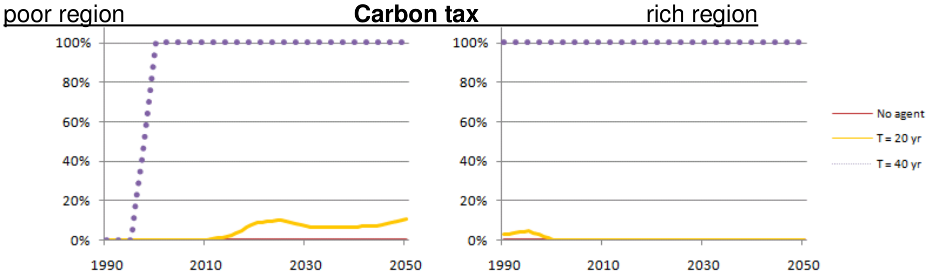
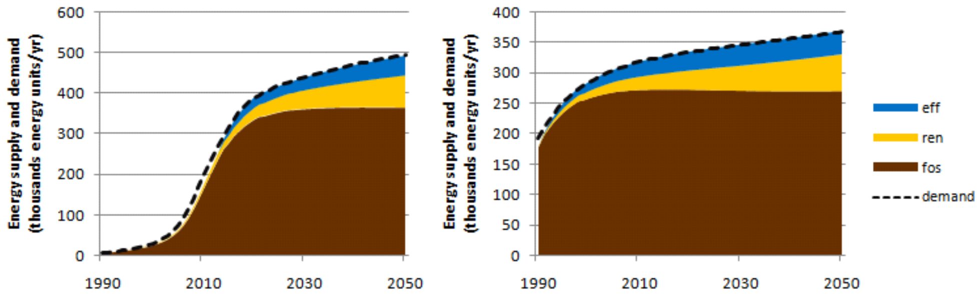

poor region **Carbon tax** rich region

figure 62 Carbon tax level for regions facing climate change, with no agent (no Ctax applied), an agent with time horizon of 20 years or an agent with time horizon of 40 years

poor region **Energy supply and demand** rich region


no agent (≈ agent with T=20)

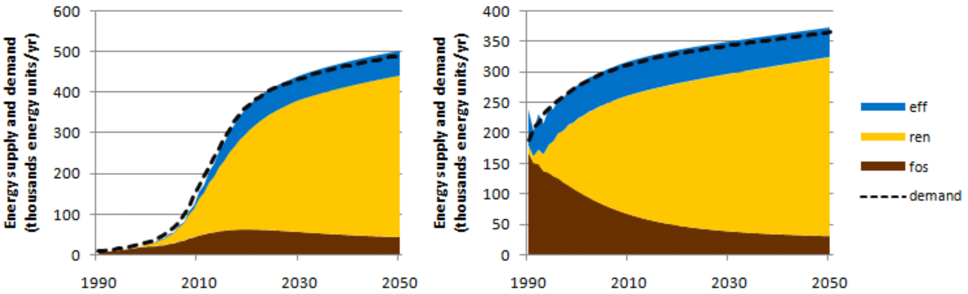

agent (T=40)

figure 63 Energy supply and demand for regions facing climate change, with no agent, an agent with time horizon of 20 years or an agent with time horizon of 40 years

5.4.3 Depletion combined with climate change

Now the combined effect of depletion and climate change is considered. This gives insight in the mutual influence of both effects on each other, as well as on the strategies for the agents.

Separate tests are performed for the two intervention variables. Either taxes or subsidies are enabled. The simultaneous use of these two is omitted, because they affect the same market share function (equation xxix).

The climate impact is mild ($\alpha = 0.05$), the initial fossil resources are set at 2.5 million energy units. The agents in these tests have a time-horizon of 40 years.

Compared to the situation with climate change and abundant resources, the impact of climate change is limited because less CO_2 is emitted in the atmosphere.
The introduction of the climate impact makes no difference regarding the use of S_{Ren} for the rich region. The fossil resources are depleted before the climate impact occurs. The agent in the poor region keeps S_{Ren} at high level during a longer period of time.

In case of agents using C_{Tax}, these taxes are already almost fully applied when the depletion effect is not taken into consideration. The depletion effect makes that also the agent in the poor region starts using C_{Tax} from the start. Agents with time horizon of 20 years (not listed in the graphs) also set the maximum C_{Tax}, in contrast to the test without depletion.

The initially installed fossil energy production capital is fully applied, but no new investments in fossil production are made. Because after the transition, fossil resources are not fully depleted, the C_{Tax} is applied until the end of the model run.

The use of C_{Tax} is slightly more successful then the use of S_{Ren}. The reasons for this are explained in paragraph 5.2.4.

Agents intervening in regions facing mild climate change and depletion (exp. 4ade)

poor region **Consumption** rich region

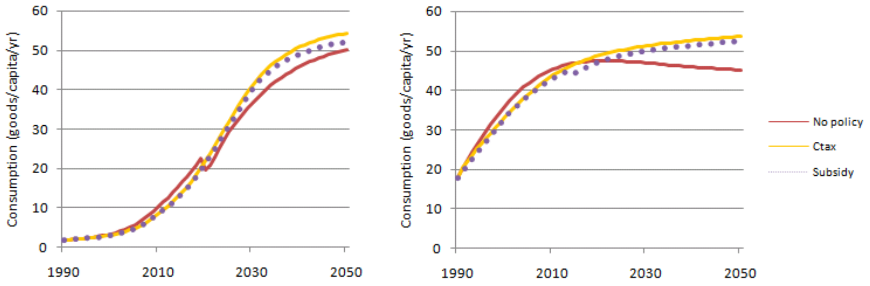


figure 64 Consumption with agent (T=40) applying no intervention options, only C_{Tax} or only S_{Ren}

poor region **Intervention variables (C_{Tax} or S_{Ren})** rich region

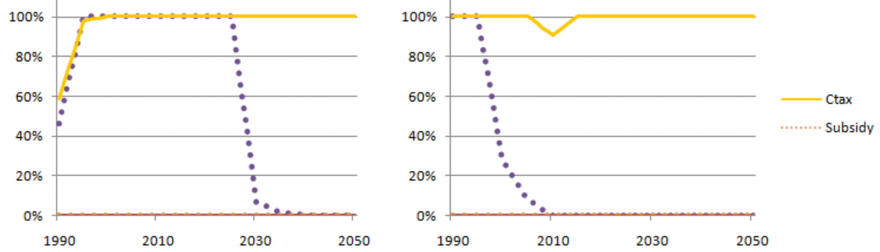
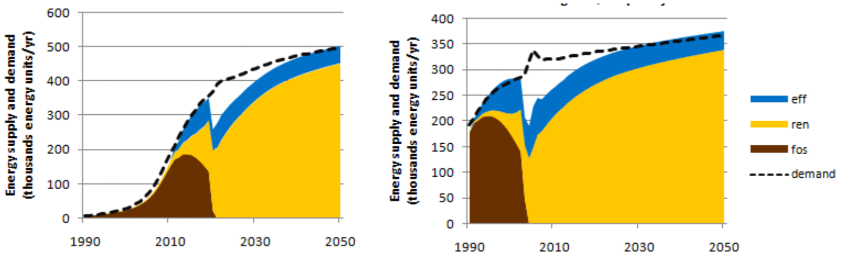


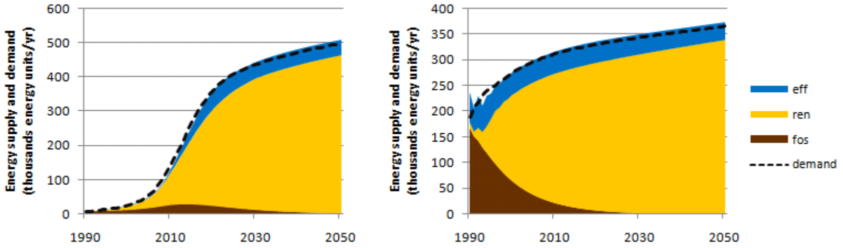
figure 65 Intervention with agent (T=40) applying no intervention options, only C_{Tax} or only S_{Ren}

poor region **Energy supply and demand** rich region

no intervention



application of carbon tax



application of subsidies

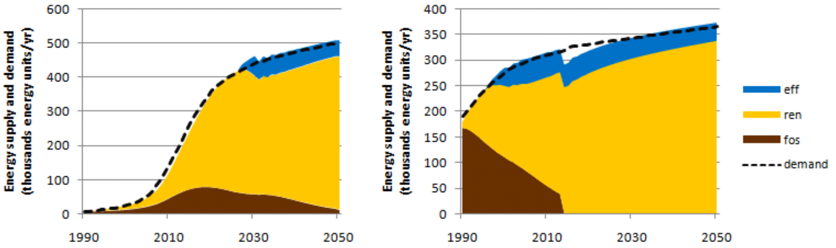


figure 66 Energy supply and demand with agent (T=40) applying no intervention, only C_{Tax} or only S_{Ren}

5.5 Synthesis of results

5.5.1 General remarks

Table 2 and table 3 compare the consumption level in several years for all tests in this chapter. Baseline is a model run for regions with abundant initial fossil resources (2500 million energy units) that do not face impacts from climate change.

The colours in these tables highlight the level of decline in consumption, relative to the baseline. The lower the value *C*, the more the cell colours towards red.

In general, the absence of intervention leads to a higher level of consumption in 2000 and 2010, but lower in 2030 and 2050.

In all cases, in the short term (2000, 2010) intervention in the poor region leads to a relatively higher loss of *C* than intervention in the rich region.

Consumption -Poor region	**2000**	**2010**	**2030**	**2050**
p1 - Baseline - no climate change, abundant resources				
p1 No intervention	100%	100%	100%	100%
p2 - Depletion - no climate change, scarce resources				
p2a No intervention	100%	96%	83%	94%
p2b Sren = 50%	95%	87%	88%	96%
p2c Sren = 100%	90%	78%	86%	96%
p2d Agent, T = 20yr	100%	91%	91%	96%
p2e Agent, T = 40yr	93%	81%	88%	96%
p3 - Climate change - medium climate impact, abundant resources				
p3a No intervention	100%	99%	90%	81%
p3b Ctax = 50%	98%	94%	89%	84%
p3c Ctax = 100%	91%	79%	87%	93%
p3d Agent, T = 20yr	100%	99%	90%	81%
p3e Agent, T = 40yr	100%	88%	89%	92%
p4 - Combined effect - medium climate impact, scarce resources				
p4a No intervention	100%	95%	77%	87%
p4b Sren = 100%, Ctax = 0%	90%	77%	83%	91%
p4c Ctax = 100%, Sren =0%	91%	77%	86%	95%
p4d Agent, T = 40yr, only Sren	91%	79%	84%	91%
p4e Agent, T = 40yr, only Ctax	92%	79%	86%	95%

table 2 Comparison of consumption levels of various model runs for the poor region

5.5.2 Depletion and energy transition

First consider the experiments that illustrate the process of depletion and energy transition. The different intervention experiments all give better results than the experiment without intervention. The differences between the intervention experiments are small.

For the rich region, the order is as expected: the agent with foresight of 40 years (*r2e*) performs better than the agent with foresight of 20 years (*r2d*); they both perform better than a fixed subsidy of 100% (*r2c*) and a fixed subsidy of 50% (*r2b*).

In the poor region, the agent with foresight of 20 years outperforms the agent with foresight of 40 years. This exception can occur because the evaluation of the goal function is performed for fixed values of the intervention variables during the whole time frame. The agent with time window of 40 years has to balance short-term benefits against long-term drawbacks. The agent with time window of 20 years is in this way more flexible.

5.5.3 Climate change

For the poor region, the climate tax is not yet beneficial in the first years, when emissions are low. The tax only hampers development, while absolute emission reduction is low. Therefore the agent with time horizon of 40 years outperforms the fixed time-path with fully applied taxes. For the rich region, the two have similar performance.

Agents with time horizon of 20 years do not set taxes in neither the rich nor the poor region The resulting model run is the same as without intervention. In case of fixed taxes of 50%, the climate impact is reduced, but the consumption level is not stabilized.

5.5.4 Combination of climate change and depletion

Compared to the situation with climate change and abundant resources, the impact of climate change is limited because less CO_2 is emitted in the atmosphere.

In the short term agents perform better than fixed time-paths with full subsidies or taxes, especially for the poor region. At the end of the model runs, the results for the two experiments with taxes are the same, just as the results for the two experiments with subsidies. The taxes always outperform the subsidies, as explained in paragraph 5.2.4.

Consumption - Rich region	**2000**	**2010**	**2030**	**2050**
r1- Baseline - no climate change, abundant resources				
r1 No intervention	100%	100%	100%	100%
r2 - Depletion - no climate change, scarce resources				
p2a No intervention	96%	81%	92%	97%
p2b Sren = 50%	92%	89%	96%	98%
p2c Sren = 100%	90%	92%	96%	98%
p2d Agent, T = 20yr	90%	93%	96%	98%
p2e Agent, T = 40yr	91%	93%	96%	98%
r3 - Climate change - medium climate impact, abundant resources				
r3a No intervention	98%	93%	83%	79%
r3b Ctax = 50%	97%	92%	85%	83%
r3c Ctax = 100%	93%	91%	90%	91%
r3d Agent, T = 20yr	98%	93%	83%	78%
r3e Agent, T = 40yr	93%	91%	89%	90%
r4 - Combined effect - medium climate impact, scarce resources				
r4a No intervention	94%	76%	85%	91%
r4b Sren = 100%, Ctax = 0%	88%	87%	89%	92%
r4c Ctax = 100%, Sren =0%	90%	90%	91%	94%
r4d Agent, T = 40yr, only Sren	90%	88%	89%	92%
r4e Agent, T = 40yr, only Ctax	90%	90%	91%	94%

table 3   Comparison of consumption levels of various model runs for the rich region

6 Discussion

6.1 Discussion

6.1.1 Significance of the SUSCLIME model

SUSCLIME is a highly stylized system dynamics model. As mentioned in the introduction, the model is not designed to give quantitative correct projections, but to provide qualitatively significant results for the understanding of the system dynamics. By varying the input settings, the long-term feedbacks of the population-economy-energy-climate system can be explored.

Most results from the model experiments can be derived from the model assumptions by structured reasoning. The model therefore does not bring exciting new insights to a person educated in the field of energy and climate sciences. This is inherent to the purpose of SUSCLIME: the model is designed to represent well-established scientific findings and give new insights to people that do not have this specific background.

On the other hand, because of its degree of abstraction and modular structure, SUSCLIME is a useful tool for exploration of the system dynamics. By changing major model properties the effect on the system dynamics can be analysed, isolated from other influences.

The model can also be easily extended for specific research goals, especially for further research on the behaviour of the agents. Some recommendations for further research are elaborated in the last paragraph of this discussion.

6.1.2 Economic system

The function for labour-productivity is chosen such that it stabilizes at a certain capital-labour ratio. Per capita values of consumption and production therefore also stabilize. This seems to contradict the economic paradigm of continuous economic growth. The introduction of an additional time-dependent technology factor could make SUSCLIME comply with this paradigm. If the economic growth is qualitative and not quantitative, this addition factor is not needed, as explained below.

The growth of the economic capital stocks in SUSCLIME only represents quantitative and not qualitative growth. Assuming increasing per-capita welfare levels in the real-world will ultimately be based on qualitative improvements in production and consumption, the current formulation in SUSCLIME is in line with the paradigm continuous economic growth.

The economic stabilization makes that economic differences easily level out on the long term. This for example makes shock effects of depletion have little impact on the long-term. Only when a negative impact remains, for example with high energy prices or climate change, it affects a region on the long term. It is therefore important not only to look at the state of the system at the end of a time period, but also consider intermediate results. This reflects the real-world situation that a generation would not accept short-term economic burden in favour of future generations.

6.1.3 Energy

The constants in the energy sub-model[19] are set such that if the fossil fuel resources are depleted in 60 years, the energy transition without intervention is fast enough to prevent a sudden energy shortage. This is an optimistic choice. In reality, especially the response to differences in prices is much lower. Lock-in problems like the change of energy distribution system, retrofit of capital and "wait and see"-behaviour make that fossil fuels are favoured.

Within SUSCLIME, an increase of the λ-value, determining price elasticity, could account for this lock-in situation. The energy transition would then start for higher differences in productivity, leading to a more bumpy transition. High taxes and subsidies would then have a relative higher gain.

SUSCLIME does not differentiate fossil fuels. For electricity production, an increase in the use of coal could reduce the problem of resource scarcity. On the other hand, on the long term coal will also be depleted. Moreover, coal cannot replace all functions of oil and gas.

Energy-intensity changes with consumption, to reflect structural changes in the process of economic development. The dominant economic activities for increasing welfare levels are assumed to be first agricultural, then industrial and finally services-based. The function of energy-intensity is reversible, which means that for high development levels, a drop in consumption level leads to an increase of energy intensity. A structural economic change backwards from service-related to industrial activities is unlikely. This reversibility can be justified by a different explanation: the economic fallback discourages the use of newest technology and therefore energy intensity will increase.

The effect of energy shortage on economic activities is now based on a rough estimation and can be further elaborated.

6.1.4 Climate change

The general formulation of the climate system is widely accepted: carbon emissions leading to increasing greenhouse gas concentrations, in turn leading to temperature change. In SUSCLIME the economic system can adapt to altered climate conditions, which is according to some an optimistic assumption.

Both the magnitude and the mechanism of impact of climate change on the economy are subject to discussion. In SUSCLIME, this impact is implemented as decrease of lifetime and productivity of capital stocks when the economy is not in adjusted to the state of the climate. This implementation is easy to explain to the users of the model. The magnitude of the impact is set high enough to have a clear effect on the model runs and is within the ranges of the Stern Review ([Stern *et al.*, 2006]).

6.1.5 Implementation of agents

The functionality of the agents in this thesis report is limited to a simple optimization procedure, which can easily be extended with for example additional boundary conditions and a variety of goal functions.

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[19] I.e. the constants for learning in case of renewable energy, depletion in case of fossil fuel and price elasticity, determined by the exponent λ in the market share function.

When evaluating the consequences of the settings for the intervention variables, an agent keeps these variables fixed during the whole time-window. A variable time path within this time-window could be advantageous. The decision structure would also improve if an agent takes into account that it can alter the decision on the use intervention variables when time proceeds, in this case every five years.
The agents have perfect foresight on the model behaviour, within a limited time-frame. In future research, a fuzziness in the accuracy of expectations can be implemented. Another approach is align the expectations of the agents to different attitudes, such as risk-taking or doom-saying.

6.2 Future research

Next to the recommendations for further research in the discussion above, a few intriguing questions can be further researched with the SUSCLIME model.

The model is only used for one region at the time. The interaction between regions deserves further elaboration, especially for the subject of climate change. Which climate policies – if any – are successful even when other regions do not implement a policy? How can negotiation and cooperation between agents be introduced? How do strategies change if the impact from climate change differs between regions?

Also, the use of intervention variables and objective functions of the agents can be extended. What is the behaviour of an agent if it does not set subsidies and taxes, but directly sets the allocation of energy investments? What happens if boundary conditions like a target of 30% efficiency improvement in 2020 are set?

An interesting development that has already started by Markus Brede and Bert de Vries is the implementation of SUSCLIME as an internet game. Not only can SUSCLIME in this way be played by anyone at anytime, it also opens doors to behavioural research. By making the players fill in a questionnaire before or after playing SUSCLIME, the relation between their choices in the game (e.g. risk taking and early action) and their attitude towards environmental and social problems or their cultural background can be analysed.

7 Summary and conclusions

7.1 The SUSCLIME model

In this thesis report, a population-economy-energy-climate system dynamics model is introduced: the SUSCLIME model. The model is constructed and analysed step-by-step.

The process of climate change, resource depletion and transition towards non-fossil energy sources are illustrated by varying the initial settings for archetypical regions. The structure of the "building blocks" and observations about results are summarized below.

7.1.1 Population and economy

A region invests in economy and energy. With investments in economy, the region balances between short-term benefits of investments for consumption (I_C) or long-term benefits of investments for production (I_P). The total investments equal production of goods of last time-step, which is basically a function of production capital and population size.

Main observations:

- The economic model, free of external effects, forces stabilization. Differences in initial settings level out.
- Poor regions need higher investments in production relative to consumption in order to increase labour productivity and reach "the plain of the rich".
- Poor regions have higher population growth, which can increase the speed of depletion and the impact from climate change

7.1.2 Energy

The use of economic capital requires energy. To reflect structural changes in the process of economic development, energy-intensity changes with consumption, reaching a maximum for modest consumption levels.

Energy investments (I_E) are set to a value that makes energy supply meet demand. Regions can invest in fossil energy production (I_{Fos}, with increasing production costs due to depletion) and renewable energy (I_{Ren}, with decreasing production costs due to learning). The market share of both options is a function of their relative costs. Efficiency investments (I_{Eff}) are made as long as they are cost-efficient.

Main observations:

- With scarce fossil resources, the energy transition from fossil to renewable energy and efficiency is too slow to be completed before the resources are depleted.
- In case of sudden depletion, the energy shortage is further intensified because lower consumption caused by shortage in turn leads to higher energy intensity.
- In case of sudden depletion, both poor and rich regions experience serious economic disruptions. The rich region endures a relative higher loss of welfare then the poor region (in the example, consumption decreases with 30% respectively 16%).
- Efficiency investments slow down the learning effect of renewable energy and also slow down the depletion effect of fossil fuels. They therefore decrease the speed of the transition from fossil to renewable energy, but also smooth the transition.

7.1.3 Climate change

The carbon emissions caused by use of fossil energy lead to increasing GHG concentration in the atmosphere and to temperature change. The economic system slowly adjusts to the new situation. If the economy is not fully adjusted, climate change has a negative impact on the economic development.

Main observations:
- Climate change affects consumption not directly from the start of a model run, but only after a decade.
- For a poor region, the initial emissions are much lower, but the impact of the climate tax on the economy is much higher. Therefore emission reduction is costly and ineffective. • Severe climate impact makes consumption decrease with 50%, mild climate impact with 25%.

7.2 Implementation of agents

7.2.1 Implementation of agents in SUSCLIME

The SUSCLIME model is extended with forward-looking agents to explore the process of adjustment of behaviour when the effects of depletion and climate change are foreseen. The agents develop strategic behaviour to cope with these issues, assuming the aspiration for consumption growth.

An agent can set intervention variables (carbon taxes and renewable subsidies) for a region. It looks forward to assess the consequences of varying the intervention variables for the objective (consumption growth). The agents adjust their behaviour to the changing circumstances and can therefore prevent impacts of sudden depletion and climate change.

Main observations:
- The intervention options and forward looking agents help to make a smooth transition towards renewable energy and reduce the negative impact of sudden fossil energy depletion and climate change
- The variable time-paths of intervention set by the agents leads to higher consumption than fixed time-paths.
- For both taxes and subsidies, intervention leads to a lower level of consumption in the short term because of higher energy costs, but higher in the long term because of prevention of external effects.
- In all cases, in the short term intervention in the poor region leads to a relatively higher loss of *C* than intervention in the rich region.
- A side-effect of the renewable subsidies is that they hamper efficiency measures.
- Taxes are more effective than subsidies, because they do not discourage efficiency investments and because the relative costs difference between the options is higher after applying taxes then after applying subsidies.
- For the poor region, the climate tax is not yet beneficial in the first years, when emissions are low. The tax only hampers development, while absolute emission reduction is small.
- In case of mild climate impact, the agents with short time window do not apply taxes. The effect of climate change gradually builds up, no sudden effect occurs as with depletion. Therefore, agents with long time-window perform better.
- Co-benefits between avoiding climate change and avoiding resource depletion are possible: when the climate impact is combined with depletion, taxes are also applied by agents with short time-window.

- In case of depletion, the agent with short time-window starts later with setting the subsidies, because the effect of depletion and energy shortage does not yet occur within their time-horizon.

7.2.2 General remarks about the use of agents in energy/climate models

In SUSCLIME, agents are implemented as forward-looking decision makers that adept their behaviour to expectations about their environment and try to maximize consumption. This use of agents has proven successful; agents outperform the use of fixed time-paths.

The agents symbolize the reality of governments, companies and people that adept their behaviour to new situations.

The functionality of the agents in this thesis report is limited to a simple optimization procedure. This research gives a good basis to extend the functionality with for example additional boundary conditions (such as 30% energy reduction in 2030), negotiation protocols and a variety of goal functions.

7.3 Parallels to the real-world

Some lessons for the real-world can be learned by drawing parallels from the behaviour that emerges from this simplified population-economy-energy-climate model. Assuming the highly stylised dynamics of SUSCLIME, the following observations can be made:

- Two policy options to reduce fossil energy use can interfere. For example the application of subsidies to promote renewable energy use reduces fossil energy use, but on the other hand discourages efficiency measures because the average energy price is lowered.

- In case of sudden depletion, both low-income and high-income regions experience serious economic disruptions. A high-income region endures a relative higher loss of welfare then a low-income region. On the other hand, the costs of intervention put a larger burden on low-income regions.

- With respect to climate change, low-income regions balance between short term emission mitigation and long-term impacts. Because intervention slows down economic growth and the initial emissions are low, It is attractive to postpone climate policy until a certain income level is reached. However, the economic 'take off' phase of surging income growth, capital accumulation and productivity increase (e.g. China's current situation) should be combined with climate policy if such policy is to be effective. Once capital is accumulated and major amounts of carbon have been emitted into the atmosphere, deployment of climate policy might be too late and ineffective.

- The costs of intervention put a larger burden on low-income regions, due to the lower economic productivity. Mitigation in the form of emission reduction in high-income counties seems not to have a major impact on their economic development. Therefore, an effective approach might be the use of investments from high-income regions to mitigate emissions in developing regions, like in the current Clean Development Mechanism (CDM) or other emission trading schemes.

8 Literature

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