Schweizerische Eidgenossenschaft
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Eidgenössisches Departement für
Umwelt, Verkehr, Energie und Kommunikation UVEK
Bundesamt für Energie BFE

Schlussbericht September 2010

Impact of Energy Conservation Policy Measures on Innovation, Investment and Long-term Development of the Swiss Economy

Results from the Computable Induced Technical Change and Energy (CITE) Model

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Die Autoren danken Frank Vöhringer für seine wertvolle Unterstützung bei der Modellierung.

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Für den Inhalt und die Schlussfolgerungen sind ausschliesslich die Autoren dieses Berichts verantwortlich.

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Policy summary in German

In diesem Projekt wird endogene Wachstumstheorie mit einem multi-sektoralen numerischen Simulationsmodell verknüpft. Im Unterschied zu anderen Studien, die die langfristige Entwicklung der Wirtschaft häufig als exogen betrachten, wird das Wachstum der Gesamtwirtschaft und der einzelnen Sektoren in diesem Modell direkt von den Akteuren in der Ökonomie beeinflusst. Getrieben wird das Wachstum in den einzelnen Sektoren durch die Entwicklung neuer Kapitaleinheiten. Je grösser die Investitionsaktivitäten in einem Sektor, desto mehr Kapitaleinheiten werden entwickelt und desto positiver ist die sektorale Entwicklung.

Mit dem Modell wurden die Effekte verschiedener energie- und klimapolitscher Massnahmen untersucht. Im ersten Szenario werden die Effekte einer langfristig orientierten Politik mit dem Ziel, die CO2- Emissionen signifikant zu reduzieren und damit die globale Erwärmung in einem kontrollierbaren Rahmen zu halten, thematisiert. Konkret lautet die Vorgabe, die Emissionen bis 2020 um 30% und bis 2050 um 80% gegenüber dem Stand von 1990 zu verringern. Die Reduktionen müssen dabei vollständig im Inland erzielt werden. Als politisches Instrument wird dazu eine Abgabe auf den Verbrauch fossiler Energien eingesetzt. Verglichen mit einem Referenzszenario (d.h. einem "business-as-usual"-Szenario), das von ungebremstem Klimawandel ausgeht und von politischen Eingriffen abstrahiert, ergibt sich ein relativ moderater Wohlfahrtsverlust von 2.6%. Verglichen mit einem realistischeren Referenzfall, der auch die Kosten eines ungebremsten Klimawandels mit einbeziehen würde, wären die Kosten der Reduktion noch bedeutend geringer. Auf sektoraler Ebene unterscheiden sich die Reaktionen auf die Einsetzung der Politik deutlich. Daraus resultiert ein signifikanter Strukturwandel. Verglichen mit dem Referenzfall können insbesondere Sektoren mit tiefem Energieanteil in der Produktion sowie wissensintensive Sektoren profitieren. Sektoren mit hoher Energieintensität entwickeln sich dagegen weniger positiv. Unter den hier angenommen Bedingungen wachsen aber nach wie vor alle Sektoren, trotz der ambitionierten Politik mit entsprechend hohem Reduktionsziel.

In einem weiteren Szenario werden die Auswirkungen einer Politik auf dem Weg zur 2000 Watt Gesellschaft analysiert. Grundlage dafür ist Szenario IV aus den Energieperspektiven. In Szenario IV wird vorausgesetzt, dass der Energieverbrauch als Zwischenziel bis 2035 um 35% (verglichen mit dem Stand von 2000) reduziert werden muss, damit ein Erreichen einer 2000 Watt Gesellschaft bis zum Ende dieses Jahrhunderts möglich ist. Die strukturellen Effekte als Folge dieser Politik sind sehr ähnlich wie im ersten Szenario, ihr Ausmass ist allerdings etwas geringer, da hier ein kürzerer Zeithorizont betrachtet wird. Gleiches gilt auch für den resultierenden Wohlfahrtsverlust. Werden die Abgabeeinnahmen als Subventionen für die sektoralen Investitionen verwendet, so steigt der Wohlfahrtsverlust in der hier betrachteten kurzen Frist noch leicht an, da die Investitionsneigung ansteigt und damit weniger konsumiert wird. Die positiven Effekte einer solchen Subvention entwickeln sich erst nach längerer Zeit. Zudem zeigt sich, dass unterschiedliche Politikmassnahmen im Ausland sowie die Anzahl der in der Ökonomie zur Verfügung stehenden Arbeitskräfte einen Einfluss auf die Ergebnisse haben. Werden in der Schweiz ambitioniertere Ziele implementiert als im Ausland, steigt der Wohlfahrtsverlust leicht an. Bei weniger strikten Reduktionszielen im Inland sind dagegen insbesondere die Auswirkungen auf sektoraler Ebene bedeutend weniger ausgeprägt. Dies verdeutlicht, dass eine Koordination der Reduktionsmassnahmen auf internationaler Ebene wünschenswert ist. Bei einer Erhöhung der Anzahl der zur Verfügung stehenden Arbeitskräfte, beispielsweise als Folge erhöhter Zuwanderung, ergeben sich unter den getroffenen Annahmen kaum zusätzliche Effekte. Entscheidend ist hier aber insbesondere die Frage, wie der zusätzliche Energiebedarf gedeckt wird.

Der Fokus des Modells liegt auf der Umsetzung des endogenen Wachstums und dessen Einfluss auf die sektorale Entwicklung. Dieser Ansatz hat, gerade im Vergleich mit Studien, die das Wachstum der Ökonomie als gegeben betrachten, wertvolle neue Einsichten geliefert. In anderen Bereichen wurde das Modell relativ einfach gehalten. So wurde bis anhin auf eine detaillierte Abbildung des Energiesektors und der in dieser Hinsicht relevanten Technologien verzichtet. Lerneffekte und damit verbundene Kostenvorteile auf neuen Technologien werden darum nicht thematisiert. Ebenso sind die Interaktionen mit dem Ausland auf vereinfachte Art dargestellt. Eine präzise Modellierung von Politikmassnahmen im Ausland ist bis anhin als Folge des gewählten Ein-Länder-Ansatzes noch nicht möglich. Das Modell wird darum in Zukunft in diese Richtungen weiter ausgebaut.

Part I.

Introduction

1. Background and motivation

1.1. Long-run perspective

In the past two centuries, the Swiss economy experienced an unprecedented increase in living standards. At the same time, the stock of various natural resources declined and the environmental conditions changed substantially. Today pollution of the atmosphere is considered as a major risk for future development. It is predicted that, without climate policy, worldwide greenhouse gas emissions would rise by 45 % by 2030 (compared to 1990 levels), which would cause an increase in the global average temperature of up to 6 degrees on average by the end of the century. According to the Stern Review (Stern 2007), the warming could entail losses equivalent to 5 -10 % or more of global GDP.

With regard to future energy use, it is undisputed that limited oil reserves and the climate problem deem it necessary to steadily replace today's dominant fossil fuels. Fossil energy sources will still be sufficient to facilitate the transition phase of the global energy system in the 21st century. However, emphasis must be placed on efficient decarbonisation of the energy system processes, with the long-run target of around 1t CO2 emissions per capita. The global energy system can also be configured in a way which is compatible with the natural environment. It has been calculated that primary energy use amounts to between 2000 and 3500 W per capita in a long-run sustainable state.

To evaluate the sustainability of a low energy and low carbon society as well as the optimum transition to this state, economic analysis and numerical simulation models are indispensable. Decreasing use of an important input like oil has not been often observed in economic history. Thus, a deeper understanding of the basic mechanisms of a market economy is needed. To analyse the properties of the predicted development paths, growth theory plays an important role. A better understanding of the mechanics of economic growth helps to direct the development process in a direction which is desired by today's generations. Another crucial part of the analysis is the quantitative part of the predictions. There is little to be gained in speculating on future development paths if they are not predictable in some way by theory and numerical simulations. Similarly, one cannot have a direct intuition about the dynamic consequences of the different policies, unless something concrete is known about the properties of feasible development paths. Thus, a profound study of sustainable growth is not possible without a sound quantitative model of endogenous economic growth.

1.2. Implementing policies

In the area of climate policy, Switzerland - as a signatory of the Kyoto Protocol in 1997 - committed itself to an 8%-reduction in emissions between 2008-2012 compared to 1990 (interpreted as a 10 percent decrease of CO2 emissions). In addition to other (insufficient) voluntary measures, the government introduced a fuel tax ("Klimarappen") in 2005. In 2008, a CO2-tax on combustible fossil fuels was came into effect. The funds that are collected through these taxes will be used respectively to improve public transportation systems, and (in part) to finance building renovation. Moreover, the new energy legislation of 2007 introduced a feed-in subsidy for renewable energy, valid for 20-25 years depending on the type of energy resource. Finally, a revised CO2 law is currently being debated with stakeholders, the parties, and the political interest groups in the so-called "Vernehmlassungsverfahren."

Today, climate scientists argue that only a small time window of ten to twenty years is open to realize a marked turnaround in global greenhouse gas emissions. If this fails, the world's climate is likely to destabilise for a long time. The warming would affect water and food supplies and evoke more frequent natural disasters with huge economic costs. In late 2009 in Copenhagen, the nearly 200 signatories to the UN Convention on Climate Change debated on how to reduce climate-damaging greenhouse gas emissions and how to adapt to the impacts of climate change. The financial architecture for the adaptation and mitigation measures and ways in which climate-friendly technologies are to be made available worldwide were further topics. However, the few results of the conference are not binding for the countries so that further negotiations are needed to implement future carbon policies in an international framework.

With regard to future Swiss energy use, different scenarios of energy perspectives up to 2035 ("Energieperspektiven") of the Swiss Federal Office of Energy (SFOE) are an excellent guideline for the policy discussion. They list options for planning a long-term and sustainable energy policy that meets the principal requirements of supply security, protection of the environment, economic viability and social acceptance. The current study is mainly inspired by scenario 4 which depicts the major elements for the transition of the Swiss economy to a 2000 Watt society, i.e. a state with an energy use of 2 kW per capita.

1.3. Level and growth effects

As in many policy areas, the impact of policies on income levels is often the subject of applied studies in energy economics. Abstracting from capital accumulation, a policy increasing the cost of energy use usually comes at a positive cost for the economy. This happens because energy inputs are diminished while the other inputs remain constant, which decreases output. The biggest challenge for economic research of energy and climate, however, is to evaluate the effects of policies on long-run economic growth. This is due to the fact that productive factors, such as human and physical capital, accumulate, and energy policy can affect their growth rates. According to the hypothesis of Hicks (Hicks 1932), increasing input prices induce innovation, which in turn makes these inputs more productive. Thus with an increase in energy prices, a dynamic substitution effect works in addition to the better-understood cost effect of energy policy. Consequently, in addition to the usual static effects, energy policy has dynamic effects on output and welfare as the economy moves to its new growth path. Especially when aiming at the long or even very long run as in the current energy and climate debate, this can make a huge difference as regards the various policy conclusions.

From theoretical reasoning, we know that the output impact of this dynamic effect is potentially very powerful (Baldwin 1992). Moreover, compared to the level effect, it can work in the opposite direction i.e. income increasing, thus alleviating or possibly even reverting negative static effects. Whether this happens depends on the impact of energy policy on capital productivity. Provided that this productivity is increased, additional capital accumulation guides the economy to a higher steady state. With decreasing returns to overall capital, the growth impact is given by a simple term including the share of capital revenue over total income; it may take a value of around 2 or even larger (Baldwin 1992). To put it explicitly, when policy is able to increase the capital return and this raises the income level by x %, income in the steady state will be another 2 x % higher in the long run. With constant returns to overall capital, as often assumed in new growth theory (e.g. in the seminal paper of Romer 1990), the dynamic effect is even larger, as it is permanent. The welfare impact of this permanent dynamic effect is also measurable. The size of the dynamic gain from energy policy depends on the wedge between social and private returns to capital, which is present due to the positive knowledge spillovers (which are externalities), and on the assumed discount rate.

A final issue is the possible emergence of a double dividend of energy policy, which says that policy measures in the environmental sphere entail a benefit for the environment as a first dividend and an improvement of the whole "system" as a second dividend (Bovenberg and de Nooij 1999). To put it more precisely, the second benefit has been primarily seen in the improvement of the tax system, which is normally distorted by the negative incentives from income taxation. Thus, when labour taxes are replaced by environmental taxes, it appears that an efficient tax substitutes for a distorted tax. However, the argument neglects the shifting of the tax burden, as e.g. firms charge higher prices with environmental taxes. Studying tax incidence it can be shown that tax burden is shifted to the immobile factors, where again labour is very prominent. Thus, the tax interpretation of the double dividend is not convincing and has been largely abandoned. But in terms of growth, there may well be a second dividend. As argued above, energy policy measures may induce innovation and evoke that knowledge extensive sectors are increasingly replaced by knowledge-intensive sectors and activities, which fosters economic growth. This is another, even more powerful form of a double dividend. A higher growth rate is normally also beneficial in terms of welfare, as the positive spillovers prevent the economy from reaching a first best state equilibrium.

1.4. Content of the project

The present project builds on the insights that (i) energy-saving measures in Switzerland are advocated because of future energy scarcity and the protection of the atmosphere and (ii) the macroeconomic effects, in particular the growth effects, need careful consideration. Specifically, targets like the 2000-watt or the 1 ton CO2 society are considered as important scenarios of a long-term policy in Switzerland, but the transition to these steady states needs to be better understood. The project is based on the premise that the application of new (endogenous) growth theories promises significant new results in this important area. Moreover, it argues that a crucial criterion for the selection and design of energy policy instruments are their impact on growth and prosperity. Consequently, the project extensively studied the growth effects, i.e. the size of induced innovation and the effects of policy on sectoral growth and structural change are for the Swiss economy.

After a thorough evaluation of the relevant growth dynamics provided by economic theory, the major effort of the project was to construct an appropriate dynamic numerical simulation model for the Swiss economy. The specific features of the newly developed "CITE-model" are described below. The set of available data and various theoretical features, like the reference of a balanced growth path, guided and constrained the modelling process. Using the data from the most recent input-output table enabled to calibrate the CITE model and to draw policy conclusions.

The results complement the existing predictions on the future of energy use based on technology development from engineering. It does so by adding the macroeconomic conclusions regarding future energy policies. The recent studies which come closest to this report are Ecoplan (2008) and Ecoplan (2009).

2. Growth in CGE models

The first CGE models were based on the assumption of exogenous growth and an autonomous amelioration of energy efficiency. They ignored interconnections between technological change and policy measures. Changes in energy prices due to political actions only resulted in substitution of other factors for energy, leaving the rate of growth in energy efficiency unchanged. In these models, the increase of energy efficiency was defined by the "autonomous energy efficiency index" (AEEI), which was a heuristic measure of all non-price driven enhancements in energy technology, including structural change in the economy and sector specific technological change. It was a separate coefficient in the production or cost functions and represented either factor augmenting or price diminishing technical change.

The main difficulty with applying an AEEI is to identify the difference in the influence of technical progress and of long-term price effects (Jones (1994)). For this reason, the AEEI parameter has been replaced later by endogenous growth mechanisms.

Models that include exogenous energy efficiency growth are, among others, Burniaux et al (1992) (GREEN), Nordhaus (1992) (DICE), Peck & Teisberg (1992) (CETA), Nordhaus & Yang (1996) (RICE).

2.1. Empirical evidence for induced innovations

The empirical evidence for the effects of energy price changes on innovation is relatively univocal and builds on Hicks' induced innovation hypothesis. Hicks (1932) proposed a theory that states that changes in relative factor prices should result in innovations that diminish the demand for the relatively expensive factor. Popp (2001) confirms this hypothesis empirically and finds that the effects of a price change can be attributed by about two thirds to factor substitution, and around one third result from induced innovation. Also Newell et al. (1999) find that increasing energy prices have an observable effect on the types of products offered in stores. Likewise, Popp (2002) finds evidence of a positive impact of energy prices and the stock of knowledge on innovation.

2.2. Endogenous growth in CGE models

Since the seminal work of Solow (1956), economists consider technology as the main driver of innovation and growth (Niosi (2008)). New growth theory is based on the observation that technological innovation is an economic activity. Profit-maximizing agents optimize their behavior according to profit incentives. Endogenous growth theory thus builds on innovation theory that states that Schumpeterian profit incentives account for a major source of technological change (Weyant & Olavson (1999), Löschel (2002)).

2.3. Learning-by-doing

Learning is a major driving force of technological change as it improves the relation of cost and performance of technologies. A learning curve describes the declining cost of a technology as a function of cumulative capacity, which can be seen as an approximation for accumulated experience (Barreto & Kypreos (2004)). Today, learning-by-doing is among the best empirically analyzed phenomena that lead to technological change (Messner (1997). Concerning energy, the evidence is in clear favor of the fact that production costs depend on cumulative experiences (McDonald, Schrattenholzer (2001)).

The first to introduce LbD in a bottom-up model was Messner (1997) in the model MESSAGE, which is a systems engineering approach that included systematic technological learning, i.e. it linked the cost to develop a new technology to the already installed cumulative capacity. Later models with learning-by-doing as major driver for growth are, for example, Messner & Strubegger (1995) (MESSAGE III), Grübler & Messner (1998), Seebregts, Kram, Schaeffer & Bos (1999), van der Zwaan et al. (2002), Gerlagh & van der Zwaan (2003), Barreto & Kypreos (2004) (MARKAL), Gerlagh et al. (2004), and Manne & Richels (2004).

2.4. Research and development

Another class of models than embody endogenous growth mechanisms include investments in R&D and are inspired by macroeconomic models of endogenous growth, such as Romer (1990), Lucas (1988), and Grossman & Helpman (1994). In these models, a carbon tax has two opposed effects on the economy. First, it causes higher factor prices and therefore diminishes knowledge accumulation and the rate of technical progress. This development results in a decline in income and output. At the same time, the price effect triggers substitution of inputs and a reallocation of knowledge to sectors that offer the largest gains from research. As this changes the technological structure of the economy, it is able to adjust more elastically to the price change. This leads to an augmentation of gross substitutability on the supply side, which eventually mitigates the loss incurred by the tax. The total effect of the tax can be even positive (Sue Wing (2003)).

Examples for these models are Goulder & Schneider (1999), Buonanno et al. (2001) (ETC-RICE), Kemfert (2002) (WIAGEM), Nordhaus (2002) (R&DICE), Buonanno et al. (2003), Popp (2004) (ENTICE), and Gerlagh (2007)
(DEMETER-1CCS).

2.5. Gains from specialization

Another possibility to endogenize growth dynamics is to assume gains from specialization, either in consumption or production. This explanation is also used in the CITE model. Different authors along the centuries referred to gains from specialization. By observing the production in a pin factory, Smith already reported as early as in 1776 that specialization immensely increases the efficiency of the workers and therefore contributes to an augmented output. The increase of specialization led larger firms to have a higher output per worker and lower average cost per pin than a small pin factory.

The empirical extent of specialization in the European Union has been estimated by Mangàni (2007), who analyzes the correlation of economic (in terms of GDP) and technological (i.e., R&D aggregate expenditure or the number of patents granted) sizes. She asserts a positive correlation between the two. She distinguishes two technological dimensions: the intensity of technological activities (intensive margin) and their variety (extensive margin). The technological variety is hereby defined as the number of technological fields in which a country is active. Both dimensions are positively correlated with the country size, i.e., larger countries have a wider spectrum of technological fields and show a larger number of patents in each technological field. In Mangàni's estimation, technological variety accounts for about 40 % of the difference in patent application between larger and smaller economies and is therefore extremely important in explaining the different technological standards.

The comparison of the dynamics of the CITE model with a model without gains from specialization and with exogenous growth shows that the endogenous growth mechanism of the CITE model yields different reactions to a carbon tax. There, capital growth generates gains of specialization and ensures endogenous growth dynamics. Investments target at a substitution of energy in the production and result in a higher productivity. This, in turn, contributes to a change in the production of the final outputs. In a model without gains from specialization and with exogenous growth, capital accumulation can only contribute to a substitution for energy but not to an increase of productivity. Accordingly, investment incentives are unlike to the CITE model.

The dissimilarity of investment incentives are reflected in the reactions of the sectors to a carbon tax. In the CITE model, most industries show a stronger sensitivity to the change in input costs than in the model with exogenous growth. Mainly three differences occur: First, the spread of output of the sectors is larger in the CITE model. Second, the speed in which the industries approach a new balanced growth path is lower in the CITE model. And finally, the structural composition of the economy is different in the two models. It can therefore be concluded that the endogenous growth mechanism in the CITE model uncovers dynamics triggered by a carbon tax, which cannot be displayed with a model with exogenous growth. These effects are explained in more detail in Appendix B.

Part II.

Constructing the CITE model

3. The general setup

The CITE model is based on growth models of Romer (1987, 1990) and Grossman & Helpman (1991) and exhibits endogenous growth dynamics based on research and development (R&D) for Hicks-neutral technical progress. It is assumed that an expanding variety of intermediate goods (i.e. horizontal innovations) enhances the productivity of the economy by gains from specialization. This growth mechanism differs from intertemporal dynamics in other models as we do not need to assume an exogenous growth rates for endowments such as labor, but all growth dynamics arise from profit incentives in the economy.

The model consists of 10 different regular sectors, an energy sector, and an oil sector, each with similar intrasectoral setups. The intrasectoral structures are based on the assumption that profit incentives of innovators create new varieties of intermediate goods x_i and as a consequence generate growth. These intermediate goods are assembled to sector specific intermediate composites Q_i, which are themselves used in the production of final goods Y_i (cf. Figure 1). The producers of final goods also use Armington goods A_{ni} of regular

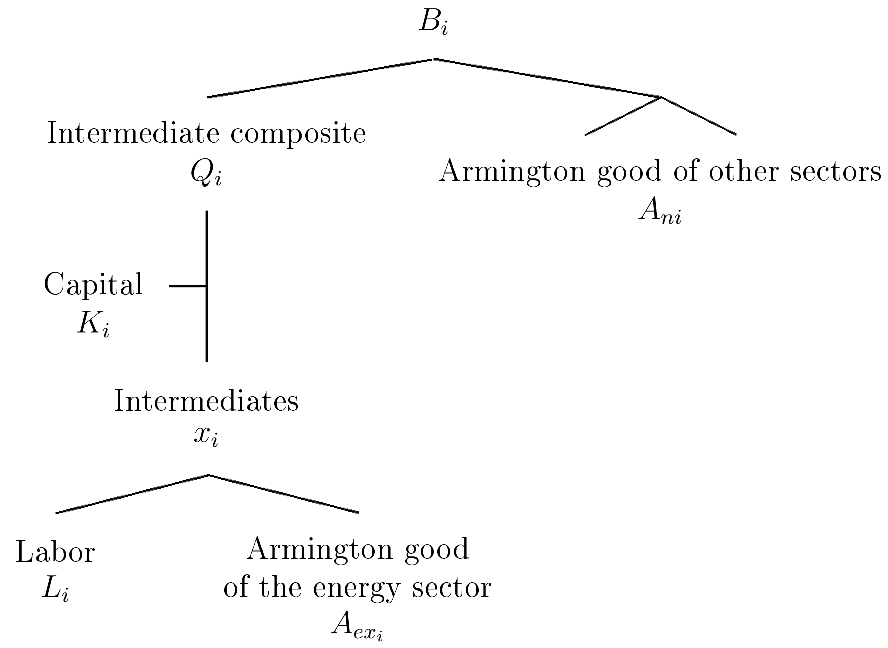

Figure 1: Production of B_i

(i.e. non-energy, non-oil) sectors in their production. These Armington goods consist of domestically produced goods and imported goods that are combined with an elasticity of substitution (Armington (1969)). The assumption of imperfectly substitutable goods ensures that trade can be modeled realistically in the sense that the same sectors can in- and export.

In the regular sectors, B_i corresponds to the final output, Y_n. The production of the energy sector requires additionally to B_e from Figure 1 imported gas and the output of the oil sector (cf. Figure 2). B_e essentially refers to the production of non-fossil energy (thus including nuclear and renewable energy). Given our nesting structure, non-fossil energy production also requires a small amount of fossil energy. Imported gas and oil are the fossil part of total energy.

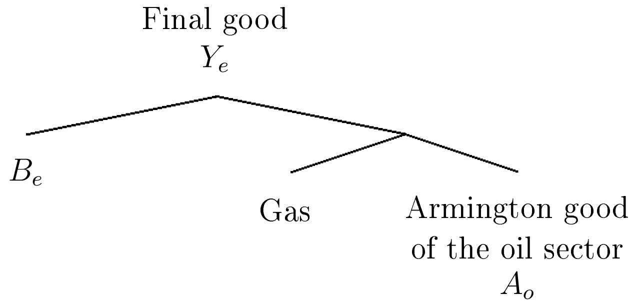

Figure 2: Production of energy

Similarly to the production of the energy sector, the oil sector also needs an additional input, namely crude oil, which is imported (cf. Figure 3). Hereby, B_o corresponds to B_i in Figure 1.

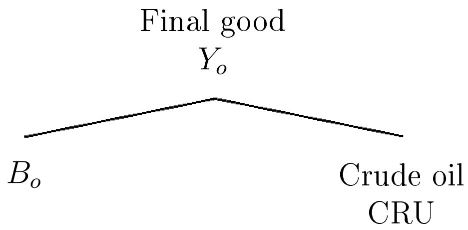

Figure 3: Production of oil

The dynamics in the model stem from the assumption that the variety of intermediate goods expands over time and generates gains of specialization. These new varieties are

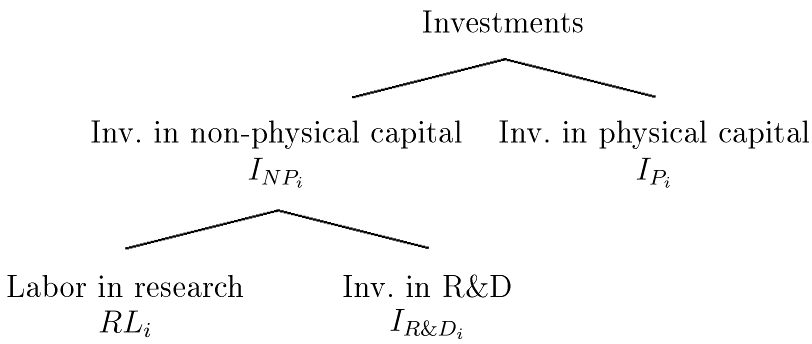

Figure 4: Investment nesting

invented by firms by investing in a capital composite consisting of physical and non-physical capital. The assumption that knowledge (and thus the capital stock) is sector specific reflects the supposition that one kind of knowledge can only be used a for particular combination of inputs (cf. Basu and Weil (1998)). Investments in new capital is nested according to Figure 4. A representative household maximizes intertemporal utility from a consumption good that consists of a final good composite and energy, as depicted in Figure 5. The final good composite includes the Armington goods of regular sectors. Agents are assumed to have perfect foresight.

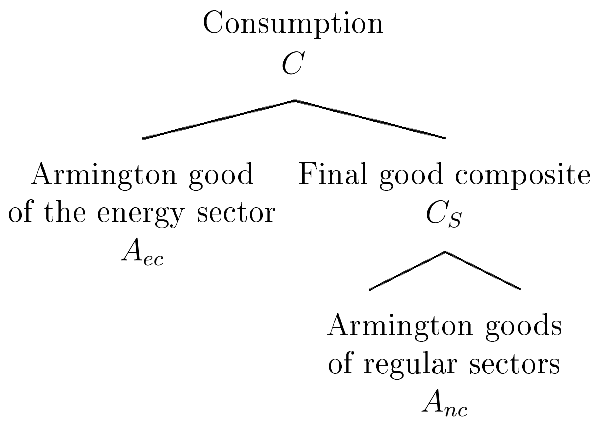

Figure 5: Consumption nesting

Due to the small size of the Swiss economy, it faces exogenously given world-market prices for crude oil and gas. Domestically, the markets for final goods, for the intermediate good composite and for labor are perfectly competitive, whereas the market for intermediate goods is monopolistic. All markets clear and the allocation- and price-vectors constitute a competitive equilibrium. The supply of labor and of a so-called non-accumulable capital that is introduced for reasons of calibration (for further details see the following chapter) is assumed to be inelastic and perfectly mobile across all firms and sectors.

4. Data and Parameters

4.1. Data

The model is based on the Swiss input-output table (hereafter named IOT) for the year 2005 (Nathani, van Nieuwkoop and Wickart, (2008)), which is the most recent version available. It gives detailed information on the flow of goods between sectors and to final demand, and also on the use of inputs and on trade. The original table contains data for 42 production sectors and differentiates between fifteen types of consumption (twelve for private households, three for public consumption) and three types of physical investments. As for the use of factor inputs, it presents information on the use of labor and capital. It is therefore an almost complete source of data for the type of model we are using.

For the purpose of our model, the original IOT was aggregated to 12 sectors (10 regular sectors, an energy sector and an oil sector, see Table 4.1 for an overview). Also, we do not differentiate between the different types of consumption and physical capital investment. Most notably, we do not separate public from private consumption, as there is no explicit representation of the government in the model. Therefore, the different types of consumptions were aggregated to one single column. The same was done with physical capital investments.

Sector	**NOGA-Classifications**
Agriculture (AGR)	01-05
Refined Oil Products (OIL)	23
Chemical Industry (CHM)	24
Machinery and Equipment (MCH)	29-35
Energy (EGY)	40
Construction (CON)	45
Transport (TRN)	60-63
Banking and Financial Services (BNK)	65
Insurances (INS)	66
Health (HEA)	85
Other Services (OSE)	50-55, 64, 70-75, 80, 90-95
Other Industries (OIN)	10-22, 25-28, 36-37, 41

Table 1: Overview of the sectors used in the model

However, the model distinguishes two types of investments, physical capital and non-physical capital investments. Non-physical capital investments mainly refers to investments in research and development. The original IOT contains no information R&D investments. Additionally, there is no reliable data available in Switzerland, especially not on a sectoral level. We therefore use the data from sector 73 ("Research & Development") to approximate these investments. Put differently, we interpret the demand for goods from sector 73, i.e. the row entries of this sector, as investments in R&D of the sectors demanding these goods. To represent this interpretation in the IOT, we transferred these entries into a new column called R&D investments. The column entries of sector 73 and its imports, exports, value added, consumption and investments were added to other services (OSE), except for the entry of labor. We use this entry as our benchmark value for research labor (LH). With this procedure, we get sectoral values for R&D investments and an aggregate measure of research labor. Total research labor is then redivided to the sectors according to their share in total capital use. This gives us a value for initial sectoral demand for research labor. Because we assume that capital accumulation is the result of investment activities including research and development, it makes sense to derive the initial sectoral labor inputs according to the sectoral shares in total capital.

Furthermore, capital had to be split into two capital types, labeled K (capital) and VK (non-accumulable capital). In the benchmark, the model is calibrated to a balanced growth path, implying that all sectors grow at the same rate. This calibration requires that the share of capital (K) in the production of intermediate goods has to be equal in all sectors. The reason for this is that the capital share (or the gains of specialization) directly affects the sectoral growth rates. Different capital shares would therefore imply different rates of growth, which would not be consistent with the calibration. In the original IOT, there are obviously large differences in these shares. We solved this issue by setting the values of capital so that its share is equal in all sectors and by defining the residual of initial capital as another input to intermediate production. This new input is then represented in a new row in the IOT. K is the part of total capital that can be accumulated via investments, while VK enters production of intermediate goods at the same level as labor and energy and cannot be accumulated. VK can be interpreted as publicly provided capital (e.g. public infrastructure or services) in the sense of Barro (1990). While helping to solve the benchmark calibration simulations show that VK has no distorting effect on the quality of the results.

4.2. Parameters

The choice of parameter values, most notably of the elasticities of substitution, may have a substantial influence on the model results. It is therefore important to choose these values carefully and reasonably. The elasticities of substitution are set in accordance with given empirical estimations and studies (see e.g. Van der Werf (2007) and Okagawa and Ban (2008) for estimations of elasticities related to the production process and Hasanov (2007) for estimates for the intertemporal elasticity of substitution in the utility function). Sectoral differences in substitutability of inputs on the different levels of the production process are taken into account by setting sectorally differentiated values for the corresponding elasticities whenever available and reasonable. An overview of the elasticities used is given in the Appendix, as well as a sensitivity analysis that tests for the robustness of the model results with respect to variations of the values of the elasticities.

A key feature of the model is that it includes the gains of specialization that stem from the accumulation of capital already in the benchmark scenario. The model is calibrated so that it reflects both projected output growth and growth rates of the capital input. To be more precise, we assume that capital grows at an annual rate of 1%. This matches the observed growth rate of capital goods in Switzerland since 1990. In our calibration, in combination with the aforementioned share of capital (1-κ), this then leads to an annual growth rate of about 1.33%, which is in line with the rate assumed in the high GDP scenario of the Energy Perspectives. The share of capital essentially defines the intensity of the spill-overs (i.e. the gains of specializations) and therefore also defines the difference between the growth rate of the inputs and the projected output growth rate. (1-κ) is set to 0.25 in all sectors. Capital depreciates at a rate starting at 0.04. This rate rises by a small amount every year, due the fact that capital and investments grow at different rates in the model. To be able to calibrate the model correctly, we have to use a non-constant depreciation rate. Using a calibration procedure by Paltsev (2004), we can then derive the interest rate r (given the depreciation rate and the benchmark values for the capital stock and investments). Given the values in our model, the interest rate is about 0.016 or 1.6%.

5. Description of the scenarios used in the simulations

Our first policy scenario (hereafter labeled 80%-target) is inspired by recent discussions on emissions reduction targets that would be necessary to keep global warming within a reasonable range. For industrialized countries, reductions in CO2 emissions between 25% and 40% until 2020 and between 80% and 95% until 2050 (compared to 1990 levels) are necessary to limit global warming to 2°C. In this scenario, we simulate a path that leads to a 30% reduction until 2020 and an 80% reduction until 2050. The fact that only one region is included in the model implies purely domestic abatement and disregards emission offsets abroad, which are often seen as being less costly. The policy instrument implemented to achieve these reduction targets is a CO2 tax. This CO2 tax increases the prices of the two fossil fuels included in the model, oil and gas. Oil (referring to the output of the oil sector) and gas are the two inputs to the production of fossil energy. Fossil energy is then again an input to production in the energy sector. The use of the two fuels is assumed to be unequally polluting. We fix the CO2-intensity of gas at 1 and set the intensity of oil to 1.34. These CO2-intensities are constant over time, i.e. there is no technological development (e.g. the introduction of CCS-technologies) that affects these intensities. The tax is directly tied to the CO2-intensity. As we assume a uniform tax rate for both fuels but a higher CO2-intensity for oil, this implies that oil is effectively taxed at a higher rate than gas.

Our model is calibrated to data from 2005, which means that the reductions have to be even a bit higher, because total CO2 emissions in 2005 were higher than in 1990. The aim of the tax is thus to reduce total carbon emissions by 32% until 2020 and by 81% until 2050. We have set the tax so that this goal is exactly met. The initial tax rate is 0.05[1]. This rate is augmented (at a higher rate after 2020) until 2050 to a value of 2.9750. The revenues from the tax are redistributed on a lump sum basis to the households. Given prices of 2005, this tax profile would imply a premium of 4.2 Rp./kWh on gas and of 0.55 Fr./l on oil in 2020 and of 21.6 Rp./kWh on gas and of 2.8 Fr./l on oil in 2050.

The second scenario implements the ideas from Scenario IV of the Energy Perspectives. Scenario IV assumes that energy use has to be reduced by 35% by the year 2035 (compared to the year 2000) if the long-term goal of a 2000-Watt society is to be met by the end of the century. Thus, in this case, we use the CO2 tax to reduce overall energy use instead of carbon emissions. Again, as our base year is 2005, effective reductions need to be even higher (37.5%) Compared to the 80% target used in the base scenario, this is a less stringent restriction, but a more general one, as it is tied to overall energy use and not just to fossil energy.

We simulate two different cases for this policy scenario. The difference between the two cases is the redistribution mechanism of the tax revenue. In the first case, the tax revenues are redistributed back to the representative household as in the base scenario. The tax rate starts at 0.07 in 2010 and is augmented gradually until 2035. Again using prices of 2005, this leads to a premium of 9.4 Rp./kWh on gas and 1.2 Fr./l on oil. This tax profile leads to the requested reduction of 37.5% under the basic assumptions. In the other case, the tax revenues are used to subsidize the build-up of non-physical capital, which can also be interpreted as a subsidy to the R&D activities in the different sectors. This mechanism may be a more purposeful way to use the revenues, because it directly supports the growth mechanism in the sectors and should thus facilitate the shift to a less energy-intensive economy. Furthermore, we simulate a couple of additional scenarios imposing e.g. different assumptions for the energy policies abroad. In all these later scenarios, the tax revenues are redistributed back to the household. In order to reach the requested reductions, different tax rates are necessary. The tax profile thus differs from scenario to scenario, while the reduction target is always the same.

The graphs displayed below show the deviations from the benchmark scenario (except where indicated differently). The benchmark scenario abstracts from climate change and includes no environmental policy measures. It is calibrated so that all activity indices are equal to one. This has the advantage that we can easily represent the differences from the benchmark in percentage points. In the graphs, the benchmark values would all be located

[1] Note that the tax rate is not expressed in percentage points, but as an absolute premium on the prices of the fossil fuels. The prices are initially set to 1. The tax rate is multiplied with the tax rate to calculate the premium on the price.

on the horizontal 0-line. Note that, as the model is calibrated to a balanced growth path, a horizontal line in the graphs does not mean that the corresponding variable is constant. If the line is horizontal, this means that the corresponding variable grows at the calibrated growth rate (for output and consumption, this rate is 1.34%). In the benchmark, all sectors as well as consumption grow at this rate. After the implementation of the policy, sectoral growth rates change. Sectors above the horizontal 0-line grow faster than in the benchmark, while sectors below grow slower. But, in all scenarios, all sectors exhibit robust growth. The percentage numbers thus indicate the deviation from the performance in the benchmark case and do not refer to losses in absolute output (or consumption). Additionally, we assume (in accordance with scenario I of the Energy Perspectives) that per capita energy use is constant in the long run even in the absence of political intervention.

An important point to consider when interpreting the aggregate effects is that our benchmark scenario is not a realistic business-as-usual case, because it abstracts from climate change and its possible negative effects. A benchmark path that comes closer to reality would thus be one that considers climate change, but does not include any political intervention. The Stern Report (Stern (2007)) includes projections of losses in GDP per capita, given undamped climate change (see Figure 6). Due to the long time horizon of

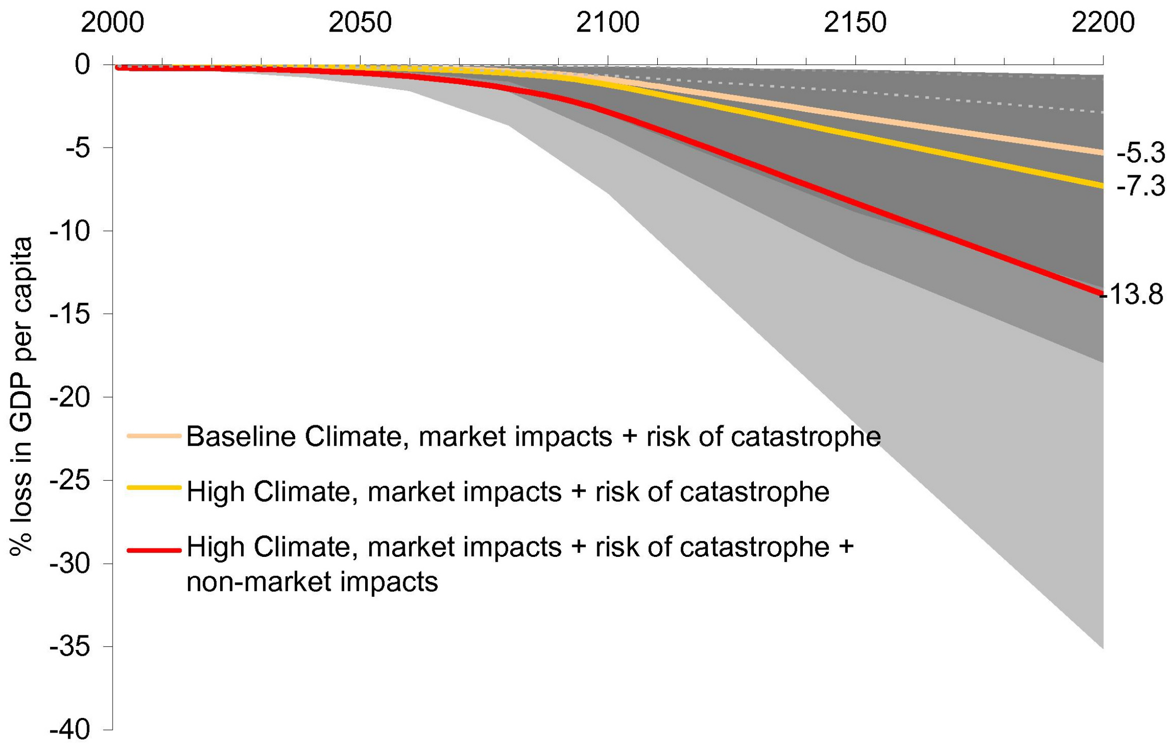

Figure 6: Projected effects of undamped climate change (Source: Stern Review)

these projections, there is obviously a considerable uncertainty on the effects on per capita GDP, and the range of possible long-term impacts is large. However, it seems clear that especially in later decades, the losses increase sharply in the absence of political intervention. Depending on the assumptions on the impacts of climate change and on what other effects are considered, losses could augment up to 35% in 2200. Policy measures aiming at mitigating climate change should thus be able to significantly reduce these losses in later decades. Thus, although it may lead to larger losses in the shorter term, implementing policy measures that mitigate climate change should be beneficial as possibly even larger losses in the long run can be avoided or at least reduced. Figure 6 may therefore be a more meaningful reference to compare the aggregate effects derived in the scenarios analyzed below.

Part III.

Results of policy simulation

6. 80%-target

We first look at the results for the 80%-target. This target is based on necessary long-term emission reductions to keep global warming within a reasonable range. The CO2 tax is set so that total carbon emissions are reduced by 30% in 2020 and by 80% in 2050. The first target is thus reached 10 years after the beginning of the model horizon, the second one after 40 years. The results are shown in Figures 7 to 9.

Given the ambition of the target and the stringency of the policy, one would expect strong impacts on consumption and welfare. However, this is not the case. The effects both on consumption and welfare are moderate. Welfare, which is measured by total discounted consumption over the entire model horizon, decreases by 2.56%. The discount rate is about 1.1%, which is a comparably low value. Additionally, there are no secondary benefits of

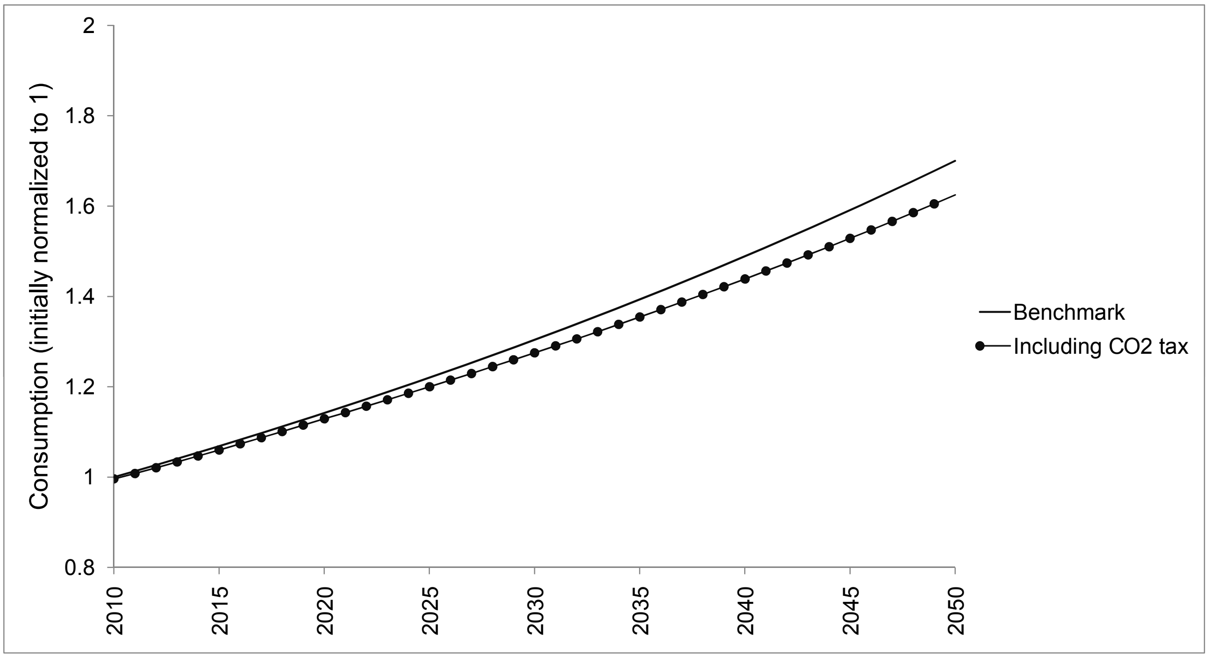

Figure 7: Comparison with benchmark consumption in absolute terms (80%-target)

energy policy or the mitigation of climate change included (such as positive effects on health costs due to cleaner air), and abatement is purely domestic and cannot be shifted abroad. The welfare loss would be even smaller if these aspects were also considered. Consumption over time declines steadily as long as the tax is rising (i.e. until 2050 when the reduction target is reached), but at a small scale. In 2020 (when the intermediate target of a 30% reduction is reached), consumption is reduced by slightly more than 1%. In 2050, it is about 4.5% lower than in the benchmark. This confirms previous findings that even relatively stringent policies are economically feasible from a consumer point of view. The relatively small difference between benchmark consumption and consumption after the implementation of the policy becomes even more apparent when we compare the growth paths (see Figure 7). The consumption level in 2050 in the tax scenario is reached about 2.5 years earlier in the benchmark. One reason for this is that energy as a whole plays a relatively small role in consumption. Its share on total consumption of final goods is around 2%. The direct effect of the tax through an increase in the relative price of energy

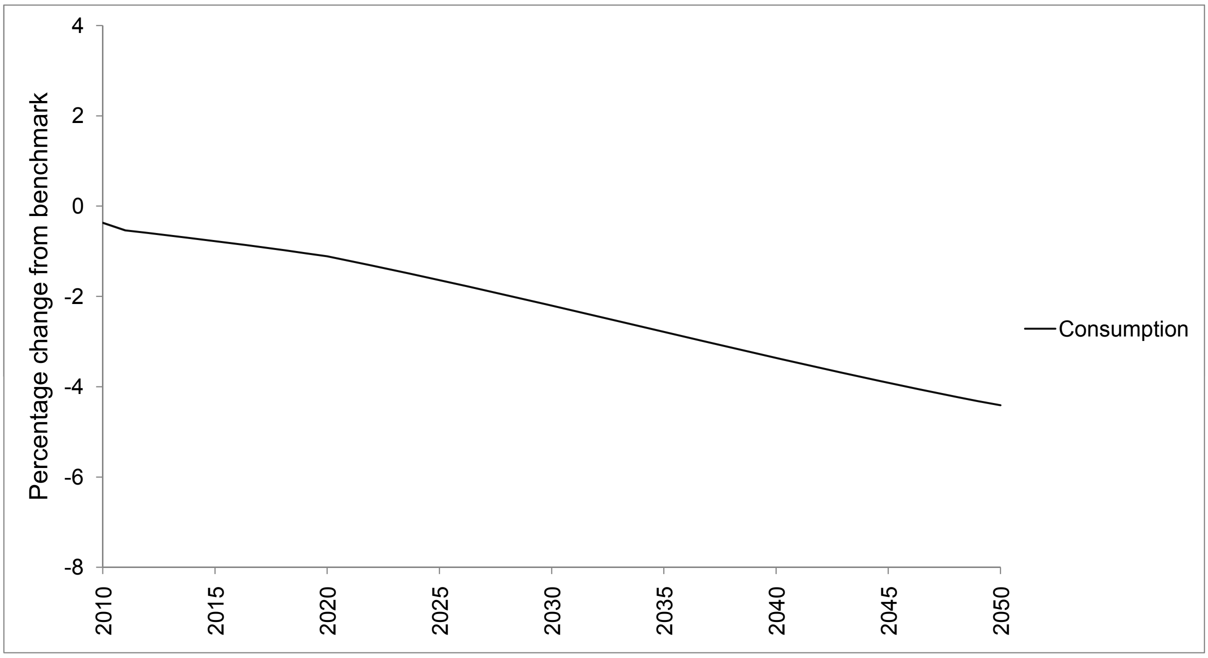

Figure 8: Aggregate consumption (80%-target)

goods is thus only minimal. The CO2 tax also affects the prices of non-energy goods, because they use energy as an input to production. Non-energy goods enter consumption on the second level of the nested function and are assumed to be good substitutes. The household thus has a relatively flexible consumption structure that facilitates substitution of energy intensive for non-energy intensive goods.

At the sectoral level, the introduction of the tax leads to pronounced structural effects (see figure 9). Reactions in sectoral output range from an increase of about 35% in the machinery industry to a decrease of more than 25% in other industries (compared to the benchmark scenario). After 2020, the range of effects slightly widens due to the higher increase in the tax rate. Three sectors perform better than in the absence of a CO2 tax, the remaining sectors are either not much affected or suffer losses. The biggest gainer of the policy is the machinery industry. It increases its output by about 35% until 2050. The chemical industry and insurances also benefit from the introduction of the CO2 tax. The chemical industry gains slightly less than 10%, insurances about 2.4%. Several sectors incur small losses in the range of 2% to 4%. These sectors include construction and most service sectors (other services, health and banking and financial services). The sectors that lose more than 10% or even 20% by 2035 are other industries, agriculture and transport. The same pattern is also observed in sectoral capital stocks. The sectors with a lower output also have lower capital stocks, those with a higher output tend to have higher capital stocks. The effects are usually a bit smaller than those on output, but still on a similar scale.

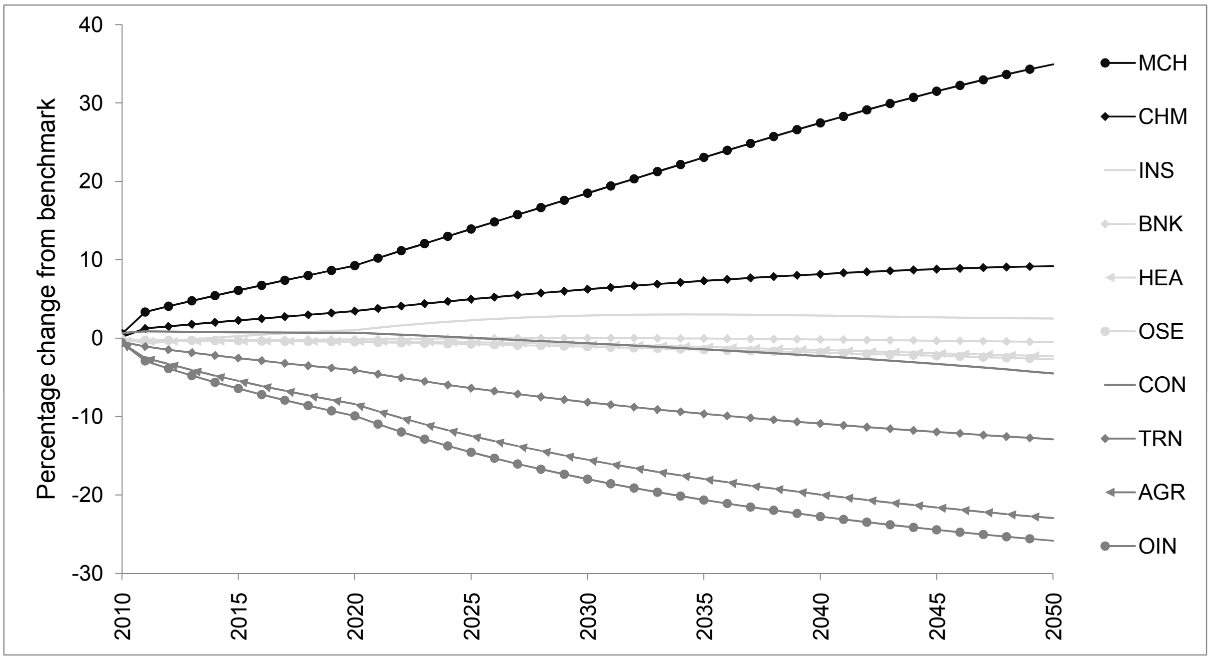

Figure 9: Sectoral outputs (80%-target)

There are various reasons for these structural changes. A first explanation is certainly the energy intensity of the sectors, i.e. the relative importance of energy as an input in the production of output of a sector. As energy enters sectoral production at the level of the intermediate varieties, we measure the energy intensity by the share of energy used in the production of the intermediate varieties ($(1 - \alpha_L - \alpha_{VK})$ in model parameters). The more energy a sector uses in its production process, the more it is exposed to the tax and the more it should be affected by the tax. Indeed, this is the most important reason for the observed effects. The sectors that suffer losses are those with the highest energy intensities. Transports, agriculture and other industries all have an energy share around 10%, which makes them the three most energy intensive sectors in the economy. Thus, the three sectors that have the highest energy intensity are those that suffer the largest losses. Construction also decreases its output compared to the benchmark, but at a smaller scale. The negative effect on the construction sector may however be overestimated in this model, because an important aspect of Swiss energy policy is excluded. Increased standards for energy efficiency for new buildings and corresponding regulations for the renovation of existing infrastructure are an important aspect of future reductions in energy demand. These regulations should clearly be favorable for the construction sector if they were included in the model, as the demand for construction services should increase significantly. This mechanism being excluded, the decrease in output of the construction sector can be readily explained by its relatively high energy intensity.

The service sectors on the other hand generally have very low energy intensities. Their shares are in a range between 2.6% for other services to 0.6% for banking and financial services. These low values show that services are clearly less exposed to the tax, and therefore their reactions to the tax are very small. The fact that they still perform slightly worse than in the benchmark can be explained by their comparably low substitution possibilities. For the service sectors, we assume a lower elasticity of substitution between the inputs in the production of the intermediate varieties. The potential to avoid the tax is smaller than other sectors, most notably than in the two industries that benefit from the introduction of the CO2-tax. This leads to a small decrease in output of most service sectors, despite the low energy shares. The machinery industry and the chemical industry also use relatively little energy in their production (the machinery industry has a high labor share, the chemical industry is very capital intensive), and they both have better substitution possibilities for energy than the service sectors (reflected by higher values of σ_X). These two characteristics give them an advantage over the other sectors and enable them to benefit from the policy.

The capital stocks (not shown here) exhibit a similar pattern than output, which means that there is a clear indication that capital is shifted to the non-energy intensive sectors. The non-energy intensive sectors are more attractive for investors in the presence of the CO2-tax, because they are less affected by the tax. This leads to higher investments and an increase in their capital stocks.

A second reason for the structural changes are the linkages of the different sectors to the energy sector and the oil sector. These linkages are reflected in the use of outputs of other sectors in the production process. As the oil sector and the energy sector reduce their output by a substantial amount due to the tax, they also require fewer inputs from the other sectors. The oil sector is strongly linked to other industries and to transport, the energy sector also relies on a lot of inputs from other industries. Outputs from the machinery industry, the chemical industry and from the service sectors (most notably from insurances) only play minor role in the production of the energy sector and the oil sector. These effects may however not be as important as the energy intensity. The oil sector is a very small sector, and the amounts of output used from transport and other industries are therefore also small. The energy sector is relatively factor intensive and relies on relatively few inputs from other sectors. Therefore, the arguments made here may not drive the results, but they add to the effects from the energy intensity.

Third, and most importantly in the dynamic context, certain sectors directly benefit from the increased investments. Physical investments require inputs from industries such as construction and the machinery industry. As capital stocks and thus also investments increase significantly in certain sectors, sectors that provide goods that are necessary to implement these investments therefore make additional gains.

The developments in the energy and the oil sector are not shown in the graphs, because the effects are mostly predetermined by the policy. Total energy output decreases by about 78%, the oil sector by about 83%. The strong reduction in the oil sector makes sense as it is obviously affected the most by the tax. The energy sector on the other hand is also directly affected by the tax (through the input of fossil energy), but has more options to avoid it. Either by substituting gas (which is taxed at a lower rate) for oil, or by substituting non-fossil energy for fossil energy. Therefore, the negative impact on the whole energy sector is not as big as on the oil sector. This also implies that the reduction in non-fossil energy must be smaller than 80%, as a larger part from the overall reduction in energy use comes through a reduction in fossil energy use. The fact that the capital stock of the energy sector does not decrease at a similar scale as output indicates that non-fossil energy is still relatively more attractive for investments than fossil-energy. As only fossil energy is taxed, investing in non-fossil energy helps to counteract the negative effects that stem from the tax as it facilitates the shift from fossil to non-fossil energy.

7. 35% reduction in energy use until 2035

7.1. Tax revenue redistributed to the household

This scenario is closely related to Scenario IV of the Energy Perspectives and the idea of the 2000 Watt society. According to Scenario IV, total energy use has to be reduced by 35% until 2035 if the goal of a 2000 Watt society is to be reached by the end of the century. The policy instrument is the same as before, but contrary to the case discussed in the previous section, the restriction now applies to overall energy use. The results are shown in Figures 10 to 12.

Compared to the 80%-target,the policy implemented in this scenario is less stringent. The requested reduction in energy use is smaller than above, and the time horizon is also shorter. In accordance with scenario IV, we do not implement any further targets for the time after 2035. Welfare loss is about 1.2% and therefore considerably smaller than in section 6. Correspondingly, the decrease in consumption over time is also very small. In

2035, consumption is just about 1% lower than in the benchmark. The reasons for these relatively small impacts are obviously the same as in the previous scenario.

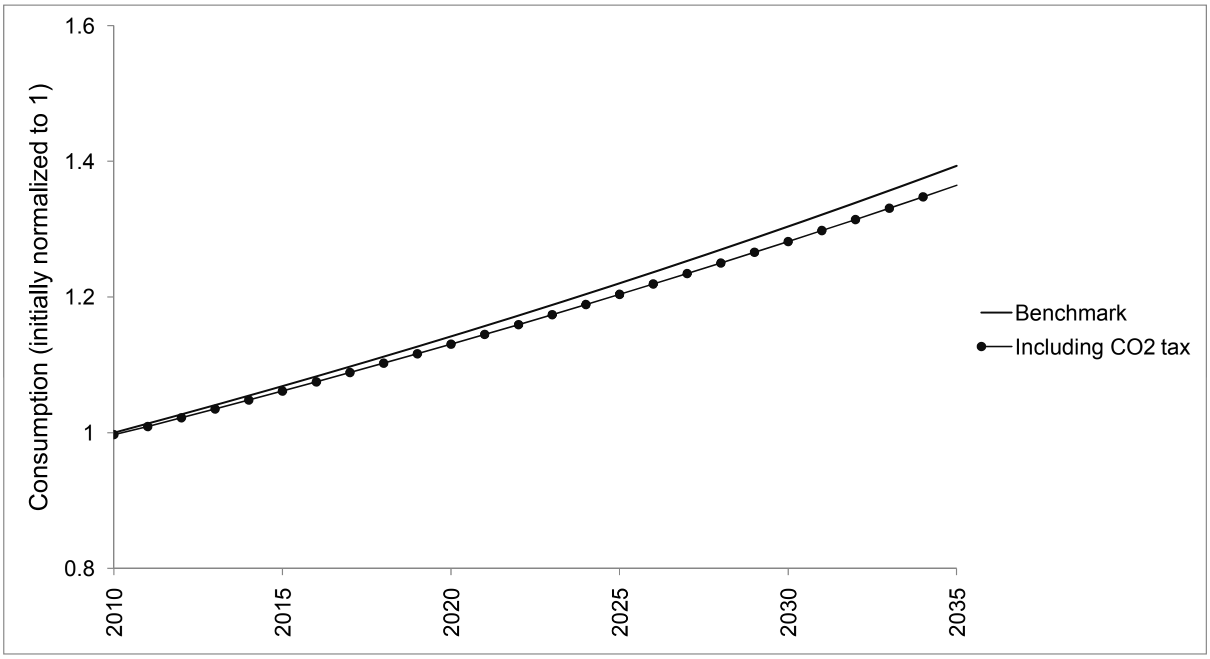

Figure 10: Comparison with benchmark consumption in absolute terms (35% reduction, redistribution to households)

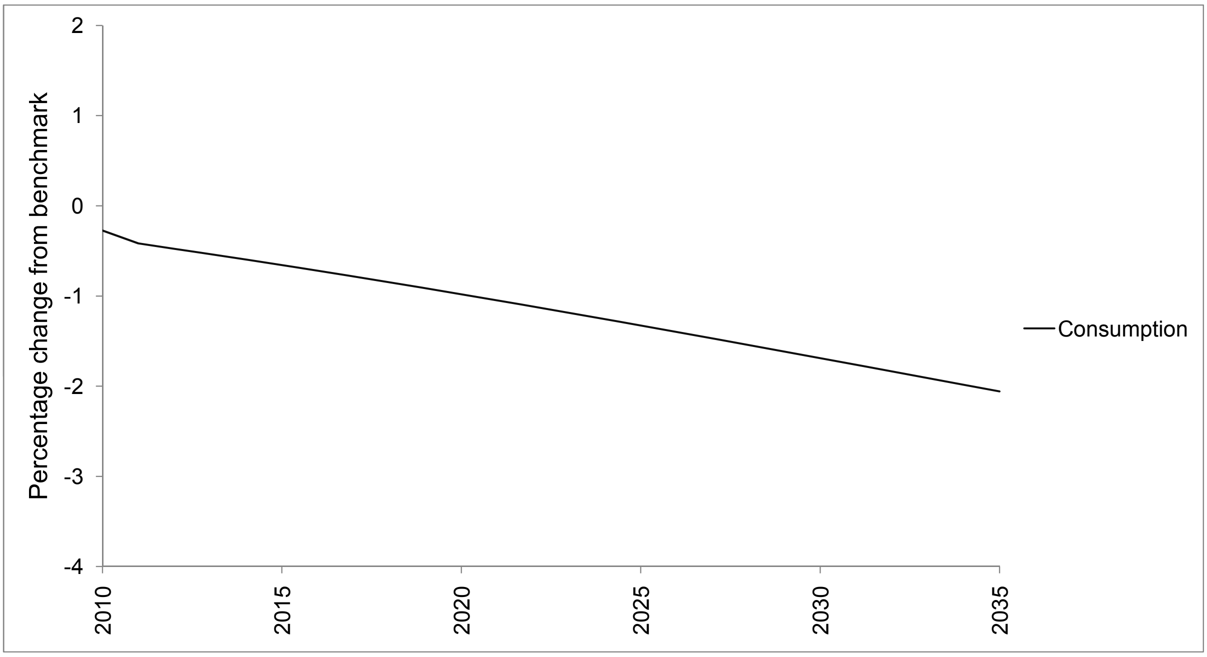

Figure 11: Aggregate consumption (35% reduction, redistribution to households)

The effects at the sectoral level are also very similar. The direction of structural change is virtually identical. The non-energy intensive sectors with a relatively high substitution potential for energy benefit from the introduction of the tax. The service sectors, having very low energy shares, but also smaller elasticities of substitution at the level of pro-

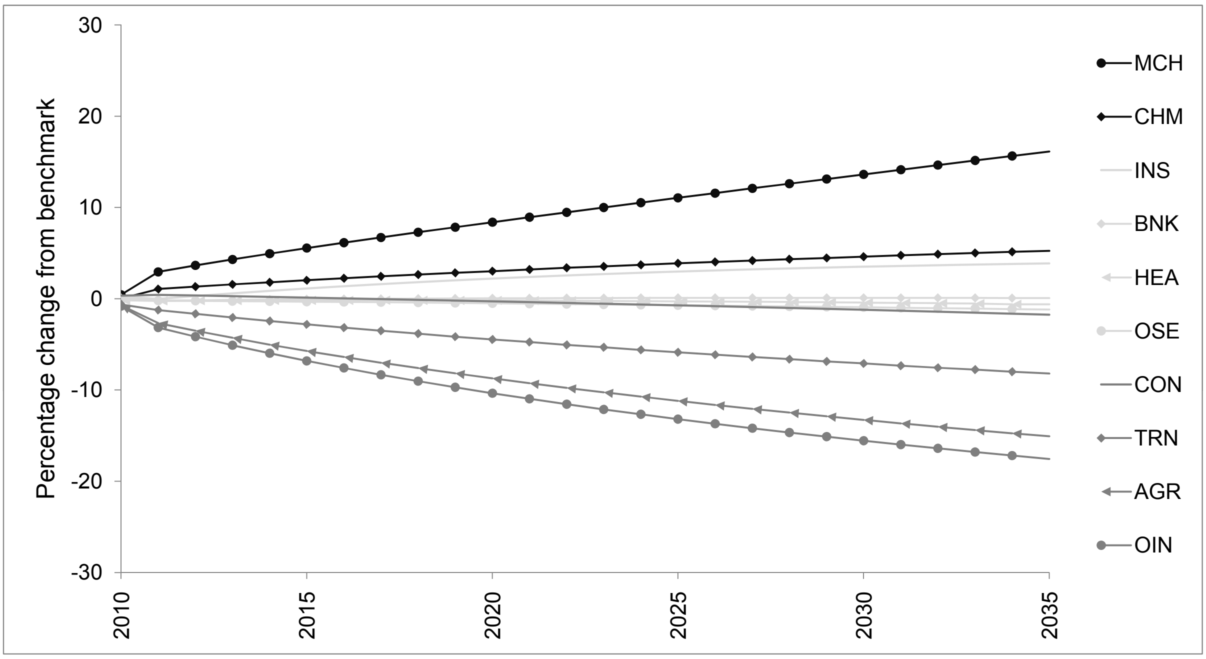

Figure 12: Sectoral output (35% reduction, redistribution to households)

duction of intermediate goods, exhibit only small reactions. On the other hand, the three most energy-intensive sectors suffer losses of 8% and more. The effects on capital accumulation again work in the same direction as output. The non-energy intensive sectors become more attractive for investors after the introduction of the tax; thus, capital is reallocated to these sectors. Structural effects are thus similar irrespective of whether the reduction target is tied to fossil energy or overall energy use, because in both cases, the energy-intensive sectors are exposed the most to the tax.

7.2. Tax revenue used as a subsidy for R&D

In this scenario, we apply an alternative approach for the redistribution of the tax revenues collected from the CO2 tax. The revenues are no longer redistributed back to the representative household, but they are now used to subsidize the build-up of the sectoral non-physical capital stocks. Due to our formulation of the investment process, this can also be interpreted as a subsidy to sectoral R&D. As already explained, the build-up of capital is the engine that drives growth in this model. This alternative way of redistribution directly supports the growth mechanism in the sectors. All regular sectors and the energy sector benefit from the subsidy. From an environmental policy point of view, it would not make sense to subsidize the oil sector as well. It is therefore excluded from the redistribution. Energy, on the other hand, is subsidized as well, as the subsidy affects only the production process of non-fossil energy. The yearly subsidy rate is calculated directly from the tax revenues and is uniform across all sectors. As we have a rising tax rate until the year 2035, the rate of subsidy is also rising during that period. To achieve the reduction target, the tax has to rise at a slightly higher rate than before. The subsidy rate starts at 0.094 in 2010 and ends up at 0.491 in 2035. The results are shown in Figures 13 to 15.

Variations in aggregate consumption are more pronounced in this scenario. Consumption declines more during the phase until the reduction target is reached. It is 2.6% lower in

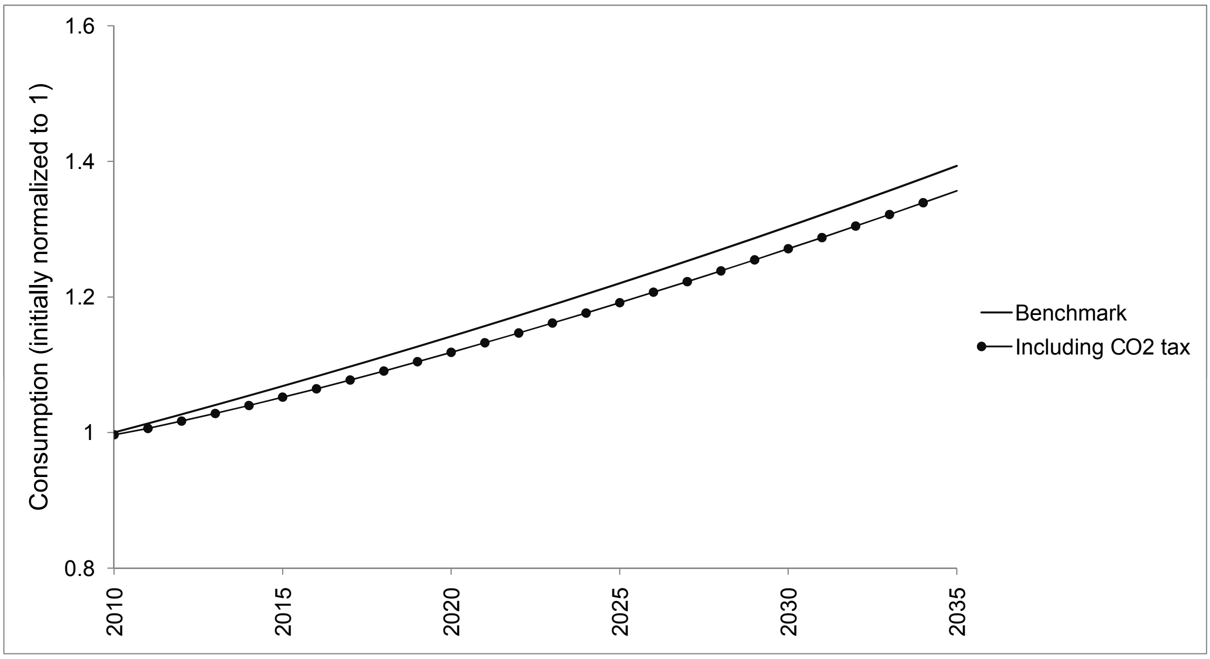

Figure 13: Comparison with benchmark consumption in absolute terms (35% reduction, R&D subsidy)

2035 compared to the benchmark, while the corresponding decrease in Section 7.1 is 2%. Correspondingly, welfare loss is also higher (2%). The sharper decrease in consumption has to be attributed to the increased investment activity. The subsidy leads to an increase in the capital stocks of almost all sectors, as both physical and non-physical investments increase significantly. Thus, compared to the case discussed above, households devote less of their income to consumption and increase their investment activity in earlier periods. An important point to consider here is that the time horizon of this policy is rather short. If we assumed a longer time horizon, the higher investment activity and thus the increased accumulation of capital would have a beneficial effect (in welfare terms) and the welfare loss would eventually become smaller than in the case with the original redistribution mechanism. Given the assumptions here, the time horizon is too short to reap the benefits

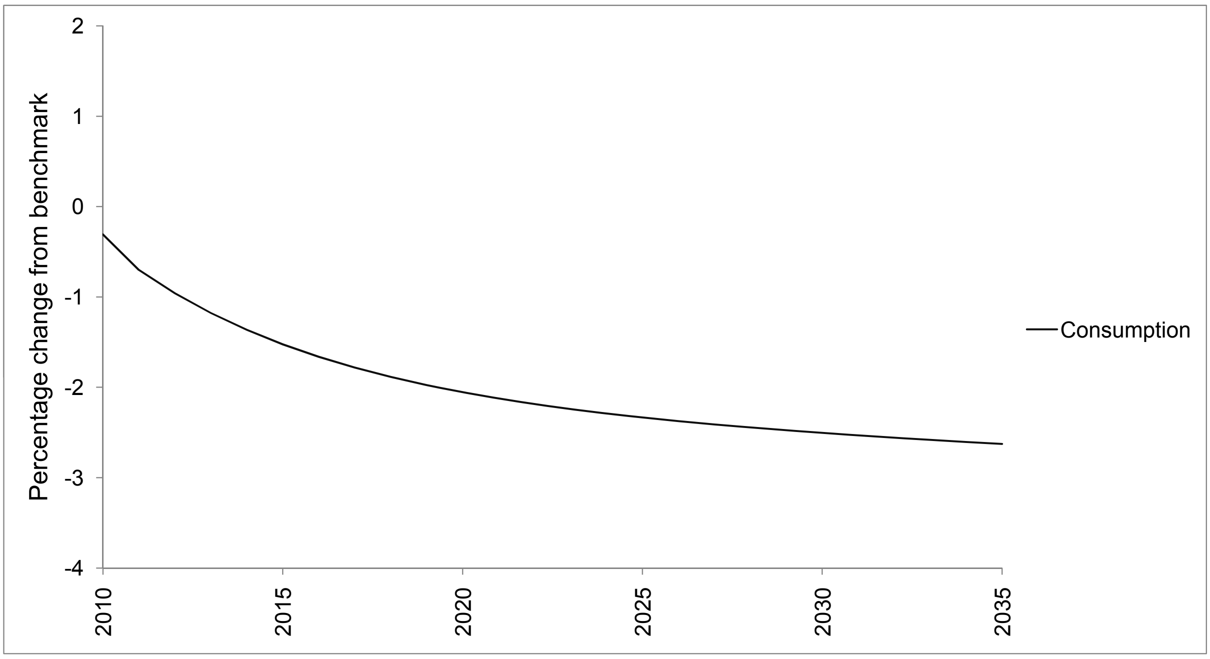

Figure 14: Aggregate consumption (35% reduction, R&D subsidy)

from the subsidy and the increased capital accumulation[2]. Comparing the growth path of consumption to the benchmark path (Figure 13), we again see that the deviation is small, but slightly higher than above.

There are a couple of changes in sectoral outputs compared to the case with the standard redistribution mechanism. First of all, there is a general shift upwards, leading to higher output in almost all sectors. This implies that the subsidy actually works as a supportive mechanism in nearly every sector that benefits from the subsidy. On the other hand, the subsidy also leads to a wider range of effects. The biggest gainers are the machinery industry, the chemical industry and construction. Additionally, banking and financial services are now also able to increase their output compared to the benchmark scenario without a tax. Insurances, previously among the winners, now suffer a small decline in output until 2035. The decrease in the two most energy-intensive sectors is now even a bit larger than before,indicating that the subsidy leads to an even more pronounced reallocation of capital.

It is obvious that the structural effects are not much different in this case. But it is also apparent that some sectors benefit more from the subsidy than others. The explanation for this is the importance of initial investments (both physical and non-physical). Capital-intensive sectors that rely heavily on investments, or sectors that have high activity in R&D experience larger upwards shifts than those where none of the two is an important

[2]It would therefore be very interesting to investigate in more detail when and under what conditions the R&D subsidy leads to a better outcome in welfare terms. This is beyond the scope of this report and is left for future research or projects.

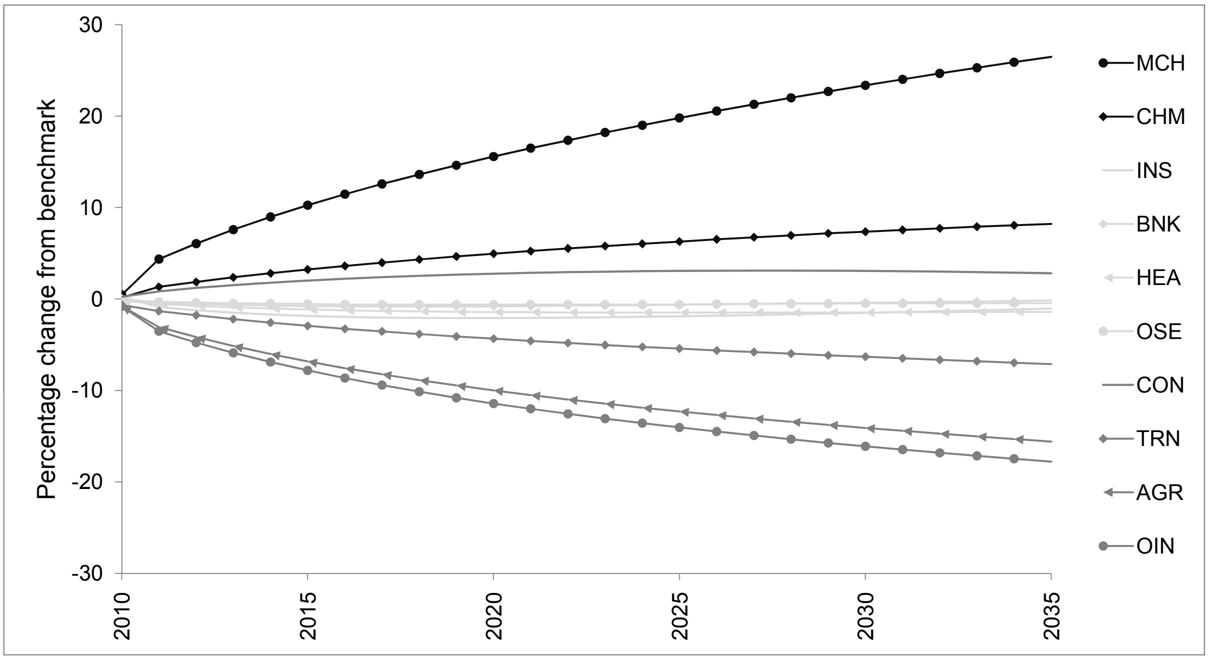

Figure 15: Sectoral outputs (35% reduction, R&D subsidy)

factor in the production process. Two examples to illustrate this point are construction and insurances. Construction has very high initial physical investments. As the subsidy indirectly also supports the build-up of physical capital, construction now benefits from the introduction of the tax and eventually becomes a gainer of the policy in this scenario. The opposite holds for insurances, where neither physical investments nor R&D are an important factor. Consequently, they are not able to benefit from the subsidy and are worse off in this case[3].

The two biggest gainers in this scenario, the machinery industry and the chemical industry, both have favorable preconditions to benefit from the subsidy. The chemical industry has large initial investments in non-physical capital, the machinery industry has relatively high physical investments, and R&D also plays a significant role. The same holds for other services, which have relatively large initial physical and non-physical investments. Thus, the subsidy, despite increasing investment activity in all sectors, is mostly beneficial for the sectors that have high initial investments. Other than that, the structural effects are similar to the previous scenario. In the presence of the subsidy, the energy-intensive sectors also suffer a decline in output and attract less capital than in the benchmark. The non-energy intensive sectors on the other hand benefit from the introduction of the tax.

Additionally, the fact that increased accumulation of capital benefits sectors that actually provide the goods and services necessary to conduct the investments has a more pro-

[3]In fact, also service sectors, most notably insurances and banking an financial services, are innovative. However, these innovations are hardly represented in the data. Results for these sectors would change if their innovative activities could be measured accordingly as well.

nounced effect here. Construction and the machinery industry, two sectors that play a role in this respect, increases their output considerably. This can be partly attributed to the increased demand for investment goods in most sectors.

The policy implemented here could have even more pronounced effects if the subsidies were more purposefully designed. One may argue that it does not make sense to subsidize the build-up of non-physical capital in sectors where it does not have a significant influence. Therefore, one could think of subsidizing only the sectors that have relevant R&D activity, or to subsidize these sectors at a higher rate than those that do not rely much on R&D. Sectors with high initial physical investments could also be included, as they benefit considerably from the subsidy as well. From the patterns that we observed, it seems reasonable to assume that such a policy should increase the range of the effects on the outputs and the capital stocks and thus increase the differences between the sectors. The winning sectors would benefit even more, and the decreases at the bottom would be larger. This is indeed the case. If only the sectors that have significant initial investments (both physical or non-physical) are subsidized, the range of effects gets wider, and both the increases and the decreases are more pronounced.

Another possible policy would be to subsidize only the non-energy intensive sectors. This again increases the range of effects, which is not surprising as we noticed above that the energy-intensive sectors are most affected by the CO2 tax. Thus, there would be an even more pronounced shift of capital from the energy-intensive to the non-energy intensive sectors, and larger adjustments in sectoral outputs.

8. Different policies abroad

It is reasonable to assume that not only the policies implemented in Switzerland itself affect the Swiss economy. The measures taken by foreign countries may also have an impact. So far, we have implicitly assumed that foreign countries implement similar reduction targets and therefore a similarly stringent policy. This, however, does not necessarily have to be the case. The discussions at the United Nations Climate Change Conference in Copenhagen showed that there is a lot of disagreement on future climate and energy policy. Future policies and reduction targets may thus considerably diverge between countries. This raises the question on how the effects of domestic policies vary if different policies are implemented abroad.

As the CITE model is a one-country model, there is no possibility to model policies in foreign countries in an explicit way. However, differences in reduction targets or CO2 taxes can be expressed by varying the trade elasticities. If environmental policy is less stringent in the rest of the world, this implies, considering our formulation of environmental policy, that foreign countries set lower taxes on CO2-emissions than Switzerland. Thus, there is a higher premium on the prices of fossil fuels in Switzerland than abroad, which means that foreign goods are relatively cheaper compared to domestically produced goods. This increases the incentives to import goods rather than producing them in Switzerland. In terms of model parameters, this means that the Armington elasticities rise, as there is an increased preference for foreign goods. At the same time, Swiss goods become less attractive for foreign consumers, as they are relatively more expensive because of the higher tax. Demand for exports decreases, which is reflected by a lower value of the elasticity of transformation. The opposite holds if we assume that Switzerland implements a less stringent CO2-tax regime than foreign countries. The premium on the fossil fuels is smaller in Switzerland, and thus Swiss goods become more attractive for foreign countries, and export demand rises. Correspondingly, the elasticity of transformation also rises. Foreign goods on the other hand are now relatively more expensive and therefore less attractive for domestic consumers, implying that domestically produced goods cannot be readily replaced with foreign goods. Therefore the Armington elasticities decrease. In both scenarios, the domestic reduction target is the same as in sections 7.1 and 7.2, i.e. Switzerland reduces its energy use by 37.5%. If foreign policy is more stringent, this means the rest of the world sets an even more ambitious target. If it is less stringent, then the reductions abroad are below 37.5%.

8.1. More stringent policy abroad

First, we assume that Switzerland does not follow the rest of the world and implements a comparably loose energy policy regime. The underlying assumption is that the rest of the world sets a higher tax rate, which corresponds to a more ambitious reduction target. To model this, we reduce all Armington elasticities by 1 and double the elasticity of transformation. The results are shown in Figures 16 to 18.

In welfare terms, implementing a less stringent tax regime hardly leads to any differences. The decrease is again about 1.2% and thus is at a similar magnitude as in the case with similar policies. This implies that consumption over time evolves in almost the same way. An important difference is that we need a higher tax rate (or a higher growth rate of the tax rate) to reach the reduction target. The tax profile of the base scenario would not lead to the requested decrease in energy use under these circumstances, indicating that the incentives to cut down energy use are smaller when foreign policy is more stringent.

Compared to the results derived with the standard values for the Armington elasticities and the elasticity of transformation, the range of percentage changes in sectoral output

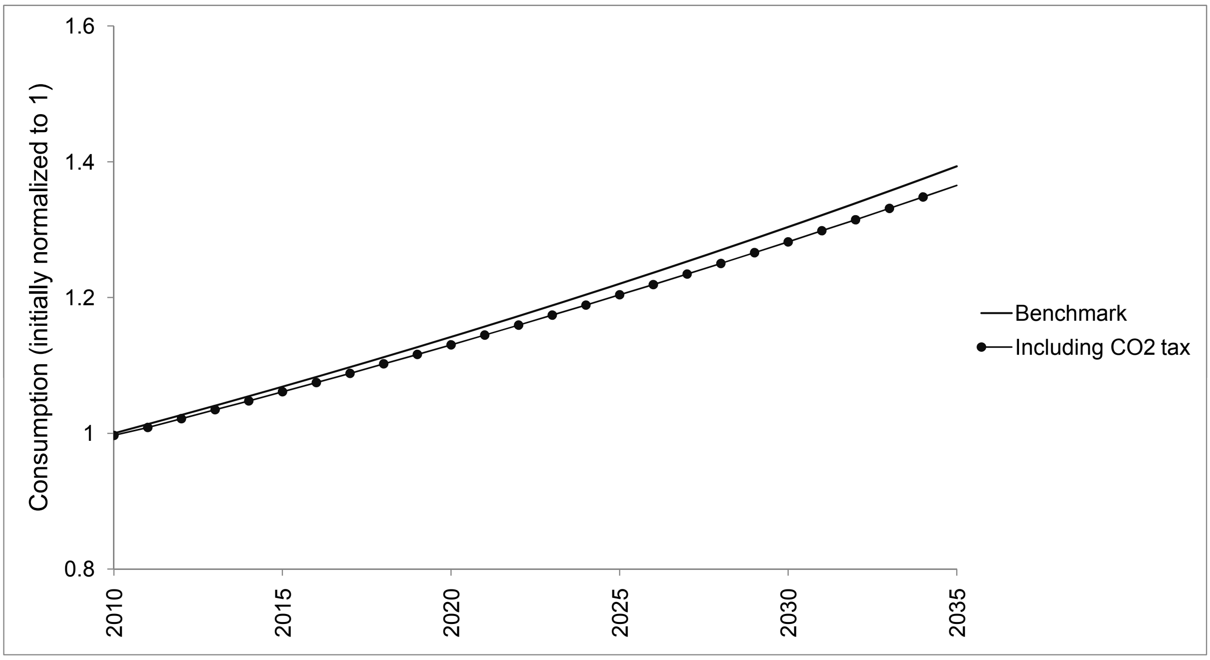

Figure 16: Comparison with benchmark consumption in absolute terms

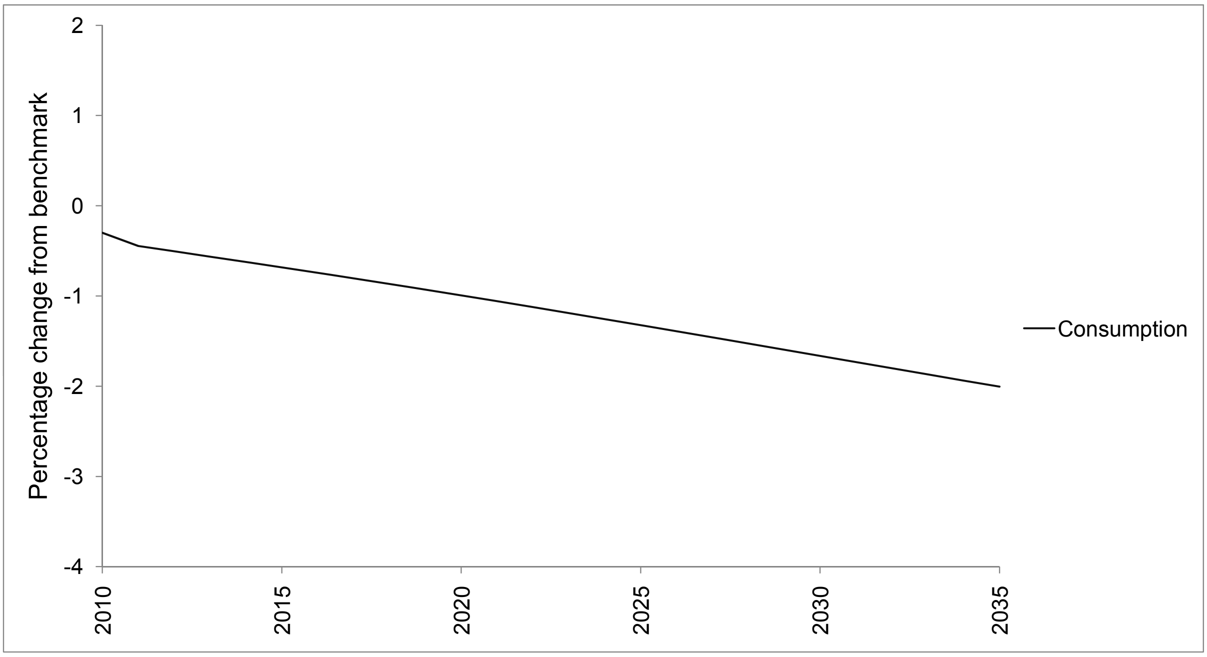

Figure 17: Aggregate consumption when foreign policy is more stringent

gets smaller. The reactions to the tax are less pronounced than in the case with similar policies. Due to the fact that domestic goods (that are affected by the tax in Switzerland) cannot be readily replaced by foreign goods, the policy has a smaller overall effect and leads to smaller adjustments, both on the positive and on the negative side. One possibility to react to the tax, namely substituting domestic for foreign goods, becomes unattractive

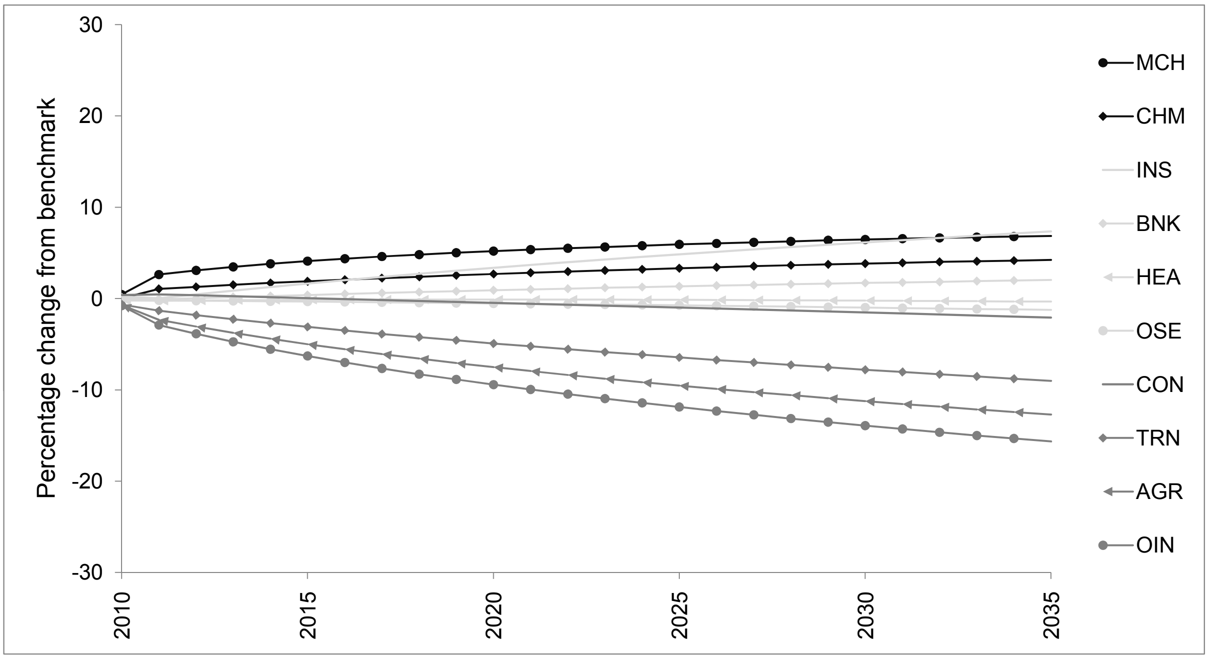

Figure 18: Sectoral outputs when foreign policy is more stringent

in this scenario, because the foreign goods are relatively more expensive. An interesting observation is that the machinery industry (a relatively trade intensive industry) is no longer the biggest winner in this scenario. Relying heavily on imports, the decrease in the corresponding Armington elasticity affects the machinery industry negatively. Insurances, a sector with comparably little trade activity, benefits the most from the circumstances. Banking and financial services are also among the winners in this scenario. This sector benefits from the increased elasticity of transformation due to its high export share. Other than that, structural change is similar in direction, but less pronounced in magnitude compared to Section 7.1. The energy-intensive sectors perform marginally better in this scenario, which leads to a smaller range of effect. Generally, adjustments are much smaller in this setup. If we implemented the tax profile from section 7.1, the reduction target would be missed. Domestic reduction incentives are thus considerably smaller when foreign policy is more ambitious.

8.2. Less stringent policy abroad

The contrary assumption that the rest of the world implements a less stringent policy than Switzerland is modeled in the opposite way compared to the case above. All Armington elasticities are increased by 1, and the elasticity of transformation is halved. Figures 19 to 21 show the results. Given that the rest of the world implements a less stringent policy, the reduction target in Switzerland can be met with a lower tax (compared to the

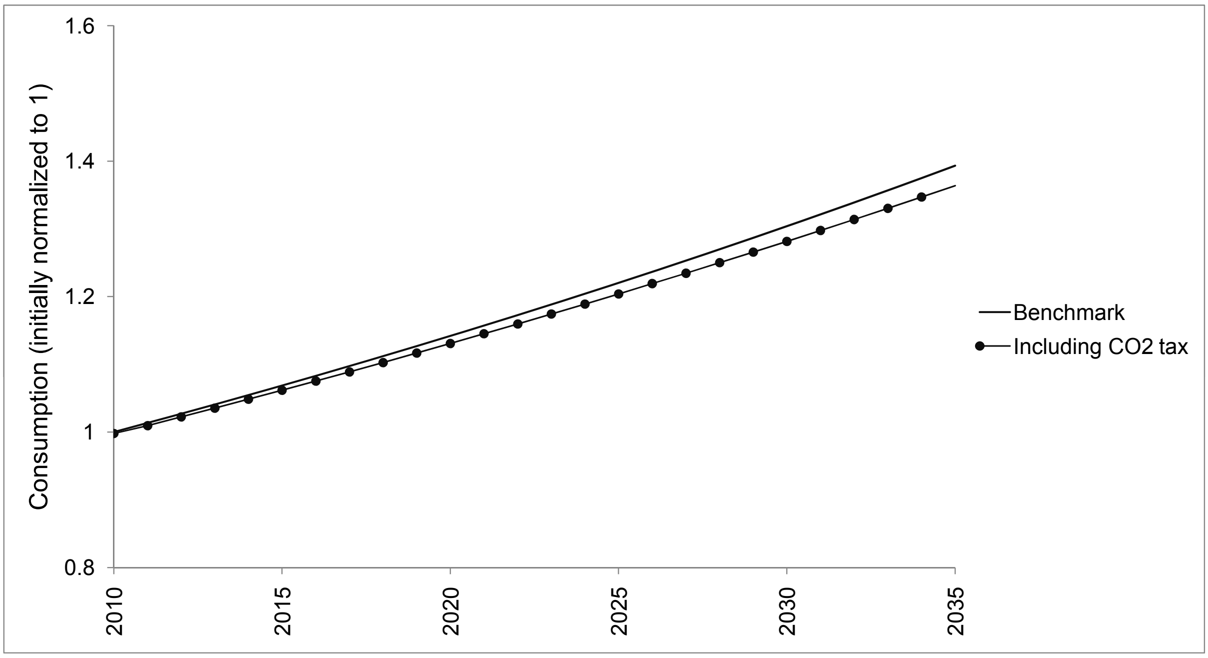

Figure 19: Comparison with benchmark consumption in absolute terms

BAU scenario), which is just the opposite compared to the case discussed in the previous section. Welfare is now reduced by almost 1.3%, and consumption over time decreases a bit more. If we implemented the same tax profile as in the base scenario, the decrease in welfare would rise considerably, and energy use would be reduced by more than the requested 37.5%. Thus, in this case, the reactions to the tax are much more pronounced. Foreign goods are now relatively cheaper than domestic goods, which translates to higher Armington elasticities. This is primarily beneficial for the sectors with high import shares, such as the machinery industry and the chemical industry. The machinery industry accordingly increases its output significantly in this scenario. The chemical industry also increases its output by more than 5%. Banking and financial services on the other hand, who were winners in the scenario with a more stringent policy abroad, now reduce their output, as the elasticity of transformation is lower. The three most energy-intensive sectors (transports, agriculture and other industries) suffer even larger losses than in the original case with similar policies. Thus, there are much more pronounced adjustments in this case, with a clearer shift towards a less energy-intensive economy. From these two scenarios, it becomes apparent that the policy of the rest of the world has a significant influence on the Swiss economy, both at the sectoral and the aggregate level. If Switzerland implements stronger regulations than the rest of the world, welfare loss increases, albeit only by a small amount. In this setting, a first-mover strategy in the sense of implementing strict regulations - no matter what the rest of the world does - is not beneficial, as welfare reductions are slightly higher than in the case with similar policies. A first-mover policy could have positive effects if learning effects were included in the model.

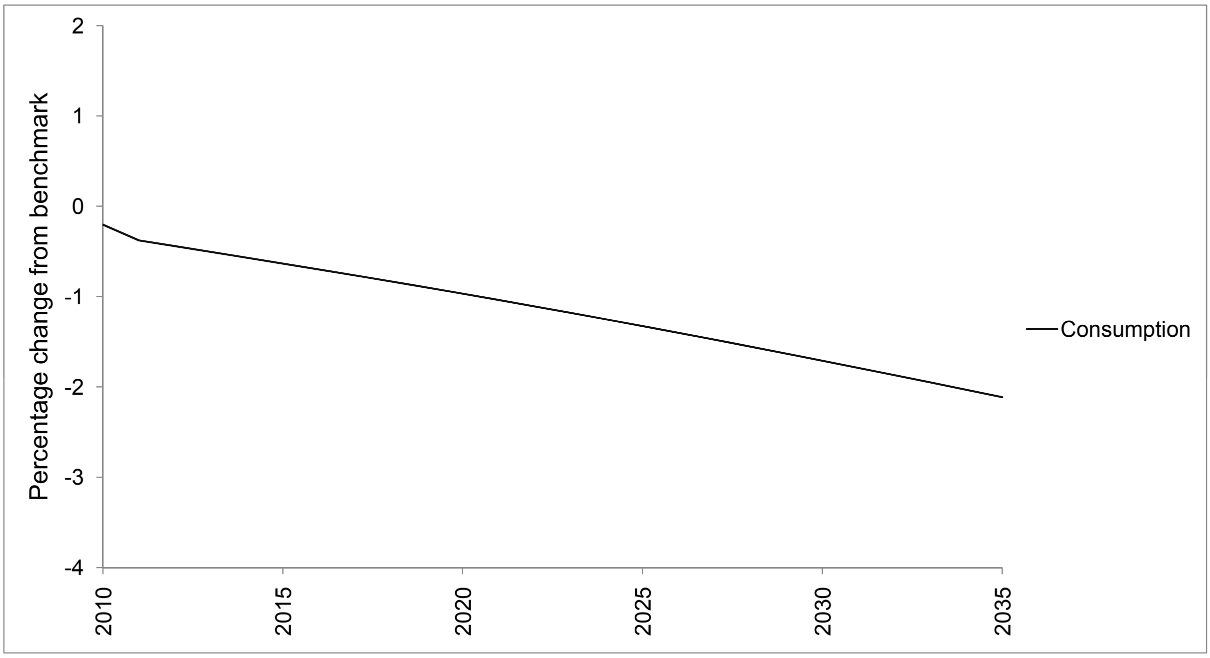

Figure 20: Aggregate consumption when foreign policy is less stringent

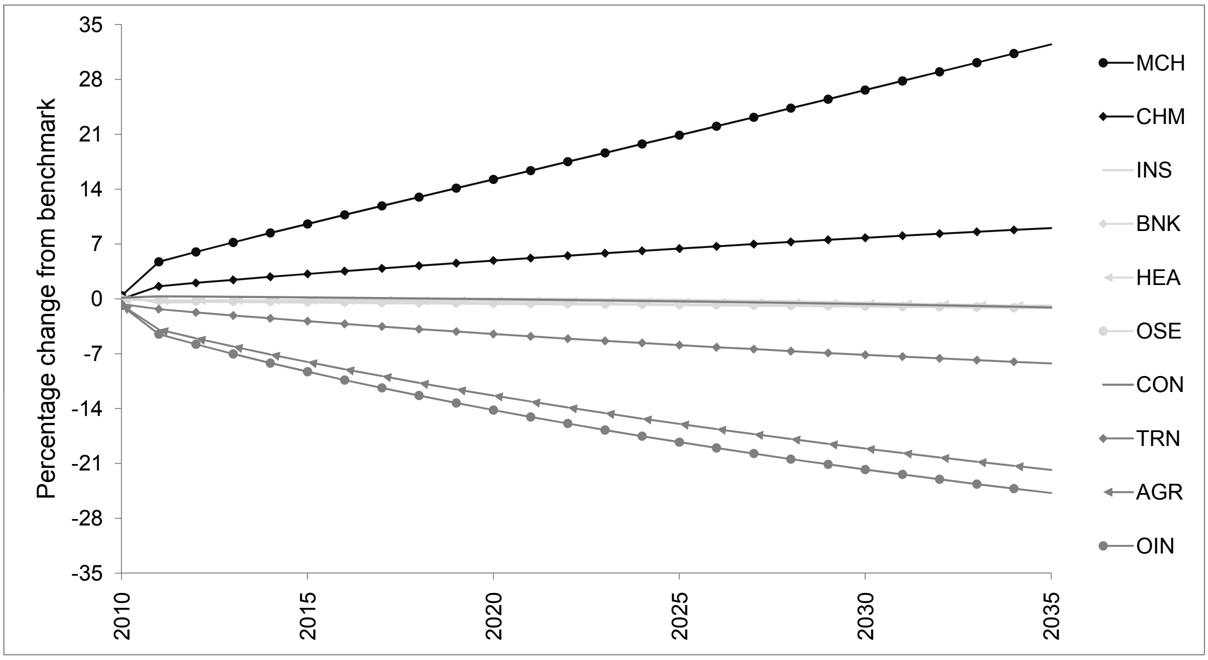

Figure 21: Sectoral outputs when foreign policy is less stringent

Setting comparably stringent reduction targets necessitates an increased use of new less energy-intensive technologies. If the use of these technologies entails learning effects, it may be beneficial in the long run if these technologies are used in production earlier than abroad. The corresponding cost reductions due to learning-by-doing may lead to considerable comparative advantages. As this effect is excluded in this analysis, the negative effects of the first-mover strategy prevail and welfare is slightly lower than in the case with similar policies.

9. Larger labor force

A prominent issue in the current political and public debate in Switzerland regards the possible effects of the recently signed agreement with the European Union concerning the "free movement of persons", which facilitates immigration for EU citizens to Switzerland. The main concern is that this agreement leads to a substantially higher inflow of citizens from the EU, and thus to a population growth rate that would push the level of residents in Switzerland close to or even beyond a bearable limit. An additional related concern is a negative effect on the wages. Thus, one may ask how high labor growth or a substantially higher population affects the results derived earlier.

Our model is calibrated so that labor growth is set to zero, i.e. the size of the labor force is constant. The inclusion of a positive growth rate of population would complicate the calibration procedure significantly. We thus abstract from analyzing the effects of an increasing labor force. Instead, we look at the effects of a larger initial (but constant) labor force. To do this, we increase overall labor input by 10%. In order not to change the sectoral shares on overall labor, we simply augment labor in each sector by 10%. In order to account for the fact that a higher initial labor force also implies a higher initial energy demand, the corresponding benchmark values are adjusted as well. We assume that this 10% increase in the labor force simply leads to a 10% increase in initial energy demand. 50% of this increase is covered by higher imports, the other 50% by higher domestic production. These adjustments increase the labor share and decrease the share of non-accumulable capital in all sectors, but leave the energy shares virtually unchanged. Due to the assumption that only 50% of the higher energy demand are covered by increased domestic production, imports are considerably higher in this case. As we assume a larger initial energy use in this scenario, this means that the reduction in energy use has to be larger than in all the scenarios previously discussed. Given the assumptions made here, energy use has to be reduced by 41% to reach the requested level. To sum up: Compared to the original data, we increased the initial labor force and initial energy demand by 10% each. One half of the additional energy demand is covered by imports, the other half by domestic production. Because energy demand is higher than in the previous scenarios, it has to be reduced by a higher percentage rate to reach the requested level. The results are shown in Figures 22 to 24. Compared to the results derived in Section 7.1, the increase in the initial labor input and in initial energy demand leads to no significant change in

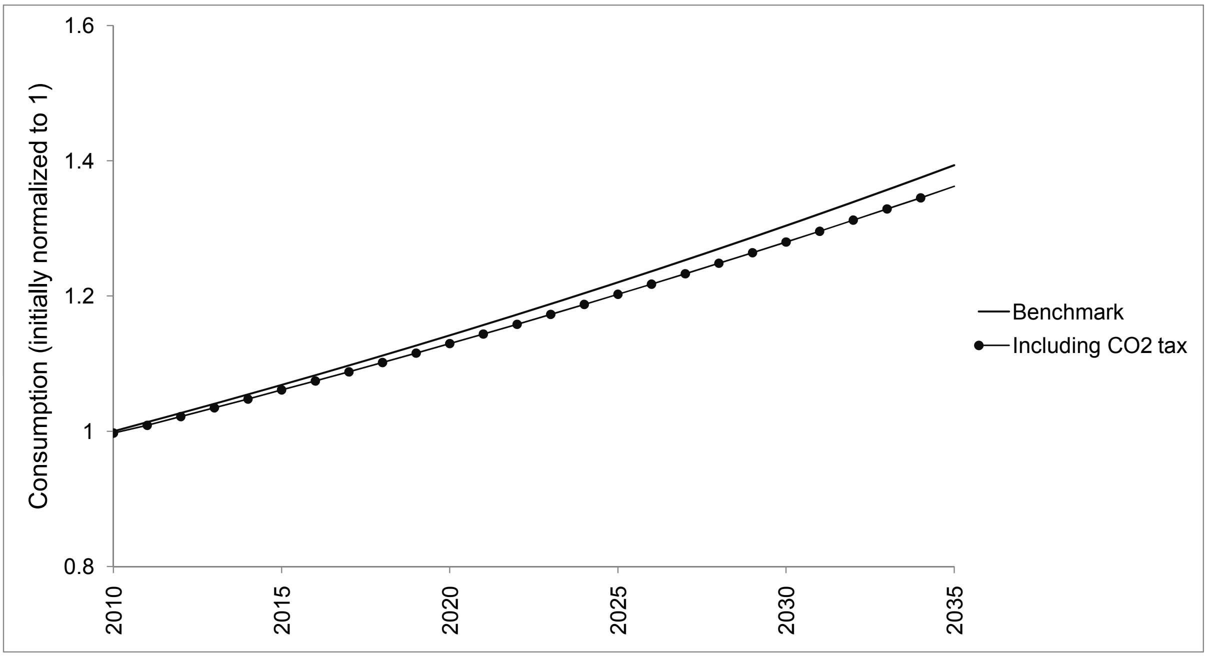

Figure 22: Comparison with benchmark consumption in absolute terms (larger labor force)

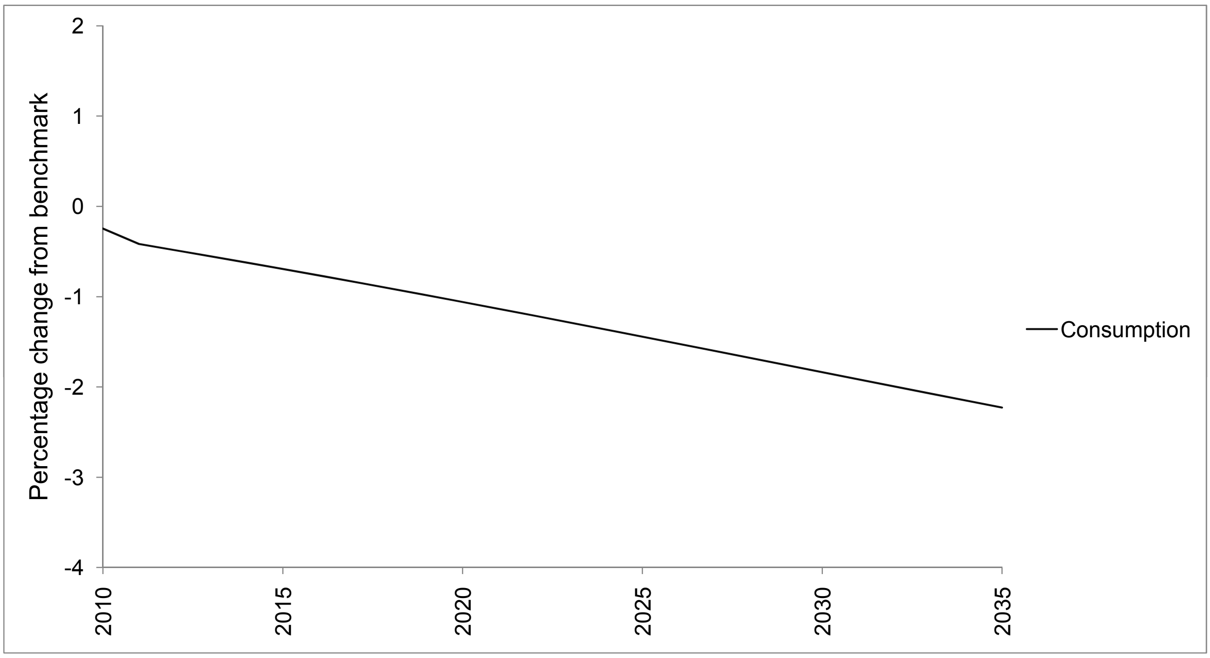

Figure 23: Aggregate consumption (larger labor force)

welfare. The reduction in welfare is again around 1.2%. In 2035, consumption is 2.2% lower than in the benchmark, which is just about the same as in the scenario with a more stringent domestic policy. Similarly, the requested reductions can be achieved with a lower tax rate than in the base scenario. This again implies that adjustments would be larger with the original tax profile. This holds for both the aggregate level (i.e. for consumption and welfare) as well as for the sectoral effects.

Interestingly, the results are mainly driven by the assumption on how much of the additional energy demand is covered by imports. In this case where we assume that 50% is covered by imports, the share of imports in total demand is higher than before. As we assume a relatively high Armington elasticity for the energy sector and thus a good substitutability between domestic and foreign energy goods, the larger share of imports in total demand, and thus the increased importance of foreign energy, leads to larger adjustments in the energy sector. If we were to assume that all of the additional energy demand were covered by increased domestic production, the adjustments would be much smaller. However, it seems reasonable to assume that a considerable share of the increased initial energy demand is covered by imports. On a sectoral level, there are only small differences

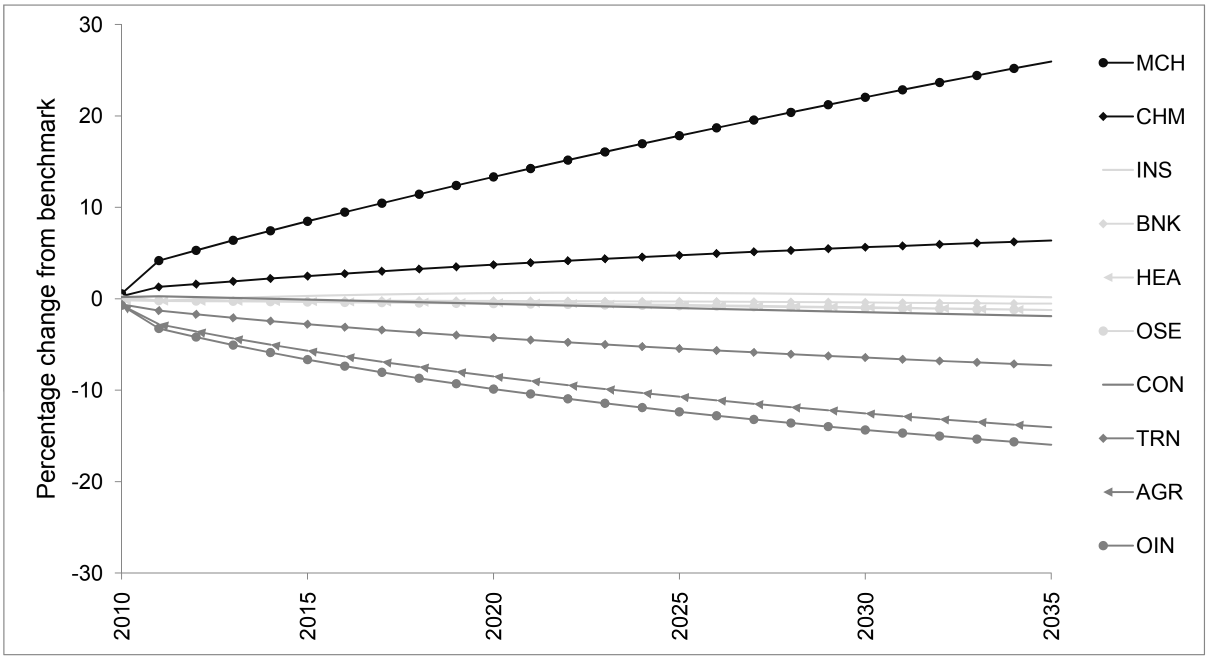

Figure 24: Sectoral outputs (larger labor force)

to Section 7.1. Most sectors have a slightly smaller output under these conditions. The two exceptions are the chemical industry, which now increases its output by almost 6%, and, most notably, the machinery industry, whose output is now more than 26% higher. Being a highly labor intensive industry, the increased availability of labor seems to be beneficial for the machinery industry. As indicated above, increasing only the labor force (and thus neglecting the fact that this implies a higher demand for energy) would lead to almost identical results as in Section 7.1. This is mainly due to the fact that the labor market is relatively inflexible in our model and not formulated in a detailed way. The only channel through which the results may be affected are thus through its influence on the energy share, or, put differently, on the relative importance of energy in production.

Additionally, as we assume that all labor is fully employed, there are no potential negative side effects such as higher unemployment. The effects are in fact minimal if we assume that all the additional energy demand can be covered by increased domestic production. What is driving the results here is how much of the additional energy demand of an increased initial labor force would be covered by additional imports. A higher import share and thus an increased importance of foreign energy leads to larger adjustments in the energy sector and to a larger decrease in welfare.

Part IV.

Conclusions

10. Concluding Remarks

The modeling of endogenous growth, and especially of sector-specific growth, has proved to be successful to evaluate effects of policies on the development of the Swiss economy over the long and very long run. We get the central finding that the Swiss economy can continue to grow even with ambitious energy and climate policies.

Energy and climate policies cause moderate, but not negligible costs in comparison to a development without climate change and energy scarcity. The simulation of an 80

The sectors react differently on energy and climate policies, depending on their tendency to invest, their energy intensity and sectoral interconnections. If the policy is domestically more ambitious than abroad, structural change is slightly more emphasized. First mover advantages are not yet considered in the model. An increase of labor in Switzerland has only marginal effects. Distribution of tax revenues has an impact on consumption and welfare which depends on the considered time horizon; for a shorter time horizon, research subsidies cannot develop their full advantages for the economy while in the long run, these subsidies are superior to the redistribution of revenues to households in welfare terms.

The model is conservative in several respects. The technology development is modeled in a top-down manner, which excludes the consideration of specific potential technologies that might be highly influential on energy efficiency. Learning effects are not a focus of the model. Accordingly, the build-up of new core competencies to be used as a comparative advantage in international trade does not emerge. The model simulates no secondary benefits, such as health problems and other economic impact of climate change. All elasticities and parameter values are assumed in a conservative way.

Possible extensions of the model include a more sophisticated representation of the energy sector and the relevant technologies (e.g. an explicit differentiation of sources of non-fossil energy). This would allow studying the effects of energy and climate policies on a technological level. With a more detailed modeling of the energy sectors, the importance of learning rates and their effects on the usage costs of new technologies could also be studied. Second, the labor market is treated in a simple way so far. Labor is fixed and inelastic in supply. With a more flexible modeling, effects on labor supply and unemployment could also be analyzed. This is left for future research.

Part V.

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Part VI.

Appendix

Appendix A:

The theoretical foundation of the CITE Model.

Appendix B:

A comparison of growth dynamics: the CITE model vs. a model with homogenous capital.

Appendix C:

The CITE Model: Data, Parametrization and Sensitivity Analysis.

Appendix D:

Long-term energy policy in Switzerland and its economic effects: Results from the CITE model.

Appendix A: *The theoretical foundation of the CITE Model.*

The theoretical foundation of the CITE Model

1 Introduction

Energy is undisputably a major input factor for economies around the globe. Securing its supply and ensuring an efficient use of it were crucial for continuing prosperity worldwide in the past years. However, coping with the negative consequences of climate change to preserve our environment is arguably one of the largest challenges humanity faces in the next decades. Within this challenge, public policy makers have a key role in identifying appropriate energy strategies with levers on both the supply and the demand side. Mankind is well advised to replace hydrocarbon energy resources with renewables, but trimming demand is still the ultimate goal en route to a sustainable energy usage.

For a conceivable amount of time, the world has enough accessible fossil reserves to secure its current pattern of supply. Although oil resources have a shorter range, natural gas resources will last at least until the end of the 21st century, and coal could even cover human energy demand for centuries. Concerning the demand side, by far the largest degree of energy consumption in the last decades has been in Western countries. Currently, the net growth in energy consumption mainly comes from the rapidly industrializing non-OECD economies like China, India, and Brazil. China alone accounts for nearly three-quarters of growth in global demand. This soaring demand resulted in non-OECD countries outpacing OECD countries, which are no longer the major contributor. This reversed energy demand has not only influenced global markets but also changed the composition of energy sources. For a sixth consecutive year, coal is the fastest-growing fossil fuel (BP, 2009). Given that coal has a comparatively high content of carbon, this is an alarming tendency and will strongly affect global carbon emissions.

Policy makers of all countries are aware of this situation and seek to find energy strategies that both secure energy supply and offer better energy efficiency. Economic models help estimate the consequences of political measures on the different industries and residents. The CITE (Computable Induced Technical change and Energy) model aims at estimating the effects of energy policies on Switzerland. It is a multi-sector growth model that includes endogenous growth dynamics in all sectors and all scenarios, including the benchmark (business-as-usual) case. This chapter provides the theoretical background for the model.

The CITE model is based on the work of Romer (1990) and Grossman and Helpman (1991) and exhibits endogenous growth dynamics based on research and development (R&D) for Hicks-neutral technical progress with the assumption of an expanding variety of intermediate goods (i.e., horizontal innovations). By including these modules both in the benchmark case and in the policy scenarios, the growth dynamics are greatly amplified compared to a neoclassical growth model. As all dynamics that arise from monopolistic competition and of gains of specialization are consistent in the cases with and without policies, dynamics are consistent among all scenarios.

The remainder of this chapter is organized in three parts. First, we give a general introduction of the environmental and political background for the energy debate. Second, we introduce the CITE model and describe markets and agents are described in some detail in Chapters 3 to 11. This part also includes an explanation of the growth dynamics.

1.1 Switzerland's energy consumption

The energy consumption of a Swiss resident is comparable to a continuing performance of about 5000 watts per year. In comparison to the global average, this is about 2.5 times higher than the average energy a human being consumes, i.e., 2000 watts per capita. In Western Europe, the average energy demand equals 6000 watts, and in the United States, the figure corresponds to 12000 watts per capita. The calls in Switzerland for regaining a consumption of 2000 watts per capita, the so-called "2k Watts Society", are ambitious, but not unachievable. In the past, Switzerland last had a consumption of 2000 watts in 1960 (Novatlantis, 2005).

Of the current 6000 watts, about 60% are produced from oil and gas products (Spreng & Semadeni, 2001; Novatlantis, 2005). Regarding the need to produce one unit of gross domestic product (GDP), carbon intensity is relatively low in Switzerland, a fact that is, among others, due to the specific composition of output (Stern, 2007). In comparison, the United States requires 50% more than the EU, and China even uses 500% more energy than the EU. Those benchmark numbers are not static; they may increase or decrease over time. When we look at the efforts of countries to reduce energy intensity, France, for example, has nowadays an energy intensity that is 30% lower than in the 1970s (EC, 2005).

Switzerland faced the global discussion about the reduction of energy consumption and carbon emissions by joining the Kyoto protocol and committing to reducing carbon emissions by 8% by the year 2012. In 2007, the Swiss progress towards this goal was still about 4% below the scheduled reductions. Only in April 2009 did the Swiss Federal Office for the Environment include effects from woods and foreign emission certificates and conclude that Switzerland will be able to comply with the Kyoto protocol (ETS, 2009). Additionally, Switzerland decided to join the official emission reduction targets of the EU to reduce emissions by 20% by the year 2020. To sum up, there is still a need for action to change the prevailing consumption pattern within the country.

1.2 Carbon emissions

Due to the increased demand for energy, the carbondioxide concentration in the earth's atmosphere has increased about 35% until 2005 compared to the preindustrial level (IPCC, 2007a). Although there is still significant uncertainty about the precise consequences for the ecosystem, some effects for the European climate can already be estimated. It should be emphasized that these estimates have only been corrected for the worse in the course of accumulating more knowledge about ecological consequences.

For Europe, it is assumed that rainfall will increase by about 10% in winter and decrease by about 20% in summer. In addition, the pattern of rainfall within the seasons will be altered. Extreme rainfall is expected to become more common, which results in an increase of floods. The general increase in temperature leads to fewer cold waves in winter. On the contrary, in summer when rain will become rarer, heat waves and droughts are expected to occur more frequently. As a result, the ecosystem in Switzerland will change in the long run (OcCC, 2007).

These ecological effects will soon have economic consequences. Tourism, for instance, might both benefit and suffer from climatic changes. Hot summers can make domestic destinations more attractive, especially at lakes in the Alps. On the other hand, as the weather will also be warmer during winter times, the rising snow line will make ski areas in the foothills of the Alps unprofitable. By the year 2050, most of the smaller glaciers are expected to have disappeared. In total, higher frequencies of tourist visits in summer will not compensate for losses of revenue in winter (OcCC, 2007, IPCC, 2007b).

Besides the effects from energy transformation to the climate there will be also a reverse effect from the changed ecosystem on energy transformation. For example, hydro and nuclear power will be negatively affected as reduced water drainage and warmer rivers will result in a smaller cooling effect. This effect will become particularly visible in summer (OcCC, 2007).

1.3 Political instability

Climate change is clearly the most important reason for the strengthened effort to reduce Switzerland's dependency on fossil fuels as well as to reduce overall energy consumption. Besides climate change, political instability in the countries that produce fossil fuels is increasingly perceived as a threat. This problem especially arises as the energy supply in Switzerland has shifted from coal to oil during the last seventy years (SFOE, 2008).

Although the IEA (2007) considers Switzerland to have a well diversified oil and gas supply in terms of the countries it imports from as well as the import routes, critical voices have emerged. In general, criticism is based on the fact that easily accessible reserves are geographically concentrated within politically instable countries (Proclim, 2007). For both oil and gas, about 80% of all reserves are each located within three areas or countries. About 60% of all oil reserves are situated in the Middle East, another 10% in South and Central America, and another 10% in Africa. Global reserves in gas also concentrate on limited areas, but are less focused in the Middle East. About 40% are located in the Middle East, 34% in Europe and Eurasia, and about 8% in Africa (BP, 2009).

1.4 Models of Swiss energy use

The Swiss Federal Office of Energy (SFOE) reacted to these challenges and formulated four distinct energy scenarios for Switzerland for the time frame until 2050. Two scenarios focus on political measures, while two focus on ecological and economic aims. All display very detailed technical analysis of energy sources and their contribution to energy supply in Switzerland (SFOE, 2007).

Schulz et al. (2008) analyze the most stringent scenario of the SFOE, the goal of a 2000 Watts Society, based on the Swiss MARKAL model. Their study includes a Reference Energy System (RES) that considers both currently available and possible future energy technologies and energy carriers. The model comprises the RES to find the least-cost energy system to saturate energy demand. Based on this analysis, if primary energy per capita consumption is given as a constraint to the model, the authors determine that carbon emissions can be reduced to an equivalent of 5% per decade at maximum. Consequently, a 3500 watts society is feasible by the year 2050 and a 2000 watts society can be maintained as the long-term aim thereafter. Comparing different kinds of objectives, primary energy per capita consumption targets yield higher costs than carbon reduction targets.

Moreover, the SFOE commissioned another set of scenarios that estimated the effects of high oil prices and drastic cuts in supply through an increase of world population, with peaks in 2010 and 2020, respectively. Interactions with international markets are quantitatively simulated and discussed, but none of these scenarios include political measures. This analysis resulted in the insight that long-term price development will possibly be less dramatic than is often projected. Nonetheless, the economic implications of high energy prices are considerable (Ecoplan, 2007).

The political debate in Switzerland focuses increasingly on two scenarios for a successive international treaty after the Kyoto protocol. Switzerland has already committed to decreasing carbon emissions by 20% by 2020 compared to 1990 and even announced that it would lower the target to 30%, depending on reduction goals of other countries. Ecoplan (2009) analyzes these scenarios in a CGE model with the assumption that no further climate relevant policies would be launched by other countries than Switzerland. The results show that the losses for welfare are negligible. Other models (e.g., Kumbaroglu & Madlener, 2001; Ecoplan, 2008; Sceia et al., 2009a; Sceia et al., 2009b) similarly show that carbon taxes have only limited effects on welfare.

In Switzerland as well as in other countries, increasing oil prices during the last decades have augmented incentives for fast efficiency measures only in the short run. A lack of sound structural measures, a deficit of information, and the absence of financial instruments could not stabilize the incentives to increase energy efficiency for a longer period (EC, 2005). To accomplish structural changes and a transition to a less CO2-intensive economy, a "fundamental change in the innovation system (e.g., research policy, education, standards, incentives, intermediates and entrepreneurial innovation" (Jochem et al., 2004) is required.

1.5 Growth and the role of variety

Since the seminal work of Solow (1956), economists have seen technology as the main driver of innovation and growth (Niosi, 2008). However, decreasing returns to capital complicated the explanation of endogenous growth, so for a considerable length of time, economic models included exogenous growth mechanisms. However, the inability to identify the right drivers that might possibly enable an economy to grow was not caused by a knowledge gap. It was rather the immense difficulty of including the insight in mathematical models.

One possibility to endogenize growth dynamics is to assume gains from specialization, either in consumption or production. This explanation is also used in the CITE model we describe in this chapter. Different authors have referred to gains from specialization. By observing production in a pin factory, Smith reported as early as 1776 that specialization immensely increases the efficiency of the workers and therefore contributes to an augmented output. The increase of specialization led larger firms to have higher output per worker and lower average cost per pin than a small pin factory.

Also, Allyn Young (1928) stated that increased specialization may generate a higher output due to externalities that arise in production. He concluded that a larger market size would lead to more steps in production by a greater number of specialized firms (Sandilands, 2000). In 1963, Rosenberg noticed that in the automobile industry, many small specialized firms each construct a limited number of tooling devices for specific mass-production processes. He concluded that this high degree of specialization not only permitted a learning process that was more effective, but also a better application of the knowledge. Historically, Rosenberg states, an important reason for innovation has been improvements in the efficiency of capital goods production.

The first attempt to include these gains from specialization in economic models was made by Spence (1976). He modeled consumer preferences that were enhanced if the amount of consumer goods rose. Dixit and Stiglitz (1977) and Grossman and Helpman (1991) refined Spence's approach. The first to combine specialization with production was Ethier (1982), who assumed that an increasing number of inputs to production would raise output (Barro & Sala-i-Martin, 2004). Romer (1987, 1990) followed Ethier (1982) and assumed that output is an increasing function of intermediate goods. Using this specification, growth can continue indefinitely.

The incentive to specialize or to invent new products in these models is always the existence of monopolistic power and therefore the possibility for an inventor to make a profit with a new product. This, in turn, leads to the situation that the market equilibrium always generates too little research, i.e., too few new product varieties, compared to the social optimum (Bretschger, 1999). This subobtimal solution can be augmented by applying a generalized production function, which yields either the social optimum or even an outcome with too much R&D (Benassy, 1998).

The empirical extent of specialization in the European Union has been estimated by Mangàni (2007), who analyzes the correlation of economic (in terms of GDP) and technological (i.e., R&D aggregate expenditure or the number of patents granted) sizes. She asserts a positive correlation between the two. She distinguishes between two technological dimensions: the intensity of technological activities (intensive margin) and their variety (extensive margin). The technological variety is hereby defined as the number of technological fields in which a country is active. Both dimensions are positively correlated with the country size, i.e., larger countries have a wider spectrum of technological fields and produce a larger number of patents in each technological field. In Mangàni's estimation, technological variety accounts for about 40% of the difference in patent application between larger and smaller economies and is therefore extremely important in explaining the different technological standards.

Many other empirical studies exist on gains from specialization in relation to trade. These models analyze the impact of specialization in exportation and importation on the productivity of the involved countries. Most of the papers find a close connection between technological innovation (growth possibilities) and export specialization patterns (Mangàni, 2007). Hummels and Klenow (2005) are close to Mangàni's (2007) results. They find that the variety of goods accounts for about 60% of the greater exports of larger economies. They also find a distinctive correlation between the size of an economy and the degree of specialization. Their results are in line with those of others, such as Hummels et al. (2001) and Furman et al. (2002).

In addition to specialization, the capital stock plays an important role in determining the growth rate of an economy. Ezcurra et al. (2008) estimate for the EU that the capital stock per worker is relevant in explaining the level of technical efficiency. The latter is defined as the relation between the amount of a fix combination of inputs and output. Ezcurra et al. find a statistically significant relation between capital and improvements in technical efficiency, i.e., growth.

2 An overview of the CITE model

The model displays a small open economy. It consists of n different regular sectors, an energy sector, and an oil sector, each with similar intrasectoral setups.

There are three types of agents in each sector. First, producers of final output Y_i use a sector-specific intermediate composite Q_i and Armington goods of regular sectors n that go to sector i, A_{ni}, in their production. These Armington goods consist of domestically produced goods and imported goods that are combined with an elasticity of substitution below unity (Armington, 1969). The assumption of imperfectly substitutable goods ensures that trade can be modeled realistically in the sense that the same sectors can import and export (for a more detailed description of trade and Armington goods, cf. Chapter 9). Second, a producer of the sector-specific intermediate composite Q_i assembles intermediate goods x_i. And third, firms produce intermediate goods and sell them to the producer of the intermediate goods composite. This setup, illustrated in Figure 1, is analogous in all sectors.

In the regular sectors, B_i corresponds to the final output, Y_n. The production of the energy sector requires as additional input imported gas and the output of the oil sector (Figure 2).

Similarly to the production of the energy sector, the oil sector also needs an additional input, namely crude oil, which is imported (Figure 3).

The dynamics in the model stem from the assumption that the variety of intermediate goods expands over time and generates gains of specialization (cf. Romer, 1987; Grossman & Helpman, 1991). These new varieties are invented by firms by investing in a capital composite consisting of physical and non-physical capital. The assumption that knowledge (and thus the capital stock) is sector-specific reflects

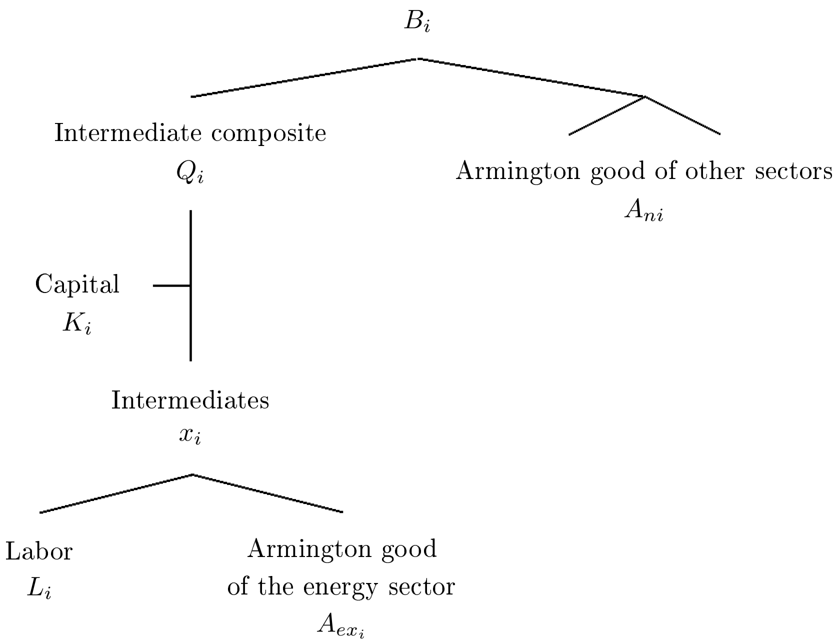

Figure 1: Production of B_i.

the supposition that one kind of knowledge can only be used for a particular combination of inputs (cf. Basu and Weil, 1998). Investments in new capital are nested according to Figure 4.

A representative household maximizes intertemporal utility from a consumption good that consists of a final goods composite and energy, as depicted in Figure 5. The final goods composite includes the Armington goods of regular sectors. Agents are assumed to have perfect foresight.

Due to the small size of the economy, it faces exogenously given world-market prices for crude oil and gas. Domestically, the markets for final goods, for the intermediate goods composite, and for labor are perfectly competitive, whereas the market for intermediate goods is monopolistic. All markets clear, and the allocation and price vectors constitute a competitive equilibrium. The supply of labor and of a so-called non-accumulable capital that is introduced for reasons of calibration is assumed to be inelastic and perfectly mobile across all firms and sectors.

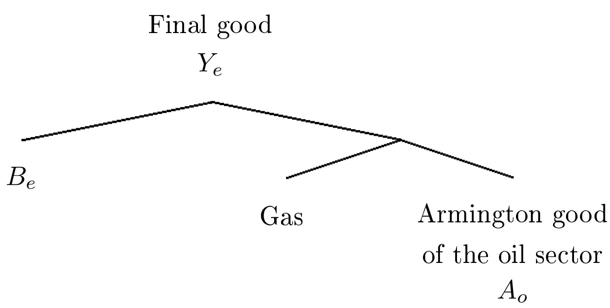

Figure 2: Production of energy.

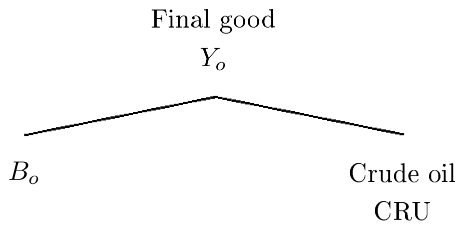

Figure 3: Production of oil.

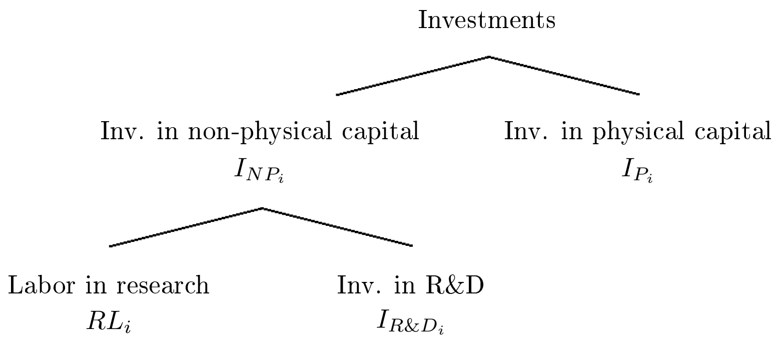

Figure 4: Investment nesting.

3 Final goods production of regular goods

The producer of final good Y_n, $n \in N$, produces in a CES framework using two types of inputs: a sector specific intermediate composite Q_n and Armington goods from regular sectors n', $A_{n'n}$, $n' \in N$. Thus, all regular final goods are used in the production of all goods, including their own production. This reflects the intersectoral connections of the sectors in the Swiss economy as reported in the input-output table (Nathani & Wickart, 2006).

$$Y_{n,t} = \left[\alpha_{X,n} Q_{n,t}^{\frac{\sigma_{Y,n}-1}{\sigma_{Y,n}}} + (1-\alpha_{X,n}) \left(\min \left(\left\{ \frac{A_{n'n,t}}{a_{n'n}} \right\}_{n' \in N} \right) \right)^{\frac{\sigma_{Y,n}-1}{\sigma_{Y,n}}} \right]^{\frac{\sigma_{Y,n}}{\sigma_{Y,n}-1}} \tag{1}$$

The elasticity of substitution between Q_n and $Y_{n'n}$, $\sigma_{Y,n}$, is assumed to be smaller than unity to reflect limited substitution possibilities between the intermediate composite and final goods as inputs. The value share of the intermediate composite is $\alpha_{X,n}$. The activity coefficients $a_{n'n}$ give the amount of each Armington good $A_{n'n}$ required for one unit of output in the Leontief function.

In the CITE model, the production structures are not described using production functions, but with cost functions. These have a similar structure as the production functions but are not as intuitive. Therefore, the analysis in this chapter is based on production functions. However, to give an idea how the cost functions are built in the CITE model, we also show the corresponding cost function to the described production function. It consists of the costs for the intermediate composite, p_{Q_n} and the prices of the Armington goods $p_{A_{n'}}$. These are combined very similarly to the CES production function:

$$p_{Y_n,t} = \left[\alpha_{X,n} p_{Q_n,t}^{1-\sigma_{Y,n}} + (1-\alpha_{X,n}) \left(\sum_{n' \in N} \alpha_{z_{n'n}} p_{A_{n'},t} \right)^{1-\sigma_{Y,n}} \right]^{\frac{1}{1-\sigma_{Y,n}}}$$

The parameter $\alpha_{z_{n'n}}$ hereby denotes the share of the costs of the Armington good $A_{n'n}$ in the Leontief cost function (all $\alpha_{z_{n'n}}$ add up to unity).

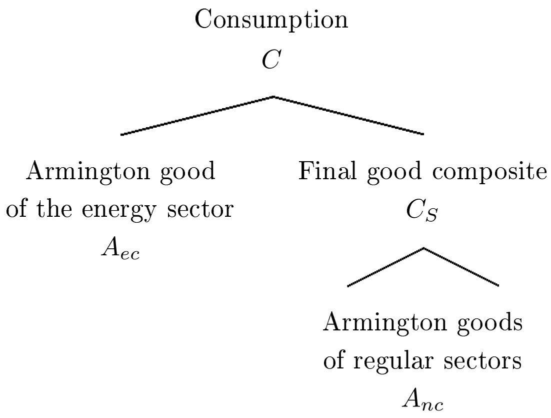

Figure 5: Consumption nesting.

Using the production functions, each sectoral producer of a final good maximizes profit

$$\max_{Q_{n,t}A_{n'n,t}} p_{Y_n,t}Y_{n,t} - p_{Q_n,t}Q_{n,t} - \sum_{n'\in N} p_{A_{n'},t}A_{n'n,t}$$

subject to (1) with p_H denoting the price for variable H. Because the market for final goods is perfectly competitive, profits are zero and the inverse demand functions are given by

$$p_{Q_n,t} = p_{Y_n,t}\alpha_{X,n}\left(\frac{Y_{n,t}}{Q_{n,t}}\right)^{\frac{1}{\sigma_{Y,n}}}$$

$$p_{A_{n'},t} = p_{Y_n,t}(1-\alpha_{X,n})\left(\frac{Y_{n,t}}{\min\left(\left\{\frac{A_{n'n,t}}{a_{n'n}}\right\}_{n'\in N}\right)}\right)^{\frac{1}{\sigma_{Y,n}}} D_{n'n}$$

with $D_{n'n}$ being the derivative of the Leontief production structure w.r.t. the input of sector n' to sector n. For a better understanding, the example of D_{11} can be helpful:

$$D_{11} = \min\left(\left\{\frac{1}{a_{11}}, \frac{A_{21}}{a_{21}}, \cdots, \frac{A_{n'1}}{a_{n'1}}\right\}_{n'\in N}\right)$$

4 Production of energy goods

Energy goods are produced very similarly to regular goods with the exception that fossil fuels are also required. Imported natural gas (GAS) and refined oil (A_o) are first combined in a Cobb-Douglas manner. This aggregate is then combined applying an elasticity of substitution smaller than unity with the function already used for regular goods B_e

$$Y_{e,t} = \left[\alpha_{TFF}\left(GAS_t^{\alpha_{FF,gas}}A_{o,t}^{\alpha_{FF,o}}\right)^{\frac{\sigma_E-1}{\sigma_E}} + (1-\alpha_{tff})B_{e,t}^{\frac{\sigma_E-1}{\sigma_E}}\right]^{\frac{\sigma_E}{\sigma_E-1}} \tag{2}$$

$$B_{e,t} = \left[\alpha_{X,e}Q_{e,t}^{\frac{\sigma_{Y,e}-1}{\sigma_{Y,e}}} + (1-\alpha_{X,e})\left(\min\left(\left\{\frac{A_{ne,t}}{a_{ne}}\right\}_{n\in N}\right)\right)^{\frac{\sigma_{Y,e}-1}{\sigma_{Y,e}}}\right]^{\frac{\sigma_{Y,e}}{\sigma_{Y,e}-1}} \tag{3}$$

Fossil fuels enter the upper nest exclusively, and the total amount of gas imported in the economy and the complete output of the oil sector are directed toward the energy sector. B_e contains only the inputs Q_e and the final outputs of other regular sectors, A_{ne}. In our model, energy is interpreted as a composite of different usages of energy, such as electricity, combustibles, and fuels. The lower nest might be interpreted as all types of energy that do not contain fossil fuels, such as renewable energies or nuclear energy. Oil and gas are mainly used to produce combustibles and fuels.

This type of production function shows similar dynamic behavior to that of regular final goods because B_e, which is to a great extent responsible for dynamic growth effect, is identical. Growth dynamics mainly occur in the sector-specific product Q_e. Therefore, the structure of this production function results in the fact that most dynamics are transmitted to non-fossil forms of energy first. Fossil energy is affected by growth dynamics via the upper CES nest.

The producer of energy goods maximizes profit assuming perfect competition according to

$$\max_{GAS_t, A_{o,t}, Q_{e,t}, A_{ie,t}} p_{Y_e,t} Y_{e,t} - p_{GAS,t} GAS_t - p_{Q_e,t} Q_{e,t} - p_{A_o,t} A_{oe,t} - \sum_{n \in N} p_{A_n,t} A_{ne,t}$$

subject to (2) and (3), which results in the following first-order conditions for fossil fuels and Q_e:

$$p_{GAS,t} = p_{Y_e,t} \alpha_{TFF} \alpha_{FF,gas} \left(\frac{Y_{e,t}}{GAS^{\alpha_{FF,gas}} A_{o,t}^{\alpha_{FF,o}}} \right)^{\frac{1}{\sigma_E}} GAS^{\alpha_{FF,gas}-1} A_{o,t}^{\alpha_{FF,o}}$$

$$p_{A_o,t} = p_{Y_e,t} \alpha_{TFF} \alpha_{FF,o} \left(\frac{Y_{e,t}}{GAS^{\alpha_{FF,gas}} A_{o,t}^{\alpha_{FF,o}}} \right)^{\frac{1}{\sigma_E}} GAS^{\alpha_{FF,gas}} A_{o,t}^{\alpha_{FF,o}-1}$$

$$p_{Q_e,t} = p_{Y_e,t} (1 - \alpha_{TFF}) \alpha_{x,e} Y_{e,t}^{\frac{1}{\sigma_E}} B_{e,t}^{\frac{\sigma_E - 1}{\sigma_E} - \frac{\sigma_{Y,e}-1}{\sigma_{Y,e}}} Q_{e,t}^{-\frac{1}{\sigma_{Y,e}}}$$

The optimal input prices of A_{ne} are denoted using the abbreviation D_{ne}, which is explained above.

$$p_{A_n,t} = p_{Y_e,t} (1 - \alpha_{TFF})(1 - \alpha_{x,e}) Y_{e,t}^{\frac{1}{\sigma_E}} B_{e,t}^{\frac{\sigma_E - 1}{\sigma_E} - \frac{\sigma_{Y,e}-1}{\sigma_{Y,e}}} \left(\min \left(\left\{ \frac{A_{ne,t}}{a_{ne}} \right\}_{n \in N} \right) \right)^{-\frac{1}{\sigma_{Y,e}}} D_{ne}$$

5 Production of oil goods

The production of (refined) oil requires a large amount of crude oil as input that is not substitutable by labor or other inputs. Therefore, crude oil is used as essential input in a Leontief production function. All other inputs are again sector-specific inputs identical to the input function of regular final goods.

$$Y_{o,t} = \min \left(\frac{CRU_t}{a_{cru}}, \frac{B_{o,t}}{a_{noncru}} \right) \tag{4}$$

$$B_{o,t} = \left[\alpha_{X,o} Q_{o,t}^{\frac{\sigma_{Y,o}-1}{\sigma_{Y,o}}} + (1 - \alpha_{X,o}) \left(\min \left(\left\{ \frac{A_{no,t}}{a_{no}} \right\}_{n \in N} \right) \right)^{\frac{\sigma_{Y,o}-1}{\sigma_{Y,o}}} \right]^{\frac{\sigma_{Y,o}}{\sigma_{Y,o}-1}} \tag{5}$$

Although the total output of the oil sector goes to the energy sector, we do not assume market power of the energy sector but perfect competition. Therefore, the optimization problem of the producer of oil looks like

$$\max_{Q_{o,t}, A_{no,t}, CRU_t} p_{Y_o,t} Y_{o,t} - p_{Q_o,t} Q_{o,t} - \sum_{i \in I} p_{A_i,t} A_{no,t} - p_{CRU,t} CRU_t$$

subject to (4) and (5). Due to the complex Leontief structure, the inverse demand functions are presented only for Q_o and CRU and not for A_{no}. However, it is straightforward to calculate.

$$p_{Q_o,t} = p_{Y_o,t} \min \left(\frac{CRU_t}{a_{cru}}, \frac{\alpha_{x,o}}{a_{noncru}} \left(\frac{B_{o,t}}{Q_{o,t}} \right)^{\frac{1}{\sigma_{Y,o}}} \right)$$

$$p_{CRU,t} = p_{Y_o,t} \min \left(\frac{1}{a_{cru}}, \frac{B_{o,t}}{a_{noncru}} \right)$$

6 Intermediate composite production

The growth rate of the economy depends on the growth rates of the sectors. These, in turn, result from an increase of the varieties of sectoral intermediate goods, which is reflected in the production of the sectoral intermediate composite Q_i, $i \in (N, E, O)$. It is produced with a Dixit-Stiglitz production function

$$Q_{i,t} = \left[\sum_{j=1}^{K_{i,t}} x_{ij,t}^{\kappa} \right]^{\frac{1}{\kappa}} \tag{6}$$

with x_{ij} being the employment of the jth type of specialized intermediate good and K_i being the size of the sector specific capital stock, which equals the number of intermediates available in sector i. Based on the assumption that diversification in production increases productivity (gains of diversification), an increase in the number of intermediates available enhances the production of the intermediate composite disproportionately (cf. Baldwin et al., 2001). The share of inputs to the production of x_{ij} other that capital, κ, is a measure for the substitutability of the intermediate goods:

$$\kappa = \frac{\sigma_Q - 1}{\sigma_Q}$$

with $\sigma_Q > 1$ being the elasticity of substitution between the intermediate goods. Technological progress takes the form of an increase in the capital stock of sector i.

Acting on a competitive market, the intermediate composite producer minimizes cost according to

$$\max_{x_{ij,t}} p_{Q_i,t} Q_{i,t} - \sum_{j=1}^{K_{i,t}} p_{x_{ij},t} x_{ij,t}$$

subject to (6) which yields her optimal demand for intermediate good x_{ij}

$$x_{ij,t} = \left(\frac{p_{Q_i,t}}{p_{x_{ij},t}} \right)^{\frac{1}{1-\kappa}} Q_{i,t} \tag{7}$$

7 Intermediate goods

In each sector, intermediate goods x_{ij} are invented and produced, each good by a single firm. One can think of these firms as in-house R&D and in-house production of intermediate goods in each sector. However, for the purpose of this chapter, the institutional structure is irrelevant.

Each new variety of an intermediate good in the horizontal innovation process is represented by a new unit of capital. Two types of capital exist in the model: Physical capital in terms of machinery, buildings etc., and non-physical capital, such as blueprints and patents. The assumption that knowledge (and thus the capital stock) is sector-specific reflects the supposition that one kind of knowledge can only be used for a particular combination of inputs (cf. Basu and Weil, 1998).

7.1 Capital accumulation

Intermediate firms conduct research and development. By investing in a capital stock composite, intermediate firms j invest in two types of capital, physical capital ($I_{P_{ij}}$) and non-physical capital ($I_{NP_{ij}}$). Both types of investment can only be intra-sectoral, i.e., investments in new capital is sector-specific. Non-physical capital is produced by investments in R&D, $I_{R\&D,ij}$, and labor in research, RL_{ij}. The formulation of $I_{R\&D,ij}$ stems from the fact that we apply data for R&D investments from the Swiss input-output table for $I_{R\&D,ij}$. It should not be confused with R&D as an activity in the production process.

$$I_{NP_{ij},t} = \left[\gamma_{N,i} RL_{ij,t}^{\frac{\sigma_{N,i}-1}{\sigma_{N,i}}} + (1-\gamma_{N,i}) I_{R\&D_{ij},t}^{\frac{\sigma_{N,i}-1}{\sigma_{N,i}}} \right]^{\frac{\sigma_{N,i}}{\sigma_{N,i}-1}}$$

Together with investments in physical capital, $I_{P,ij}$, non-physical capital is then used in the production of a capital composite K_{ij}.

$$K_{ij,t+1} = \left[\gamma_i I_{P_{ij},t}^{\frac{\sigma_{I,i}-1}{\sigma_{I,i}}} + (1-\gamma_i) I_{NP_{ij},t}^{\frac{\sigma_{I,i}-1}{\sigma_{I,i}}} \right]^{\frac{\sigma_{I,i}}{\sigma_{I,i}-1}} + (1-\delta) K_{ij,t} \quad (8)$$

δ depicts the depreciation rate of capital. Consequently, the increase of capital per sector is equal to

$$K_{i,t+1} - K_{i,t} = \triangle\, K_{i,t+1} = \left[\gamma_i I_{P_i,t}^{\frac{\sigma_{I,i}-1}{\sigma_{I,i}}} + (1-\gamma_i) I_{NP_i,t}^{\frac{\sigma_{I,i}-1}{\sigma_{I,i}}} \right]^{\frac{\sigma_{I,i}}{\sigma_{I,i}-1}} - \delta K_{i,t} \quad (9)$$

The growth index g_K of the capital composite of the sector amounts to

$$g_{K_i} = \frac{K_{i,t+1}}{K_{i,t}} = \frac{\left[\gamma_i I_{P_i,t}^{\frac{\sigma_{I,i}-1}{\sigma_{I,i}}} + (1-\gamma_i) I_{NP_i,t}^{\frac{\sigma_{I,i}-1}{\sigma_{I,i}}} \right]^{\frac{\sigma_{I,i}}{\sigma_{I,i}-1}}}{K_{i,t}} + (1-\delta) \quad (10)$$

This relation implies several aggregations. First, investments in physical capital and in R&D of the j producers of intermediate goods in each sector i can be added up to investments of the sector in physical and non-physical capital and in R&D according to

$$I_{P_i,t} = \sum_{j=1}^{K_{i,t}} I_{P_{ij},t}$$

$$I_{NP_i,t} = \sum_{j=1}^{K_{i,t}} I_{NP_{ij},t}$$

$$I_{R\&D_i,t} = \sum_{j=1}^{K_{i,t}} I_{R\&D_{ij},t}$$

The same must hold for the capital composite K_i, assuming $K_{ij,t} = 1$:

$$K_{i,t} = \sum_{j=1}^{K_{i,t}} K_{ij,t}$$

Given that each new blueprint is produced with labor and investments in physical capital and in R&D, each intermediate firm minimizes research cost according to

$$\max_{RL_{ij,t}, I_{P_{ij},t}, I_{R\&D_{ij},t}} p_{K_{ij},t+1} \triangle K_{ij,t+1} - w_{R,t} RL_{ij,t} - p_{A_i,t}(I_{P_{ij},t} + I_{R\&D_{ij},t})$$

Optimization w.r.t. RL_{ij}, $I_{P,ij}$ and $I_{R\&D,ij}$ leads to the inverse demand functions for labor and investments in the R&D process according to

$$w_{R,t} = p_{K_{ij},t+1}(1-\gamma_i)\gamma_{N,i} \left(\frac{\triangle K_{ij,t+1}}{I_{NP_{ij},t}} \right)^{\frac{1}{\sigma_{I,i}}} \left(\frac{I_{NP_{ij},t}}{RL_{ij,t}} \right)^{\frac{1}{\sigma_{N,i}}}$$

$$p_{A_i,t} = p_{K_{ij},t+1}(1-\gamma_i)(1-\gamma_{N,i}) \left(\frac{\triangle K_{ij,t+1}}{I_{NP_{ij},t}} \right)^{\frac{1}{\sigma_{I,i}}} \left(\frac{I_{NP_{ij},t}}{I_{R\&D_{ij},t}} \right)^{\frac{1}{\sigma_{N,i}}}$$

$$p_{A_i,t} = p_{K_{ij},t+1}\, \gamma_i \left(\frac{\triangle K_{ij,t+1}}{I_{P_{ij},t}} \right)^{\frac{1}{\sigma_{I,i}}}$$

where w_R denotes the wage rate of labor in research.

Intermediate firms need to finance their research activities in advance. More specifically, labor and investments that are necessary to invent a new intermediate good for period $t+1$ need to be paid in period t. To do so, intermediate firms borrow $p_{K,t} I_{ij,t}$ from the representative household:

$$p_{K,t} I_{ij,t} = w_{R,t} RL_{ij,t} + p_{A_i,t}(I_{P_{ij},t} + I_{R\&D_{ij},t})$$

After the discovery of a new blueprint, they re-pay the household the remaining profits from the production of the intermediate (see subsection 5.2).

7.2 Production of the intermediate good

After obtaining a perpetual patent on each new type of intermediate varieties, i.e., on each newly produced unit of the capital composite, intermediate firms produce the newly invented goods. Each firm faces a CES production function for good x_{ij} with inputs labor L_{ij} (which is different from labor in research), non-accumulable capital VK_{ij}, and energy $A_{ex_{ij}}$:

$$x_{ij,t} = \left[\alpha_{L,i} L_{ij,t}^{\frac{\sigma_{X,i}-1}{\sigma_{X,i}}} + \alpha_{VK,i} VK_{ij,t}^{\frac{\sigma_{X,i}-1}{\sigma_{X,i}}} + (1-\alpha_{L,i}-\alpha_{VK,i}) A_{ex_{ij},t}^{\frac{\sigma_{X,i}-1}{\sigma_{X,i}}}\right]^{\frac{\sigma_{X,i}}{\sigma_{X,i}-1}} \tag{11}$$

The optimization of the intermediate good producer consists of two steps. First, cost minimization leads to the optimal correlation between inputs and output. The monopolist uses an imaginary output price $p^i_{x_{ij}}$, which is the price that would be charged under perfect competition:

$$\max_{L_{ij,t}, VK_{ij,t}, A_{ex_{ij},t}} \; p^i_{x_{ij},t} x_{ij,t} - w_t L_{ij,t} - p_{VK,t} VK_{ij,t} - p_{A_e,t} A_{ex_{ij},t}$$

subject to (11). The resulting inverse demand functions are (w denotes the wage rate)

$$w_t = \alpha_{L,i} p^i_{x_{ij},t} \left(\frac{x_{ij,t}}{L_{ij,t}}\right)^{\frac{1}{\sigma_X}} \tag{12}$$

$$p_{VK,t} = \alpha_{VK,i} p^i_{x_{ij},t} \left(\frac{x_{ij,t}}{VK_{ij,t}}\right)^{\frac{1}{\sigma_X}} \tag{13}$$

$$p_{A_e,t} = (1-\alpha_{L,i}-\alpha_{VK,i}) p^i_{x_{ij},t} \left(\frac{x_{ij,t}}{A_{ex_{ij},t}}\right)^{\frac{1}{\sigma_X}} \tag{14}$$

Since the production of a specific intermediate good requires the rights according to a patent, each intermediate good is produced by only one firm, which can charge monopoly prices. Profit maximization consequently takes account of the demand function of the Q_i producer according to

$$\max_{p_{x_{ij},t}} p_{x_{ij},t} x_{ij,t} - p^i_{x_{ij},t} x_{ij,t}$$

subject to (7). This yields the relation between the market price of each x_{ij} and the imaginary price $p^i_{x_{ij}}$

$$p_{x_{ij},t} = \frac{1}{\kappa} p^i_{x_{ij},t}$$

Inserting this in equations (12), (13), and (14) yields

$$\frac{1}{\kappa} w_t = \alpha_{L,i} p_{x_{ij},t} \left(\frac{x_{ij,t}}{L_{ij,t}}\right)^{\frac{1}{\sigma_X}}$$

$$\frac{1}{\kappa} p_{VK,t} = \alpha_{VK,i} p_{x_{ij},t} \left(\frac{x_{ij,t}}{VK_{ij,t}}\right)^{\frac{1}{\sigma_X}}$$

$$\frac{1}{\kappa} p_{A_e,t} = (1-\alpha_{L,i}-\alpha_{VK,i}) p_{x_{ij},t} \left(\frac{x_{ij,t}}{A_{ex_{ij},t}}\right)^{\frac{1}{\sigma_X}}$$

where κ denotes the markup over marginal costs. Profits from the production of the intermediate goods amount for each intermediate firm

$$\pi_{ij,t} = (1-\kappa) p_{x_{ij},t} x_{ij,t}$$

In equilibrium, the sum of the discounted profits need to be equal to the funds borrowed from the household (r denotes the interest rate).

$$p_{K,t} K_t = \sum_{\tau=t}^{\infty} (1+r_\tau)^{t-\tau} \Pi_\tau$$

Investments in capital need to satisfy the no-arbitrage condition

$$p_{K,t+1}K_{t+1} - p_{K,t}K_t = r_{t+1}p_{K,t}K_t - \Pi_{t+1}$$

These two equations are not explicitly modeled in the CITE model. However, the calibration of the model complies with these assumptions.

8 Representative household

A representative, infinitely-lived household allocates income between consumption and investment in accordance with intertemporal utility maximization with perfect foresight. It faces an intertemporal utility function U with a consumption good C as only variable yielding utility and ρ denoting the discount rate of the household.

$$U = \sum_{t=0}^{\infty} \left(\frac{1}{1+\rho}\right)^t \frac{C_t^{1-\theta} - 1}{1-\theta}$$

This additively separable utility function has the same intertemporal characteristics as the linearly homogeneous utility function included in the CITE model (cf. Rutherford, 2004):

$$\hat{U} = \left[\sum_{t=0}^{\infty} \left(\frac{1}{1+\rho}\right)^t C_t^{1-\theta}\right]^{\frac{1}{1-\theta}}$$

Therefore, the intertemporal maximization of utility in the CITE model is in accordance with the results shown in the following theoretical calculations.

The consumption good is composed of a final goods composite C_S and energy A_{ec}:

$$C_t = \left[(1-\beta)C_{S,t}^{\frac{\sigma_C - 1}{\sigma_C}} + \beta A_{ec,t}^{\frac{\sigma_C - 1}{\sigma_C}}\right]^{\frac{\sigma_C}{\sigma_C - 1}} \tag{15}$$

The final goods of all sectors go into the final goods composite according to

$$C_{S,t} = \prod_{n \in N} A_{nc,t}^{\beta_{NE,n}}$$

with A_{nC} denoting the part of regular final good n that goes into consumption and $\beta_{NE,n}$ being the share of final good n in the final goods composite. We further assume constant returns to scale: $\sum_{n \in N} \beta_{NE,n} = 1$. The household faces the budget constraint

$$\begin{aligned} p_{V,t+1}V_{t+1} = &(1 + r_{t+1})p_{V,t}V_t + w_t L_t + w_{R,t}RL_t + p_{VK,t}VK_t \\ &- p_{A_e,t}A_{ec,t} - \sum_{n \in N} p_{A_n,t}A_{nc,t} - \sum_{i \in I} p_{V,t}I_{i,t} \end{aligned}$$

Hereby, V denotes the assets of the household. It holds that total investments of the household must equal investments in physical and in non-physical capital, $I_{i,t} = I_{P_i,t} + I_{NP_i,t}$. As energy is assumed to be owned by the consumer, income from energy also goes to the consumer as factor income. The budget constraint is explicitly modeled in CITE to ensure that income from endowments and capital are equal to consumption plus investments.

To indicate the dynamic behavior of consumption, i.e., the Euler equation, depending on the price of the consumption good, the cost functions for the consumption good and the final goods composite are applied for the calculation:

$$p_{C,t} = \left[(1-\beta)^{\sigma_C} p_{C_S,t}^{1-\sigma_C} + \beta^{\sigma_C} p_{A_e,t}^{1-\sigma_C}\right]^{\frac{1}{1-\sigma_C}}$$

$$p_{C_S,t} = \prod_{n \in N} \left(\frac{p_{A_n,t}}{\beta_{NE,n}}\right)^{\beta_{NE,n}}$$

Accordingly, the budget constraint can be formulated differently to include the price of consumption according to:

$$\begin{aligned} p_{V,t+1}V_{t+1} = &(1+r_{t+1})p_{V,t}V_t + w_t L_t + w_{R,t}RL_t + p_{VK,t}VK_t \\ &- p_{C,t}C_t - \sum_{i\in I} p_{V,t}I_{i,t} \end{aligned} \tag{16}$$

The augmented Lagrangian for the household is

$$\begin{aligned} \mathfrak{L} = &\frac{C_t^{1-\theta}-1}{1-\theta} + \frac{1}{1+\rho}\lambda_{t+1}((1+r_{t+1})p_{V,t}V_t + w_t L_t + w_{R,t}RL_t \\ &+ p_{VK,t}VK_t - p_{C,t}C_t - \sum_{i\in I} p_{V,t}I_{i,t}) - \lambda_t p_{V,t}V_t \end{aligned}$$

and the optimization yields

$$C_t^{-\theta} = \frac{1}{1+\rho}\lambda_{t+1}p_{C,t}$$

$$\lambda_t = \frac{1}{1+\rho}\lambda_{t+1}(1+r_{t+1})$$

with $\lambda > 0$ being the shadow price of consumption.
From the FOCs of household optimization, we can calculate the growth index of consumption g_C

$$g_C = \left[\frac{1+r_{t+2}}{1+\rho}\frac{p_{C,t}}{p_{C,t+1}}\right]^{\frac{1}{\theta}} \tag{17}$$

9 Trade

The basic assumptions for trade are, first, that final goods of every sector are both imported and exported, and, second, that foreign goods differ in some way from domestically produced goods (cf. Armington, 1969). This implies that foreign and domestically produced goods are not simply exchangeable but have an elasticity of substitution smaller than unity. Imported foreign goods, $A_{imp,i}$, and domestically produced goods that remain inland, $Y_{dom,i,t}$, are assembled in a CES function and can then be demanded by sectors and the household. Thus, every final good demanded in the economy needs to be an Armington aggregate and is produced according to

$$A_{i,t} = \left(\alpha_{M,i}A_{imp,i,t}^{\frac{\sigma_A-1}{\sigma_A}} + (1-\alpha_{M,i})Y_{dom,i,t}^{\frac{\sigma_A-1}{\sigma_A}}\right)^{\frac{\sigma_A}{\sigma_A-1}}$$

Because outputs of all sectors remain inland and are also used abroad, every Y_i is transformed by a constant elasticity of transformation (CET) function to exports ($Y_{ex,i}$) and domestic deployment ($Y_{dom,i}$, which is used in the composition of the Armington aggregate above).

$$Y_{i,t} = \left(\alpha_{EX,i}Y_{ex,i,t}^{\frac{\sigma_T+1}{\sigma_T}} + (1-\alpha_{EX,i})Y_{dom,i,t}^{\frac{\sigma_T+1}{\sigma_T}}\right)^{\frac{\sigma_T}{\sigma_T+1}}$$

As all markets clear, the value of domestically produced goods that remain inland must equal the value of the share of Armington goods that is not imported:

$$p_{Y_i,t}Y_{dom,i,t} = p_{Y_i,t}(1-\alpha_{M,i})A_{i,t}$$

Likewise, the foreign trade balance needs to be satisfied. The value of the exported goods must equal the value of the goods imported by our domestic economy (all in world market prices p_{FX} that reflect the terms of trade).

$$\sum_{i\in I} p_{FX,i,t}Y_{ex,i,t} = \sum_{i\in I} p_{FX,i,t}A_{imp,i,t} + p_{FX,GAS,t}GAS_t + p_{FX,CRU,t}CRU_t$$

10 Equilibrium

The competitive equilibrium is characterized by a system of prices at which all markets clear. The final output of each sector is divided among four uses. It can either be used in a sector as input, invested in R&D, invested in the accumulation of physical capital, or it can be consumed. Thus, it must hold that

$$p_{A_i,t}A_{i,t} = \sum_{i' \in I} p_{A_i,t}A_{ii',t} + p_{A_i,t}I_{R\&D_i,t} + p_{A_i,t}I_{P_i,t} + p_{A_i,t}A_{ic,t}$$

The markets for endowments clear, and thus it must hold that

$$L_t = \sum_i \sum_j L_{ij,t} = constant$$

$$RL_t = \sum_i \sum_j RL_{ij,t}$$

$$VK_t = \sum_i \sum_j VK_{ij,t} = constant$$

The endowments of labor and non-accumulable capital stay constant over time, and the endowment of labor in research grows. This stems from the fact that we assume labor in research to be an effective input, meaning that it constitutes the labor force size augmented by human capital, which is assumed to grow over time (cf. also Davis, 2008).

As all intermediate goods in each sector are symmetric, i.e., $x_{ij} = x_i$, the production function of Q_i, (6), can be rewritten as

$$Q_{i,t} = K_{i,t}^{\frac{1}{\kappa}} x_{i,t} = K_{i,t}^{\frac{1-\kappa}{\kappa}} X_{i,t} \tag{18}$$

with

$$X_i = K_i x_i \tag{19}$$

Because the prices for all sectoral intermediate goods must also be equal, it must hold that the inputs to the production of the intermediate composite have the same value as the output.

$$p_{Q_i,t}Q_{i,t} = p_{x_i,t}X_{i,t}$$

The capital stock $K = \sum_{i \in I} K_i$ is equal to the assets of the household V. In a symmetric equilibrium it will therefore emerge that $p_V = p_K$. Accordingly, the budget constraint of the household (16) changes to

$$p_{C,t}C_t = w_t L_t + w_{R,t} RL_t + p_{VK,t} VK_t + \Pi_t - \sum_{i \in I} p_{V,t} I_{i,t}$$

Also, the Euler equation (from (17)) can be reformulated as

$$\frac{C_{t+1}}{C_t} = \left[\frac{1 + r_{t+2}}{1+\rho} \frac{p_{C,t}}{p_{C,t+1}} \frac{p_{K,t+1}}{p_{K,t}} \right]^{\frac{1}{\epsilon}}$$

Additionally, the markets of both types of labor, L and RL, and non-accumulable capital, VK, clear when their prices are the same across sectors.

To ensure that the optimal path is always followed, the transversality condition must also hold. It requires that the present value of capital must converge to zero as the planning horizon approaches infinity. It must therefore hold that

$$\lim_{\tau \to \infty} \left(\frac{1}{1+\rho} \right)^{\tau} p_{K,\tau} K_\tau = 0$$

Given this transversality condition, the optimal path must always be maintained, and no alternative path, for which capital deviates from the optimum at each time and increases discounted utility, is possible.

11 Growth dynamics

Economic growth is determined by the endogenously determined growth rate of the capital stock, which reflects investment decisions of the representative household. If $g_H = \frac{H_{t+1}}{H_t}$ denotes the growth index of variable H, the growth index of consumption can be derived by dividing consumption in period $t+1$ through consumption in period t (cf. 15):

$$g_C = \left(\frac{(1-\beta) C_{S,t+1}^{\frac{\sigma_C - 1}{\sigma_C}} + \beta A_{ec,t+1}^{\frac{\sigma_C - 1}{\sigma_C}}}{(1-\beta) C_{S,t}^{\frac{\sigma_C - 1}{\sigma_C}} + \beta A_{ec,t}^{\frac{\sigma_C - 1}{\sigma_C}}} \right)^{\frac{\sigma_C}{\sigma_C - 1}}$$

Using $\overline{g_H} = \left(\frac{H_{t+1}}{H_t}\right)^{\frac{\sigma_C - 1}{\sigma_C}}$ for an adjusted growth index the above equation can be simplified to

$$\overline{g_C} = \frac{(1-\beta) C_{S,t+1}^{\frac{\sigma_C - 1}{\sigma_C}} + \beta A_{ec,t+1}^{\frac{\sigma_C - 1}{\sigma_C}}}{(1-\beta) C_{S,t}^{\frac{\sigma_C - 1}{\sigma_C}} + \beta A_{ec,t}^{\frac{\sigma_C - 1}{\sigma_C}}} \tag{20}$$

To determine which variables influence the growth index of consumption, (20) can be decomposed in the two terms before and after the "plus" symbol on the right hand side according to

$$\overline{g_C} = \frac{(1-\beta) C_{S,t+1}^{\frac{\sigma_C - 1}{\sigma_C}}}{(1-\beta) C_{S,t}^{\frac{\sigma_C - 1}{\sigma_C}} + \beta A_{ec,t}^{\frac{\sigma_C - 1}{\sigma_C}}} + \frac{\beta A_{ec,t+1}^{\frac{\sigma_C - 1}{\sigma_C}}}{(1-\beta) C_{S,t}^{\frac{\sigma_C - 1}{\sigma_C}} + \beta A_{ec,t}^{\frac{\sigma_C - 1}{\sigma_C}}} \tag{21}$$

After rearranging and inserting the growth index for C_S, the first term on the right hand side of (21) can be rewritten as

$$\frac{(1-\beta) C_{S,t+1}^{\frac{\sigma_C - 1}{\sigma_C}}}{(1-\beta) C_{S,t}^{\frac{\sigma_C - 1}{\sigma_C}} + \beta A_{ec,t}^{\frac{\sigma_C - 1}{\sigma_C}}} = \frac{1-\beta}{(1-\beta) + \beta \left(\frac{A_{ec,t}}{C_{S,t}}\right)^{\frac{\sigma_C - 1}{\sigma_C}}} g_{C_S}^{\frac{\sigma_C - 1}{\sigma_C}}$$

Analogously, the second term on the right hand side of equation (21) can be arranged as

$$\frac{(1-\beta) A_{ec,t+1}^{\frac{\sigma_C - 1}{\sigma_C}}}{(1-\beta) C_{S,t}^{\frac{\sigma_C - 1}{\sigma_C}} + \beta A_{ec,t}^{\frac{\sigma_C - 1}{\sigma_C}}} = \frac{\beta}{(1-\beta) \left(\frac{C_{S,t}}{A_{eC,t}}\right)^{\frac{\sigma_C - 1}{\sigma_C}} + \beta} g_{A_{ec}}^{\frac{\sigma_C - 1}{\sigma_C}}$$

Applying these terms in (21), the adjusted growth rate of consumption can be reformulated as

$$\overline{g_C} = \psi_{C_S} \overline{g_{C_S}} + \psi_{A_{ec}} \overline{g_{A_{eC}}}$$

with

$$\psi_{C_S} = \frac{1-\beta}{(1-\beta) + \beta \left(\frac{A_{ec,t}}{C_{S,t}}\right)^{\frac{\sigma_C - 1}{\sigma_C}}} \tag{22}$$

$$\psi_{A_{ec}} = \frac{\beta}{(1-\beta) \left(\frac{C_{S,t}}{A_{ec,t}}\right)^{\frac{\sigma_C - 1}{\sigma_C}} + \beta} \tag{23}$$

It can be shown that $\psi_{A_{ec}} = 1 - \psi_{C_S}$. Therefore, the adjusted growth index of consumption is equal to

$$\overline{g_C} = \psi_{C_S} \overline{g_{C_S}} + (1 - \psi_{C_S}) \overline{g_{A_{ec}}} \tag{24}$$

This equation implies that the demand for both inputs to this CES function with an elasticity of substitution smaller than unity ($\sigma_C < 1$) must grow at the same rate on a balanced growth path. The proof is done by contradiction: Assuming $g_{A_{ec}} < g_{C_S}$, it follows that

$$\lim_{t\to\infty}\left(\frac{C_{S,t}}{A_{ec,t}}\right)^{\frac{\sigma_C-1}{\sigma_C}}=0$$

and

$$\lim_{t\to\infty}\left(\frac{A_{ec,t}}{C_{S,t}}\right)^{\frac{\sigma_C-1}{\sigma_C}}=\infty$$

Therefore, the shares of C_S and of A_{ec} must evolve according to (cf. (22) and (23)) like

$$\lim_{t\to\infty}\psi_{C_S}=0$$

$$\lim_{t\to\infty}\psi_{A_{ec}}=1$$

Inserting in (24) yields

$$\lim_{t\to\infty}g_C=g_{A_{ec}}$$

From this it follows that the use of C_S must grow at the same rate as C and A_{ec} on a balanced growth path to avoid excess demand.

Applying similar calculations as above, it can be shown that

$$g_{C_S}=\prod_{n\in N}\left(g_{Y_{nc}}\right)^{\beta_{NE,n}}$$

The growth index of Q_i can be calculated straightforwardly. Knowing its production function from (18) and the growth index of capital from (10), and applying a similar calculation as above, g_{Q_i} is equal to

$$g_{Q_i}=\left[\frac{\left[\gamma_i I_{P_i,t}^{\frac{\sigma_{I,i}-1}{\sigma_{I,i}}}+(1-\gamma_i)I_{NP_i,t}^{\frac{\sigma_{I,i}-1}{\sigma_{I,i}}}\right]^{\frac{\sigma_{I,i}}{\sigma_{I,i}-1}}}{K_{i,t}}+(1-\delta)\right]^{\frac{1}{\kappa}}g_{x_i}=g_{K_i}^{\frac{1}{\kappa}}g_{x_i}\tag{25}$$

As the growth of the intermediate goods equals zero and therefore the growth index g_{x_i} must be one, (25) is equal to

$$g_{Q_i}=g_{K_i}^{\frac{1}{\kappa}}\tag{26}$$

The above equation is the central relationship in the model as is ensures endogenous growth through gains of specialization in the production of intermediate goods. The economy is able to grow even without growth of the inputs to intermediate goods, i.e., labor and energy.

12 Specialties of Calibration

The CITE model differs from other CGE models by the calibration of the benchmark scenario. The main difference is that we use the microfoundation of the model and calibrate it in the benchmark to a balanced growth path including gains of specialization. These gains and the resulting difference between growth of inputs and of outputs represents an challenge to the realization in GAMS.

12.1 Different growth rates

As can be seen from equation (26), there are three different steady state growth rates in the economy: The growth rate of labor and non-accumulable capital, which is zero (the growth index equals one), the growth rate of capital, and the growth of outputs, both being larger than zero (the growth indices are larger than one). To implement the model in GAMS, we used an approach that takes this specialty into account.

As we know from equation (19) that X_i grows at the rate of capital K_i, we can related the two growth indices as

$$g_{X_i} = g_{K_i}$$

Thus, we know that if we model X_i instead of x_i, we only need to take two different growth rates into account. We can model the growth indices of labor, non-accumulable capital, and intermediate goods like the growth index of capital.

For the calibration we proceed as follows. First, we introduce a growth rate for sectoral outputs Y_i and sectoral intermediate composites Q_i and call it $(1 + gr)$. We also introduce a growth rate for capital K_i, $(1 + grk)$. The relation of both growth rates can be derived using the production function for Q_i:

$$Q_{i,t} = \left[\sum_{j=1}^{K_{i,t}} x_{ij,t}^{\kappa} \right]^{\frac{1}{\kappa}}$$

As the sum of intermediate goods continues to grow, we assume the equilibrium version with identical production of intermediate goods (18):

$$Q_{i,t} = K_{i,t}^{\frac{1-\kappa}{\kappa}} X_{i,t} \tag{27}$$

To analyze the intertemporal dynamics we can rewrite the above equation like

$$\frac{Q_{t+1}}{Q_t} = \left(\frac{K_{t+1}}{K_t} \right)^{\frac{1-\kappa}{\kappa}} \frac{X_{t+1}}{X_t}$$

As we know that

$$\frac{Q_{t+1}}{Q_t} = 1 + gr \tag{28}$$

$$\frac{K_{t+1}}{K_t} = 1 + grk$$

$$\frac{X_{i,t+1}}{X_{i,t}} = 1 + grk \tag{29}$$

we can relate the two growth rates according to

$$1 + gr = (1 + grk)^{\frac{1}{\kappa}}$$

with $(1 + gr)$ being larger than $(1 + grk)$ (as κ is smaller than 1). The difference in the two growth indices has its origin in gains from specialization. Other CGE models do not consider gains of specialization as driving force for endogenous growth for the whole economy, so these do not consider two different growth rates in the benchmark. In our model, however, we includes them, which leads to growth dynamics that are structurally identical to the dynamics of policy scenarios. We regard this attribute as an outstanding advantage of our model.

How can be made sure that X_i behaves exactly like K_i? We define the development of X_i (expressed by the appendix ".L" for "level" after a variable) equal to that of K_i:

$$X_i.L = K_i.L$$

The input-output-table of the Swiss economy gives clear indications for the size of X_i. But as Q_i represents a theoretical variable we cannot assign a value for it from the Swiss input-output-table. Fortunately, we do not need to find out the size of Q_i as it can be replaced after some calculations:

For the purpose to differenciate between the theoretical calculations above and GAMS notation, a specific syntax is introduced. Values from the Swiss input-output-table are labeled with an bar, such as $\overline{X_i}$ denotes the value of intermediate goods that is added up from labor input, energy input, and input of non-accumulable capital. We also know that $\overline{X_i}$ grows with the growth rate $(1+grk)$ due to the fact that $\overline{X}_i = \overline{K}_i\overline{x}_i$. $\overline{X}_i$ does not change, neither in the benchmark case nor in the policy scenarios.

Each value is then combined with a variable of the same name, in our case $\widetilde{X}_i$, which denotes an activity index. The variables are calibrated to unity in the benchmark case, but they can change in the policy scenarios. The combination of the activity index with the value of a variable, $\widetilde{X}_i\overline{X}_i$, yields the possibility to calculate with original data and the flexibility to change the resulting value in policy scenarios.

Rewriting (27) in GAMS notation we get

$$\widetilde{Q}_{i,t}\overline{Q}_{i,t} = \widetilde{K}_{i,t}^{\frac{1-\kappa}{\kappa}}\widetilde{X}_{i,t}\overline{X}_{i,t} \tag{30}$$

Relation (27) must also hold in the benchmark case, so we know that

$$\overline{Q}_{i,t} = \overline{X}_{i,t}\left((1+grk)^t\right)^{\frac{1-\kappa}{\kappa}} \tag{31}$$

Inserting (31) in (30) and rearranging yields the development of Q_i

$$\widetilde{Q}_{i,t} = \widetilde{X}_{i,t}\left(\frac{\widetilde{K}_{i,t}}{(1+grk)^t}\right)^{\frac{1-\kappa}{\kappa}} \tag{32}$$

All variables in GAMS are calibrated to unity, so we face an obstacle in this equation. $\widetilde{K}_i$ does not grow and therefore cannot yield any growth dynamics. We thus introduce an auxiliary variable $\widetilde{N}_i$, which grows at the rate of capital and apply it to equation (32):

$$\widetilde{Q}_{i,t} = \widetilde{X}_{i,t}\left(\frac{\widetilde{N}_{i,t}}{(1+grk)^t}\right)^{\frac{1-\kappa}{\kappa}}$$

To be sure that N_i behaves exactly like K_i we proceed threefold. First, we define the development of N_i equal to K_i augmented by the growth rate of capital:

$$\widetilde{N}_i.L = \widetilde{K}_i.L(1+grk)^t$$

Second, we make sure that the price for N_i equals the rental price of capital rk_i:

$$p_{N_i,t} = rk_{i,t}$$

Third, we introduce an equation that equals the stock of capital to the size of $N0_i$:

$$RK_{i,t}\widetilde{K}_{i,t}\overline{K}_{i,t} = p_{N_i,t}\widetilde{N}_{i,t}\overline{N}_{i,t}$$

12.2 Depreciation rate

Due to the fact that sectoral investments need to grow at the same rate as consumption and thus like sectoral output (with $1+gr$) and the fact that capital grows at a lower rate $(1+grk)$, there is a disequilibrium between the two growth rates. Thus, the calibration of capital accumulation (cf. (9)) needs an auxiliary assumption for a balanced growth path (BGP). In order to be able to calibrate capital growth, we assume an increasing depreciation rate over time. It compensates for higher growth of investments than growth of capital. This assumption appears realistic as capital in a higher developed economy is highly specialized and therefore subject to a higher depreciation than generally applicable capital in a lower developed economy.

Starting with the equation for capital accumulation

$$K_{i,t+1} = I_{i,t} + (1-\delta(t))K_{i,t}$$

we assume a discount rate that acts as adjustment factor. We can calculate the development of the depreciation rate applying GAMS relations.

$$\delta_{i,t} = \left(\frac{1+gr}{1+grk}\right)^t \delta_{i,0} + grk\left(\left(\frac{1+gr}{1+grk}\right)^t - 1\right)$$

We see that the depreciation rate depends on its initial value, both growth rates and the value of the growth index of capital, grk. This growth rate ensures a constant growth rate of capital, g_{K_i}.

12.3 Changes in energy efficiency

Energy is used in the production of intermediate goods. As energy is a sectoral output it grows at a higher rate than intermediate goods. To ensure a balanced growth path, the difference between both growth rates needs to be adjusted by an efficiency index, $enef_i$, that is introduced in the production of intermediate goods:

$$X_{i,t} = \left[\alpha_{L,i} L_{X_i,t}^{\frac{\sigma_{X,i}-1}{\sigma_{X,i}}} + \alpha_{VK,i} VK_{X_i,t}^{\frac{\sigma_{X,i}-1}{\sigma_{X,i}}} + (1-\alpha_{L,i}-\alpha_{VK,i}) enef_{i,t} A_{eX_i,t}^{\frac{\sigma_{X,i}-1}{\sigma_{X,i}}}\right]^{\frac{\sigma_{X,i}}{\sigma_{X,i}-1}}$$

This efficiency index behaves according to

$$enef_{i,t} = \left(\frac{1+gr}{1+grk}\right)^t$$

Thus, the amount of energy demanded by the X_i-producer can also be interpreted as energy services that show a lower growth rate than energy itself.

Labor is used both in the production of intermediate goods and also in the production of capital. As labor in the production of X_i goods does not grow and labor in research needs to grow at the rate of investments, $(1+gr)$, we introduced two types of labor to allow for this difference. This results in a timely change in the ratio of both, i.e. labor in research increases in relation to labor in production. This can be due to an exogenous increase in human capital, which is not modeled in more detail. Reasons for this can for example be migration, better schooling, a higher level of university education or a sophisticated system of continuing education.

12.4 Capital demand, kappa, investments

The growth rate of outputs, $(1+gr)$, depends on the size of κ. On a balanced growth path all sectors in the economy must grow at the same rate. Therefore, κ must be identical across sectors. At the same time, $(1-\kappa)$ describes the capital intensity of the sector, i.e. the share capital in the production of intermediate goods. As the capital intensity is not the same across sectors in the input-output-matrix, the original capital stock from each sector from the input-output-matrix, $K_{IO,i}$, need to be divided into two capital stocks: One serves as endogenous driver for growth and equals the share $(1-\kappa)$, which is K_i, and the other one includes the remaining capital, VK_i:

$$K_{IO,i,t} = K_{i,t} + VK_{i,t};$$

VK_i cannot be accumulated by the household, it grows exogenously at the rate of the other inputs, $(1+grk)$, and serves as input in the production of intermediate goods (cf. (11)). Only K_i is exposed to investment decisions by the household and is thus the driver of endogenous growth. We chose VK_i to be a sectoral independent factor (similar to labor) due to the reason that a sectoral specific and in its quantity invariant factor would constitute fixed cost to each sector. It must hold that

$$\sum_{i\in I} VK_{i,t} = VK_t$$

Demand for capital by intermediate good producers, i.e. the rental price they pay each period for capital, is in constant relation to the interest rate r, the depreciation rate δ_i, the sectoral capital stock K_i and sectoral investments in steady state I_i (cf. Paltsev (2004)). We calculate it for the first period like

$$K_{i,0} = \frac{I_{i,0}}{\delta_{i,0} + grk}$$

and

$$K_{i,0} = \frac{rk_{i,0}K_{i,0}}{r + \delta_{i,0}}$$

From the above equations we know that the following relation must hold:

$$I_{i,0} = \frac{(\delta_{i,0} + grk)rk_{i,0}K_{i,0}}{r + \delta_{i,0}}$$

Non-accumulable capital VK is supplied by the household independently of these relations.

12.5 Prices

Due to different growth rates of capital and outputs and the fact that all benchmark values of quantities are assumed to be unity, the initialization of prices needs to be adjusted. All prices that belong to goods that grow with the higher growth rate $(1 + gr)$ remain unity in the benchmark case. The prices of the goods that grow as fast as capital $(1 + grk)$ must adjust so that the value of inputs always equals the value of outputs in each production function. The exact dynamics can be derived from the production function of Q_i as the value of outputs must equal the value of inputs:

$$p_{Q_i,t}Q_{i,t} = p_{x_i,t}X_{i,t}$$

As the dynamics can be analyzed according to

$$\frac{p_{Q,t+1}}{p_{Q,t}}\frac{Q_{t+1}}{Q_t} = \frac{p_{x_i,t+1}}{p_{x_i,t}}\frac{X_{i,t+1}}{X_{i,t}}$$

and we know that (28), (29) and

$$\frac{p_{Q_i,t+1}}{p_{Q_i,t}} = 1$$

it must hold that

$$p_{x_i,t} = \left(\frac{1 + gr}{1 + grk}\right)^t$$

Accordingly, also the prices of inputs to X_i (labor, non-accumulable capital, the rental price of capital, and therefore also the price for N_i) must grow at this rate.

12.6 Terminal condition

The terminal condition regulates the state of the model in the last period T. As the model is assumed to be on a balanced growth path in the last period, the growth rate of investments in each sector must equal the growth rate of production of that sector:

$$\frac{Inv_{i,T}}{Inv_{i,T-1}} = \frac{Y_{i,T}}{Y_{i,T-1}}$$

This equation ensures that the dynamic behavior of the model is not uncontrolled but complies certain assumptions. The most important one is the fact that investments do not suddenly drop to zero in the last time period but stay on a level that would ensure a continued growth of the economy. If this condition was missing, an optimizing household would decrease investments towards the end of the time horizon to zero and would use up all capital. This would obviously strongly influence also all other periods in an unrealistic way. Hence, the terminal condition ensures that the economy exists also after the last period of simulation.

13 Conclusion

The CITE model can be used to run policy scenarios and to estimate influences of political measures on different sectors of the Swiss economy. The microfoundation of the model ensures the propinquity to up-to-date endogenous growth theory. All growth dynamics that are applied in policy scenarios also influence the benchmark case. Gains of specialization ensure that the model economy grows without growth of endowments that are used in production, and it can therefore be said that our model is a major advance in CGE modeling. It features endogenous growth dynamics that exclude the dependence on growth on input factors.

The specialty of our model is clearly in the implementation of microeconomically based endogenous growth theory on the basis of Grossman and Helpman (1991). Aside from this strength, there are several possibilities for enhancing the model's performance. First and foremost, the existing energy sector is a greatly simplified version and can be modeled in more detail. In this regard, it might also be interesting to combine the CITE model with a bottom-up model that gives more information about different sources and uses of energy. This would also strongly improve the acceptability of the model in political discussions because practitioners might criticize on the simplification of the energy sector.

The model also shows interesting opportunities for enlargement in the area of knowledge spillovers from abroad. The version of the model at hand assumes that the stock of knowledge is exclusively increased by research and development effected in Switzerland. However, it needs to be taken account the fact that Switzerland is a small economy and that a large portion of knowledge comes from abroad. These additions to knowledge could also be modeled in a more detailed way.

Third, the rest of the world might be the center of interest for further enhancement of the model. Policies that are undertaken abroad, such as climate policies in the EU, might strongly affect the terms of trade for Switzerland and therefore its international competitiveness. If foreign policies could be included more explicitly in the model, scenarios with different combinations of Swiss and foreign energy policies would greatly contribute to the determination of appropriateness of Swiss energy policies.

Fourth, the basic setup of the model can also be used to build CGE models for other countries. The general growth dynamics could be maintained, but energy and energy-related inputs would need to be redesigned. This universality of the growth mechanisms could even lead to a multi-country-model that shows Switzerland and its most important trade partners.

14 Literature

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15 Appendix - Utility functions

In Section 8 we stated that the additively separable utility function

$$U = \sum_{t=0}^{\infty} \left(\frac{1}{1+\rho}\right)^t \frac{C_t^{1-\theta} - 1}{1-\theta}$$

and the linearly homogeneous utility function

$$\hat{U} = \left[\sum_{t=0}^{\infty} \left(\frac{1}{1+\rho}\right)^t C_t^{1-\theta}\right]^{\frac{1}{1-\theta}}$$

have the same intertemporal characteristics. To proof this, we refer to Rutherford (2004) and recall that a monotonic transformation of utility has no influence on the underlying preference ordering. If we assume that $\hat{U}$ is a function $V(U)$ and that the first derivative is larger than zero ($V' > 0$), the optimization of U and $\hat{U}$ yield identical demand functions.

To show this, we assume that

$$\hat{U} = V(U) = [aU + \omega]^{\frac{1}{\mu}} \tag{33}$$

where

$$\omega = \sum_{t=0}^{\infty} \left(\frac{1}{1+\rho}\right)^t = \frac{1+\rho}{\rho} \tag{34}$$

and

$$\mu = 1 - \theta \tag{35}$$

If we insert ω, μ, and U in $\hat{U}$ we get

$$\hat{U} = \left[(1-\theta)\left[\sum_{t=0}^{\infty} \left(\frac{1}{1+\rho}\right)^t \frac{C_t^{1-\theta} - 1}{1-\theta}\right] + \sum_{t=0}^{\infty} \left(\frac{1}{1+\rho}\right)^t\right]^{\frac{1}{1-\theta}} \tag{36}$$

which exactly equals the notation of $\hat{U}$ above.

Alternatively, the equivalence of dynamics can be shown by regarding the marginal rate of substitution. It is in both models identical to

$$\frac{\frac{\partial U}{\partial C_{t+1}}}{\frac{\partial U}{\partial C_t}} = \frac{1}{1+\rho} \left(\frac{C_t}{C_{t+1}}\right)^\theta \tag{37}$$

As this defines the preference orderings, both utility functions show the same intertemporal characteristics.

Appendix B: *A comparison of growth dynamics: the CITE model vs. a model with homogenous capital.*

A comparison of growth dynamics: the CITE model vs. a model with homogenous capital

1 Introduction

Mankind's impact on the natural environment and the resulting consequences for climate change are acknowledged by most scientific reports, such as the latest IPCC report. The increasing atmospheric greenhouse gas concentration will severely impact the global climate with tremendous effects on ecological and economic systems (Kemfert, 2002).

Consequently, a major task for the world's economies in the next decades will be to decrease total emissions of greenhouse gases (GHG) and to change the carbon intensity of production. Since a significant part of carbon dioxide emissions results from the usage of energy, two major options can be envisaged for GHG reduction. The direct way would be to proportionately reduce energy use and GHG emissions by substituting labor and capital for energy (e.g., public transport instead of privately owned vehicles). However, the essential role of energy for production yields only limited possibilities for this option. Generally, energy and other inputs to production can yield only insufficient abatement levels and have hence only moderate effects (Löschel, 2002; Gerlagh et al., 2004; Gerlagh and Lise, 2005). The second possibility is to transform energy production by using fossil fuels with less carbon or to reduce energy intensity in production. This form of induced technical change typically needs more time and can therefore become significant rather in the medium- to long-term (Knapp, 1999). The short-term effects of an energy price change can therefore be distinct from the allocation of inputs in the long run (Bretschger, 2007).

Generally, changes in energy use are subject to supply and demand decisions in markets. Demand, in turn, is affected by changes in the energy price based on the price elasticity that induces factor substitution (Löschel, 2002). Public policies thus have a central role as they affect prices and also incentives that can modify energy use. As a result, new energy services or the amelioration of existing ones can emerge (Kverndokk et al., 2004). However, political and regulatory measures can result in a variety of societal and welfare outcomes (Jaffe et al., 2002; Otto et al., 2007). It is therefore crucial to analyze the characteristics of technologies to understand the reaction of technology on the economic incentives created by politicians.

Many relevant issues concerning the consequences of energy policies cannot be addressed entirely by theoretical models or on the basis of empirical research. The methodological foundation to approach these questions needs to include multiple viewpoints (Jaffe et al., 2002). A remedy to approximate the consequences of energy policies is the concept of computable general equilibrium (CGE) models that combine theoretical economic models with actual economic data. A multitude of CGE models aim at estimating the effects of energy policies on different industries in an economy and on the rate and direction of technical change. These Arrow-Debreu models involve the analysis of the interaction of consumers and producers in markets. The requirement of a general equilibrium yields a framework to analyze price-dependent interactions between the energy system and the other sectors (Löschel, 2002; Jaffe et al., 2003). Scenarios produced by CGE models help balance advantages and disadvantages of policies and emphasize the importance of technical change.

Technical change can be modeled in diverse ways. Differences in model structures may have considerable effects on the outcome of policy scenarios (Buonanno et al., 2003). The aim of this chapter is to identify some approaches to model induced technical change and to emphasize the differences between the CITE model (based on endogenous growth dynamics) and a model with homogeneous capital and exogenous growth. The CITE model can be considered an expansion of the group of models with endogenous technical change by including gains from specialization as driver for growth. These gains are assumed to be present in the benchmark case without political measures as well as in the policy scenarios.

The CITE model is a top-down model that describes of the energy sector in a highly aggregated way. Like other top-down models, it characterizes industries by means of neoclassical production functions that include possibilities to substitute production inputs. Technical change in these models amends the cost of production at the industry level. As opposed to the top-down approach, bottom-up models use detailed specifications of energy systems and typically do not comprise a detailed modeling of the overall macroeconomy. They are usually employed to "compute the least-cost method of meeting a given demand for final energy or energy services subject to various system constraints, such as exogenous emission reduction targets" (Löschel, 2002). Bottom-up models illustrate the diffusion of new technologies on the basis of costs and performance characteristics. Technical change is present in these models if one technology is substituted for another (Löschel, 2002). The difference in the description of induced technological change appears to be the main reason for the different results of top-down and bottom-up models in assessing economic costs of energy policies (Carraro & Galeotti, 1997).

1.1 CGE models with purely exogenous growth

The first CGE models were based on the assumption of exogenous growth and the autonomous amelioration of energy efficiency. They ignored interconnections between technological change and policy measures. Changes in energy prices due to political actions only resulted in substitution of other factors for energy, leaving the rate of growth in energy efficiency unchanged. As energy policies have yet an impact on the price of fuels and therefore on the incentives to invest R&D, they are strongly linked to technological change. Such policies might cause research efforts to concentrate on the discovery of new production methods or of entirely new products that depend less on energy. Moreover, energy policies can influence the accumulation of knowledge via learning-by-doing (LbD) related to experience with alternative energy fuels or energy-conserving processes. Including these endogenous growth mechanisms increases the intertemporal connections and therefore more strongly connects the cost of emission reduction in the future and measures taken today (Dasgupta & Heal, 1974; Boyd & Uri, 1991; Goulder & Mathai, 2000).

In the first generation of CGE models, the autonomous increase of energy efficiency was defined by the "autonomous energy efficiency index" (AEEI), which is a heuristic measure of all non-price driven enhancements in energy technology, including structural change in the economy and sector-specific technological change. It is a separate coefficient in the production or cost functions and represents either factor-augmenting or price diminishing technical change. The basic assumption of the AEEI is that an energy efficiency increase results from a large number of minor innovations that evolve mainly from a common stock of knowledge that grows gradually (Löschel, 2002). The main difficulty with applying an AEEI is to identify the difference in the influence of technical progress and long-term price effects (Jones, 1994).

Nordhaus (1992) first introduced a top-down model and estimated the consequences of energy policies on the economy. The DICE (Dynamic Integrated Climate-Energy) model comprised very simplified growth dynamics. In the RICE (Regional Integrated model of Climate and the Economy) model, Nordhaus and Yang (1996) expanded the DICE model and included a number of regions to reflect the world economy. Their main focus, however, was not on an amelioration of growth dynamics. Rather, they analyzed national strategies with three different levels of international cooperation and their effects on emission reduction. Another example of a model that used an AEEI parameter is the CETA (Carbon Emissions Trajectory Assessment) model of Peck and Teisberg (1992), which is based on Manne and Richels (1992) and focuses on the path of an optimal carbon tax. For a more detailed overview of models with AEEI parameters, see also Jorgenson and Wilcoxen (1993).

1.2 Empirical evidence for induced innovation

The empirical evidence for the effects of energy price changes on innovation is relatively univocal and builds on Hicks' induced innovation hypothesis. Hicks (1932) proposes that changes in relative factor prices should result in innovations that diminish the demand for the relatively expensive factor. Popp (2001) confirms this hypothesis empirically and finds that the effects of a price change can be attributed by about two-thirds to factor substitution, and around one-third result from induced innovation. Also Newell et al. (1999) find that increasing energy prices have an observable effect on the types of products offered in stores. Likewise, Popp (2002) finds evidence of a positive impact of energy prices and the stock of knowledge on innovation.

One of the leading views on the positive impact of energy prices on innovation is ascribed to Porter and van der Linde (1995), who argue that environmental regulation can result in innovations and economic gains. This effect is even more amplified if the innovations can be exported to other regions or countries.

They argue that a country that adopts stricter environmental policies than others will have a boost in innovations and become a net exporter of the newly developed environmental technologies. On the firm's individual level, Porter and van der Linde (1995)'s claim means that environmental regulations have a "net beneficial effect on firm's competitiveness" (Sue Wing, 2003). However, econometric tests at the firm level have yielded mixed results (Sue Wing, 2003).

At the country level, however, Porter and van der Linde (1995)'s hypothesis was affirmed by Bretschger (2007), who finds that lower energy input induces investments in physical, human, and knowledge capital. This, in turn, fosters the growth rate of these countries. Bretschger shows that for OECD countries, the simple correlation between energy use and growth is negative. Jaffe and Palmer (1997) show that lagged environmental compliance expenditures have a significant positive effect on R&D expenditures. Carraro and Galeotti (1997) find similar results.

2 CGE models with endogenous growth mechanisms

New growth theory is based on the observation that technological innovation is an economic activity. Profit-maximizing agents optimize their behaviors according to profit incentives. Endogenous growth theory thus builds on innovation theory, which states that Schumpeterian profit incentives account for a major source of technological change (Weyant & Olavson, 1999; Löschel, 2002).

Technology growth is specified in endogenous growth theory as an endogenous process that focuses on increasing productivity. If climate policy is introduced, the role of innovations becomes more complicated as they are directed toward reducing energy use. Such a alteration changes the growth trajectory of overall productivity. These effects may not be negligible, and therefore a good perception of the relationship of the energy system and the economy-wide productivity is substantial (Azar & Dowlatabadi, 1999).

This section provides an overview of CGE models that introduced two specific forms of endogenous growth mechanisms, specifically learning-by-doing and research. These growth assumptions differ crucially from the endogenous growth dynamics of the CITE model, which are based on gains from specialization in production.

2.1 Learning-by-doing as the main driver of growth

Learning is a major driving force of technological change because it improves the relation of cost and performance of technologies. A learning curve describes the declining cost of a technology as a function of cumulative capacity, which can be seen as an approximation for accumulated experience (Barreto & Kypreos, 2004). Today, LbD is among the best empirically analyzed phenomena that lead to technological change (Messner, 1997). Concerning energy, the evidence is in clear favor of the fact that production costs depend on cumulative experiences (McDonald & Schrattenholzer, 2001).

The first paper about learning effects was written by Wright (1936). He described the relation of costs and quantity in the aircraft industry and concluded that there exists a interrelation between accumulated experience and the performance in the production processes. His observations were generalized by Arrow (1962), who became known as a pioneer for LbD.

The first to introduce LbD in a bottom-up model was Messner (1997) in the model MESSAGE, which is a systems-engineering approach that included systematic technological learning; that is, it linked the cost of developing a new technology to the already installed cumulative capacity. The model minimized the discounted costs of supplying energy, subject to an exogenously given level of final energy demand and assumptions on costs, efficiencies, and market penetration constraints. She evaluates the effects of including LbD and thus induced technical change (ITC) and concludes that ITC lowers the necessary investment level and that investments in expensive technologies start earlier.

Based on a later version of the model (MESSAGE III from Messner & Strubegger, 1995), Grübler and Messner (1998) combine the LbD dynamics with a carbon cycle component and include research and development to analyze the time path of a carbon tax for a given carbon concentration stabilization limit. They find that global emissions rise initially but stabilize later and eventually decline. ITC in this model results in a higher level of abatement than in a model with exogenous technology.

Both these models yield the "typical pattern of a discrete and complete switch" (Löschel, 2002) toward an alternative and environmentally friendlier technology as soon as the technology becomes competitive. Yet the diffusion of new technologies in reality is never a discrete switch, but typically follows an S-shaped curve (Löschel, 2002). Gerlagh et al. (2004) face this criticism and combine the MESSAGE (1997) model with the DEMETER model from van der Zwaan et al. (2002) and Gerlagh and van der Zwaan (2003) in a top-down approach with LbD. They model niche markets for new technologies, which enables them to gradually become competitive. Their results yield a low level of carbon taxes needed to accomplish a given reduction compared to the DICE model.

Less optimistic regarding the difference between ITC and exogenous growth models in bottom-up setups are Manne and Richels (2004). They conclude that LbD does not significantly change the results. The only considerable impact is on the cost of emission abatement, which is, however, substantial.

Another bottom-up model with LbD as main driving force is the one of Barreto and Kypreos (2004), which is based on the MARKAL (MARKet ALlocation by Fishbone and Abilock, 1981) from the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency. It is a multi-regional model of the global energy system and includes LbD across sectors so that there are linkages between the cost of technologies across regions. Their results show that LbD only slightly reduces emissions compared to the case without LbD.

2.2 Growth resulting from R&D

Models that include investments in R&D are inspired by macroeconomic models of endogenous growth, such as those of Lucas (1988), Romer (1990), and Grossman and Helpman (1994). In these models, a carbon tax has two opposite effects on the economy. First, it causes higher factor prices and therefore diminishes knowledge accumulation and the rate of technical progress. This development results in a decline in income and output. At the same time, the price effect triggers substitution of inputs and a reallocation of knowledge to sectors that offer the largest gains from research. Because this changes the technological structure of the economy, it can adjust more elastically to price changes. This leads to an augmentation of gross substitutability on the supply side, which eventually mitigates the loss incurred by the tax. The total effect of the tax can be even positive (Sue Wing, 2003).

Based on his DICE model, Nordhaus (2002) introduced R&D (R&DICE) into the analysis and adds a carbon-intensive energy input to the production function. He includes two forms of technological change, an economy-wide technological change (Hicks neutral and exogenous) and a carbon-energy-saving technological change (CESTS), which reduces carbon emissions per unit of output. The model also accounts for diminishing returns to research (cf. also Popp (2002) for an empirical analysis on diminishing returns). Thus, the rate of energy efficiency varies with research, but there is no possibility of developing a carbon-free energy source to reduce carbon emissions independently of energy use. This setup might explain why Nordhaus finds that direct substitution of capital and labor for energy has a much greater influence on the results than ITC (Bretschger, 2005).

Buonanno et al. (2001) enhance the RICE model of Nordhaus and Yang (1996) and include ITC in their ETC-RICE model. A world wide stock of knowledge that all countries can use in their production has a reducing effect on their emission-output ratios (cf. also Böhringer & Rutherford (2002) on the welfare implications of international spillovers). These spillovers take into account international entanglement through trade, capital flows, and technology transfers. They analyze the pros and cons of introducing ceilings on emission trading (i.e., of having a maximum fraction of emissions that can be traded via international emission trading systems) and find that ITC has limited influence on growth. In a later paper (Buonanno et al., 2003), they additionally introduce sectoral spillovers within countries and human capital, which result in increasing returns to scale. Their paper suggests that ITC does reduce costs and that incentives to invest in R&D are smaller if international knowledge spillovers are accounted for due to free-riding incentives.

One key difference between Nordhaus (2002) and Buonanno et al. (2003) is their assumptions about the potential opportunity costs of R&D. Nordhaus assumes a fixed amount of total R&D spending in the economy and therefore crowding-out of R&D in other industries by the energy sector. On the contrary, Buonanno et al. model a single R&D stock that simultaneously enhances total factor productivity and lowers the carbon intensity of the economy. Consequently, ITC increases overall productivity, which is in accordance with Popp (2004). However, Popp (2004) finds that both assumptions are extreme presuppositions and states that only partial crowding out is realistic. In his ENTICE model (ENdogenous Technical change in the DICE model), he incorporates 50% crowding out and finds that ITC does reduce opportunity costs of lowering fossil fuel emissions.

Goulder and Schneider (1999) also introduce in their model the possibility of crowding out of research and deal with the criticism of the need to include different kinds of energy sources by including fossils and renewables (with limited substitutability). They find that carbon abatement policies have very different impacts on research across sectors and do not necessarily increase the economy-wide rate of technological progress. Although ITC yields lower cost for achieving a given target (as net benefits increase), gross costs (i.e., costs before netting out environmentally related benefits) of a given carbon tax are higher. Other papers that include research as the main driver for growth are, for example, Kemfert (2002) with WIAGEM (World Integrated Assessment General Equilibrium Model) and Gerlagh (2007) with the DEMETER-1CCS model.

Another focus of research is the timing of climate policy. Wigley et al. (1996) argued that a "wait and see" strategy should be realized by politicians to have the time to develop new technologies and to "reoptimize" the capital stock. This point stirred up intense debate. For example, Gerlagh et al. (2009) assume that the abatement sector grows according to Romer (1990) with positive spillovers to innovation from the previous stock (standing on shoulders) and additionally with negative externalities from aggregate current research (fishing out) (on the importance of R&D spillovers see also Griliches, 1992). Their result is that the timing of optimal emission reduction crucially depends on the policy instrument applied (i.e., R&D targeting or carbon taxes).

2.3 Comparison of impact of LbD and R&D

Some models compare the impact of LbD and research. Goulder and Mathai (2000), for instance, use a partial equilibrium model of knowledge accumulation in which a firm decides upon the time paths of abatement and R&D investment to minimize the costs corresponding to a particular emission target. They compare two different forms of endogenous technical change analytically and numerically. First, they apply LbD while assuming that the stock of knowledge is a function of the level of abatement. Second, they include R&D in the analysis. For both forms, they assume that the stocks of capital are sector-specific. For the LbD simulation, they include the MESSAGE model from Messner (1997) in energy production. Their analysis is centered on the application of two different criteria on the evaluation of LbD and R&D: cost-effectiveness (Given a specific target for the atmospheric concentration, what would be the abatement profile at minimum cost?) and cost-benefit (What would be the optimal concentration target from maximizing the benefits from avoided climate change damages minus abatement cost?). They find that given a cost-effective setting ITC always leads to a lower time profile of optimal carbon taxes. In a cost-benefit analysis the results are similar as long as damages are convex in the atmospheric carbon concentration. The impact of ITC on the optimal abatement path is equivocal: If R&D is applied, abatement is shifted in the future. On the contrary, if LbD is present in the model, the timing is analytically ambiguous.

In the DEMETER-2E model, Gerlagh and Lise (2005) compare the two channels of innovation and also two types of energy (fossil fuels and a carbon-free energy). This model considers only the energy sector of the DEMETER model, i.e., total energy demand is exogenous. Their results are congruent to the folk theorem, which states that cheap (easily accessible) resource reserves are exhausted before more expensive energy sources are exploited. The continuous exhaustion of cheap reserves creates a shadow price or resource rent, which is comparable to the Hotelling resource rent. They also conclude that ITC has a positive impact on costs.

2.4 Related approaches

Apart from these models, other approaches cover similar research questions. For instance, Böhringer (1998) and Böhringer and Rutherford (2008) demonstrate how to integrate bottom-up activity analysis into top-down models (hybrid approach).

Another type of model focuses on the role of uncertainty for an optimal carbon tax. Kolstad (1996) and Ulph and Ulph (1997) both analyze the impact of the possibility of gaining more knowledge about the damage caused by global warming. Their results show that current abatement should be lower if the possibility existed of having better information in the future.

Dowlatabadi (1998) and Dowlatabadi and Oravetz (2006) argue that historic trends are inconsistent with an AEEI factor and include an endogenous formulation in their models, which relates to the influence of price expectations (contrary to price changes ex post) on the energy intensity of the economy. They call this form of technical change price-induced efficiency (PIE). The result is that energy price changes modify expectation and the overall energy efficiency of the economy with a time lag.

On the question of the timing of the optimal carbon or energy tax, a number of authors have reported contradictory results (cf. Nordhaus, 1982; Sinclair, 1994; Farzin & Tahvonen, 1996; Ha-Duong et al., 1997). Azar (1998) consolidated the opinions by showing that the optimal time path depends on the carbon stabilization target chosen. In the case of low targets (for example smaller than 450 ppm), then early abatement is cost efficient. If high stabilization targets are chosen (e.g., larger than 600 ppm), then abatement should be conducted later.

3 Structure of the models

The two models compared in this chapter are the CITE model and a model with homogeneous capital and exogenous growth. Both have a decentralized structure, and each contains a Ramsey optimizer that maximizes utility by deciding about the extent of investments in different time periods. Therefore, the savings rates are endogenous in the two models. Both models represent open economies with trade modeled with Armington goods. The principal production structures are identical. The main difference is in the inclusion of gains from specialization and therefore of heterogeneous capital in the CITE model. The incentives to accumulate capital generate endogenous growth dynamics. In comparison, in the model with homogeneous capital, growth is assumed to come from endowments that grow by an exogenously defined rate in each period. This growth comes at no cost ("manna from heaven").

In the theoretical calculations in this section, we abstract from Armington goods to keep the analysis as simple as possible.

3.1 Final output

The production of final output is nearly identical in both models. Regular goods as well as final goods in the oil and in the energy sector have the same production structure. The main difference is attributed to the intermediate goods. In the model with homogeneous capital (HK model), intermediate goods enter the production of final goods directly, whereas in the CITE model, the intermediate goods are first combined to an intermediate composite (cf. Chapter 3.2) and then enter the production of the final goods.

Starting with the CITE model, we can see that output of regular goods Y_n are produced using a sector-specific intermediate composite Q_n and the final goods of all regular sectors n' that go to sector n, $Y_{n'n,t}$.

$$Y_{n,t} = \left[\alpha_{X,n} Q_{n,t}^{\frac{\sigma_{Y,n}-1}{\sigma_{Y,n}}} + (1-\alpha_{X,n}) \left(\min_{n' \in N} \left(\frac{Y_{n'n,t}}{y_{n'n}} \right) \right)^{\frac{\sigma_{Y,n}-1}{\sigma_{Y,n}}} \right]^{\frac{\sigma_{Y,n}}{\sigma_{Y,n}-1}} \tag{1}$$

The production functions for energy goods and oil goods resemble the production function above. In the production of energy goods, the above shown production structure is additionally combined with a Cobb-Douglas function of imported gas and the final good of the oil sector.

$$Y_{e,t} = \left[\alpha_{TFF} \left(GAS_t^{\alpha_{FF,gas}} Y_{o,t}^{\alpha_{FF,o}} \right)^{\frac{\sigma_E - 1}{\sigma_E}} + (1-\alpha_{tff}) B_{e,t}^{\frac{\sigma_E - 1}{\sigma_E}} \right]^{\frac{\sigma_E}{\sigma_E - 1}}$$

$$B_{e,t} = \left[\alpha_{X,e} Q_{e,t}^{\frac{\sigma_{Y,e}-1}{\sigma_{Y,e}}} + (1-\alpha_{X,e}) \left(\min_{n \in N} \left(\frac{Y_{ne,t}}{y_{ne}} \right) \right)^{\frac{\sigma_{Y,e}-1}{\sigma_{Y,e}}} \right]^{\frac{\sigma_{Y,e}}{\sigma_{Y,e}-1}}$$

The production in the oil sector also resembles the production of regular goods, and it uses as additional input crude oil, which is added with a Leontief function.

$$Y_{o,t} = \min \left(\frac{CRU_t}{y_{cru}}, \frac{B_{o,t}}{y_{noncru}} \right)$$

$$B_{o,t} = \left[\alpha_{X,o} Q_{o,t}^{\frac{\sigma_{Y,o}-1}{\sigma_{Y,o}}} + (1-\alpha_{X,o}) \left(\min_{n \in N} \left(\frac{Y_{no,t}}{y_{no}} \right) \right)^{\frac{\sigma_{Y,o}-1}{\sigma_{Y,o}}} \right]^{\frac{\sigma_{Y,o}}{\sigma_{Y,o}-1}}$$

In comparison, in the HK model, no intermediate goods composite exists because gains from specialization are completely absent. As a result, it is abstracted from a number of different intermediate goods, but we assume that only one intermediate good per sector, $\tilde{X}_i$, exists. Consequently, instead of an intermediate composite, the intermediate goods $\tilde{X}_i$ enter the production functions of the sectors. The production function of regular goods then changes to

$$\tilde{Y}_{n,t} = \left[\alpha_{X,n} \tilde{X}_{n,t}^{\frac{\sigma_{Y,n}-1}{\sigma_{Y,n}}} + (1-\alpha_{X,n}) \left(\min_{n' \in N} \left(\frac{\tilde{Y}_{n'n,t}}{y_{n'n}} \right) \right)^{\frac{\sigma_{Y,n}-1}{\sigma_{Y,n}}} \right]^{\frac{\sigma_{Y,n}}{\sigma_{Y,n}-1}}$$

We choose to display variables that are distinct in the HK model compared to corresponding variable in the CITE model with an tilde. The production of energy goods equals

$$\tilde{Y}_{e,t} = \left[\alpha_{TFF} \left(GAS_t^{\alpha_{FF,gas}} Y_{o,t}^{\alpha_{FF,o}} \right)^{\frac{\sigma_E-1}{\sigma_E}} + (1-\alpha_{tff}) \tilde{B}_{e,t}^{\frac{\sigma_E-1}{\sigma_E}} \right]^{\frac{\sigma_E}{\sigma_E-1}}$$

$$\tilde{B}_{e,t} = \left[\alpha_{X,e} \tilde{X}_{e,t}^{\frac{\sigma_{Y,e}-1}{\sigma_{Y,e}}} + (1-\alpha_{X,e}) \left(\min_{n \in N} \left(\frac{\tilde{Y}_{ne,t}}{y_{ne}} \right) \right)^{\frac{\sigma_{Y,e}-1}{\sigma_{Y,e}}} \right]^{\frac{\sigma_{Y,e}}{\sigma_{Y,e}-1}}$$

The production of oil in the HK model corresponds to

$$\tilde{Y}_{o,t} = \min \left(\frac{CRU_t}{y_{cru}}, \frac{\tilde{B}_{o,t}}{y_{noncru}} \right)$$

$$\tilde{B}_{o,t} = \left[\alpha_{X,o} \tilde{X}_{o,t}^{\frac{\sigma_{Y,o}-1}{\sigma_{Y,o}}} + (1-\alpha_{X,o}) \left(\min_{n \in N} \left(\frac{\tilde{Y}_{no,t}}{y_{no}} \right) \right)^{\frac{\sigma_{Y,o}-1}{\sigma_{Y,o}}} \right]^{\frac{\sigma_{Y,o}}{\sigma_{Y,o}-1}}$$

3.2 Intermediate goods composite and intermediate goods

This section illustrates the main differences in both models. As already explained above, the intermediate goods are combined in the CITE model to an intermediate composite, whereas in the HK model, the intermediate good directly enters the production function of the final good. In this section, the aggregation to the intermediate composite in the CITE model as well as the resulting differences for the optimization problems of the intermediate good producers are explained.

In the CITE model, the intermediate goods composite Q_i is produced from a number of different intermediate goods x_{ij}. The amount of intermediate goods is assumed to equal the capital stock in each sector.

$$Q_{i,t} = \left[\sum_{j=1}^{K_{i,t}} x_{ij,t}^{\kappa} \right]^{\frac{1}{\kappa}}$$

As all intermediate goods x_{ij} are produced symmetrically with the same production structure, we can assume $x_{ij} = x_i$ and the above production function can be rewritten as

$$Q_{i,t} = K_{i,t}^{\frac{1}{\kappa}} x_{i,t} = K_{i,t}^{\frac{1-\kappa}{\kappa}} X_{i,t}$$

with

$$X_i = K_i x_i$$

The intermediate goods are assumed to be produced with labor, L_{ij}, non-accumulable capital, VK_{ij}, and energy, Y_e, according to

$$x_{ij,t} = \left[\alpha_{L,i} L_{ij,t}^{\frac{\sigma_{X,i}-1}{\sigma_{X,i}}} + \alpha_{VK,i} VK_{ij,t}^{\frac{\sigma_{X,i}-1}{\sigma_{X,i}}} + (1-\alpha_{L,i}-\alpha_{VK,i}) Y_{ex_{ij},t}^{\frac{\sigma_{X,i}-1}{\sigma_{X,i}}} \right]^{\frac{\sigma_{X,i}}{\sigma_{X,i}-1}}$$

The optimization of each x_{ij} producer yields the inverse demand functions

$$\frac{1}{\kappa}w_t = \alpha_{L,i} p_{x_{ij},t} \left(\frac{x_{ij,t}}{L_{ij,t}}\right)^{\frac{1}{\sigma_X}}$$

$$\frac{1}{\kappa}p_{VK,t} = \alpha_{VK,i} p_{x_{ij},t} \left(\frac{x_{ij,t}}{VK_{ij,t}}\right)^{\frac{1}{\sigma_X}}$$

$$\frac{1}{\kappa}p_{Y_e,t} = (1-\alpha_{L,i}-\alpha_{VK,i}) p_{x_{ij},t} \left(\frac{x_{ij,t}}{Y_{ex_{ij},t}}\right)^{\frac{1}{\sigma_X}}$$

where $\frac{1}{\kappa}$ denotes the markup over marginal costs. It is important to note that each x_{ij} has a constant quantity of production over time. Thus, the growth index of x_{ij} equals one.

In comparison, the HK model includes only one intermediate good per sector, $\tilde{X}_i$, which grows at the rate of its inputs. Of these inputs, the growth rates of VK_i and L_i are exogenously given. Therefore, all growth dynamics depend on the growth rates of these inputs. The production function for the intermediate good is given as

$$\tilde{X}_{i,t} = \left[\alpha_{L,i} L_{i,t}^{\frac{\sigma_{X,i}-1}{\sigma_{X,i}}} + \alpha_{VK,i} VK_{i,t}^{\frac{\sigma_{X,i}-1}{\sigma_{X,i}}} + \alpha_{K,i} K_{i,t}^{\frac{\sigma_{X,i}-1}{\sigma_{X,i}}} + (1-\alpha_{L,i}-\alpha_{VK,i}-\alpha_{K,i}) Y_{e\tilde{X}_i,t}^{\frac{\sigma_{X,i}-1}{\sigma_{X,i}}}\right]^{\frac{\sigma_{X,i}}{\sigma_{X,i}-1}} \quad (2)$$

The intermediate good $\tilde{X}_i$ of the HK model is comparable to X_i in the CITE model. However, there exist some crucial differences. First of all, capital is used directly in the production function of $\tilde{X}_i$. Second, the total amount of $L_{i,t}$, $VK_{i,t}$, and $Y_{e\tilde{X}_i,t}$ in the HK model must equal the sum of each used by the intermediate good producers in the CITE model in the first period:

$$L_{i,0} = \sum_j L_{ij,0}$$

$$VK_{i,0} = \sum_j VK_{ij,0}$$

$$Y_{e\tilde{X}_i,0} = \sum_j Y_{ex_{ij},0}$$

The most important distinction between $\tilde{X}_i$ and X_i lies in the dynamics. These are different because the inputs in the HK model exogenously grow over time whereas they remain constant in the CITE model.

The maximization problem for the intermediate good producer in the HK model is

$$\max_{L_{i,t},VK_{i,t},K_{i,t},Y_{e\tilde{X}_i,t}} p_{\tilde{X}_i,t}\tilde{X}_{i,t} - w_t L_{i,t} - p_{VK,t} VK_{i,t} - p_{K,t} K_{i,t} - p_{Y_e,t} Y_{e\tilde{X}_i,t}$$

s.t. (2). The resulting inverse demand functions are

$$w_t = \alpha_{L,i} p_{\tilde{X}_i,t} \left(\frac{\tilde{X}_{i,t}}{L_{i,t}}\right)^{\frac{1}{\sigma_X}}$$

$$p_{VK,t} = \alpha_{VK,i} p_{\tilde{X}_i,t} \left(\frac{\tilde{X}_{i,t}}{VK_{i,t}}\right)^{\frac{1}{\sigma_X}}$$

$$p_{K,t} = \alpha_{K,i} p_{\tilde{X}_i,t} \left(\frac{\tilde{X}_{i,t}}{K_{i,t}}\right)^{\frac{1}{\sigma_X}}$$

$$p_{Y_e,t} = (1-\alpha_{L,i}-\alpha_{VK,i}) p_{\tilde{X}_i,t} \left(\frac{\tilde{X}_{i,t}}{Y_{e\tilde{X}_i,t}}\right)^{\frac{1}{\sigma_X}}$$

Comparing the FOCs of the intermediate producer(s) in both models, it is striking that in the CITE model, each intermediate good producer can charge a mark-up on the marginal costs. As in the HK model, we assume competitive markets in which prices always equal marginal costs.

3.3 Consumption

The intertemporal allocation of factors is optimized in both models by a representative household that maximizes utility having perfect foresight. Utility U is drawn from a consumption good C and is discounted at the rate ρ over time. The utility function of the household is identical in the models:

$$U = \sum_{t=0}^{\infty} \left(\frac{1}{1+\rho}\right)^t \frac{C_t^{1-\theta} - 1}{1-\theta}$$

Consumption consists of two goods, energy Y_{ec} and a final good composite C_S composed of the final goods of the regular sectors.

$$C_t = \left[(1-\beta) C_{S,t}^{\frac{\sigma_C - 1}{\sigma_C}} + \beta Y_{ec,t}^{\frac{\sigma_C - 1}{\sigma_C}}\right]^{\frac{\sigma_C}{\sigma_C - 1}} \tag{3}$$

$$C_{S,t} = \prod_{n \in N} Y_{nc,t}^{\beta_{NE,n}}$$

Hereby, Y_{nC} denotes the part of the final output of sector n that is used for consumption. $\beta_{NE,n}$ is the value share of final good n in the composite $C_{S,t}$ and the sum of these shares, $\sum_{n \in N} \beta_{NE,n}$, adds up to one to assume constant returns to scale. The budget constraint of the household in both models equals

$$\begin{aligned} p_{V,t+1} V_{t+1} = &(1 + r_{t+1}) p_{V,t} V_t + w_t L_t + w_{R,t} RL_t + p_{VK,t} VK_t \\ &- p_{Y_e,t} Y_{ec,t} - \sum_{n \in N} p_{Y_n,t} Y_{nc,t} - \sum_{i \in I} p_{V,t} I_{i,t} \end{aligned}$$

The household is able to hold assets V on the capital market, which includes that total investments made by the household must equal investments in physical and in non-physical capital, $I_{i,t} = I_{P_i,t} + I_{NP_i,t}$. Energy is assumed to be an endowment of the household, and therefore income from energy goes to the consumer.

3.4 Demand for the intermediate good

To gain a better understanding of the growth dynamics, we need to consider the transmissibility of the models from the intermediate good(s) to the final output. The intuition behind this is that we want to know how and to what extent dynamics from intermediate good(s) influence the dynamics of the intermediate goods composite in the CITE model and then, for both models, the influence on final output. To keep the analysis as simple as possible, we only consider the output of regular sectors.

Because the producer of the intermediate goods composite in the CITE model needs intermediate goods to produce, the demand function for each intermediate good is

$$x_{nj,t} = \left(\frac{p_{Q_n,t}}{p_{x_{nj},t}}\right)^{\frac{1}{1-\kappa}} Q_{n,t}$$

Since all intermediate goods are symmetric, we can assume that $X_n = K_n x_n$, and thus the above equation equals

$$\frac{X_{n,t}}{K_{n,t}} = \left(\frac{p_{Q_n,t}}{p_{x_{nj},t}}\right)^{\frac{1}{1-\kappa}} Q_{n,t}$$

Rearranging yields the inverse demand function for X_n by the producer of the intermediate composite

$$p_{Q_n,t} = \left(\frac{X_{n,t}}{K_{n,t} Q_{n,t}}\right)^{1-\kappa} p_{x_{nj},t}$$

To make the above equation comparable to the corresponding one in the HK model, we also need to take account of the prices. Due to the relation $X_n = K_n x_n$, we know that $p_{X_n} = K_n p_{x_n}$ must also hold. This yields for $p_{Q_n,t}$

$$p_{Q_n,t} = \left(\frac{X_{n,t}}{K_{n,t}Q_{n,t}}\right)^{1-\kappa} \frac{p_{X_n,t}}{K_{n,t}} \tag{4}$$

The intermediate composite is demanded by the producer of the final good. The inverse demand function of the latter for Q_n is

$$p_{Q_n,t} = p_{Y_n,t}\alpha_{X,n} \left(\frac{Y_{n,t}}{Q_{n,t}}\right)^{\frac{1}{\sigma_{Y,n}}} \tag{5}$$

By inserting (5) in (4) and by rearranging we get for $p_{X_n,t}$

$$p_{X_n,t} = p_{Y_n,t}\alpha_{X,n} \left(\frac{Y_{n,t}}{Q_{n,t}}\right)^{\frac{1}{\sigma_{Y,n}}} K_{n,t} \left(\frac{K_{n,t}Q_{n,t}}{X_{n,t}}\right)^{1-\kappa}$$

The intermediate composite does not exist in the HK model. Accordingly, we need to replace Q_n in the above equation by $Q_{n,t} = K_{n,t}^{\frac{1-\kappa}{\kappa}} X_{n,t}$. This yields for the inverse demand for X_n by the final good producer Y_n

$$p_{X_n,t} = p_{Y_n,t}\alpha_{X,n} \left(\frac{Y_{n,t}}{X_{n,t}}\right)^{\frac{1}{\sigma_{Y,n}}} K_{n,t}^{\frac{1}{\kappa} - \frac{1-\kappa}{\kappa}\frac{1}{\sigma_{Y,n}}} \tag{6}$$

A comparable relation can be derived in the HK model by the optimization of the final good producer. She maximizes

$$\max_{\tilde{X}_{n,t}Y_{n'n,t}} p_{\tilde{Y}_n,t}\tilde{Y}_{n,t} - p_{\tilde{X}_n,t}\tilde{X}_{n,t} - \sum_{n' \in N} p_{Y_{n'},t}Y_{n'n,t}$$

subject to (1).

The resulting inverse demand function is

$$p_{\tilde{X}_n,t} = p_{\tilde{Y}_n,t}\alpha_{X,n} \left(\frac{\tilde{Y}_{n,t}}{\tilde{X}_{n,t}}\right)^{\frac{1}{\sigma_{Y,n}}} \tag{7}$$

If we compare equations (6) and (7), we can see that the demand for $\tilde{X}_n$ depends in the HK model only on the prices of $\tilde{Y}_n$ and of $\tilde{X}_n$, the parameter $\alpha_{X,n}$ and the quantity of output, $\tilde{Y}_n$. In the CITE model, however, the demand also depends on the capital stock, which renders the demand even more dynamic.

From these equations, we can see that the dynamics of X_n are transmitted in both models to final output production. Although this seems to be similar, there are different dynamics hidden within. In the HK model, $\tilde{X}_n$ grows exogenously at a constant rate. In the CITE model, X_n grows endogenously at the same rate as capital. Therefore, the stock of capital enters the demand function (6) twice, once directly via K_n and again indirectly via X_n. To show this effect of the CITE model more explicitly, we consider the demand or the output producer for an intermediate good x_n. Therefore, we assume again $X_n = K_n x_n$, which yields for the inverse demand function

$$p_{X_n,t} = p_{Y_n,t}\alpha_{X,n} \left(\frac{Y_{n,t}}{x_{n,t}}\right)^{\frac{1}{\sigma_{Y,n}}} K_{n,t}^{\frac{1}{\kappa}\left(1-\frac{1}{\sigma_{Y,n}}\right)} \tag{8}$$

In the above equation, x_i does not grow and the influence of capital dynamics can directly be seen.

For a comparison with the HK model, we need to assume two artificial variables that do not exist in the model. First, we know that capital is an input to the production of the intermediate good with an elasticity of substitution smaller than 1. As a result, capital grows on a balanced growth rate that is always the same rate as the exogenously growing inputs. We therefore assume D_t being the size of capital in the first period that grows at the exogenously given rate grk.

$$D_t = K_{n,0}(1 + grk)^t$$

Second, we assume that $\tilde{X}_{n,t}$ can be split in a number of $x_{n,t}$, which together equal $\tilde{X}_{n,t}$:

$$\tilde{X}_{n,t} = x_{n,t}D_t = x_{n,t}K_{n,0}(1 + grk)^t$$

If we insert this in (7) we get

$$p_{X_n,t} = p_{Y_n,t}\alpha_{X,n}\left(\frac{Y_{n,t}}{x_{n,t}}\right)^{\frac{1}{\sigma_{Y,n}}} D_t^{-\frac{1}{\sigma_{Y,n}}} \tag{9}$$

The comparison of equations 8 and 9 shows exactly the point at which capital growth enters the demand functions. In the HK model, the exogenously growing capital stock enters the demand function with an exponent of $-\frac{1}{\sigma_{Y,n}}$ (the growth of the capital stock depends on the exogenously given growth rate of inputs on a balanced growth path). In the CITE model, the capital stock enters the demand function with a different exponent $\frac{1}{\kappa}\left(1-\frac{1}{\sigma_{Y,n}}\right)$. Also, the size of the capital stock is subject to endogenous dynamics.

3.5 Capital formation and incentives to invest

This section shows how the demand functions calculated above translate to capital formation and to incentives to invest on a balanced growth path. Capital formation is identical in the models. Capital is produced through investments in physical and non-physical capital, the latter itself being a function of labor in research and investments in R&D.

$$I_{NP_{ij},t} = \left[\gamma_{N,i} RL_{ij,t}^{\frac{\sigma_{N,i}-1}{\sigma_{N,i}}} + (1-\gamma_{N,i}) I_{R\&D_{ij},t}^{\frac{\sigma_{N,i}-1}{\sigma_{N,i}}}\right]^{\frac{\sigma_{N,i}}{\sigma_{N,i}-1}}$$

$$K_{ij,t+1} = \left[\gamma_i I_{P_{ij},t}^{\frac{\sigma_{I,i}-1}{\sigma_{I,i}}} + (1-\gamma_i) I_{NP_{ij},t}^{\frac{\sigma_{I,i}-1}{\sigma_{I,i}}}\right]^{\frac{\sigma_{I,i}}{\sigma_{I,i}-1}} + (1-\delta)K_{ij,t}$$

After optimization for investments in physical capital (the same calculation can be done for investments in non-physical capital) we have

$$p_{Y_n,t} = p_{K_n,t+1}\gamma_n\left(\frac{\triangle\, K_{n,t+1}}{I_{P_n,t}}\right)^{\frac{1}{\sigma_{I,n}}}$$

If we insert the above equation in (8) for the CITE model we arrive at the magnitude of optimal investments in physical capital in both models. In the CITE model, investments are equal to

$$I_{P_n,t} = p_{X_n,t}^{-\sigma_{I,n}}\left(p_{K_n,t+1}\gamma_n\alpha_{X,n}K_{n,t}^{\frac{1}{\kappa}\left(1-\frac{1}{\sigma_{Y,n}}\right)}\right)^{\sigma_{I,n}}\left(\frac{Y_{n,t}}{x_{n,t}}\right)^{\frac{\sigma_{I,n}}{\sigma_{Y,n}}}\triangle\, K_{n,t+1}$$

Similarly, for the HK model we arrive at

$$I_{P_n,t} = p_{X_n,t}^{-\sigma_{I,n}}\left(p_{K_n,t+1}\gamma_n\alpha_{X,n}D_t^{-\frac{1}{\sigma_{Y,n}}}\right)^{\sigma_{I,n}}\left(\frac{Y_{n,t}}{x_{n,t}}\right)^{\frac{\sigma_{I,n}}{\sigma_{Y,n}}}\triangle\, K_{n,t+1}$$

Investments depend on, among others, the aspired growth in capital. As the capital stock in the HK model evolves with an exogenously given growth rate on a balanced growth path, we can rewrite $\triangle\, K_{n,t+1}$ as

$$\triangle\, K_{n,t+1} = K_{n,t+1} - K_{n,t} = K_{n,0}((1+grk)^{t+1} - (1+grk)^t) = K_{n,0}(1+grk)^t grk$$

Using this in the optimal function for physical investments in the HK model, investment incentives become equal to

$$I_{P_n,t} = p_{X_n,t}^{-\sigma_{I,n}}\left(p_{K_n,t+1}\gamma_n\alpha_{X,n}D_t^{-\frac{1}{\sigma_{Y,n}}}\right)^{\sigma_{I,n}}\left(\frac{Y_{n,t}}{x_{n,t}}\right)^{\frac{\sigma_{I,n}}{\sigma_{Y,n}}} D_t\; grk$$

In the HK model, capital enters as an exogenously defined variable. Investment incentives are given by the growth rate of inputs on a balanced growth path. In the CITE model, however, investment incentives are derived from the stock of capital and the absolute increase of capital, which are both derived endogenously. The investment decision in the CITE model evolves entirely from the optimization results from market participants. Depending on the monopolistic power of the producers of intermediate goods (thus, how large κ is), the incentives to invest change. If the Chamberlinian large group assumption yields that each producer of an intermediate good can charge a large markup on the cost (thus, if κ is small), the incentives to innovate and therefore to accumulate capital rise. If the markup on the cost is small (thus if κ is large), the incentives to innovate and investments in capital fall.

3.6 Growth indices

Another way to look at the dependency of the growth rate of output on the model setups is to regard the growth indices. From the capital accumulation equation, we know that the growth index of capital is in both models equal to

$$g_{K_i} = \frac{K_{i,t+1}}{K_{i,t}} = \frac{\left[\gamma_i I_{P_i,t}^{\frac{\sigma_{I,i}-1}{\sigma_{I,i}}} + (1-\gamma_i) I_{NP_i,t}^{\frac{\sigma_{I,i}-1}{\sigma_{I,i}}}\right]^{\frac{\sigma_{I,i}}{\sigma_{I,i}-1}}}{K_{i,t}} + (1-\delta)$$

In the CITE model, the growth index of final goods equals to the growth index of the intermediate composite good, which in turn is

$$g_{Y_i} = g_{K_i}^{\frac{1}{\kappa}} \; g_{x_i} = g_{K_i}^{\frac{1}{\kappa}}$$

as the production of each intermediate good stays constant over time. We can see that the growth of output in the CITE model completely depends on the growth of capital. In the HK model, the growth index of output equals the growth index of $\tilde{X}_i$. We can therefore write

$$g_{Y_i} = g_{\tilde{X}_i}$$

Consequently, in the HK model, output grows at the same rate as capital, $(1+grk)$, and in the CITE model, output grows at a higher rate than capital $(1+gr) = (1+grk)^{\frac{1}{\kappa}}$. In other words, the growth of the intermediate good in the HK model completely determines the growth rate of output.

4 Calibration of the models

The models are calibrated according to the input-output table of the Swiss economy. The latter provides information about the intermediate demands as well as the sectoral share in investments and consumption. Additionally, labor and capital as inputs to production are displayed.

This section gives some information about the calibration of the CITE model and of the HK model with which it is compared. Moreover, the calibration of the HK model is then modified and the capital stock is defined differently. This calibration of the HK model without non-accumulable capital is then compared to the calibration with non-accumulable capital in the next section. The comparison is done to give an intuition of the importance of capital calibration and contributes to a better understanding of the effects of the capital calibration in the CITE model.

The capital stocks of the CITE model and of the HK model with non-accumulable capital are calibrated by dividing the capital stock from the input-output table in two parts. The definition of capital is based upon the assumption that the size of the capital stock has a significant influence on the growth rate in the CITE model. The non-accumulable capital is the difference between the calibrated capital stock and the capital stock from the input-output table. In the calibration without non-accumulable capital, the capital stocks in the HK model are fully congruent with the capital stock in the input-output table.

For the comparison of the relations in Table 1, it must be taken into account that X_i is defined differently in the CITE model than in the HK model. In the CITE model, X_i is produced using labor, energy, and non-accumulable capital. The capital stock is needed exclusively as a precondition to produce X_i and is thus not included in the calculation of X_i from the input-output table. On the contrary, in the HK model, capital is a direct input to the production of the intermediate good and is therefore also included in the calculation of the intermediate good. This difference in the definitions is essential for interpreting the capital, energy, and labor shares.

If we regard the relation of energy to final output Y_i in the sectoral production in Table 1, it is striking that the energy sector has by far the largest share (38%). The sectors agriculture and transport follow only with a large gap (4% and 5%, respectively). The oil, banking, and insurance industries have the smallest share of energy in final output. Comparing the sectoral shares of energy in the production of the intermediate good, a similar picture emerges. The different energy intensities of the sectors result in divers sensitivities of the sectors to energy policies. However, the size and the dynamics of the capital stocks also strongly influence the economic consequences of policies.

Thus, the capital stocks are defined differently in the calibrations. The CITE model and the calibration with non-accumulable capital have a smaller capital stock compared to the calibration without non-accumulable capital (VK). This distinction is also reflected in the relations in Table 1. In the calibration with VK, the capital stock constitutes by definition 25% of the value of the intermediate good. Comparing this with the calibration without VK, we can see that the latter calibration has much higher shares of capital in X_i in some sectors (e.g., oil, chemical, and agriculture), while in other sectors the shares remain almost the same (such as in construction and health). The difference, VK, therefore varies greatly (between 1% and 39%).

The accumulation of the capital stock drives growth and determines the dynamics of X_i in the CITE model. Hence, a comparison of X_i to final output gives an intuition to what extent the intra-sectoral growth dynamics contribute to the development of a sector. In the CITE model, the sectoral shares of X_i to final output Y_i varies considerably between 6% in the oil sector and 54% in the health sector. Accordingly, the health sector can rely on strong intra-sectoral dynamics, whereas the oil industry mainly depends on the dynamics of other sectors and of imported crude oil. In comparison, the share of the intermediate good in final output in the HK models is distributed even more unevenly. The share in the oil industry is as low as 9%, whereas the health sector needs the intermediate good for as much as 72% of final output.

The relation of the intermediates to final output also affects the share of capital to final output. In the CITE model and the calibration with VK, the shares are the highest in the sectors of energy, banking, health, and other services. A structurally different result emerges if we consider the calibration without VK. Here, the sectors of agriculture, chemical, banking, and other services have the highest capital share.

Concerning the shares of labor in X_i, the different calibrations have a similar distribution. The construction and the health sector have the largest shares. On the contrary, the energy sector has by far the smallest share of labor in the intermediate production.

5 Influence of the size of the capital stock

The CITE model as well as the calibration with VK of the HK model have capital stocks that are not congruent with the capital stock in the Swiss input-output table. The reason for adapting the capital stocks is that they must fulfill certain conditions in the CITE model. As a consequence, the capital stocks in the calibration with VK have also been adjusted to ensure the comparability of the dynamics of both models.

The modification of the capital stocks results in smaller capital stocks that are subject to investments. This change affects different dynamics. This section aims to give an intuition for the impact of a quantitative change in the capital stock. Two calibrations of the HK model are compared with the focus on dynamics. One calibration has the same capital stock as the CITE model, and the other incorporates a capital stock that is identical to the input-output table. These assumptions about the capital stocks are the only differences in the calibrations. Therefore, all changes in dynamics are the result of different calibrations of the capital stocks.

The dynamics of the sectoral outputs after the introduction of a tax on carbon follow different patterns in the two calibrations (Figures 1 and 2). In the calibration with non-accumulable capital, the output of most sectors show only limited reactions. They vary by less than 1% compared to the benchmark. The two exceptions are the energy and the oil sector, which drop by 4.3% and 6.2%, respectively. Since the carbon tax is tied to the output of the oil sector and to imported gas, and since both are used in the energy sector, this result is not surprising.

In comparison to these effects, the response of the industries in the calibration without VK is more dynamic. Most sectors show a small sensitivity to the carbon tax (again with the exceptions being energy and the oil industry). However, the production of some industries needs a long time to adapt to the new situation and varies more than in the other calibration. For example, the chemical industry continues to grow over the total time horizon and has even then not yet reached a new balanced growth path. The effect of the tax on this sector is very strong, as it still grows by more than 2% in the last period. Another interesting industry is the machinery and equipment sector, which has a larger output in the

		AGR	OIL	CHM	MCH	EGY	CON	TRN	BNK	INS	HEA	OSE	OIN
E/Y		0.04	0.00	0.01	0.01	0.38	0.02	0.05	0.00	0.00	0.01	0.01	0.03
E/X	CITE	0.10	0.04	0.04	0.03	0.82	0.05	0.13	0.01	0.01	0.02	0.03	0.08
E/X	NK with & w/o VK	0.08	0.03	0.03	0.02	0.62	0.04	0.10	0.00	0.01	0.02	0.02	0.06
K/X	NK with VK	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
K/X	NK w/o VK	0.58	0.64	0.64	0.31	0.31	0.26	0.31	0.43	0.40	0.26	0.39	0.32
VK/X	NK with VK	0.33	0.39	0.39	0.06	0.06	0.01	0.06	0.18	0.15	0.01	0.14	0.07
X/Y	CITE	0.36	0.06	0.32	0.28	0.47	0.38	0.35	0.50	0.28	0.54	0.49	0.30
X/Y	NK with & w/o VK	0.48	0.09	0.42	0.37	0.62	0.51	0.47	0.67	0.38	0.72	0.65	0.40
K/Y	CITE & NK with VK	0.12	0.02	0.11	0.09	0.16	0.13	0.12	0.17	0.09	0.18	0.16	0.10
K/Y	NK w/o VK	0.28	0.05	0.27	0.12	0.19	0.13	0.15	0.29	0.15	0.19	0.26	0.13
VK/Y	CITE & NK with VK	0.16	0.03	0.17	0.02	0.04	0.01	0.03	0.12	0.06	0.01	0.09	0.03
L/X	CITE	0.46	0.44	0.44	0.89	0.10	0.94	0.79	0.75	0.79	0.96	0.78	0.83
L/X	NK with & w/o VK	0.35	0.33	0.33	0.67	0.08	0.70	0.59	0.56	0.60	0.72	0.59	0.62

Table 1: Specific relations in the models. The sectoral abbreviations are AGR - agriculture; OIL - oil; CHM - chemistry - MCH - machinery; EGY - energy; CON - construction; TRN - transport; BNK - banking; INS - insurance; HEA - health; OSE - other services; OIN - other industries.

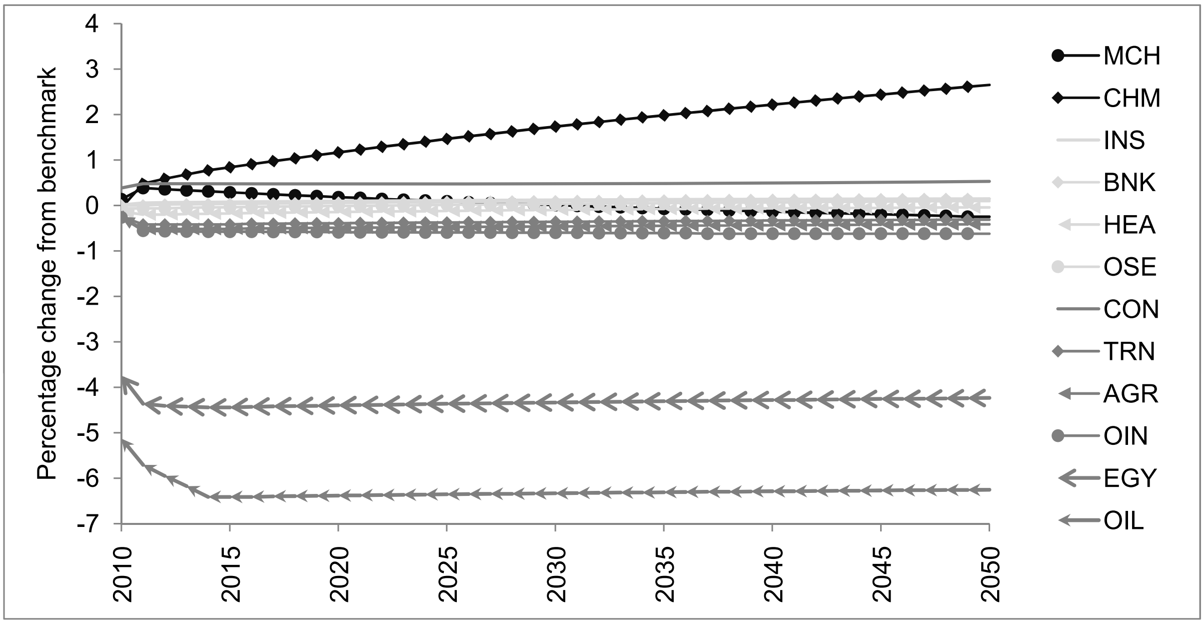

Figure 1: Sectoral outputs in the HK model without VK.

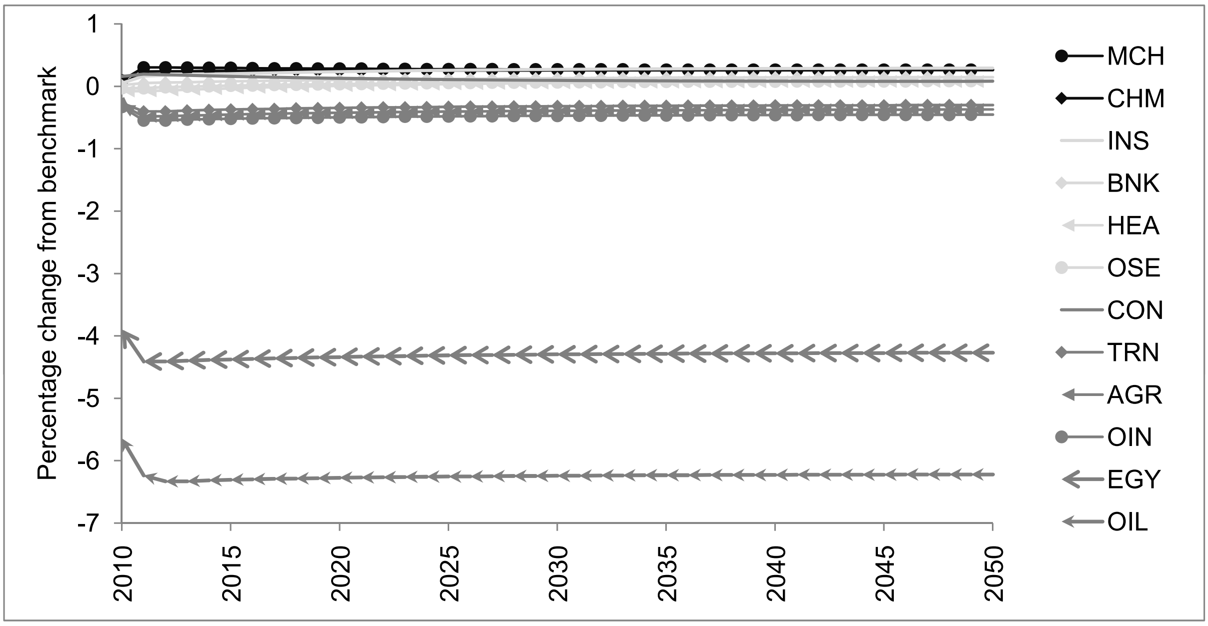

Figure 2: Sectoral outputs in the HK model.

periods after the introduction of the tax and then shrinks so much that at the end of the time horizon, output is smaller than in the benchmark.

The distinctive dynamics of the sectors in the two calibrations result from different evolutions of the capital stocks. Figures 3 and 4 depict the sectoral capital stocks and their development over time. The dynamics are comparable to those of final production. Because capital is an important input to the production of the intermediate good and is crucial for its dynamics, the behavior of output is also heavily influenced. Due to the larger capital stock in the calibration without non-accumulable capital, the adaptation to the new balanced growth path needs more time for both the capital stock and the final output.

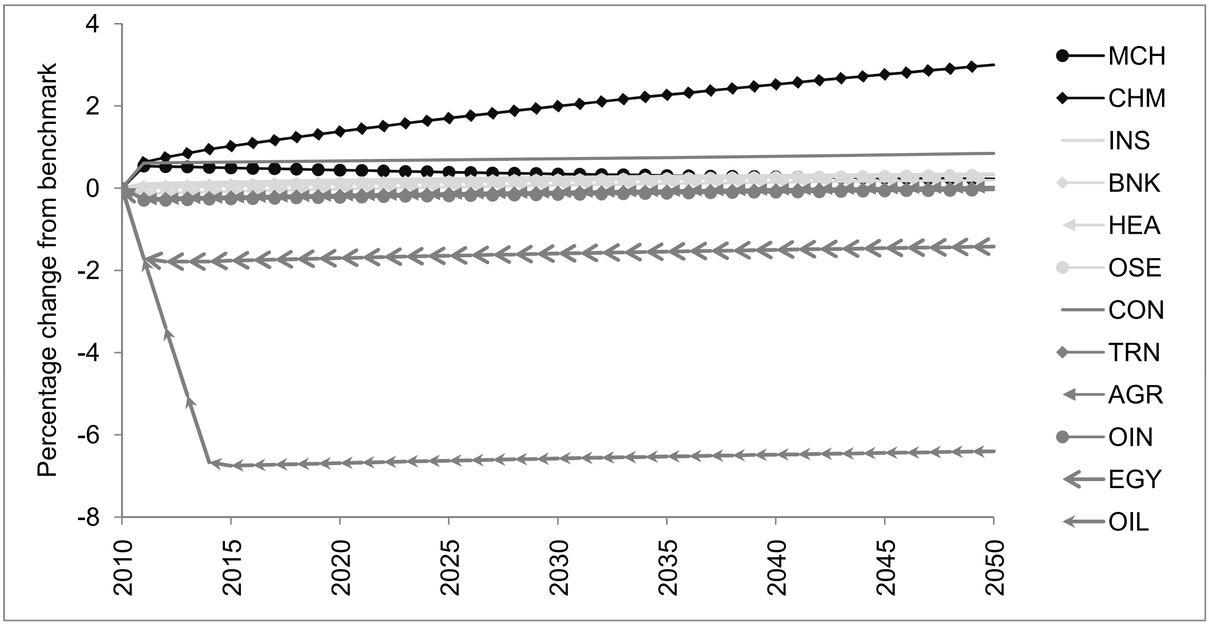

Figure 3: Capital stocks in the HK model without VK.

6 Dynamic of the CITE and a HK growth model

The dynamics of the CITE model are based on gains from specialization that rise with an increasing capital stock. This section compares these dynamics with those of a HK model with exogenous growth. The capital stock of this model is calibrated identically to that of the CITE model to ensure that the differences in the dynamics arise only from the general growth dynamics and not from the quantitative difference of the capital stocks. The center of interest is the effects of the different investment incentives on intertemporal dynamics and structural change.

The policy scenario is based on a carbon tax that is based on the carbon intensity of the output of the oil sector and of imported gas. The tax on gas amounts to 8% of the price in the first period, and thereafter the absolute value remains constant over time. As oil contains 34% more carbon than gas, the tax is initially 10.72% and then stays constant. The revenues from the tax are redistributed with a subsidy on R&D that goes to all sectors except the oil sector. The amount each sector gets is optimized during the simulations.

6.1 Effects on production, capital, and consumption

After the introduction of a carbon tax, all sectors in the economy must adjust to the new situation. The tax increases the prices of fossil fuels, which directly affects production and investments.

The reaction of final output in the CITE model differs considerably from that in the HK model in three regards (Figures 5 and 2). First, the effects of the tax are in most sectors very small in the HK model; their production changes only less than 1% compared to the benchmark case. Only the energy and the oil sector show a strong reduction in output (4.3% and 6.2%, respectively). On the contrary, in the CITE model, most of the sectors react in a more pronounced way, which leads to a larger spread in the figure. The production of the energy and the oil sector decreases even more, whereas the machinery sector gains and has an increased production of 2.6% in the last period. This positive reaction is at least partly ascribable to the small energy share of the machinery sector. The direct effects of the carbon tax are hence limited. Other sectors have large energy shares, such as the sectors of agriculture and other industries and suffer more because of the tax. Additionally, the machinery sector has a high elasticity of substitution between energy and other inputs for the production of intermediate goods. The production of the agriculture industry decreases by 1.4%, and output of other industries drops by 1.7%.

The second difference between the two models is the speed in which the sectors approach a new balanced growth path after the introduction of a carbon tax. The adaptation lasts much longer in the CITE model than in the HK model with non-accumulable capital (HKwVK); indeed, it takes decades for

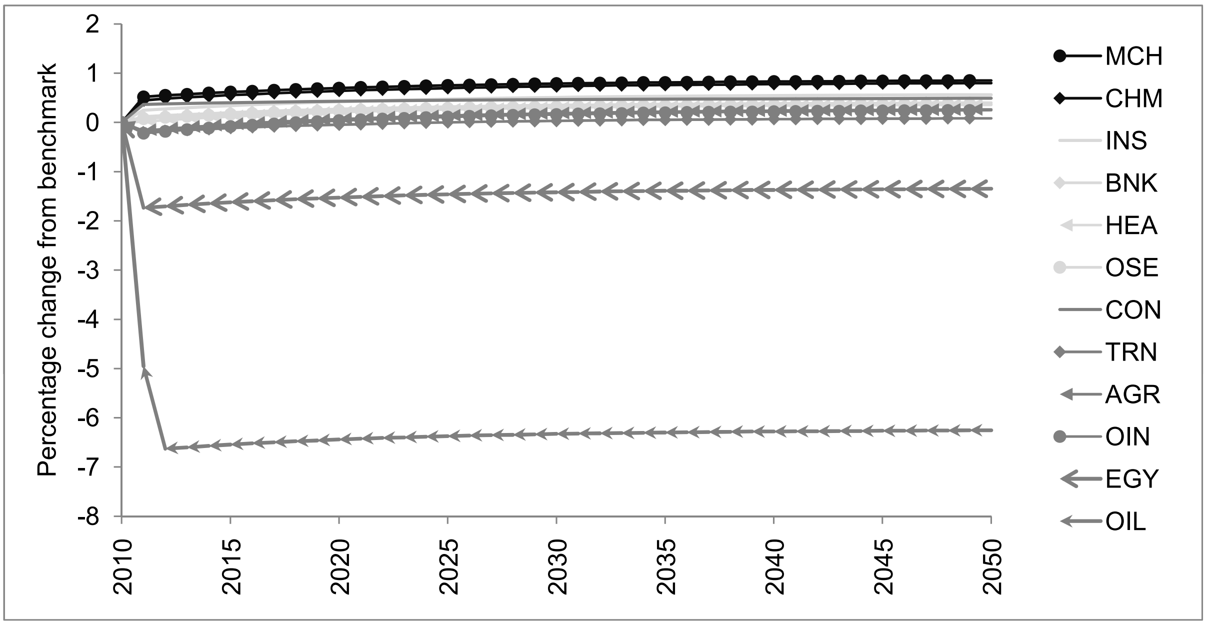

Figure 4: Sectoral capital stocks in the HK model.

the sectors to adjust to the new situation. In the HKwVK, all industries reach the new balanced growth path very quickly and then remain there for the rest of the time horizon. This difference in the dynamics results from the fact that only labor and non-accumulable capital can substitute for energy in the CITE model. This yields limited possibilities to adapt, so the industries need to invest in capital to increase their productivity. The slow adjustment is due to the fact that capital accumulation takes time. In the HKwVK, capital can additionally and immediately substitute for energy, which results in a fast change of the composition of inputs to production. As a consequence, the level of production adjusts very quickly to the tax. On the other hand, capital cannot, as in the CITE model, enhance total productivity of the intermediate good.

The third main distinction concerns the structural composition of the economy. The sectoral reactions to the carbon tax are different in the models, which yields different relations of the sizes of the industries. In the CITE model, the machinery and equipment sector benefits most from the tax. This sector has a small energy share and also a relatively small share of capital in final output. Due to these conditions, the machinery sector can react very flexibly to the tax. The impact on costs is very limited because energy costs are only a small fraction of total costs. Additionally, the small share of capital enables the sector to proportionately increase its capital share with relatively small investments. These investments, in turn, contribute to higher productivity, which overcompensates for the increase in energy prices. This mechanism is not possible in the HKwVK. Here, the machinery sector can only substitute capital for energy, but cannot increase the total productivity of the intermediate good. As the elasticity of substitution is lower than 1, the possibility of using capital instead of energy is limited. As a result, the machinery sector does not increase production in the HKwVK as much as in the CITE model.

The consequences of the difference in the growth dynamics can also be seen in other sectors. The insurance industry, for example, decreases production initially in the CITE model and then intensifies production over time due to an increase of the capital stock. At the end of the time period, output is slightly above the benchmark level. In the HKwVK, however, output rises directly after the introduction of the tax and remains high, so that at the end of the time frame, the insurance sector has the largest rise of output.

Since the development of production is tightly connected to the evolution of capital, all three dissimilarities can also be seen there (Figures 6 and 4). First, the spread of the capital stock is much larger in the CITE model. Second, the time until the capital stocks reach the new balanced growth path is longer in the CITE model. Finally, the structural composition of the sectoral capital stocks changes. Additionally, the evolution of the capital stock of the energy sector is very interesting. In the HKwVK, the capital stock behaves similarly to the output. Both strongly decrease compared to the benchmark. In the CITE model, however, we can see that the capital stock is even higher in the new balanced growth

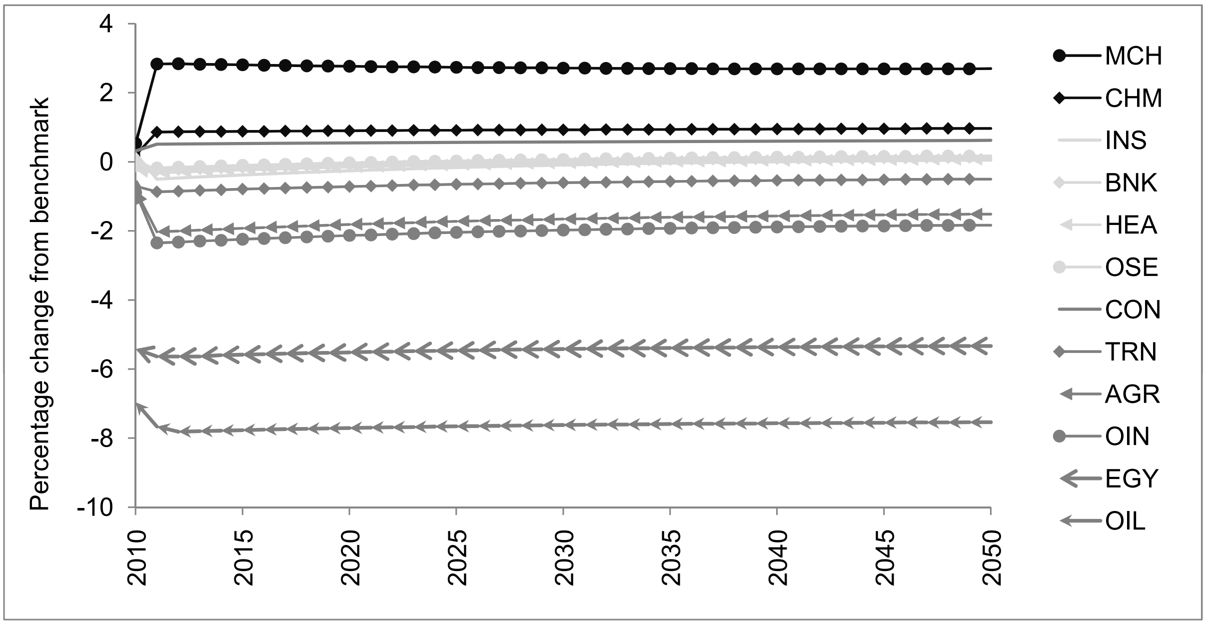

Figure 5: Sectoral outputs in the CITE model.

path than in the benchmark. This observation shows again the difference in the investment incentives in the two models.

The changing combination of inputs to production also influences on the demand for other inputs than capital, such as fossil fuels (Figures 7 and 8). The imports of crude oil and gas decrease more in the CITE model than in the HK model. Crude oil drops in the CITE model by 7.5% at the end of the time horizon, which is 1.2% more than in the HKwVK. The difference in gas importation is smaller at about 0.5%.

After the introduction of a carbon tax, the production structure of the economy changes in both models. Despite these changes, the negative consequences for consumption and welfare remain very limited (Figures 9 and 10). Although consumption initially falls by around 0.4% and 0.16% in the CITE

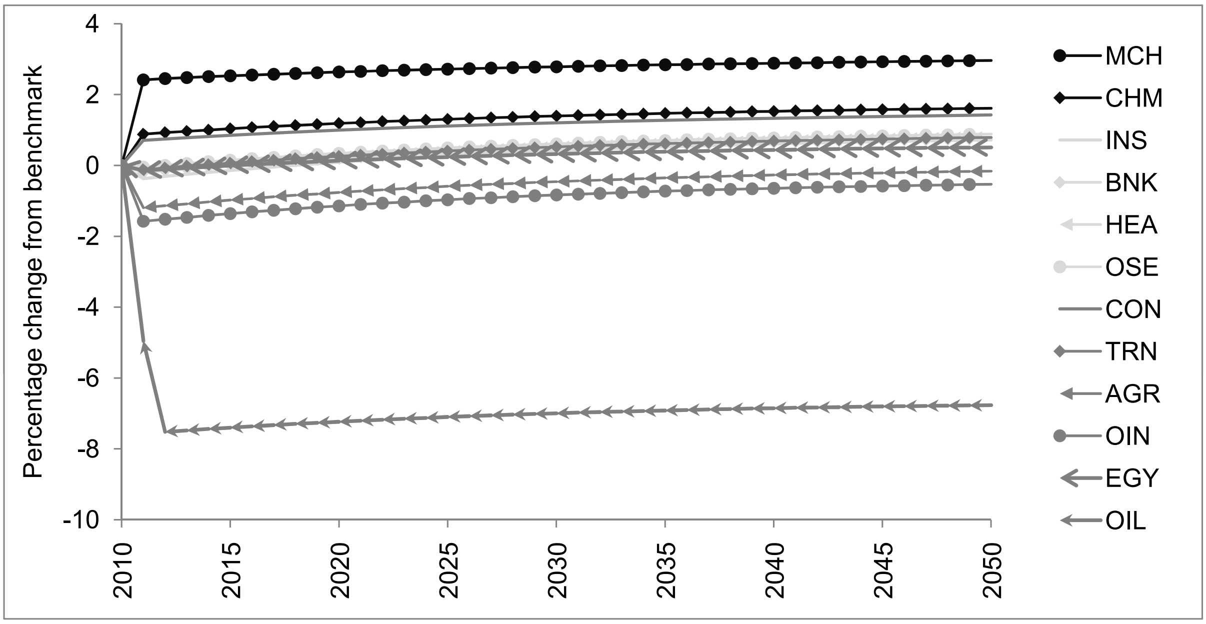

Figure 6: Sectoral capital stocks in the CITE model.

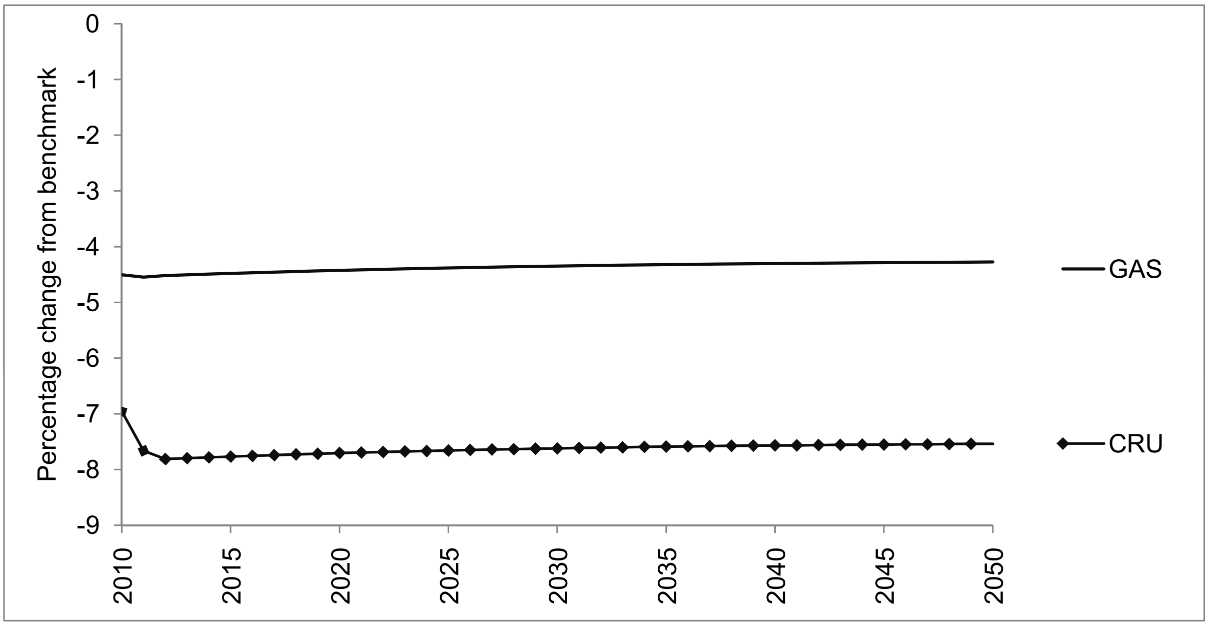

Figure 7: Import of fossil fuels in the CITE model.

and the HKwVK, respectively, it quickly recuperates and is in the last period only slightly below the benchmark level. Welfare is very similar in both models and decreases only slightly (less than 1%) compared to the benchmark.

6.2 Effects on endowments

The consequences of a carbon tax for labor is structurally similar to output in both models (Figures 11 and 12). The spread of demand for labor is larger in the CITE model than in the HK model. The demand in both models needs some time to adapt, although the CITE model shows a longer time period for adaption in most sectors (except for the chemical industry and the construction sector). The main difference compared to output is the behavior of the energy sector in the CITE model, which has a very

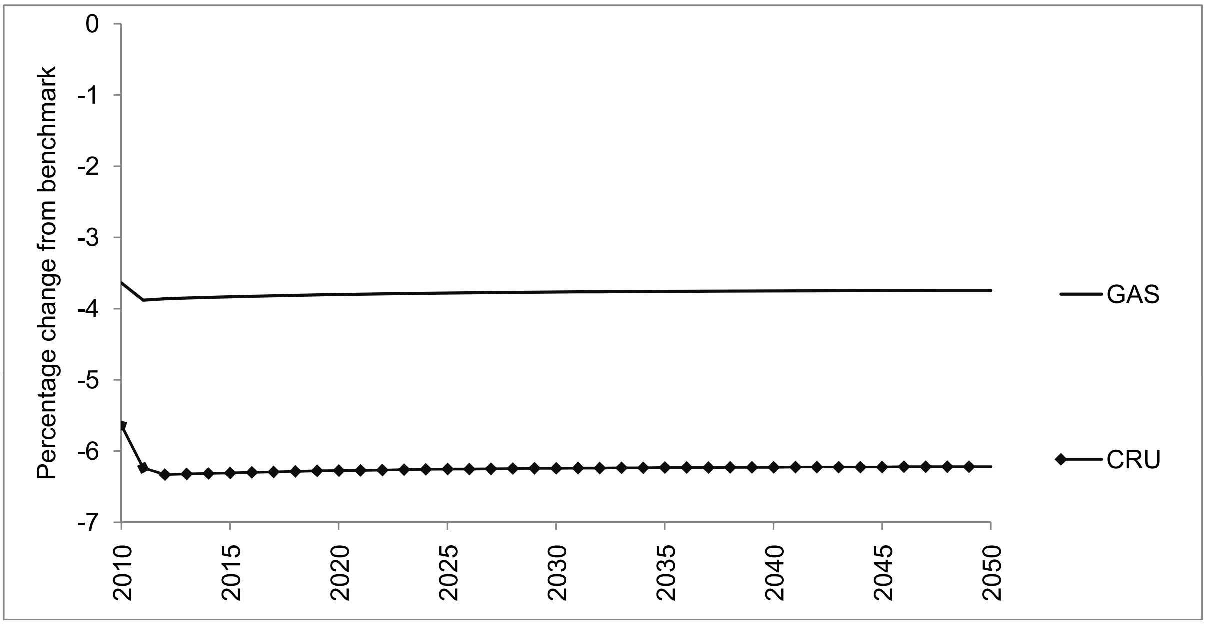

Figure 8: Import of fossil fuels in the HK model.

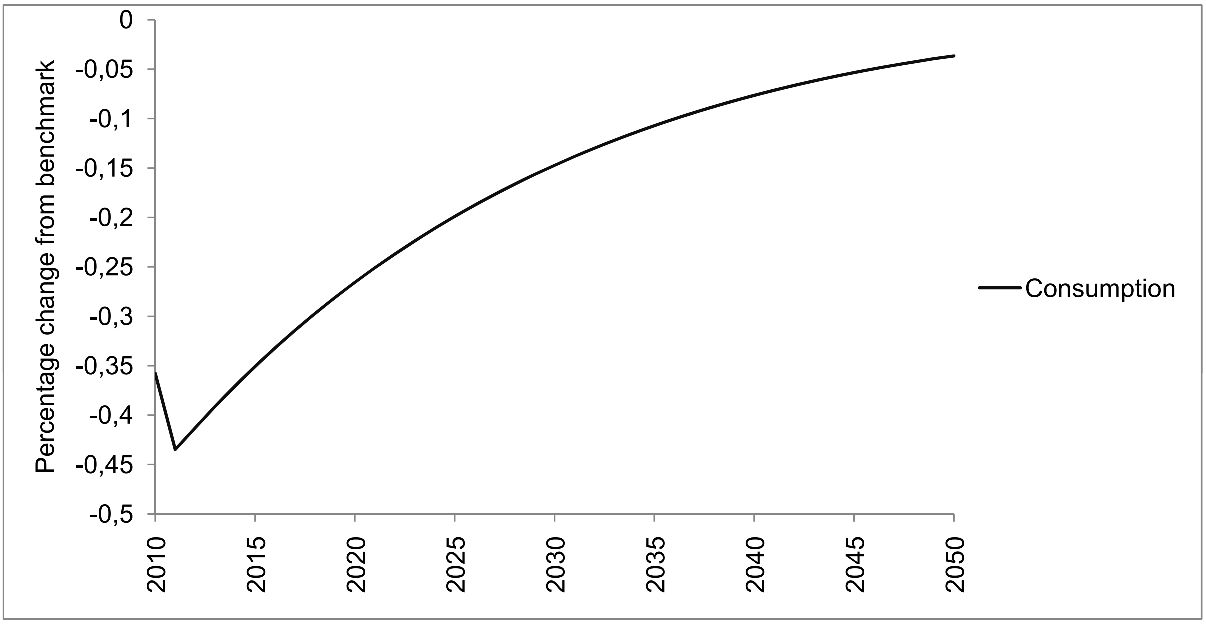

Figure 9: Consumption in the CITE model.

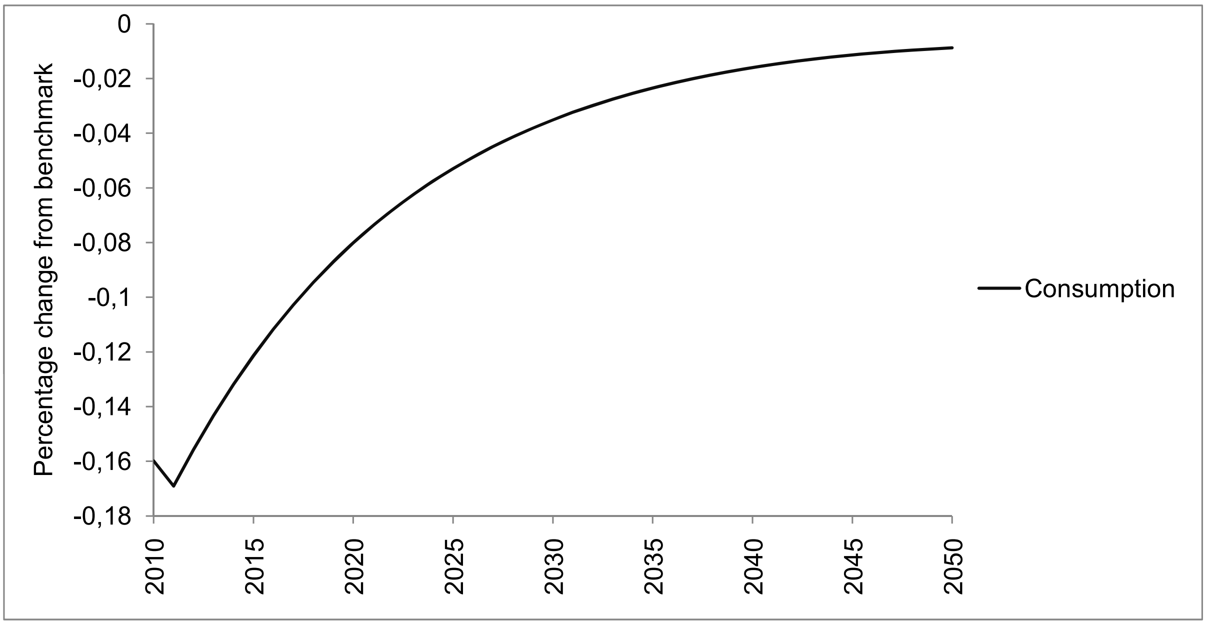

Figure 10: Consumption in the HK model.

high demand for labor.

Similarly to the demand for labor that almost duplicates the patterns of output, labor in research shows a similar behavior compared to the capital stock (Figures 13 and 14). This result is very intuitive, and at the same time it yields some insights into the development of the labor market. The proportion of labor between the sectors changes compared to the benchmark, as does the intrasectoral relation of labor to labor in research.

The changes in demand are also reflected in the prices. If we regard the wage for labor in research in Figures 15 and 16, we find that it increases in both models, but it remains at a higher level in the CITE model. We can conclude that the marginal product of labor in research stays higher in the CITE model than in the HK model in the long run. This difference is also a consequence of the different roles of capital in the models. In both models, labor in research contributes to investments, which raises the

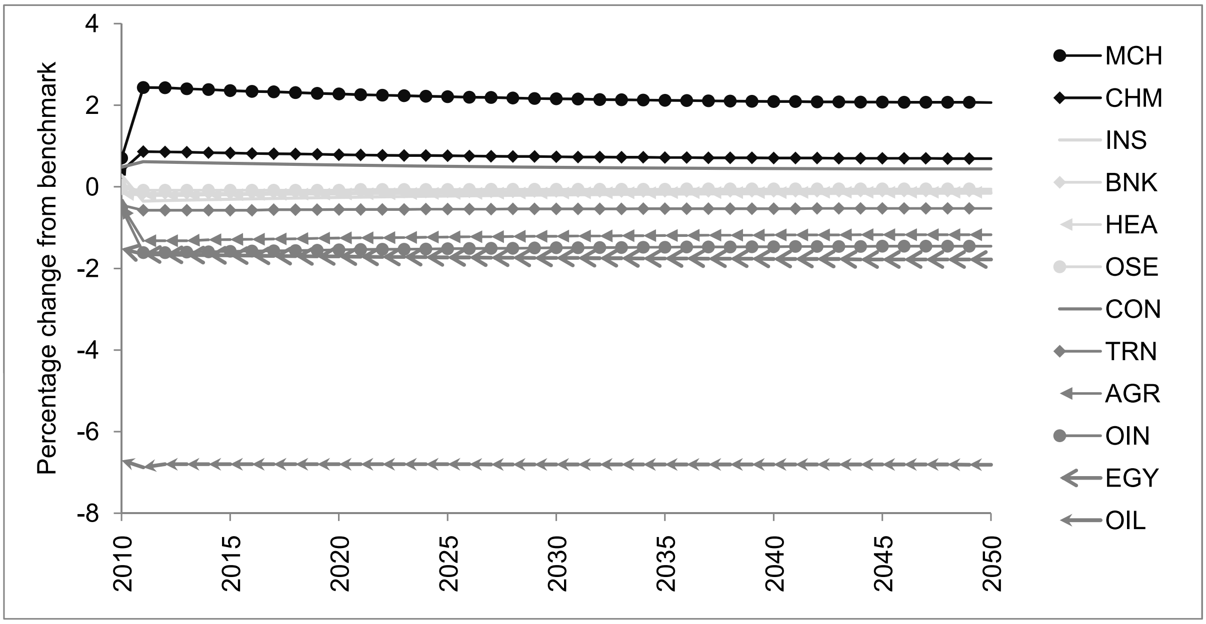

Figure 11: Labor demand in the CITE model.

capital stocks. However, capital has a larger effect on production and therefore a larger marginal product in the CITE model because it increases overall productivity of the intermediate composite good. In the HK model, an increase in capital can only enhance production of intermediates by substitution and not by a productivity factor. It has therefore a smaller possibility to influence output. This fact is reflected in the wage of labor in research.

7 Sensitivity analysis

The influence of capital on the dynamics become in both models clearer if we regard the reactions of the models to a change in two important elasticities. As capital goes in the HK model in the production of

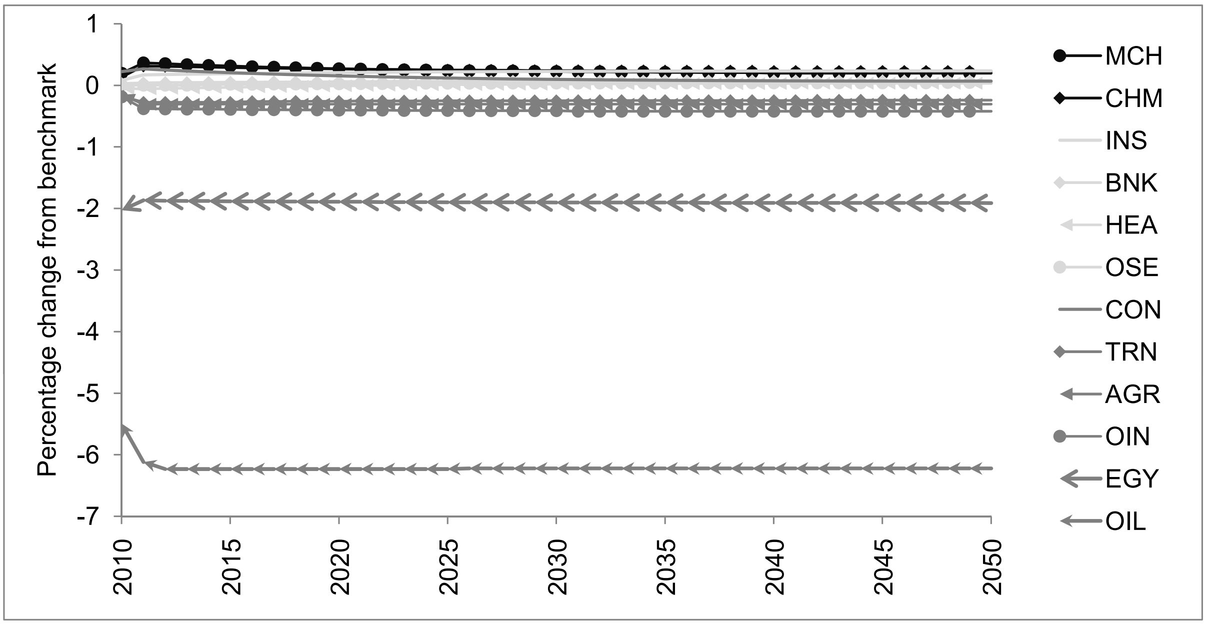

Figure 12: Labor demand in the HK model.

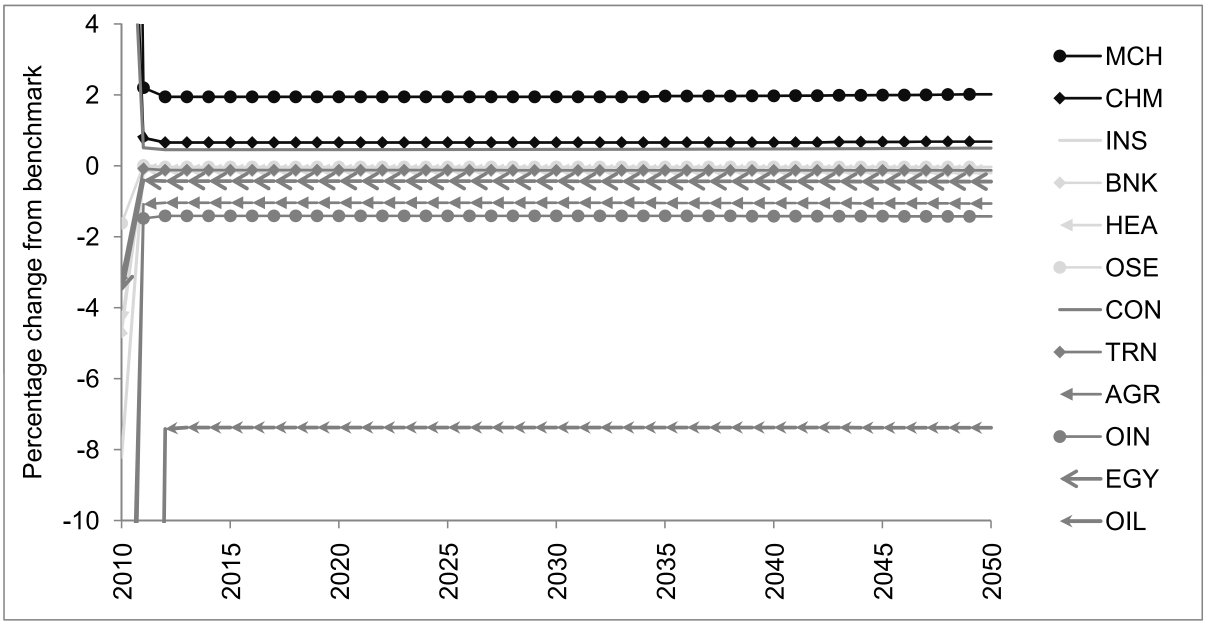

Figure 13: Demand for labor in research in the CITE model.

the intermediate good, the elasticity that connects $\tilde{K}_i$ with the other inputs in the production of $\tilde{X}_i$, $\sigma_{X,i}$, plays an important role. Moreover, the elasticity in the production of the final good that connects the intermediate good (the intermediate composite in the CITE model) and the inputs from other sectors, $\sigma_{Y,i}$ influences the outcomes. To find out how sensitively the models react to a change in the elasticities, we ran the counterfactual with elasticities that are doubled. Some of them then take very high values, and it must be kept in mind that these values are unrealistic.

Taking a closer look at the reaction of the CITE model to doubling $\sigma_{X,i}$ in all sectors (i.e., non-accumulable capital, energy, and labor are in the production of x_i more substitutable), it is clear that the model is fairly reactive (Figures 17 and 18). The machinery sector has a lower output of 0.4% compared to the policy scenario with the original value of $\sigma_{X,i}$. At the same time, the production of the energy

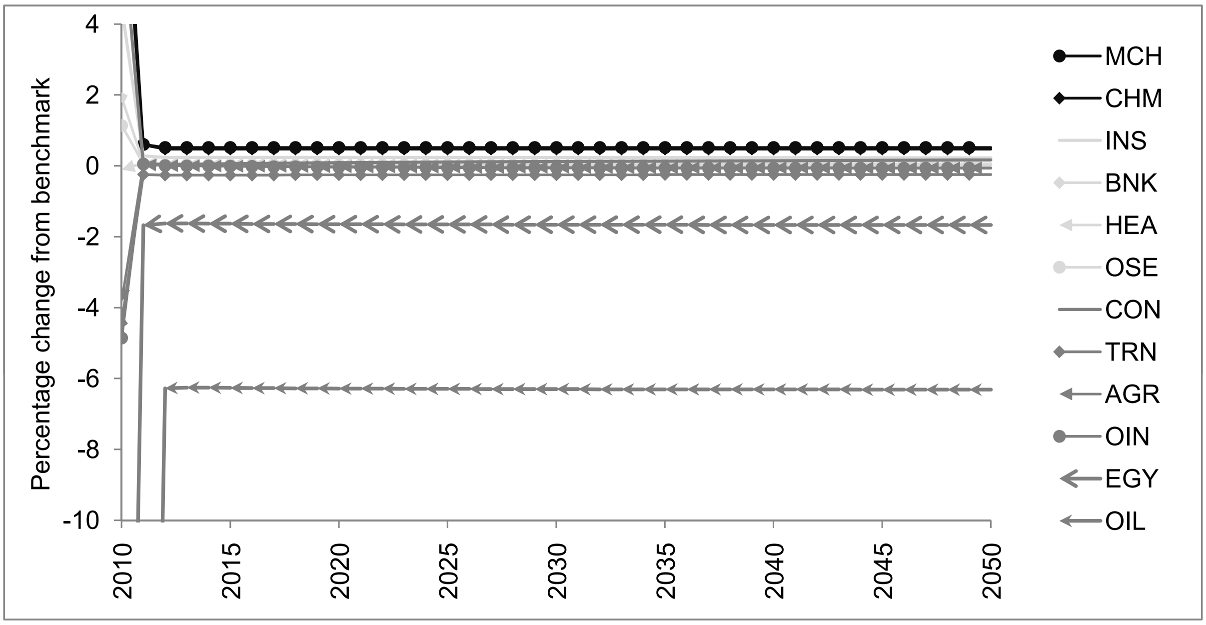

Figure 14: Demand for labor in research in the HK model.

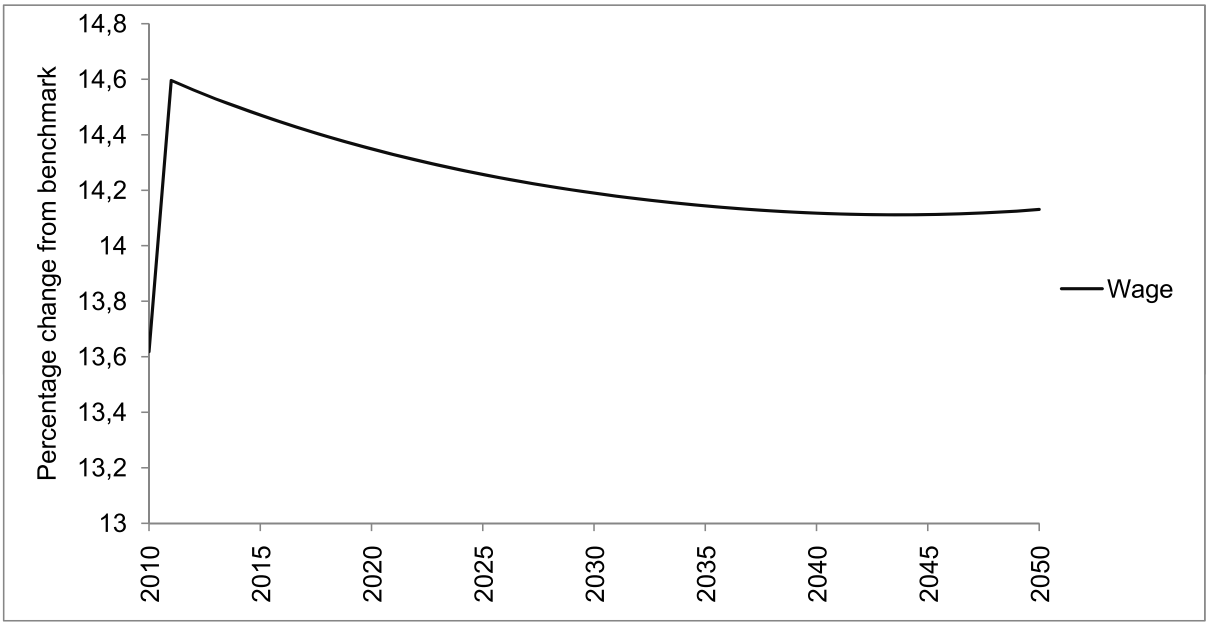

Figure 15: Wage in research in the CITE model.

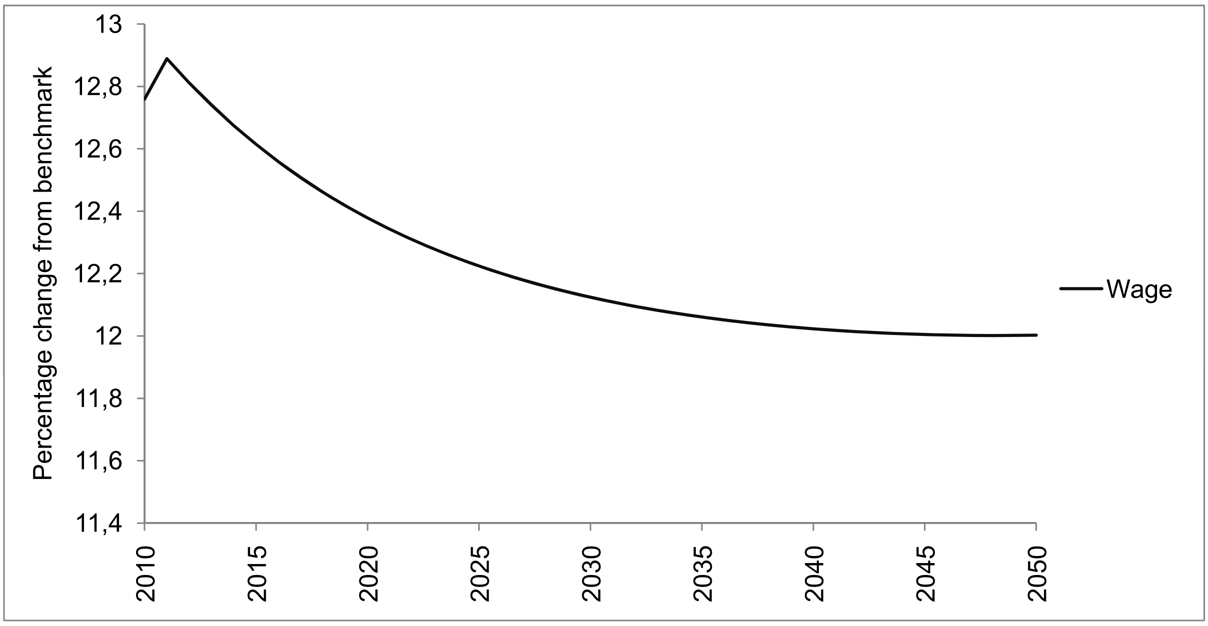

Figure 16: Wage in research in the HK model.

and oil sectors shrinks by 3.2% and 3.1%, respectively. This development seems to be an effect of the ability of the other sectors to better substitute labor and non-accumulable capital for energy. Therefore, the demand for energy decreases and thus for the output of the oil sector. The production of the other sectors changes about as much as in the scenario with the original value of $\sigma_{X,i}$.

If we compare these results with the reactions of the industries in the HK model, we find that they are less sensitive to a change in $\sigma_{X,i}$. The energy and oil sectors' production drops more than before (about 2.2%), but the other sectors show few deviations. Some structural changes take place, but overall, the economy shows little sensitivity.

Another important elasticity for transmitting growth dynamics is $\sigma_{Y,i}$. It connects the intermediate good (intermediate composite) with other inputs and therefore influences to what extent the dynamics of capital accumulation can drive growth of the final output. It is thus interesting to take a look at the

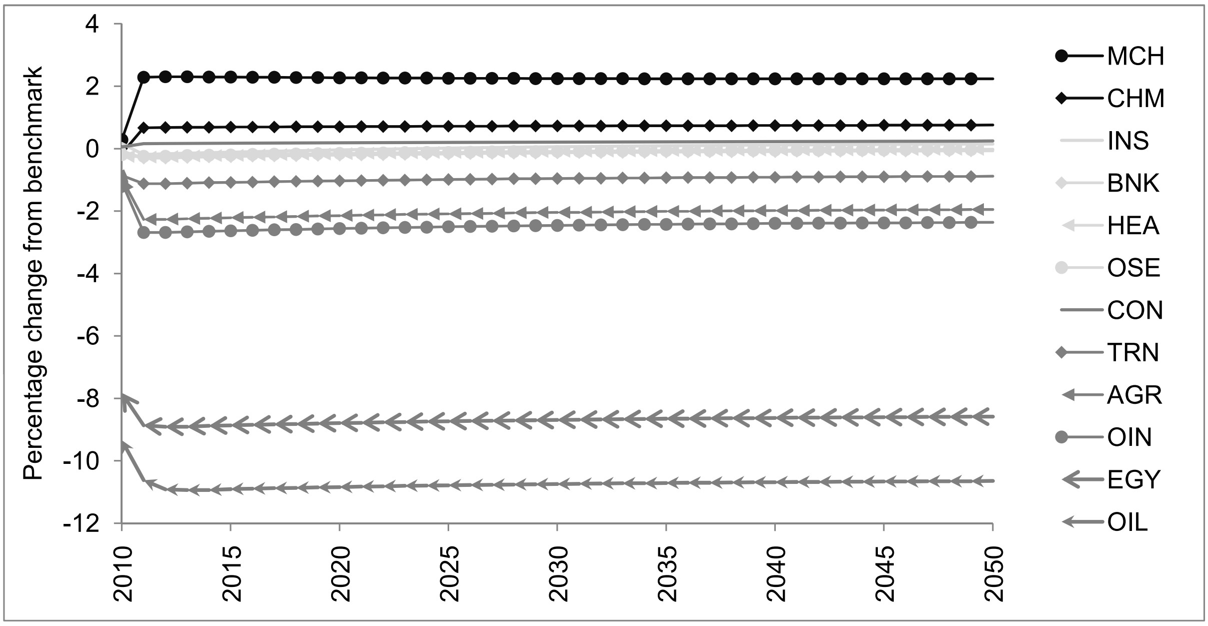

Figure 17: Output in the CITE model.

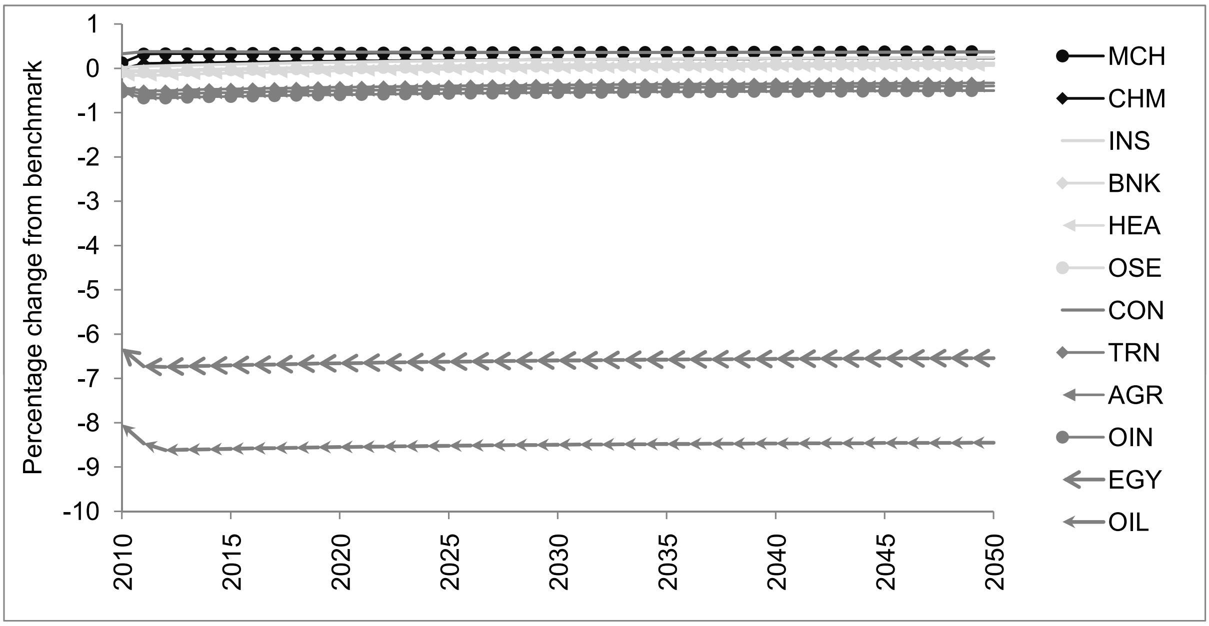

Figure 18: Output in the HK model.

reactions of the models to a change in $\sigma_{Y,i}$ in Figures 19 and 20.

In the CITE model, we see that doubling $\sigma_{Y,i}$ affects on a number of industries. The machinery sector increases production, and the energy and oil sectors have a slightly lower output. Also, the agriculture sector and the other industries produce less than before. In total, the effects are limited, but are still stronger than those in the HKwVK. There, the changes are negligible.

To sum up, the reactions of the models to changes in elasticities are quite small, and the models are very stable. The CITE model is slightly more reactive to changes than the HKwVK, which showed few effects of doubling the elasticities.

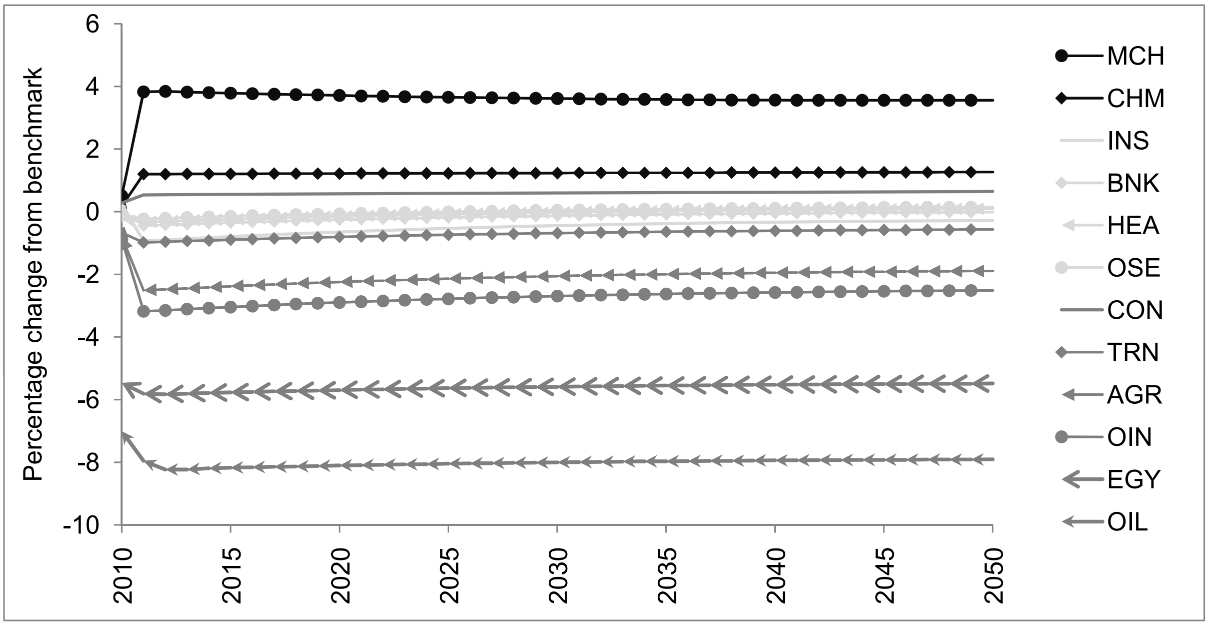

Figure 19: Output in the CITE model.

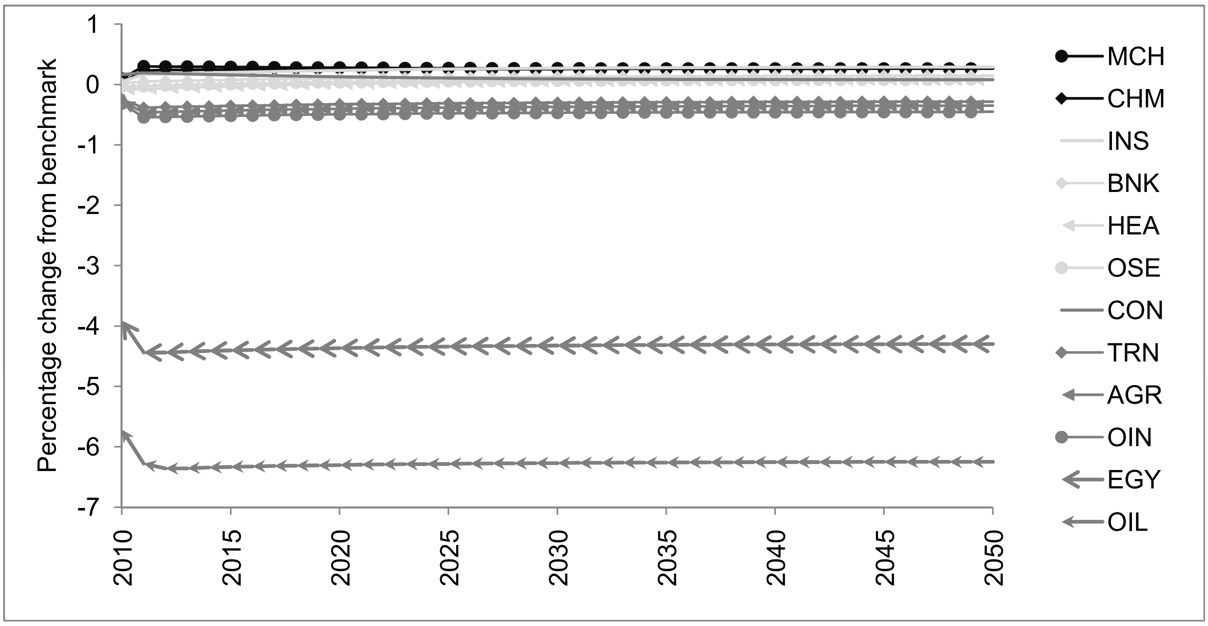

Figure 20: Output in the HK model.

8 Conclusion

The comparison of the dynamics of the CITE model with a HK model with exogenous growth shows that the endogenous growth mechanism of the CITE model yields different reactions to a carbon tax. In the CITE model, capital growth generates gains from specialization and ensures endogenous growth dynamics. These dynamics are influenced by a carbon tax as the incentives to invest change. Investments target a substitution of energy in production and result in a higher productivity of the intermediate composite. This, in turn, contributes to a change in the production of the final outputs. In the HK model, capital accumulation can only contribute to a substitution for energy, but not to an increase in productivity. Accordingly, investment incentives are different compared to the CITE model.

The dissimilarity of investment incentives are reflected in the reactions of the sectors to a carbon tax.

In the CITE model, most industries show a stronger sensitivity to the change in input costs than in the HK model. Three differences mainly emerge: First, the spread of output of the sectors is larger in the CITE model. Second, the speed in which the industries approach a new balanced growth path is lower in the CITE model. Finally, the structural composition of the economy is different in the two models. It can therefore be concluded that the endogenous growth mechanism in the CITE model uncovers dynamics triggered by a carbon tax that cannot be discovered with a HK model.

9 Literature

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Appendix C: *The CITE Model: Data, Parametrization and Sensitivity Analysis.*

The CITE Model: Data, Parametrization and Sensitivity Analysis

1 Introduction

In the last couple of years, climate and energy policy has become one of the most prominent issues and is on top of the agendas of both industrialized and developing countries. Climate change necessitates action on a global as well as on a regional scale in order to counteract the projected negative effects. Effective and efficient measures in climate and energy policy are therefore a key to ensure the welfare of future generations. Besides globally coordinated action and agreements, individual measures on a country level are also necessary.

Switzerland addresses this issues with several programs and measures. A central part of all these measures is the so called CO2-law. It's aim is to make sure that Switzerland is able to fulfil its reduction targets that were set in the Kyoto protocol. It includes several instruments and targets for the reduction of the use of fossil energy and of CO2 emissions. An important instrument is a CO2-tax that has been put in place in 2008. It directly taxes fossil fuels like oil and gas when used for energetic purposes, most notably for heating (the use of fossil fuels in transportation is not taxed). However, firms have various possibilities to avoid this tax, for example by complying to binding restriction targets. For the time after 2012, no definite regime has been put in place yet. In a recent message ("Botschaft über die Schweizer Klimapolitik nach 2012", August 2009), the Federal Council announced that Switzerland will set binding constraints for emissions reductions until 2020. The target will be a 20% reduction or even a 30% reduction if other European countries agree on targets in a similar dimension.

A basic foundation for long-term Swiss energy climate policy is a large project initiated by the Swiss Federal Office of Energy, called Energy Perspectives ("Energieperspektiven"). Its results are an important guideline for the design of future energy policy. Based on various scenarios (see Prognos (2007) for an in-depth description) that differ most notably in stringency of reduction targets and in targets for the use of renewable energy, it gives a detailed outlook for future energy supply and demand and its economic impacts until the year 2035. The most ambitious and also the most restrictive scenario (scenario IV) takes up the idea of a 2000 Watt society. This basically means that in the long run, constant per capita energy use has to be cut down to 2000 Watt, which is about the global average. According to Prognos (2007), the current value in Switzerland lies around 5000 Watt. The global average obviously also includes low income and developing countries with a smaller dependency on energy, so for Switzerland as a high income country, the challenge to reach this target is certainly significant.

This scenario is the basis for the analysis conducted here. It assumes that by 2035, per capita energy use must be reduced by 35% (compared to the year 2000) in order to get on a path towards a 2000 Watt society. The key political instrument that is provided in scenario IV is a tax on fossil energy use. We implement such a tax in our model and set its value so that the reduction target is exactly met. The tax is augmented every year until 2035 and remains constant afterwards. In accordance with Energy Perspectives, we do not set any further constraints for the time after 2035. The 35% reduction proposed here should be viewed as an intermediate target on the way to a 2000 Watt society. If this intermediate target is not met, it may become more and more unrealistic that the goal of a 2000 Watt society can be achieved within a reasonable time frame.

Recently, several studies have investigated the economic effects of future energy and climate policy in Switzerland. Ecoplan (2007a) looks at the impacts of high oil prices. They find that a constantly high oil price leads to reductions in GDP from -2.3% to -3.7% in 2035, depending on the assumptions for the development of the oil price. Welfare reductions by 2035 are in the range of -3.6% to - 5.53%. These relatively strong effects are though mostly driven by the fact that there is no good substitute for oil in the model. The economic effects of the before mentioned scenarios in Energy Perspectives have been analyzed by Ecoplan (2007b). They find relatively small reductions in GDP (compared to a baseline without any new measures in climate policy). In the most restrictive scenario, GDP is reduced by less than 0.4% in 2035. Similarly small are the effects on consumption, which is reduced by about 0.45% in 2035 in scenario IV. Welfare (measured by discounted consumption) is reduced by less than 0.25%. A third recent study by Ecoplan (2008) looked at the economic effects of possible Post-Kyoto policies, most notably of a CO2 tax that aims at reducing greenhouse gas emissions in Switzerland by 20% by 2020. Again compared to a business-as-usual scenario without any climate policy, they find a reduction in GDP of 0.66%. Welfare is reduced by about 0.5%. The projected macroeconomic effects seem therefore to be small, even under the assumption that relatively stringent measures and targets are put in place. Ecoplan (2009) finally also looks at Post-Kyoto policies and focuses on the targets that have been proposed in the Message of the Federal Council mentioned above. They also find relatively small reductions in GDP and welfare in a similar range compared to Ecoplan (2008). On a sectoral level, the policies mostly affect the energy- and carbon-intensive industries, while the sectors that do not rely heavily on energy suffer only small losses or even slightly increase their output.

Swiss climate policy and its economic effects have also been analyzed extensively by the Research Group on the Economics and Management of the Environment in Lausanne. Recent papers include the coupling of a multi-regional top-down model (GEMINI-E3, see Bernard and Vielle (2008) for a technical description) with a Swiss version of the MARKAL model (e.g. used in Schulz et al. (2008)), which provides a detailed representation of the energy system and the relevant technologies. The two coupled models have been used to analyze post Kyoto policies both on a national and an international level (Altamirano et al. (2008)) and revisions and extensions of the Swiss CO2 law (Sceia, Thalmann and Vielle (2009)). In line with the studies mentioned above, effects on welfare and on production sectors generally turn out to be moderate.

This paper is part of a series that describe the CITE model, its theoretical foundation and the simulation results. The CITE model was developed for a project in collaboration with the Swiss Federal Office of Energy as a tool to analyze economic effects of future energy policy measures in Switzerland. In contrast to the models that were previously used in a similar context, the CITE model includes an endogenous growth mechanism that takes into account the relationship between investments into different (sectoral) capital stocks and growth. It therefore includes a more profound representation of the mechanisms that drive economic growth than e.g. the studies cited above. The aim of this paper is to describe the work on the data, to give an overview of the most important parameter values and to test for the robustness of the model results when the parameter values are varied. We find that the model is not very sensitive to changes in most model parameters. Mostly, we only see small effects on the levels of output and the capital stocks, and minimal reactions in consumption and welfare.

The rest of the paper is organized as follows. Section 2 gives a brief overview of the model. Section 3 describes the data, Section 4 the parametrization. In Section 5, we check for the stability of the model with respect to the parameter values chosen. Section 6 concludes.

2 The Model

In this section, we give a brief overview of the CITE model. The theoretical foundation and the particularities of its implementation in the GAMS software are presented in detail in Schwark (2010). The nested production functions of the output sectors and the nestings of consumption and investments are shown in the Figures in the Appendix.

The CITE model is a computable general equilibrium model that is particularly suitable for energy policy analysis. The simulations are performed using the software GAMS/MCP. The focus of the CITE model is on the growth effects of energy policies, both on an aggregate and on a sectoral level. The CITE model includes an endogenous growth mechanism in the fashion of Romer (1990). In the model of Romer, economic growth comes about through new intermediate varieties. A new variety the result of an underlying innovative process. The number of varieties is equal to the size of the capital stock (which is in our case sector specific). The accumulation of capital (and thus the production of intermediate varieties) has a positive effect on the productivity of the sectors. This effect is often referred to as gains of specialization. The higher the capital stock in a sector, the higher its degree of specialization and consequently the higher its gains of specialization. This means that the growth rate of the different sectors can be increased by investing in new intermediate varieties, i.e. by augmenting the sectoral capital stocks. The growth rate of a sector is therefore closely related to its innovative activity.

The model contains twelve production sectors that produce final output (see Section 3 for an overview), ten regular sectors and two energy sectors. The regular sectors all share the same production structure (see Figure 1 in the Appendix), but obviously differ in their factor input shares and their substitution possibilities. They use an intermediate composite and output of other sectors to produce final output. The intermediate composite captures the growth dynamics explained above. It is produced using a Dixit-Stiglitz production function (cf. Dixit and Stiglitz (1977)) and combines all the different intermediate varieties to one good. The κ in the exponent is equal to 1 minus the share of capital and reflects the gains of specialization. The higher κ, the lower the share of capital and therefore the lower the gains of specialization. The individual intermediate varieties are produced using labor, energy and non-accumulable capital (explanations on this input are given in Section 3) as inputs. The capital stock (see Figure 5 in the Appendix) can be augmented by two types of investments: Investments in physical capital, and investments in R&D. Investments in R&D and research labor are used to build up non-physical capital, which then together with the investments in physical capital forms the total capital stock. These capital stocks are all sector specific, and investments in the capital stock of one sector do not entail any spill-overs to other sectors. Investments into the capital stock of a sector therefore only affect the growth rate in this specific sector. Labor and non-accumulable capital on the other hand are free to move across sectors. The production factors are all owned by a representative household. This representative household allocates its factor income between consumption of energy and final goods (see Figure 4 in the Appendix), physical investments and investments into R&D. Utility (or welfare) is derived from discounted inter-temporal consumption. Production, investments and consumption are represented in the model using nested CES functions that allow for substitution between the inputs at the different levels of the production process.

The two energy sectors have a slightly different production structure (see Figures 2 and 3 in the Appendix). The oil sector uses crude oil in addition to the other inputs at the top level of the production function. The output of the oil sector then forms, together with gas, fossil energy, which is an additional input to the energy sector. The other input of the energy sector, non-fossil energy, is produced in the way described above.

We simulate the effects of a 35% reduction of energy use by the year 2035 (compared to the year to 2000). The base year for the analysis is the year 2005. Because energy use in 2005 was a bit higher than in the year 2000, it has to be reduced by 37.5% rather than by 35%. The only policy instrument that we use (in analogy to scenario IV) is a CO2 tax. The tax is levied directly on the CO2 emissions of the two fossil fuels, oil and gas. We assume a uniform tax rate for both fossil fuels, but a higher CO2 intensity for oil, which means that oil is effectively taxed at a higher level than gas. Scenario IV assumes that the tax revenues are redistributed directly to the households and firms. We use the same mechanism as well, but alternatively, we also simulate a scenario where the tax is redistributed as a subsidy to R&D investments in all sectors except the oil sector. The aim of this subsidy is to directly support capital build-up and therefore the growth mechanism of the model.

3 Data

The model is based on the Swiss input-output table (hereafter named IOT) for the year 2005 (Nathani, van Nieuwkoop and Wickart, (2008)), which is the most recent version available. It gives detailed information on the flow of goods between sectors and to final demand and also on the use of inputs and on trade. The original table includes data for 42 production sectors and differentiates between fifteen types of consumption (twelve for private households, three for public consumption) and three types of physical investments. As for the use of factor inputs, it contains information on the use of labor and capital. It is therefore an almost complete source of data for the type of model we are using. A simplified version of the original IOT is shown in Table 1. Field I represents intermediate demand, i.e. flows of goods between sectors. Rows denote sectoral output, columns denote the use of sector i's products by sector j. The entries in field I therefore indicate how much of sector i's output is used in the production of sector j. Field II contains information on final demand in consumption, investments, and exports. In field III, we have total production of sector j, given by the sum of the respective row. The tax row gives information on value added taxes, tariffs and subsidies. Field IV represents value added of the respective sector, divided into the expenditures for labor and capital. Field V contains sectoral imports. Field VI then is the sum of total inputs in the sectors. In a balanced IOT, the sums in field VI are obviously equal to those in field III, implying that total output is equal to total inputs in every sector.

In order to ensure compatibility of the IOT and our our model, several adjustments had to be made. First of all, we aggregated the data from the original table from 42 to 12 sectors. The choice of the sectors was made based on their relative importance in terms of their share on overall production and in accordance with existing studies (e.g. Ecoplan, 2007a). The sectors that are not analyzed separately have been summed up to an aggregated category for industries or services (see Table 2). Also, we do not differentiate between the different types of consumption and physical investment. Most notably, we do not separate public from private consumption, as we do not have an explicit representation of the government in the model. Therefore, the different types of consumption were aggregated to one single

	INTERM. DEM. Sectors 1...j	FINAL DEMAND $C_{(1...15)}$ $I_{(1..3)}$ Exp.	Σ
... Sectors 1...i ...	I	II	III
Taxes			
L K	IV IV		
Imp.	V		
Σ	VI		

Table 1: Original Input-Output table before adjustments

column. The same was done with physical investments. These assumptions were made for simplification and have no distorting effects on the results.

The model distinguishes two types of investments, physical and non-physical investments. Non-physical investments mainly refers to investments in research and development. The original IOT contains no information on these types of investments. Additionally, there is no reliable data on R&D investments available in Switzerland, especially not on a sectoral level. We therefore use the data from sector 73 ("Research & Development") to have measure these investments. Put differently, we interpret the demand for goods from sector 73, i.e. the row entries of this sector, as investments in R&D of the sectors demanding these goods. To represent this interpretation in the IOT, we transferred these entries into a new column labeled R&D investments. The column entries of sector 73 and its imports, exports, value added, consumption and investments were added to other services (OSE), except for the entry of labor. We use this entry as our benchmark value for research labor (LH). With this procedure, we get sectoral values for R&D investments and an aggregate measure of research labor. Total research labor is then redivided to the sectors according to their share in total capital use. This gives us a value for initial sectoral demand for research labor. Because we assume that capital accumulation is the result of investment activities including research and development, it makes sense to derive the initial sectoral labor inputs according to the sectoral shares in total capital. Thus, the more a sector contributes to the initial total capital, the higher its starting value for research labor.

To have a more detailed and realistic representation of the production processes in the oil sector and the energy sector, we added two fossil fuels, crude oil and gas, to the IOT. The corresponding entries have been estimated from data from the Swiss Energy Statistic (Schweizerische Gesamtenergiestatistik 2005). Both are fully imported, so on the supply side, there is only an entry in the row for imports. Crude oil is then demanded only by the oil sector, gas only by the energy sector. Also, as we assume that all output from the oil sector serves as an input to the energy sector, we added the row entries of the oil sector to the respective entries of the energy sector. The same was done with final demand for oil sector output. The column entries of the oil sector have been left unchanged, as there is a domestic production of refined oil products similar to the other sectors (except for the fact that it also uses crude oil as an input). A further disaggregation of the energy sector and the inclusion of more energy sources (most notably of renewables) would certainly be desirable. However, the availability of sectorally disaggregated data on energy use (divided by source) is currently very limited. A more detailed representation of the energy sector will be included as soon as the necessary data is available.

Three more adjustments were made: First, capital had to be split into two capital types, labeled K (capital) and VK (non-accumulable capital). In the benchmark, the model is calibrated to a balanced growth path. This calibration requires that the share of capital (K) in the production of intermediate goods has to be equal in all sectors. The reason for this is that the capital share (or the gains of specialization) directly affects the sectoral growth rates. Different capital shares would therefore imply different rates of growth. In the original table, there are obviously large differences in these shares. We solved this issue by setting the value of capital so that its share is equal in all sectors and by defining the residual of initial capital as another input to intermediate production. An equal share of capital implies a uniform sectoral growth rate. This new input is then represented in a new row in the IOT. K is the part of total capital that can be accumulated via investments and thus influences sectoral growth, while VK enters production of intermediate goods at the same level as labor and energy and cannot be accumulated. VK can be interpreted as publicly provided capital (e.g. public infrastructure or services)

Sector	NOGA-Classifications
Agriculture (AGR)	01-05
Refined Oil Products (OIL)	23
Chemical Industry (CHM)	24
Machinery and Equipment (MCH)	29-35
Energy (EGY)	40
Construction (CON)	45
Transport (TRN)	60-63
Banking and Financial Services (BNK)	65
Insurances (INS)	66
Health (HEA)	85
Other Services (OSE)	50-55, 64, 70-75, 80, 90-95
Other Industries (OIN)	10-22, 25-28, 36-37, 41

Table 2: Overview of the sectors used in the model

in the sense of Barro (1990). While helping to solve the benchmark calibration simulations show that VK has no distorting effect on the quality of the results.

Second, as we abstract from trade and budget policy, the trade balance needs to be equalized initially, thus total exports need to be equal to total imports. To correct this, we added the surplus in the trade balance in the original data to consumption. Because the CITE model is a one-region model, this has no distorting effects. Third, the last adjustment concerns taxes and tariffs. As already indicated above, the original IOT also contains information on certain taxes and tariffs (such as value-added taxes or import tariffs). As none of these taxes are subject to political intervention in our scenarios, we did not include them in the model. Put differently, this means that there are no benchmark taxes in the model. This make the calibration of the model a lot easier and has no effect on the results. The CO2-tax that is used as an instrument to achieve the given reduction targets is introduced as a policy scenario in the counterfactuals, but is not included in the benchmark. We thus focus on direct taxation of the polluting inputs to meet the reduction targets and abstract from other fiscal instruments. Taxes included in the original IOT were therefore removed. To sum up, our newly constructed IOT (see Table 3) has an additional column in the

	INTERM. USE			FINAL DEMAND				Σ
	CRU	AGR...ROI	*Gas*	C	I_P	$I_{R\&D}$	Exp.	
CRU								
AGR...ROI		I			II			III
Gas								
LH					VII			
VK								
L		IV						
K								
Imp.		V						
Σ		VI						

Table 3: Adjusted Input-Output table

final demand block for investments in R&D and a new row in the value-added block for non-accumulable capital. Additionally, there are two new "sectors" for crude oil and gas. The benchmark value for research labor (LH) is entered in a new row in field VII. On the other hand, we reduced the total number of sectors and merged the different types of consumption and physical investments to one single column each and removed the benchmark taxes. The IOT is then directly read into GAMS using a script similar to the one presented in Rutherford and Paltsev (1999). This script basically converts the IOT from Excel to GAMS format by constructing a parameter that holds all the values from the original table. From this parameter, we can then directly define the benchmark values for intermediate and final demand, factor supply and demand, imports and exports and output. The remaining benchmark values (i.e. those that cannot be taken directly from the IOT) can readily be calculated using values from the table. We can therefore rely on the IOT as a complete and consistent data source for our model.

4 Parameters

This section gives some insight on the choice of the most important model parameters, most notably the elasticities of substitution. The choice of these parameter values is crucial in the set-up of a CGE model and should therefore be made carefully. Whenever possible, they have been chosen in accordance with existing studies or empirical estimations. Due to the fact that the structure of our model is quite different from similar studies, parameter values from existing studies could not always be used. Whenever this was the case, we assumed seemingly reasonable values. Some reasoning on the choice of these values is given below. When it made sense and when we could resort to existing studies, we used sector specific values for the substitution elasticities. Otherwise, the same values apply for all sectors. An overview of the values used is given in Table 4.

Parameter	**Description**	**Value**
$\sigma_{Y,i}$	Elasticity of substitution between Q and inputs from other sectors	0.392 (AGR) 0.848 (OIL, CHM) 0.518 (MCH) 0.100 (EGY) 1.264 (CON) 0.352 (TRN) 0.568 (OIN) 0.492 (rest)
$\sigma_{X,i}$	Elasticity of substitution between the three inputs (energy, labor and VK)	0.7 (AGR, OIL, CHM, EGY) 0.8 (MCH) 0.52 (CON) 0.82 (OIN) 0.4 (rest)
σ_E	Elasticity of substitution between fossil and non-fossil energy	0.3
σ_I	Elasticity of substitution between physical investments and non-physical capital	0.3
σ_N	Elasticity of substitution between investments in R&D and research labor	0.3
σ_C	Elasticity of substitution between energy and non-energy goods in consumption	0.5
σ_W	Inter-temporal elasticity of substitution in the welfare function	0.6
$\sigma_{A,i}$	Armington elasticities	3.2 (AGR) 4.6 (MAS) 3.8 (EGY, OIN) 2.9 (rest)
σ_T	Elasticity of transformation	1

Table 4: Parameter values

On the production side, we assume sector specific elasticities of substitution in the top nest between the intermediate composite and output from other sectors. The values used for σ_Y are based on estimations by Okagawa and Ban (2008), who provide estimates for almost 20 sectors using data from OECD countries. Values of this study have also been used in Ecoplan (2008) and Ecoplan (2009). The structures estimated in this paper are not exactly equal to the nesting we use here. However, it seems reasonable to assume that the top level elasticity may be similar irrespective of the structure on the levels below. The values differ considerably from sector to sector, with a range from 0.1 for the energy sector to 1.264 for construction. Outputs from other sectors entering the production function are assumed not to be substitutable. Shares in intermediate demand are thus fixed. This is a common assumption for models using a similar setup.

In the production of intermediate goods, we use sectorally differentiated values for σ_X, which is the parameter capturing the substitutability between labor, energy and non-accumulable capital. We use values from Van der Werf (2007) where applicable, which is the case for most industrial sectors. Obviously, only estimates for the substitutability between labor and energy are available, but we assume that these estimates also hold when non-accumulable capital is added. Elasticities in the industrial sectors are relatively high (between 0.52 and 0.82)[1]. Unfortunately, Van der Werf (2007) does not provide estimations for service sectors. We assume a lower and uniform value (0.4) for the service sectors. The reasoning behind this assumption is that it is probably easier to automatize (and thus to replace labor with other inputs) certain steps of the production process in the industrial sectors than in the service sectors. In the production of the oil sector, we assume that the share of crude oil that is needed for production is fixed. Refined oil products then enter the production of energy along with gas as fossil energy. Gas and oil are assumed to be good substitutes (the same assumption is also used in Ecoplan (2007a)), while there is only a limited potential of substitution between fossil and non-fossil energy.

Energy enters consumption along with output from the remaining sectors in the top nest of the consumption function. We assume relatively good but limited substitution between energy and non-energy output (captured by σ_C) and good substitutability between the non-energy products. Both of these assumptions were again made in accordance with Ecoplan (2007a). The inter-temporal elasticity of substitution in the welfare function (σ_W) is set to 0.6, which on the upper ranger of estimations that are available. However, these estimates vary considerably depending on the choice of the model and the data used in the estimations. Hasanov (2007) provides a good overview of previous results. The capital stock is built up using physical and non-physical capital. The two capital types are assumed to be substitutable at a rather low degree (σ_I), which captures the fact that they are exchangeable to a certain extent, but still both are necessary in the capital build-up. On the lower nest, we also set a low value for the elasticity of substitution between investments in R&D and research labor (σ_N). The reasoning here is that the research sector obviously needs both the investments in R&D and the people who conduct the research. This is a similar argument to the one made just above for σ_I. R&D investments and research labor may be substitutable at a certain extent, but one can never fully replace the other.

Goods of all sectors are imported, domestically produced and exported. Exceptions are crude oil and gas (which are both only imported) and refined oil, whose exports are included in those of the energy sector. Trade is represented using the well known assumption that domestic and foreign goods are imperfectly substitutable (Armington, 1969). Imported goods are therefore a good but not a perfect substitute for domestically produced goods. The GTAP database provides detailed estimations for sectoral Armington elasticities (see Donnelly, Johnson, Tsigas and Ingersoll (2004)) which describe the degree of substitutability between imported and domestic commodities. These values are also used here. On the export side, we use a CET function to differentiate between domestic and foreign demand. The corresponding elasticity of transformation is set to 1.

From Table 4, it can be seen that most values for the elasticities are set below unity. Exceptions are the trade elasticities and $\sigma_{Y,CON}$. This implies a certain rigidity, especially in the production process, and possibly limits the effects of political intervention as inputs are not well substitutable on certain levels. There are two comments on this. Most of the values are based on given estimations that prove that substitution possibilities are indeed limited[2]. And secondly, our model is still relatively flexible in comparison to other models (e.g. Ecoplan 2007a), who are even more stringent as far as the values for the elasticities in the production processes are concerned. The Armington elasticities differ from the rest in the sense that they are all set considerably above one. This basically reflects the fact that it is of limited relevance where the goods have been produced, neither for production nor for consumption. This seems to be a reasonable assumption and is also common in similar analyses.

A key feature of the model is that it includes the gains of specialization that stem from the accumulation of capital already in the benchmark scenario. The model is calibrated such that it reflects both projected output growth and growth rates of the capital input. To be more precise, we assume that capital grows at an annual rate of 1%. This matches the observed growth rate of capital goods in Switzerland since 1990. In our calibration, in combination with the before mentioned share of capital (1-κ), this then leads to annual growth rate of about 1.33%, which is in line with the rate assumed in the high GDP scenario of the Energy Perspectives. The share of capital essentially defines the intensity of the spill-overs (i.e. the gains of specializations) and therefore also defines the difference between the growth rate of the inputs and the projected output growth rate. (1-κ) is set to 0.25 in all sectors. Capital

[1] Another reference for similar estimations is Kemfert (1998). The values in this paper are, however, considerably smaller both than in Van der Werf (2007) and than in other studies, f.e. in Ecoplan (2007a). In order to avoid too conservative assumptions, we use the values from Van der Werf (2007).

[2] Van der Werf (2007) e.g. tests for Cobb-Douglas functions (i.e. an elasticity of substitution of 1) as a representation of the substitutability between labor, energy and capital and proves that it is not an empirically valid assumption.

depreciates at a rate starting at 0.04. This rate rises by a small amount every year, due the fact that capital and investments grow at different rates in the model. To be able to calibrate the model correctly, we have to use a non-constant depreciation rate. Using a calibration procedure by Paltsev (2004), we can then derive the interest rate r (given the depreciation rate and the benchmark values for the capital stock and investments). Given the values in our model, the interest rate is about 0.016 or 1.6%. Compared to similar studies, this is a comparably low value (Ecoplan (2008) e.g. sets a value of 5%).

5 Sensitivity analysis

It has to be observed that the model results of computable general equilibrium models may be sensitive to the parameter values chosen. In other words, the choice of the values for the key parameters may have a strong influence on the results the model produces. It is therefore crucial to test the robustness of the model with respect to changes in the values of the most important parameters. This is done here by augmenting and decreasing the values of the elasticities of substitution and then comparing the outcome with the results produced with the original values. We examine the differences in consumption, fossil fuel imports, output and capital accumulation at the end of the model horizon in the year 2035 when we have reached the target of a 35% reduction in energy use (using the original values). Additionally, we compare the effects on welfare, which is measured over the entire time horizon. As output and the capital stocks are sectoral variables, we only look at the change of the highest and of the lowest value compared to the original case. Therefore, we can see how the range of the effects on output and capital accumulation is affected. We conduct a separate sensitivity analysis for both scenarios, as the effects may be different depending on how the tax revenues are redistributed.

In the sensitivity analysis, parameter values were doubled and halved to check the effects of large variations. In one case (for the variations of the Armington elasticities), we made smaller adjustments because the doubled values would have become unrealistically large and prevent the model from solving. We did this check for all the elasticities of substitution used in the model. Differences are expressed as deviations from the results in the original case, i.e. from the results using the values listed in Table 4. They should be read as follows. If for example the tax leads to an increase in output of a sector of 2.4%, an entry of -0.001 in the following tables means that the increase is only 2.3% if the corresponding elasticity is adjusted. Y_{top} and K_{top} refer to output and capital stock of the sector with the highest value (which is always the machinery industry). Y_{bot} and K_{bot} denote the values of the sector that is most negatively affected. Not surprisingly, this is always the oil sector. FF refers to the imports of crude oil and gas respectively. C denotes consumption, W welfare.

5.1 Tax revenue redistributed to the household

We first look at the effects of different parameter choices in the scenario where the tax is redistributed directly to the household. The results are listed in Tables 5 and 6.

Generally, we see that the model is relatively robust with respect to the choices of the values for the elasticities of substitution. Most notably, there are only minimal differences in the effects on consumption and welfare. Effects on sectoral output are, except for changes in the values of the trade elasticities, also relatively small, and the structural effects only change marginally. Put differently, the values of the parameters mostly have only (small) level effects on output and capital accumulation, but they do not affect the structural changes in the economy induced by the tax.

First of all, it can be seen that changing the elasticities in the nesting for investments (σ_I and σ_N) has almost no impact on the results. Even if we set the values to 0.9 (not shown in the table), there are no significant effects. This makes sense as the innovation process is not subject to any additional policy intervention here. Similarly small effects are observed when we change the inter-temporal elasticity of substitution in the welfare function (σ_W). There are only minor changes in output, the capital stocks and fossil fuel imports. Doubling σ_W leads to smaller effects, while halving σ_W leads to a slightly bigger impact of the tax. Welfare and consumption are virtually unaffected. Changing σ_C has slightly more pronounced effects. σ_C captures the substitutability between energy and non-energy goods in consumption. The higher σ_C, the easier it is for the representative household to substitute energy for non-energy goods. Therefore, energy use decreases more if we have a higher elasticity of substitution. Also, fossil fuel imports are reduced more when σ_C is higher. Hence, the impact of the tax is bigger if we allow for better substitutability of energy. This is also reflected by the fact that there is a general downward shift in the levels of output and the capital stocks. The opposite is true when the value of σ_C

	Y_{top}	Y_{EGY}	Y_{bot}	K_{top}	K_{EGY}	K_{bot}
$\sigma_C(doub)$	-0.003	-0.068	-0.055	0.000	-0.081	-0.055
$\sigma_C(half)$	0.002	0.040	0.032	-0.002	0.046	0.032
$\sigma_E(doub)$	-0.019	0.038	-0.024	-0.018	0.067	-0.025
$\sigma_E(half)$	0.009	-0.016	0.010	0.007	-0.029	0.011
$\sigma_I(doub)$	0.001	0.000	0.000	0.000	0.000	0.000
$\sigma_I(half)$	0.000	0.000	0.000	-0.001	0.000	0.000
$\sigma_N(doub)$	0.001	0.000	0.000	0.000	0.000	0.000
$\sigma_N(half)$	0.000	0.000	0.000	-0.001	0.000	0.000
$\sigma_W(doub)$	-0.021	-0.004	-0.002	-0.030	-0.010	-0.007
$\sigma_W(half)$	0.030	0.004	0.002	0.038	0.012	0.008
$\sigma_{Y,i}(doub)$	0.052	-0.006	-0.011	0.065	-0.011	-0.094
$\sigma_{Y,i}(half)$	-0.017	0.002	0.004	-0.022	0.005	0.037
$\sigma_{X,i}(doub)$	-0.064	-0.125	-0.101	-0.050	-0.172	-0.103
$\sigma_{X,i}(half)$	0.035	0.075	0.060	0.025	0.095	0.060
$\sigma_{A,i}(+1)$	0.386	-0.154	-0.145	0.321	-0.208	-0.143
$\sigma_{A,i}(-1)$	-0.120	0.077	0.076	-0.103	0.099	0.073
$\sigma_T(doub)$	0.107	-0.013	-0.018	0.085	-0.018	-0.016
$\sigma_T(half)$	-0.029	0.008	0.010	-0.025	0.013	0.010

Table 5: Effects of changing parameter values when the tax revenue is redistributed to the household

is low. If consumption possibilities are less flexible, the tax has a smaller impact because energy cannot be readily replaced in consumption. σ_E shows a clear pattern. If we double its value, this means that the substitutability between fossil and non-fossil energy rises. This implies better possibilities for the energy sector to avoid the tax by replacing fossil energy. Consequently, output of the oil sector decreases, as well as the imports of fossil fuel. The energy sector as a whole benefits, because investing in the capital stock of non-fossil energy is now more attractive. The decrease in the use of fossil energy is thus overcompensated by an increase in the use of non-fossil energy. When σ_E is halved, the opposite holds. This results in a lower capital stock and a lower output for the energy sector, but higher values for the oil sector and higher imports of crude oil and gas.

Changing σ_Y, the elasticity of substitution between the intermediate composite and the inputs from other sectors in final goods production, primarily has effects on the range of the structural effects. When the values of σ_Y are doubled, the top levels of output and capital rise, while those at the bottom decrease. The effect of the tax on energy and oil is slightly higher than before, and the imports of fossil fuels decrease further. Using smaller values for σ_Y leads to opposite outcomes compared to using higher ones. The range of the structural effects gets smaller, the highest output is lower than in the original case, and the lowest output is higher. The same holds for the capital stocks. Generally speaking, if we allow for more flexibility in the production of final output, structural change is more pronounced as there are better possibilities to react to the tax. The sectors that benefit from the introduction of a CO2 tax benefit even more if final output production is more flexible. The opposite holds for the sectors that are negatively affected by the tax. If we alter the values of σ_X, there are similar effects compared to those for σ_C. Doubling the values leads to a stronger effect of the tax in all sectors, resulting in a decrease of almost all levels of output and the capital stocks. The reason is that the total amounts of labor and non-accumulable capital are fixed (i.e. labor and non-accumulable capital can only be reallocated between sectors), which means that the sectors cannot readily replace energy by these two inputs. Therefore, the tax just results in lower output levels. The opposite holds again when substituting for energy is less easy (reflected by smaller values of σ_X). The impact of the tax is smaller in this case, resulting in higher levels of all outputs and capital stocks and higher imports of fossil fuels.

The trade elasticities have relatively large effects, especially when they are increased. The machinery industry, which is the sector with the largest positive effects on output and capital, has large imports and exports and is, alongside with the chemical industry, the most trade intensive sector. Changing the elasticity of transformation has quite a big impact on this sector. If we set its value to 2, the output of MAS increases significantly compared to when σ_T is equal to unity. The other sectors are, however, not that sensitive in this respect, but the range of the structural effects still gets considerably larger. Decreasing σ_T triggers opposite effects, however on a much lower scale. Increasing the Armington elasticities results

	FF_{CRU}	FF_{GAS}	C	W
$\sigma_C(doub)$	-0.055	-0.067	-0.001	-0.001
$\sigma_C(half)$	0.032	0.039	0.001	0.001
$\sigma_E(doub)$	-0.024	-0.030	0.002	0.001
$\sigma_E(half)$	0.010	0.013	0.000	0.000
$\sigma_I(doub)$	0.000	0.000	0.000	0.000
$\sigma_I(half)$	0.000	0.000	0.000	0.000
$\sigma_N(doub)$	0.000	0.000	0.000	0.000
$\sigma_N(half)$	0.000	0.000	0.000	0.000
$\sigma_W(doub)$	-0.002	-0.004	-0.001	0.003
$\sigma_W(half)$	0.002	0.004	0.001	-0.002
$\sigma_{Y,i}(doub)$	-0.011	-0.005	0.000	0.000
$\sigma_{Y,i}(half)$	0.004	0.002	0.001	0.001
$\sigma_{X,i}(doub)$	-0.101	-0.126	-0.005	-0.002
$\sigma_{X,i}(half)$	0.060	0.075	0.004	0.002
$\sigma_{A,i}(+1)$	-0.145	-0.153	-0.008	-0.004
$\sigma_{A,i}(-1)$	0.076	0.076	0.003	0.002
$\sigma_T(doub)$	-0.018	-0.012	0.000	0.000
$\sigma_T(half)$	0.010	0.008	0.001	0.001

Table 6: Effects of changing parameter values when the tax revenue is redistributed to the household (continued)

in similar effects, but they are even more pronounced. The machinery industry benefits a lot, while the sectors at the bottom suffer losses. The tax leads to larger adjustments in this case, which again results in a wider range of structural effects. The opposite holds again if we decrease the Armington elasticities. This is actually the only case where the machinery industry is no longer the sector with the highest output and the highest capital stock. The sectors at the bottom on the other hand increase their output, and the tax has a smaller effect on energy output. Investment incentives in the energy sector are high under these conditions (therefore its capital stock is higher than in the original case), and consequently, energy output also increases. Changing the trade elasticity mostly affects the trade intensive sectors. They show strong reactions when the conditions for trade are varied, and they therefore mostly drive the adjustments that take place here.

To sum up, we see relatively small effects for most parameter variations. Structural changes is identical to the case with original values, but it may be more or less pronounced. A general observation is that the model is most sensitive to changes in parameter values that are based on given empirical estimations, which underlines the importance of having reliable estimates for these parameters. The values of the elasticities that could not be taken from existing studies play only a minor role. And even in the cases with the biggest effects and output and capital, overall welfare never changes significantly.

5.2 Taxes revenue redistributed as a subsidy for the R&D sector

Our second scenario presents a different use of the tax revenues collected from the CO2 tax. Instead of redistributing the revenues back to the representative household, they are used as a subsidy for the R&D sector. Because this alternative way of redistribution directly affects the incentives to invest in new capital goods, the effects of changing certain parameter values may be different from those described in the previous section. We therefore conduct the same sensitivity analysis as above for this scenario. The results are presented in Tables 7 and 8.

We can see from the two tables that the effects are generally very similar to those described above, both in direction and magnitude. The arguments made in the previous section therefore also hold for this scenario. There are only two cases where the effects are clearly different. When the tax revenues are redistributed to the household, changing the values of the elasticities in the investment functions (σ_I and σ_N) only has minimal effects. This is different here, where the subsidy directly benefits the investments. When σ_I is lowered such that physical and non-physical investments are almost complements, the effect of the subsidy is slightly more positive. The capital stocks and output of all sectors rise. This is due to the fact that if the two investment types are complementary, physical investments have to be augmented as well if non-physical investments are subsidized. However, the effect is not big enough here to have an

	Y_{top}	Y_{EGY}	Y_{bot}	K_{top}	K_{EGY}	K_{bot}
$\sigma_C(doub)$	-0.012	-0.067	-0.053	-0.008	-0.084	-0.053
$\sigma_C(half)$	0.006	0.040	0.032	0.004	0.047	0.030
$\sigma_E(doub)$	-0.026	0.040	-0.024	-0.024	0.069	-0.030
$\sigma_E(half)$	0.011	-0.016	0.010	0.011	-0.031	0.010
$\sigma_I(doub)$	-0.008	0.000	0.001	-0.012	-0.003	-0.001
$\sigma_I(half)$	0.004	0.001	0.000	0.006	0.002	0.000
$\sigma_N(doub)$	0.015	0.001	0.000	0.017	0.003	0.002
$\sigma_N(half)$	-0.027	0.000	0.001	-0.031	-0.005	-0.003
$\sigma_W(doub)$	-0.002	-0.002	-0.002	-0.007	-0.005	-0.004
$\sigma_W(half)$	0.009	0.003	0.002	0.015	0.006	0.004
$\sigma_{Y,i}(doub)$	0.059	-0.007	-0.012	0.081	-0.012	-0.100
$\sigma_{Y,i}(half)$	-0.021	0.003	0.005	-0.028	0.005	0.039
$\sigma_{X,i}(doub)$	-0.081	-0.123	-0.098	-0.068	-0.176	-0.099
$\sigma_{X,i}(half)$	0.052	0.074	0.059	0.042	0.095	0.057
$\sigma_{A,i}(+1)$	0.405	-0.155	-0.146	0.346	-0.215	-0.144
$\sigma_{A,i}(-1)$	-0.134	0.078	0.078	-0.115	0.102	0.073
$\sigma_T(doub)$	0.137	-0.013	-0.019	0.012	-0.019	-0.017
$\sigma_T(half)$	-0.041	0.009	0.011	-0.033	0.013	0.010

Table 7: Effects of changing parameter values when the tax revenue is used to subsidize non-physical investments

effect on overall welfare. If we double σ_I, we get the opposite effect on the capital stocks, but again at a very low scale. Altering the value of σ_N also leads to small changes. The higher the flexibility in the build-up of non-physical capital, the higher is the effect of the subsidy on sectoral outputs and capital stocks. But again, this effect is very small.

Other than that, the model shows very similar reactions as when the household gets the tax revenue. The value of the inter-temporal elasticity in the welfare function (σ_W) only has a slightly bigger but still very small effect here. The consumption profiles are minimally different depending on whether inter-temporal substitutability is easily possible or not, but the overall effects are very small. Changes in σ_C lead to almost identical variations in the results as before. A better substitutability of energy and non-energy goods leads to a stronger reaction on the tax and a lower energy use. The opposite holds when σ_C is halved. For σ_E, we have the same pattern as before. The reactions are almost identical, and they can obviously be explained by the same reasoning as in the previous section.

Changing the values of the elasticities that affect the production processes also leads to very similar variations in the results as before. For σ_Y, the magnitude of the effects is again almost identical. We have again a wider range in sectoral output if we allow for more flexibility in the production of final goods. Similarly to above, we get relatively large negative reactions if the original values of σ_X are doubled. The effects are even a bit larger in this scenario. For the lower values of σ_X, we have just about the same effects as above. The effects of the values of the trade elasticities are also again relatively large here and even slightly more pronounced, both at the top and at the bottom.

Summing up, we see that the model also works reliably when we choose a different mechanism for the redistribution of the tax revenues. The effects are mostly very similar compared to those presented in section 5.1, except for the fact that also the elasticities in the investment nesting have some impacts here. Not included in this sensitivity analysis are variations of the interest rate or the share of capital (1-κ). This may be interesting as well, but is problematic as it would require changes in the original data. If we would want to vary the interest rate, we would (according to the calibration procedure in Paltsev (2004)) either have to adjust the depreciation rate of capital as well, or we would have to change the initial capital stocks. This then translates into different growth rates compared to the original case, which makes the comparison difficult. The same holds if we would want to check for different gains of specialization (i.e. a different initial capital share). This again requires changes in the original data, and the results would not be comparable to the original case.

	FF_{CRU}	FF_{GAS}	C	W
$\sigma_C(doub)$	-0.053	-0.066	-0.001	0.000
$\sigma_C(half)$	0.032	0.039	0.000	0.001
$\sigma_E(doub)$	-0.024	-0.030	0.002	0.001
$\sigma_E(half)$	0.010	0.013	-0.001	0.000
$\sigma_I(doub)$	0.001	0.000	0.000	0.001
$\sigma_I(half)$	0.000	0.000	0.000	0.000
$\sigma_N(doub)$	0.000	0.000	0.000	0.001
$\sigma_N(half)$	0.001	0.000	0.002	0.002
$\sigma_W(doub)$	-0.002	-0.002	-0.002	0.001
$\sigma_W(half)$	0.002	0.003	0.001	-0.001
$\sigma_{Y,i}(doub)$	-0.012	-0.006	-0.001	0.000
$\sigma_{Y,i}(half)$	0.005	0.002	0.000	0.000
$\sigma_{X,i}(doub)$	-0.098	-0.124	-0.004	-0.001
$\sigma_{X,i}(half)$	0.059	0.073	0.002	0.001
$\sigma_{A,i}(+1)$	-0.146	-0.155	-0.007	-0.004
$\sigma_{A,i}(-1)$	0.078	0.077	0.002	0.002
$\sigma_T(doub)$	-0.019	-0.012	0.000	0.000
$\sigma_T(half)$	0.011	0.008	0.000	0.000

Table 8: Effects of changing parameter values when the tax revenue is used to subsidize non-physical investments (continued)

6 Conclusions

This paper is part of a series that describes the CITE model, its theoretical background and its results. The aim of this paper was to give some insight on the data and the parameters used in the model. Additionally, we tested the model results for their robustness with respect to changes in the values of the elasticities of substitution.

The latest input-output table for Switzerland is the most important source of data for the model. After a couple of adjustments, it holds all the necessary benchmark values for output, consumption, investments, factor inputs and trade that are needed. The most notable changes were the introduction of R&D investments and the differentiation of two different capital types. The parameters values were, whenever possible, based on existing studies and estimations. Because of some particularities of our model, especially in the production processes of the output sectors, this was not always possible. The values that could not be taken from existing work were set as reasonably as possible. The sensitivity analysis showed that the model results are not very sensitive to changes in the parameter values, irrespective of whether the tax revenues are redistributed to the household or used to subsidize non-physical investments. Welfare and consumption are very robust and generally not affected by the changes that were made. Also the structural effects were not different compared to the original case in most of the variations that were tested. The elasticities that affect the flexibility of the production processes and trade seem to have the largest impacts. This highlights the importance of being able to rely on profound estimates for these parameters. The elasticities in the consumption and investment functions have only very small or no effects at all. Generally, environmental policy has bigger structural effects if there are better substitution possibilities for the taxed inputs. The more room there is for the economy to adjust, the larger is the decline in energy use and fossil fuel imports. Or put differently: If it were easier to replace energy (and especially the fossil fuels) in the production process, the targets for the reduction of energy use could be met with lower taxes.

A limitation of the model that is used here may be its very simple formulation of the labor market. The fact that labor supply is fixed and inelastic mostly drives the effects that we observe when the values of σ_X are varied. As there is no good substitute for energy in the production of intermediate varieties, higher values of σ_X simply result in larger decreases in output of all sectors. As this may be different if we had a more sophisticated representation of the labor market, this would certainly be an interesting extension of the model.

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8 Appendix

8.1 Nestings

The following figures describe the production structure of the sectors used in the model (Figures 1 to 3) and the nestings of consumption (Figure 4) and of investments (Figure 5).

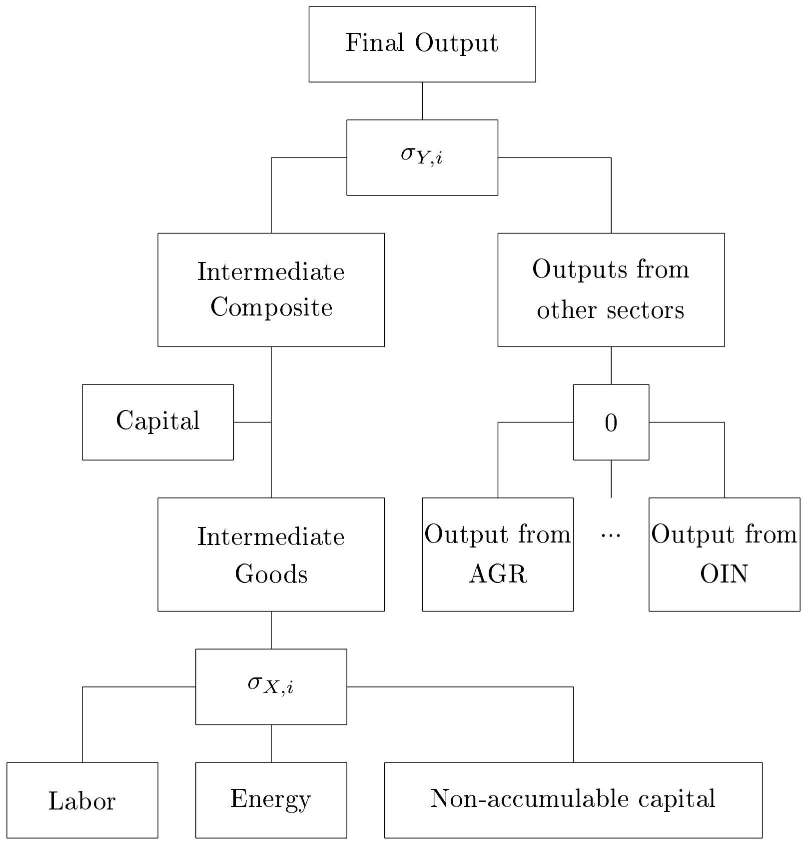

Figure 1: Nested production function of output sectors (except energy and oil)

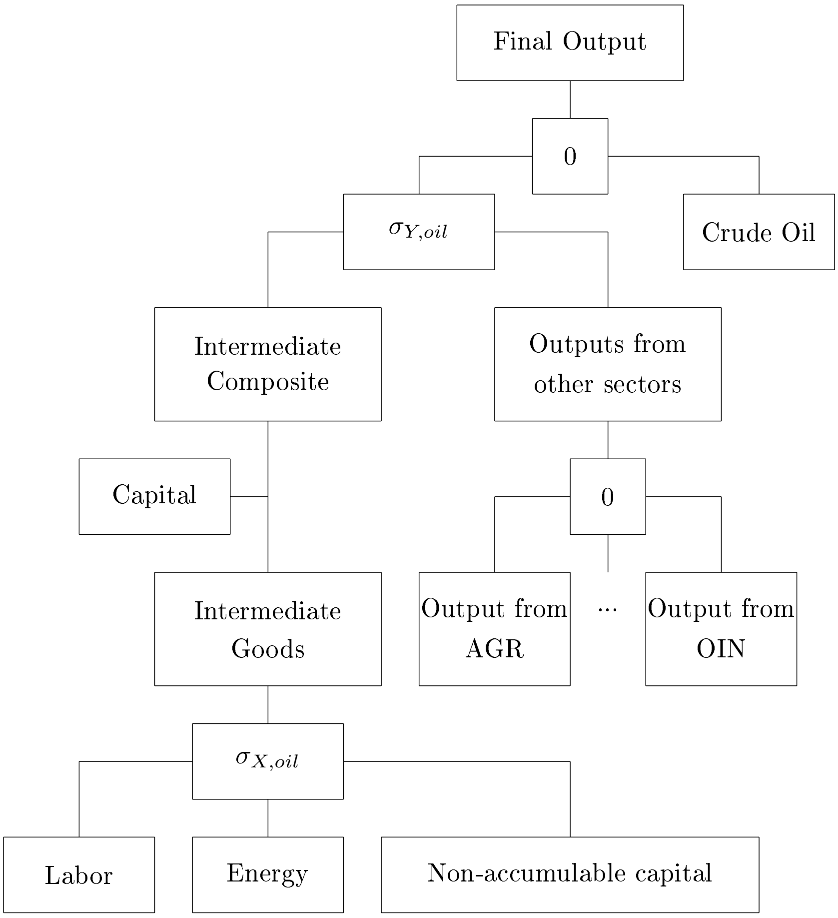

Figure 2: Nested production function for the oil sector

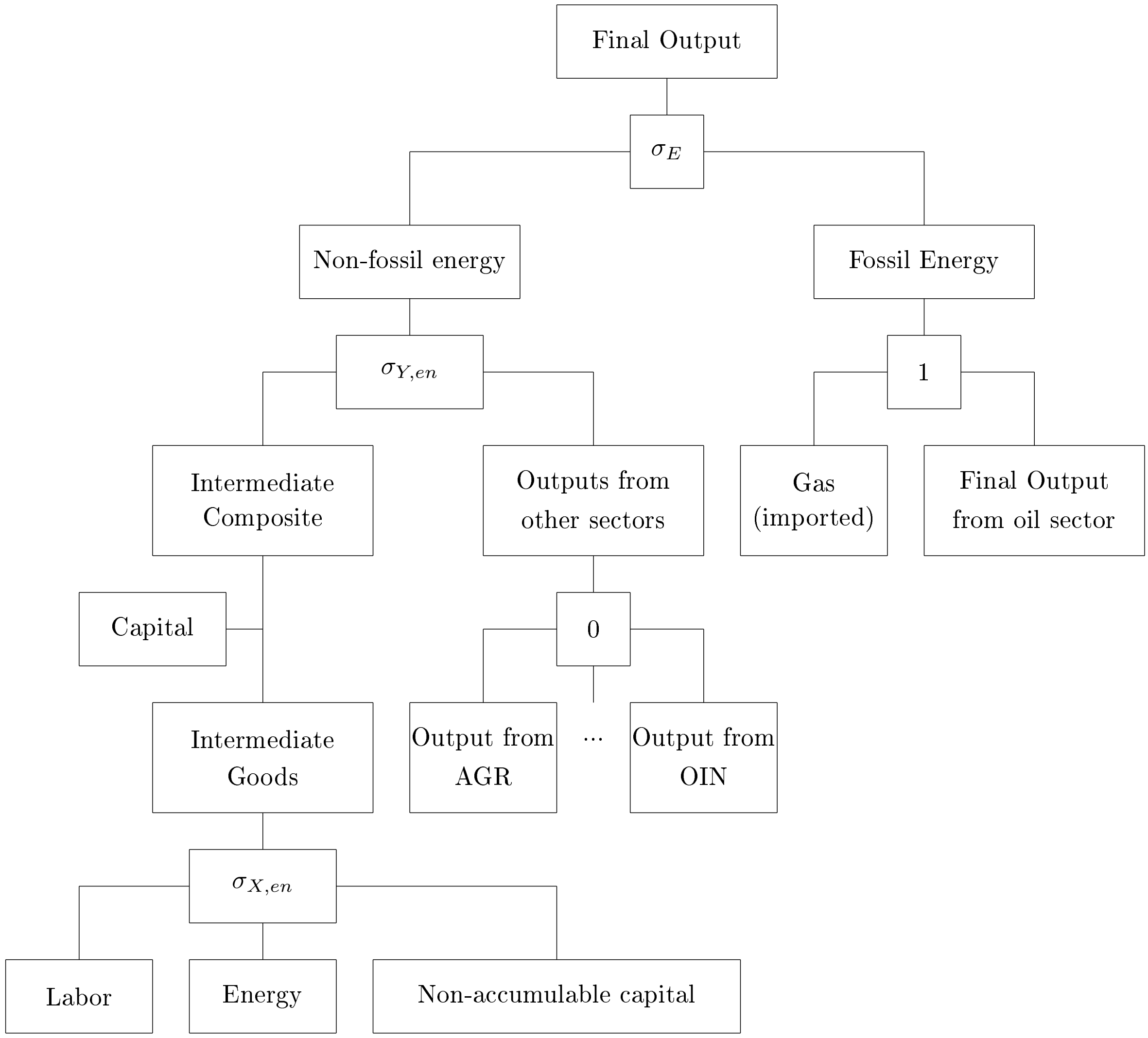

Figure 3: Nested production function for the energy sector

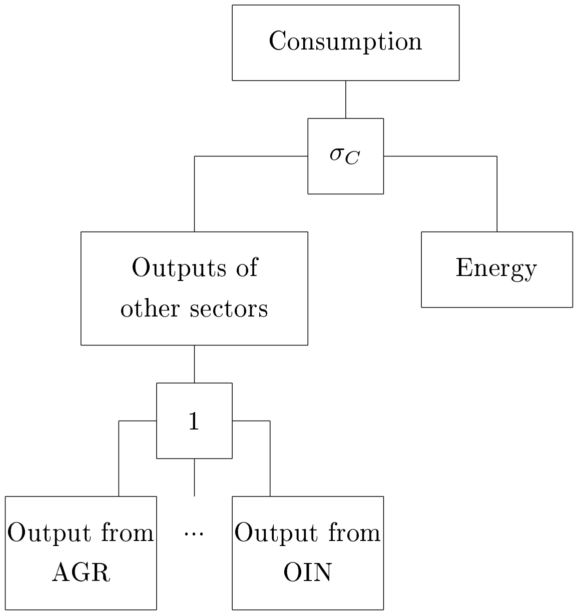

Figure 4: Nested consumption function

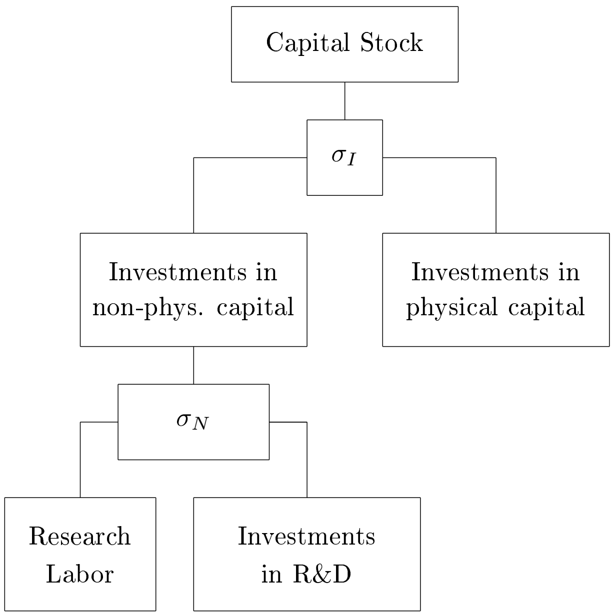

Figure 5: Nested investment function (equal for all sectors)

Appendix D: *Long-term energy policy in Switzerland and its economic effects: Results from the CITE model.*

Long-term energy policy in Switzerland and its economic effects: Results from the CITE model

1 Introduction

The climate problem is arguably one of the biggest and most important issues that have to be addressed by policy makers. As the problem has a global dimension and may have impacts on various levels, coordinated action is necessary to counteract the projected negative effects. Besides globally coordinated action, energy and climate policy on a country level is also crucial.

In Switzerland, the debates in the field of energy and climate policy have drawn more and more attention recently. On the one hand, there is the discussion on future reduction targets for CO2 emissions and the policy measures that have to be implemented to meet the given targets. The CO2-law, whose aim is to ensure the fulfilment of the reduction targets that have been set in the Kyoto Protocol, is the central part of climate policy in Switzerland until 2012. For the time after 2012, no binding targets have been set yet. However, the Federal Council has announced that Switzerland will comply to a reduction of CO2 emissions of 20% until 2020. The target may be augmented to 30% if other countries or regions (most notably the European Union) set similar constraints. At the climate summit in Copenhagen, no binding constraints have been set, but there is at least an agreement that the global temperature increase has to be limited to 2 degrees Celsius. In order to reach that target, CO2 reductions should be in a range of 25% to 40% until 2020 and 80% to 95% until 2050 for industrialized countries (compared to 1990 levels). Considering these numbers, it is foreseeable that a reduction target of 30% until 2020 is more realistic.

Apart from these discussions on a global level, there is also a controversy in Switzerland in the field of energy policy regarding the supply of power. Within the next 10 years, three nuclear power plants will have to be shut down. According to the most recent Electricity Statistics (Schweizerische Elektrizitaetsstatistik (2008)), about 40% of total power was produced by the six nuclear power plants in 2008. About a third of total nuclear energy came from the three power plants that will be shut down in the next couple of years (Benznau I and II and Muehleberg). This has led to uncertainties concerning the future security of power supply, as a considerable amount of current power production would have to be replaced. This issue is not resolved yet and still subject to ongoing discussions.

An obvious way to address this problem is to implement policies that aim directly at reducing energy demand substantially in the years to come. An ambitious target in this respect is the idea of the 2000-Watt society, which also forms the basis for the scenarios applied in this analysis. It postulates that in the long-run, constant per capita energy use in Switzerland has to be reduced to 2000 Watt. This idea is also one of the scenarios discussed in Energy Perspectives ("Energieperspektiven"). Within four scenarios that differ mostly in stringency of energy policy and assumptions on the development and use of renewable energy (see Prognos (2007)), future developments of energy use are discussed. The fourth and most stringent scenario (hereafter referred to as "scenario IV") directly refers to the idea of the 2000-Watt society. A second part (Ecoplan 2007)) then discusses the economic effects of implementing the four scenarios. A similar goal is pursued in a scenario in this study (yet restricted only to scenario IV).

The technical feasibility of a 2000-Watt society has been shown (see Jochem et al. (2004)). Given plausible assumptions on future technological developments, Jochem et al. show that the 2000-Watt society is a realistic target from the engineer point of view. The economic consequences however are still not very well known. A directly comparable reference is Ecoplan (2007). This study discusses the economic effects of the scenarios given in Energy Perspectives using a simulation model as well. They find a welfare loss of 0.25% using a time horizon up to 2035 for Scenario IV, which is less than the corresponding result of our study (we find a welfare loss of 0.6% for this scenario). This difference can however be explained by different modeling approaches and the higher discount rate (5%, while we have a discount rate of about 1.1%) in the Ecoplan study. Additionally, the treatment of technological change and economic growth is clearly more simplified and also contributes to the difference between the two outcomes.

It is the aim of this analysis to give some new insights on the effects of such ambitious targets for future energy use using a model that incorporates an endogenous growth mechanism. The analysis here is conducted using the CITE model. The CITE model is a CGE (Computable General Equilibrium) model that is especially suitable for the analysis of the economic effects of different energy policies. The central aim of the CITE model is to give a more sophisticated representation of the mechanisms that drive economic growth. Rather than assuming that economic growth is an exogenous variable, our model explicitly incorporates the relationships between the investments into new capital varieties and sectoral productivity and growth. The basic idea (explained in more detail in Section 2) is that investing in new capital varieties entails a positive effect on the productivity in the respective sector. Sectoral growth is therefore primarily driven by the investment decisions. These decisions in turn (or rather the investment incentives) are sensitive to the policies that are implemented. Energy policy thus can enforce technical change by altering the attractiveness of different sectors for investments.

The rest of the paper is organized as follows. Section 2 gives an overview of the relevant literature. Section 3 briefly describes the model and the data. The policy scenarios are explained in Section 4, and Section 5 presents the results. Section 6 discusses the implications of different policies abroad. Section 7 then offers some conclusions.

2 Literature overview

The issue of climate change has increased the need for research in the field of energy and climate policy. CGE models are a valuable tool that allows to study various aspects in this context, such as the timing and the efficiency of policy measures, the resulting changes in the energy system and so on. The models can be roughly divided into two categories. Top-down models focus on the macro-effects of climate change and related policy measures. The energy sector is then usually represented in a highly aggregated way without a detailed description of the different technologies. These models thus concentrate on aggregate effects and abstract from am explicit differentiation of energy technologies. The CITE model fits in this category as well. Bottom-up models on the other hand usually feature a detailed representation of the energy system and the relevant technologies. The focus in these models is therefore primarily on the developments in the energy sector and the respective technologies. Substitution of different energy sources and innovations of new technologies or processes are the key points of interest. More recently, a new class of models tries to combine the two approaches. This has the advantage that both aspects (the macro-effects and the changes on a technological level) can be taken into account. This, however, comes at the cost of an increasing complexity of the models.

In both approaches, an important issue is the modeling of technological change and the improvement of the productivity or the efficiency on different levels of the production process. Early models such as the GREEN model (Burniaux et al. (1992)) or the RICE model by Nordhaus and Yang (1996) assume that technological change is purely exogenous and therefore not influenced by policy. Technological progress is then simply introduced as a given parameter. If it is related to the energy sector, it is usually referred to as an AEEI (autonomous energy efficiency improvement) parameter. Energy efficiency thus increases at a given rate that is independent of the behavior of the agents in the model. This is obviously an unsatisfactory treatment of technological change as it neglects the fact that technological change can be influenced in many ways. A possible representation of endogenous technical change is the notion of learning-by-doing. This approach is especially common in bottom-up models. It captures the fact that the costs of different technologies decline if the technologies are more widely used and adopted. The different technologies usually have different learning curves that define how the costs evolve over time. Prominent examples in this field are the MESSAGE model (Messner (1997)), the MARKAL model (for example used in Seebregts, Kram, Schaeffer and Bos (1999)), the DEMETER model (see van der Zwaan, Gerlagh, Klaassen and Schrattenholzer (2002) and Gerlagh and van der Zwaan (2003)) and Manne and Richels (2004). Most of these models additionally use an AEEI parameter to represent technological change at the level of final output production. Endogenous technical change is therefore only present in the energy sector.

The second frequently used representation of endogenous technical change is the usage of knowledge stocks. The knowledge stocks are usually accumulated by R&D investments and may feature additional inputs capturing innovative activity (such as labor in the research sector). Knowledge may either have an impact on overall productivity or may be restricted to specific sectors, most notably to the energy sector. These effects on productivity are often referred to as spill-overs. If the knowledge stocks are energy-specific, investments in R&D and thus the accumulation of knowledge aims at increasing the efficiency of energy use. This is done in Kemfert (2002) and in the ENTICE model of Popp (2004) and the ENTICE-BR model (Popp (2006)), which is an extension of the original version. Endogenous technical change through knowledge accumulation and R&D investments not only restricted to energy is featured in Goulder and Schneider (1999), Nordhaus (2002), Buonanno, Carraro and Galeotti (2003), Sue Wing (2003), Otto, Loeschel and Delink (2005) and Otto, Loeschel and Reilly (2006). Bye et al. (2008) take up the ideas from Romer (1990) to model innovative activity and its effects on sectoral productivity. It has specific formulations both for the production of blueprints and of the capital varieties. An application of this model can be found in Heggedal and Jacobsen (2008).

Some models also combine the two approaches. Goulder and Mathai (2000) compare the effects of different accumulation mechanisms of a knowledge stock related to CO2 abatement. Knowledge is either learning-by-doing-based (it is augmented with increasing abatement) or R&D-based (and therefore a result of R&D investments). A similar approach is taken in Castelnuovo, Galeotti, Gambarelli and Vergalli (2003). Other models including both learning-by-doing elements and R&D investments are MIND (Edenhofer, Bauer and Kriegler (2005) and Edenhofer, Lessmann and Bauer (2006)), Bosetti, Carraro and Galeotti (2006) in an extension of the RICE model, and Kypreos (2007). More details on the underlying differences in modeling technical change can be found in Loeschel (2002).

3 The Model and the Data

This section briefly describes the model and the data used in the simulations. A detailed description of the theoretical foundation of the model is available in Schwark (2010), while the data and the parametrization of the model are discussed in Ramer (2010). The nested functions of production, consumption and investments can be found in the Appendix (Figures 18 to 22).

Sector	**NOGA-Classifications**
Agriculture (AGR)	01-05
Refined Oil Products (OIL)	23
Chemical Industry (CHM)	24
Machinery and Equipment (MCH)	29-35
Energy (EGY)	40
Construction (CON)	45
Transport (TRN)	60-63
Banking and Financial Services (BNK)	65
Insurances (INS)	66
Health (HEA)	85
Other Services (OSE)	50-55, 64, 70-75, 80, 90-95
Other Industries (OIN)	10-22, 25-28, 36-37, 41

Table 1: Overview of the sectors used in the model

The CITE model includes 12 production sectors (10 regular sectors and two energy sectors) that produce final output (see Table 1 for an overview). Production functions are symmetric across all sectors, with two notable exceptions. Sectors obviously differ in their input mix and the factor shares. They produce final output using outputs from the other sectors (which reflects the linkages between the sectors given in the input-output table) and an intermediate composite. The intermediate composite incorporates the endogenous growth dynamics driven by the expanding varieties approach. Using a Dixit-Stiglitz production function (Dixit and Stiglitz (1977)), it assembles the different intermediate varieties to one composite good. The exponent in the Dixit-Stiglitz function represents the gains of specialization. These gains of specialization increase with the number of varieties, which is equal to the size of the sectoral capital stock. Investing in new capital varieties has therefore a positive productivity effect, because it increases the gains of specialization and thus the sectoral growth rate. The intermediate varieties are produced using energy, labor and non-accumulable capital. A representative household owns the factor inputs and allocates its factor income between consumption and investments into the sectoral capital stocks. These capital stocks are built up by two different types of investment. Investments in R&D, together with research labor, is an input to the build-up of non-physical capital. The capital stock is then formed with non-physical capital and physical investments. Consumption is divided into consumption of energy and of outputs from the remaining sectors. The CITE model is essentially a one country model. Trade is included via Armington goods (Armington (1969)), which means that goods are differentiated according to their origin. Imported and domestically produced goods are treated as imperfect substitutes, implying that a foreign good is not a perfect replacement for a domestic good. Exports are included using a CET (constant elasticity of transformation) function that differentiates between domestic and foreign demand.

The oil sector and the energy sector have different production functions compared to the other sectors (see Figures 19 and 20 in the Appendix). The oil sector uses crude oil as an additional input on the top level of the nested production function. The output of the oil sector then forms, together with gas, fossil energy, which is an input in the production of the energy sector. Non-fossil energy is produced analogously to the other 10 sectors. Fossil and non-fossil energy enter the production of the energy sector at the top level and are therefore directly substitutable.

The data comes from the Swiss input-output table for the year 2005, which is the most recent version available (see Nathani, Wickart and van Nieuwkoop (2008) for a description). After a couple of adjustments, the input-output table holds all the necessary benchmark values for outputs, intermediate and final demand, factor inputs and exports and imports. The values for the elasticities of substitution have been chosen in accordance with existing studies or empirical estimations whenever possible. The values are listed in Table 4 in Ramer (2010). This paper also includes a sensitivity analysis that tests the stability of the model with respect to changes in the parameter values.

4 Description of the scenarios

Our first policy scenario (hereafter labeled 80%-target) is inspired by recent emissions reduction targets that would be necessary to keep global warming within a reasonable range. For industrialized countries, reductions in CO2 emissions between 25% and 40% until 2020 and between 80% and 95% until 2050 (compared to 1990 levels) are necessary to limit global warming to 2°C. In this scenario, we simulate a path that leads to a 30% reduction until 2020 and an 80% reduction until 2050. The fact that only one region is included in the model implies purely domestic abatement and disregards emission offsets abroad, which are often seen as being less costly. The policy instrument implemented to achieve these reduction targets is a CO2 tax. This CO2 tax increases the prices of the two fossil fuels included in the model, oil and gas. Oil (referring to the output of the oil sector) and gas are the two inputs to the production of fossil energy. Fossil energy is then again an input to production in the energy sector. The use of the two fuels is assumed to be unequally polluting. We fix the CO2-intensity of gas at 1 and set the intensity of oil to 1.34. These intensities are assumed to be fixed over time and can therefore not be influenced by new technologies (e.g. by CCS). The tax is directly tied to the CO2-intensity. As we assume a uniform tax rate for both fuels but a higher CO2-intensity for oil, this implies that oil is effectively taxed at a higher rate than gas. Our model is calibrated to data from 2005, which implies that the reductions have to be even a bit higher, because total CO2 emissions in 2005 were higher than in 1990. The aim of the tax is thus to reduce total carbon emissions by 32% until 2020 and by 81% until 2050. We have set the tax so that this goal is exactly met. The initial tax rate is 0.05[1]. This rate is augmented until 2050 (at a higher rate after 2020) to a value of 2.9750. The revenues from the tax are redistributed back to the household and enter the budget constraint of the household as an additional income.

The second scenario takes up the ideas from Scenario IV of the Energy Perspectives. Scenario IV assumes that energy use has to be reduced by 35% by the year 2035 (compared to the year 2000) if the long-term goal of a 2000-Watt society is to be met by the end of the century. Thus, in this case, we use the CO2 tax to reduce overall energy use instead of carbon emissions. Again, as our base year is 2005, effective reductions need to be even higher (37.5%). Compared to the 80%-target, this is a less stringent restriction, but a more general one, as it is tied to overall energy use and not just to fossil energy. We simulate two different cases for this policy scenario. The difference between the two cases is the redistribution mechanism of the tax revenue. In the first case, the tax revenues are again redistributed back to the the representative household. In the other case, the tax revenues are used to subsidize the build-up of non-physical capital, which can also be interpreted as a subsidy to the R&D activities in the different sectors. This mechanism may be a more purposeful way to use the revenues, because it

[1] Note that the tax rate is not expressed in percentage points, but as an absolute premium on the prices of the fossil fuels. The prices are initially set to 1. The tax rate is multiplied with the carbon intensity to calculate the premium on the price.

directly supports the growth mechanism in the sectors and should thus facilitate the shift to a less energy intensive economy.

An implicit assumption of the model is that the rest of the world implements similarly stringent energy policy measures. In Section 6, we relax this assumption and consider the effects of diverging policies. We differentiate two cases. First, we assume that Switzerland implements a less stringent reduction target and thus sets a lower CO2 tax than the rest of the world. This is done by a corresponding variation of the trade elasticities. A lower CO2 tax in Switzerland means that foreign goods are relatively more expensive and thus less attractive as substitute for domestic goods. Therefore, the Armington elasticities have to be lowered. Foreign demand for Swiss goods on the other hand rises, which is modeled by a higher elasticity of transformation. The opposite holds when we assume that Switzerland introduced a more

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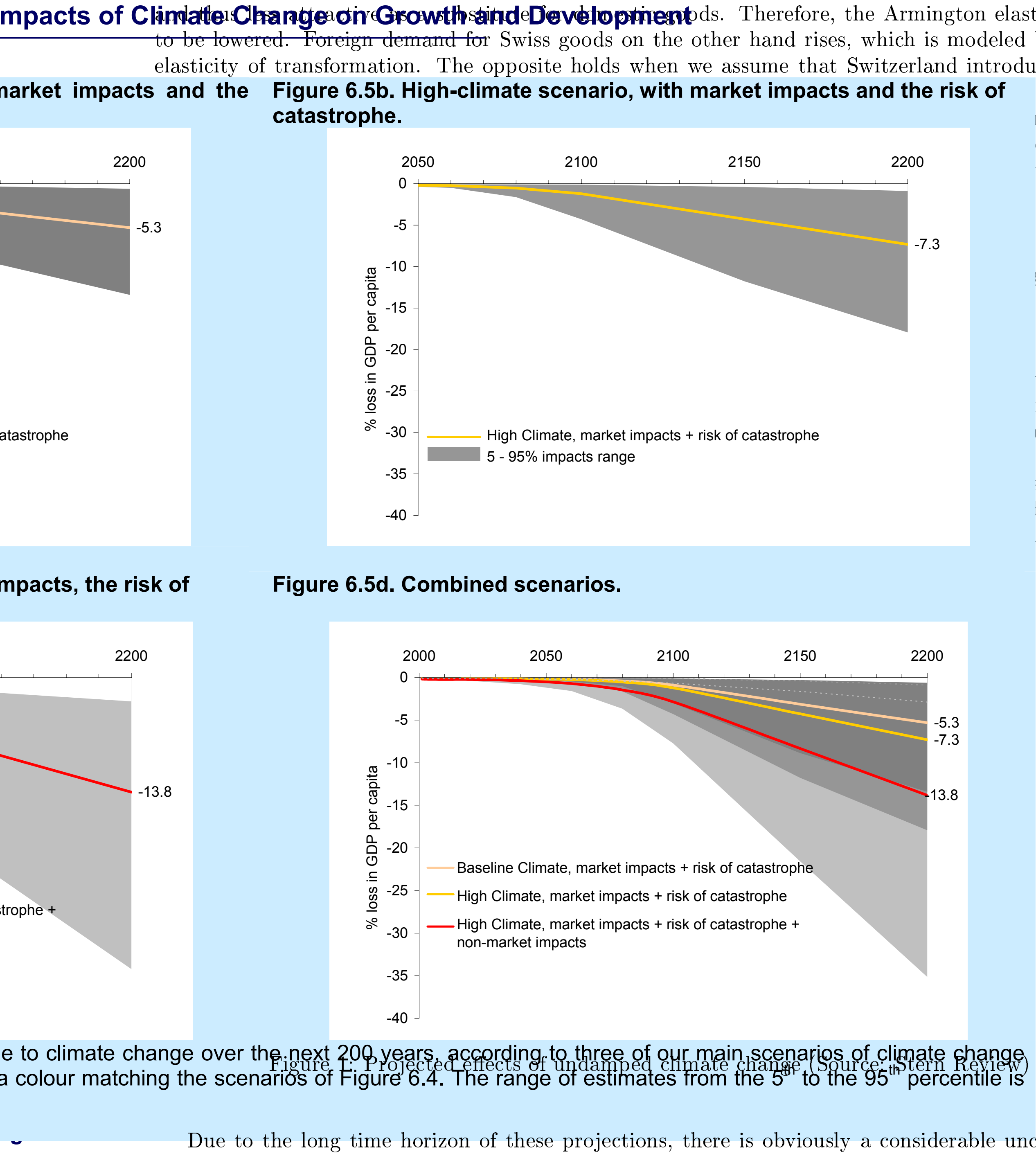

Figure 1: Projected effects of undamped climate change (Source: Stern Review)

Due to the long time horizon of these projections, there is obviously a considerable uncertainty on the effects on per capita GDP, and the range of possible long-term impacts is large. However, it seems clear that especially in later decades, the losses increase sharply in the absence of political intervention. Depending on the assumptions on the impacts of climate change and on what other effects are considered, losses could augment up to 35% in 2200. Policy measures aiming at mitigating climate change should thus be able to significantly reduce these losses in later decades. Thus, although it may lead to larger losses in the shorter term, implementing policy measures that mitigate climate change should be beneficial as possibly even larger losses in the long run can be avoided or at least reduced. Figure 1 may therefore be a more meaningful reference to compare the aggregate effects derived in the scenarios analyzed below.

5 Model Results

5.1 80%-Target

We first look at the results for the 80%-target. This target is based on necessary long-term emission reductions to keep global warming within a reasonable range. The CO2 tax is set so that total carbon emissions are reduced by 30% in 2020 and by 80% in 2050 (compared to 1990 levels). The first target is thus reached 10 years after the beginning of the model horizon, the second one after 40 years. The results are shown in Figures 2 to 4.

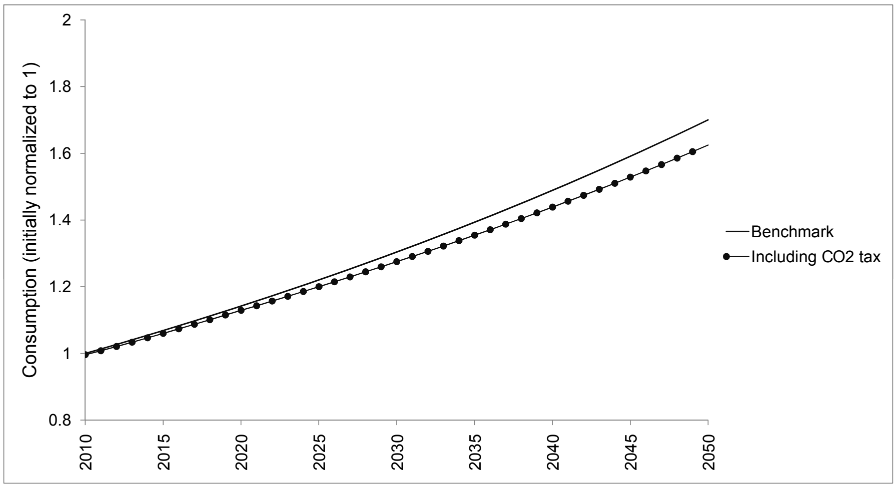

Figure 2: Growth paths of consumption, 80%-target

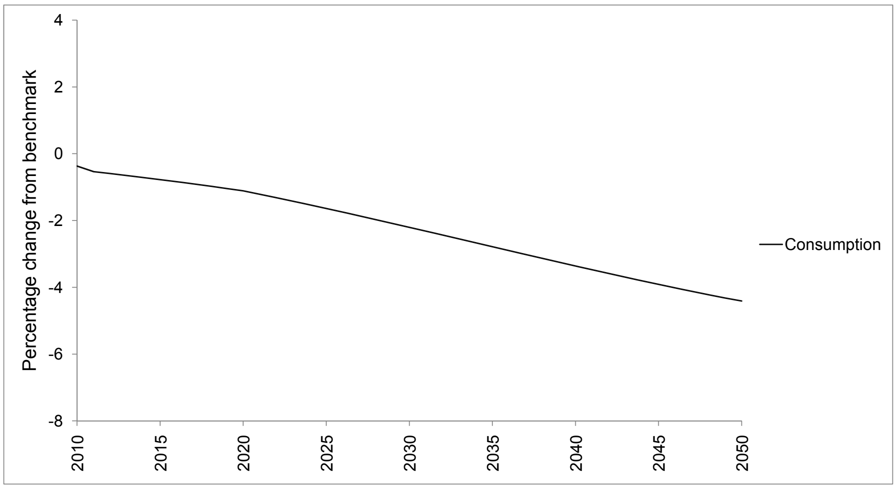

Figure 3: Aggregate consumption, 80%-target

Given the ambition of the target and the stringency of the policy, one would expect strong impacts on consumption and welfare. However, this is not the case. The effects both on consumption and welfare are moderate. Welfare, which is measured by total discounted consumption over the entire model horizon, decreases by 2.6%. The discount rate is about 1.1%, which is a comparably low value. Considering this and the stringency of the policy, a reduction of 2.6% seems to be a feasible (yet not negligible) cost. Additionally, there are no secondary benefits of energy policy or the mitigation of climate change included (such as positive effects on health costs due to cleaner air), and abatement is purely domestic and cannot be shifted abroad. The welfare loss would be even smaller if these positive side effects were also considered. Consumption over time declines steadily as long as the tax is rising (i.e. until 2050 when the reduction target is reached), but at a small scale. In 2020 (when the intermediate target of a 30% reduction is reached), consumption is reduced by slightly more than 1%. In 2050, it is about 4.5% lower than in the benchmark. This confirms previous findings that even relatively stringent policies are economically feasible from a consumer point of view. The relatively small difference between benchmark consumption and consumption after the implementation of the policy becomes even more apparent when we compare the growth paths (see Figure 2). The consumption level in 2050 in the tax scenario is reached about 2.5 years earlier in the benchmark scenario. One reason for these moderate effects is that the share of energy in total consumption is only 2% and therefore very small. The direct effect of the tax through an increase in the relative price of energy goods is thus only minimal. The CO2 tax also affects the prices of non-energy goods, because they use energy as an input to production. Non-energy goods enter consumption on the second level of the nested function and are assumed to be good substitutes, implying that the household has a relatively flexible consumption structure that facilitates substitution of energy intensive for non-energy intensive goods.

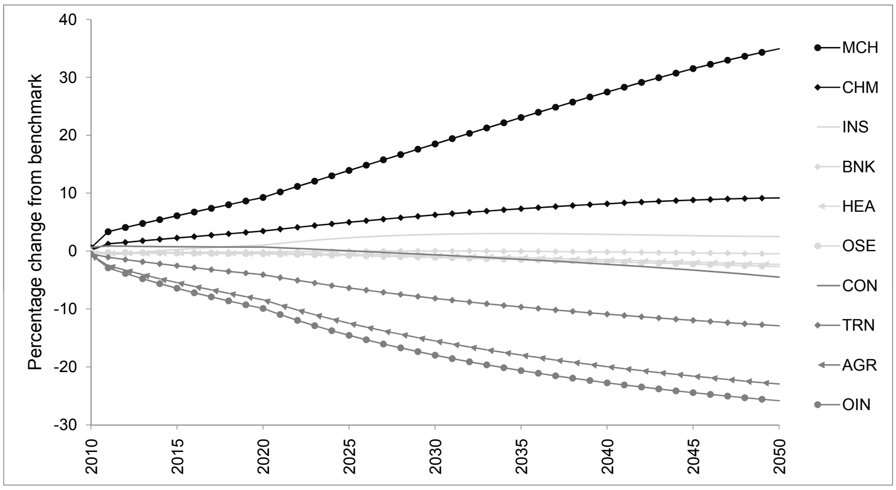

Figure 4: Sectoral outputs, 80%-target

At the sectoral level, the introduction of the tax leads to pronounced structural effects (see figure 4). Reactions in sectoral output range from an increase of about 35% in the machinery industry to a decrease of more than 25% in other industries (compared to the benchmark scenario). After 2020, the range of effects slightly widens due to the higher increase in the tax rate. Three sectors perform better than in the absence of a CO2 tax, the remaining sectors are either not much affected or suffer losses. The biggest gainer of the policy is the machinery industry. It increases its output by about 35% until 2050. The chemical industry and insurances also benefit from the introduction of the CO2 tax. The chemical industry gains slightly less than 10%, insurances about 2.4%. Several sectors incur small losses in the range of 2% to 4%. These sectors include construction and most service sectors (other services, health and banking and financial services). The sectors that lose more than 10% or even 20% by 2050 are other industries, agriculture and transport. The same pattern is also observed in sectoral capital stocks. The sectors with a lower output also have lower capital stocks, those with a higher output tend to have higher capital stocks. The effects are usually a bit smaller than those on output, but still on a similar scale.

There are various reasons for these structural changes. A first explanation is certainly the energy intensity of the sectors, i.e. the relative importance of energy as an input in the production of output of a sector (see table 2 in the Appendix for an overview). As energy enters sectoral production at the level of the intermediate varieties, we measure the energy intensity by the share of energy used in the production of the intermediate varieties ($(1 - \alpha_L - \alpha_{VK})$ in model parameters). The more energy a sector uses in its production process, the more it is exposed to the tax and the more it should be affected by the tax. Indeed, this is the most important reason for the observed effects. Transports, agriculture and other industries all have an energy share around 10%, which makes them the three most energy intensive sectors in the economy. Thus, the three sectors that have the highest energy intensity are those that suffer the largest losses. Construction also decreases its output compared to the benchmark, but at a smaller scale. The negative effect on the construction sector may however be overestimated in this model, because an important aspect of Swiss energy policy is excluded. Increased standards for energy efficiency for new buildings and corresponding regulations for the renovation of existing infrastructure are an important aspect of future reductions in energy demand. These regulations should clearly be favorable for the construction sector if they were included in the model, as the demand for construction services should increase significantly. This mechanism being excluded, the decrease in output of the construction sector can be readily explained by its relatively high energy intensity.

The service sectors on the other hand generally have very low energy intensities. Their shares are in a range between 2.6% for other services to 0.6% for banking and financial services. These low values show that services are clearly less exposed to the tax, and therefore their reactions to the tax are very small. The fact that they still perform slightly worse than in the benchmark can be explained by their comparably low substitution possibilities. For the service sectors, we assume a lower elasticity of substitution between the inputs in the production of the intermediate varieties. The potential to avoid the tax is smaller than other sectors, most notably than in the two industries that benefit from the introduction of the CO2-tax. This leads to a small decrease in output of most service sectors, despite the low energy shares. The machinery industry and the chemical industry also use relatively little energy in their production (the machinery industry has a high labor share, the chemical industry is very capital intensive), and they both have better substitution possibilities for energy than the service sectors (reflected by higher values of σ_X). These two characteristics give them a comparative advantage over the other sectors and enable them to benefit from the policy.

The capital stocks (not shown here) exhibit a similar pattern to output, which means that there is a clear indication that capital is shifted to the energy-extensive sectors. These sectors are more attractive for investors in the presence of the CO2-tax, because they are less affected by the tax. The energy-intensive sectors on the other hand suffer considerable outflows of capital, as investment is reduced and reallocated towards the energy-extensive sectors. This then translates to higher sectoral growth rates in the energy-extensive sectors, while the growth rates of the energy-intensive sectors decrease.

A second reason for the structural changes are the linkages of the different sectors to the energy sector and the oil sector. These linkages are reflected in the use of outputs of other sectors in the production process. As the oil sector and the energy sector reduce their output by a substantial amount due to the tax, they also require fewer inputs from the other sectors. The oil sector is strongly linked to other industries and to transport, the energy sector also relies on a lot of inputs from other industries (apart from gas and oil). Outputs from the machinery industry, the chemical industry and from the service sectors (most notably from insurances) only play a minor role in the production process of the energy sector and the oil sector. These linkages may however not be as important as the energy intensity. The oil sector is a very small sector, and the amounts of output used from transport and other industries are therefore also small. The energy sector is relatively factor intensive and relies on few inputs from other sectors. Therefore, the arguments made here may not drive the results, but they add to the effects that stem from the energy intensity. Third, certain sectors also benefit from the increased investments. Physical investments require inputs from industries such as construction and the machinery industry. As capital stocks and thus also investments increase significantly in certain sectors, sectors that provide goods that are necessary to implement these investments therefore additionally benefit.

The developments in the energy and the oil sector are not shown in the graphs, because the effects are mostly predetermined by the policy. Total energy output decreases by about 78%, the output of the oil sector by about 83%. The strong reduction in the oil sector makes sense as it is obviously affected the most by the tax. The energy sector on the other hand is also directly affected by the tax (through the input of fossil energy), but has more options to avoid it. Either by substituting gas (which is taxed at a lower rate) for oil, or by substituting non-fossil energy for fossil energy. Therefore, the negative impact on the whole energy sector is not a big as on the oil sector. This also implies that the reduction in non-fossil energy must be smaller than 80%, as a larger part from the overall reduction in energy use comes through a reduction in fossil energy use. The fact that the capital stock of the energy sector does not decrease at a similar scale as output indicates that non-fossil energy is still relatively more attractive for investments than fossil-energy. As only fossil energy is taxed, investing in non-fossil energy helps to counteract the negative effects that stem from the tax as it facilitates the shift from fossil to non-fossil energy.

Figure 4 shows the deviations from the benchmark path in percentage terms. In this figure, the benchmark path is given by the horizontal 0-line. This path incorporates an annual growth rate of 1.34% for all sectors. After the implementation of the tax, sectors deviate from this path and no longer grow at a uniform rate. The growth paths of the sectors under the new policy regime are shown in Figure 5.

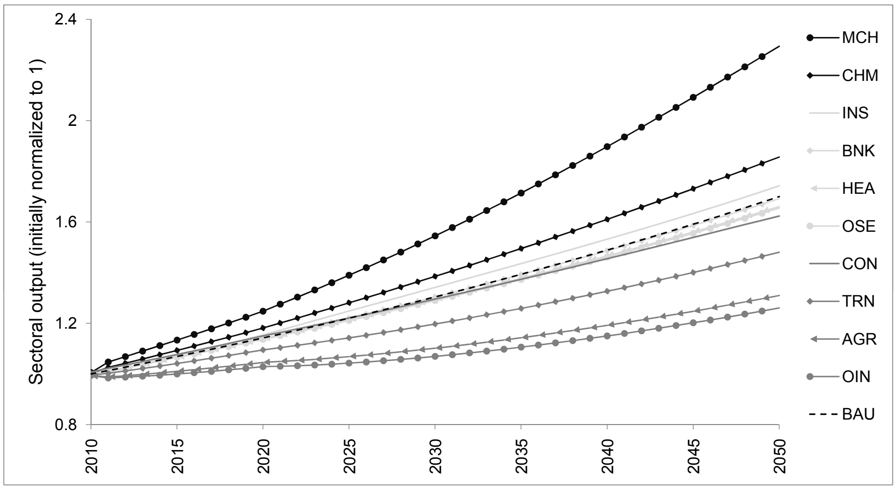

Figure 5: Sectoral growth paths, 80%-target

For simplicity, initial output levels have been normalized to 1. The benchmark path is indicated by the dashed line (denoted "BAU"). The figure shows that despite the ambitious policy, all sectors still exhibit positive growth. Nonetheless, growth paths differ significantly after the implementation of the CO2 tax. Annual growth rates range from 2.2% for the machinery industry to 0.4% for other industries. Structural change is therefore pronounced, but even the sectors that are negatively affected by the policy (meaning that their growth rates are smaller than the benchmark growth rate) grow at a positive rate. This result contradicts the view that stringent policies may be harmful for economic development. And keeping in mind that the benchmark path may very well be too optimistic (because it abstracts from the negative effects of climate change), the results derived here seem even more promising.

5.2 35% reduction in energy use until 2035

5.2.1 Tax revenues redistributed to the household

This scenario is closely related to scenario IV of the Energy Perspectives and the idea of the 2000 Watt society. According to scenario IV, total energy use has to be reduced by 35% until 2035 if the goal of a 2000 Watt society is to be reached by the end of the century. The policy instrument is the same as before, but contrary to the case discussed in the previous section, the restriction now applies to overall energy use. The tax rate starts at 0.07 and is then gradually augmented up to 1.29875 in 2035. The results are shown in Figures 6 to 8.

Compared to the 80%-target, the policy implemented in this scenario is less stringent. The requested reduction in energy use is smaller than above, and the time horizon is also shorter. In accordance with scenario IV, we do not implement any further targets for the time after 2035. Welfare loss is about 1.2% and therefore considerably smaller than in section 5.1. Correspondingly, the decrease in consumption over time is also very small. In 2035, consumption is just about 2% lower than in the benchmark. Put differently, the "delay" is now just about 1.5 years, meaning that the consumption level reached in 2035 corresponds approximately to the level reached in the middle of the year 2033 in the benchmark scenario. The reasons for these relatively small impacts are the same as in the previous scenario.

The effects at the sectoral level are also very similar. The direction of structural change is virtually identical. The non-energy intensive sectors with a relatively high substitution potential for energy benefit from the introduction of the tax. The service sectors, having very low energy shares, but also smaller elasticities of substitution at the level of production of intermediate goods, exhibit only small reactions. On the other hand, the three most energy-intensive sectors suffer losses of 8% and more. The effects on capital accumulation again work in the same direction as output. The non-energy intensive sectors

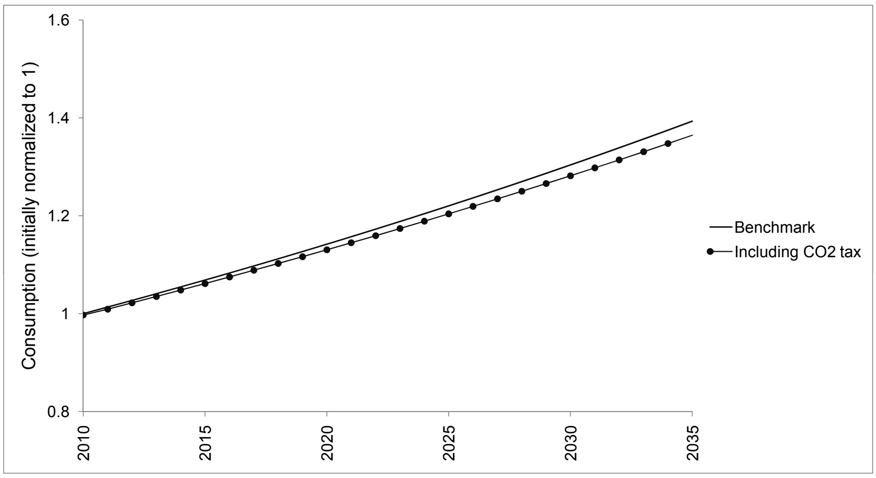

Figure 6: Growth paths of consumption, 35% reduction

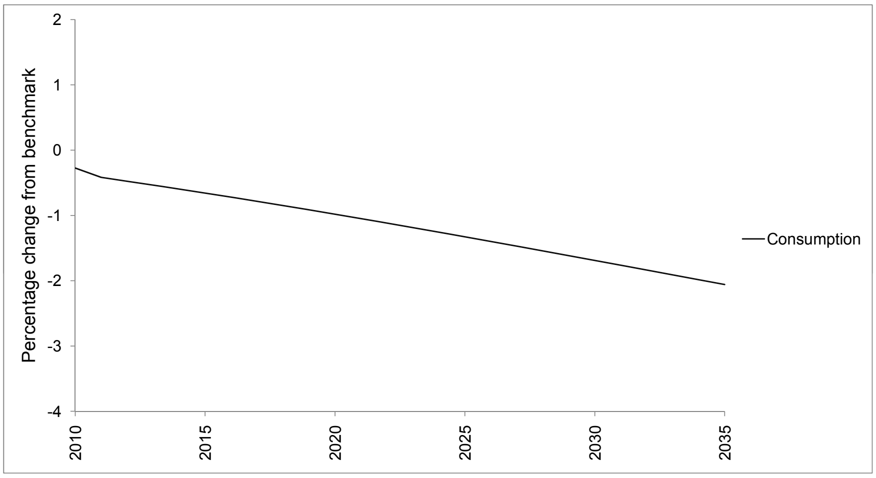

Figure 7: Aggregate consumption, 35% reduction

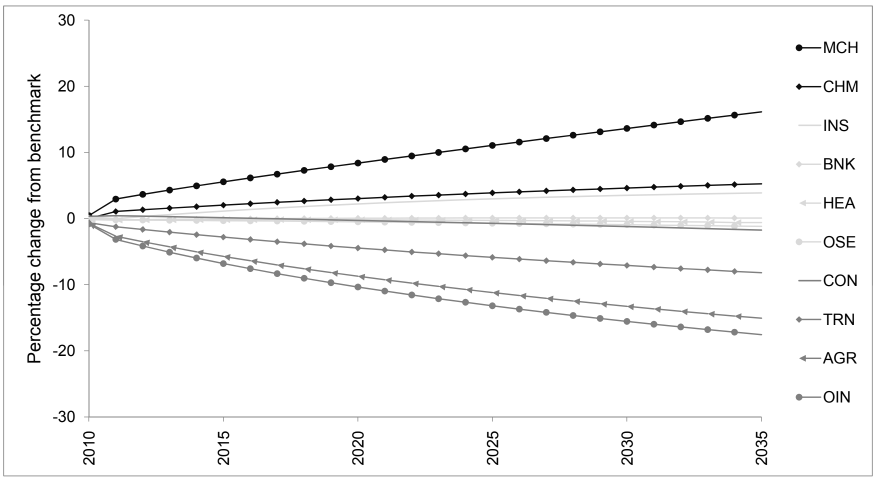

Figure 8: Sectoral outputs, 35% reduction

become more attractive for investors after the introduction of the tax, thus capital is reallocated to these sectors. Structural effects are thus similar irrespective of whether the reduction target is tied to carbon emissions or overall energy use, because in both cases, the energy-intensive sectors are exposed the most to the tax.

5.2.2 Tax revenues used as a subsidy for R&D

In this scenario, we apply an alternative approach for the redistribution of the revenues collected from the CO2 tax. The revenues are no longer redistributed back to the representative household, but they are now used to subsidize the build-up of the sectoral non-physical capital stocks. Due to our formulation of the investment process, this can also be interpreted as a subsidy to sectoral R&D. As already explained, the build-up of capital is the engine that drives growth in this model. This alternative way of redistribution directly supports the growth mechanism in the sectors. All regular sectors and the energy sector benefit from the subsidy. From an environmental policy point of view, it would not make sense to subsidize the oil sector as well. It is therefore excluded from the redistribution. Energy, on the other hand, is subsidized as well, as the subsidy affects only the production process of non-fossil energy. The yearly subsidy rate is calculated directly from the tax revenues and is uniform across all sectors. As we have a rising tax rate until the year 2035, the rate of subsidy is also rising during that period. To achieve the reduction target, the tax has to rise at a slightly higher rate than before. The subsidy rate starts at 0.094 in 2010 and ends up at 0.491 in 2035. The results are shown in Figures 9 to 11.

Variations in aggregate consumption are more pronounced in this scenario. Consumption declines more during the phase until the reduction target is reached. It is 2.6% lower in 2035 compared to the benchmark, while the corresponding decrease in Section 5.2.1 is 2%. Correspondingly, welfare loss is also higher (2%). The sharper decrease in consumption has to be attributed to the increased investment activity.

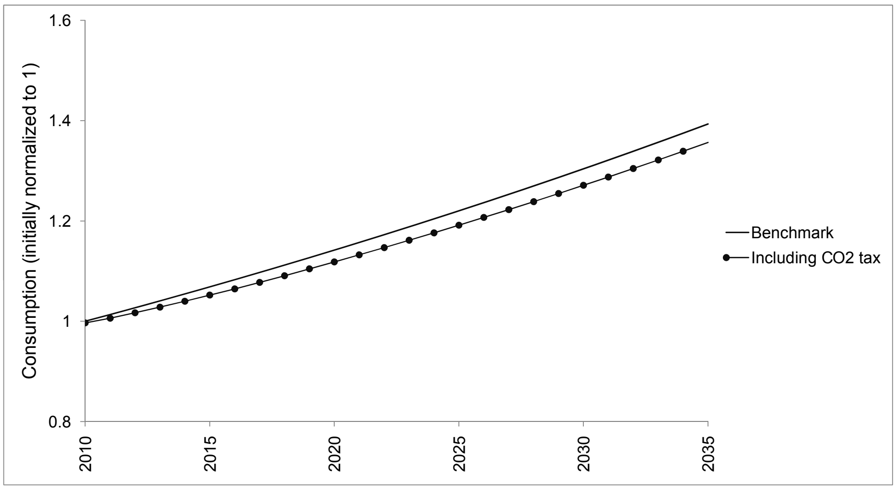

Figure 9: Growth paths of consumption, R&D subsidy

The subsidy leads to an increase in the capital stocks of almost all sectors, as both physical and non-physical investments increase significantly. Thus, compared to the case discussed above, households devote less of their income to consumption and increase their investment activity in earlier periods. An important point to consider here is that the time horizon of this policy is rather short. If we assumed a longer time horizon, the higher investment activity and thus the increased accumulation of capital would have a beneficial effect and the welfare loss would eventually become smaller than in the case with the original redistribution mechanism. Given the assumptions here, the time horizon is too short to reap the benefits from the subsidy and the increased capital accumulation. Comparing the growth path of consumption to the benchmark path (Figure 9), we again see that the deviation is small, but slightly higher than above.

There are a couple of changes in sectoral outputs compared to Section 5.2.1. First of all, there is a general shift upwards, leading to higher output in almost all sectors. This implies that the subsidy actually works as a supportive mechanism in nearly every sector that benefits from the subsidy. On the

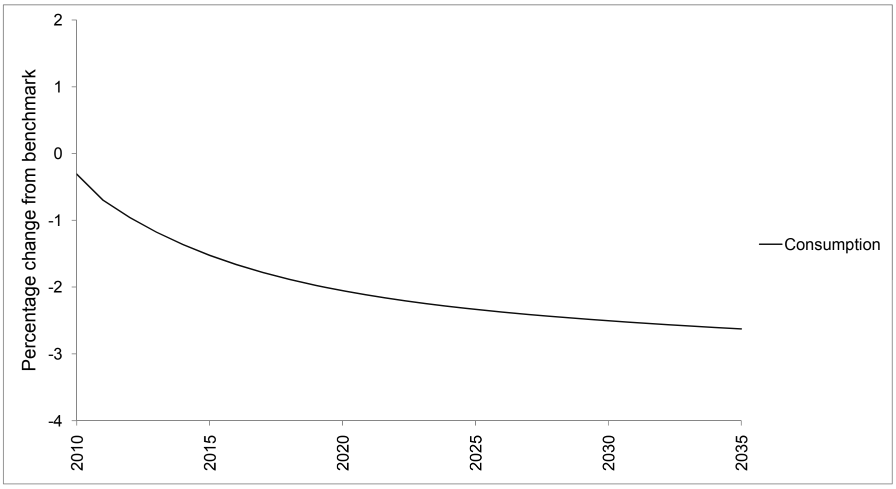

Figure 10: Aggregate consumption, R&D subsidy

other hand, the subsidy also leads to a wider range of effects. The biggest gainers are the machinery industry, the chemical industry and construction. Additionally, banking and financial services are now also able to increase their output compared to the benchmark scenario. Insurances, previously among the winners, now suffer a small decline in output until 2035. The decrease in the two most energy-intensive sectors is now even a bit larger than before,indicating that the subsidy leads to an even more pronounced reallocation of capital.

It is obvious that the structural effects are not much different from Section 5.2.1. But it is also apparent that some sectors benefit more from the subsidy than others. The explanation for this is the importance of initial investments (both physical and non-physical). Capital-intensive sectors that rely heavily on investments, or sectors that have high activity in R&D (and thus a high knowledge-intensity) experience larger upwards shifts than those where none of the two is an important factor in the production process. Two examples to illustrate this point are construction and insurances. Construction has very high initial physical investments. As the subsidy indirectly also supports the build-up of physical capital, construction now benefits from the introduction of the tax and eventually becomes a gainer of the policy in this scenario. The opposite holds for insurances, where neither physical investments nor R&D are an important factor. Consequently, they are not able to benefit from the subsidy and perform worse than before. The two biggest gainers in this scenario, the machinery industry and the chemical industry,

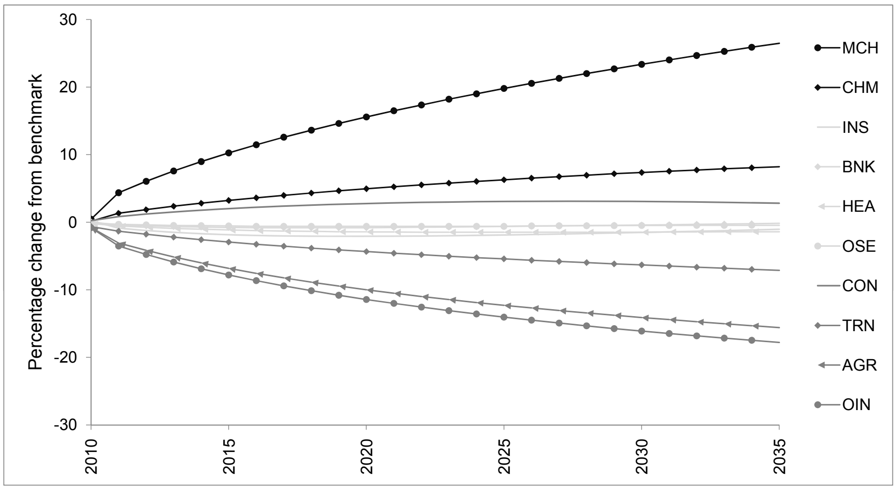

Figure 11: Sectoral outputs, R&D subsidy

both have favorable preconditions to benefit from the subsidy. The chemical industry has large initial investments in non-physical capital, the machinery industry has relatively high physical investments, and R&D also plays a significant role. The same holds for other services, which have relatively large initial physical and non-physical investments. Thus, the subsidy, despite increasing investment activity in all sectors, is mostly beneficial for the sectors that have high initial investments. Other than that, the structural effects are similar to the previous scenario. In the presence of the subsidy, the energy-intensive sectors also suffer a decline in output and attract less capital than in the benchmark. The energy-extensive sectors on the other hand benefit from the introduction of the tax.

Additionally, the fact that increased accumulation of capital benefits sectors that actually provide the goods and services necessary to conduct the investments has a more pronounced effect here. Construction and the machinery industry, two sectors that play a role in this respect, increases their output considerably in this scenario. This can be partly attributed to the increased demand for investment goods in most sectors.

The policy implemented here could have even more pronounced effects if the subsidies were more purposefully designed. One may argue that it does not make sense to subsidize the build-up of non-physical capital in sectors where it does not have a significant influence. Therefore, one could think of subsidizing only the sectors that have relevant R&D activity, or to subsidize these sectors at a higher rate than those that do not rely much on R&D. Sectors with high initial physical investments could also be included, as they benefit considerably from the subsidy as well. From the patterns that we observed, it seems reasonable to assume that such a policy should increase the range of the effects on the outputs and the capital stocks and thus increase the differences between the sectors. The winning sectors would benefit even more, and the decreases at the bottom would be larger. This is indeed the case. If only the sectors that have significant initial investments (both physical or non-physical) are subsidized, the range of effects gets wider, and both the increases and the decreases are more pronounced.

Another possible policy would be to subsidize only the non-energy intensive sectors. This again increases the range of effects, which is not surprising as we noticed above that the energy-intensive sectors are most affected by the CO2 tax. Thus, there would be an even more pronounced shift of capital from the energy-intensive to the energy-extensive sectors, and larger adjustments in sectoral outputs.

Both of these policies may be beneficial in the sense that the subsidy is concentrated on the sectors that actually have the prerequisites to benefit from the policy instruments that are implemented here. However, both of them only have a limited potential to be accepted. In both cases, all sectors pay the tax, but only some of them benefit from the redistribution. A second argument against a concentration of the subsidies to certain sectors is that it may lead to instabilities because of the structural shifts. This obviously also entails effects on the labor market (a point that is not analyzed in detail here), which may be a threat to economic stability. Therefore, it may be more reasonable to ensure that all sectors are treated uniformly.

6 Different policies abroad

It is reasonable to assume that not only the policies implemented in Switzerland itself affect the Swiss economy. The measures taken by foreign countries may also have an impact. So far, we have implicitly assumed that foreign countries implement similar reduction targets and therefore a similarly stringent policy. This, however, does not necessarily have to be the case. The discussions at the United Nations Climate Change Conference in Copenhagen showed that there is a lot of disagreement on future climate and energy policy. Future policies and reduction targets may thus considerably diverge between countries. This raises the question on how the effects of domestic policies vary if different policies are implemented abroad.

As the CITE model is a one-country model, there is no possibility to model policies in foreign countries in an explicit way. However, differences in reduction targets or CO2 taxes can be expressed by varying the trade elasticities. If environmental policy is less stringent in the rest of the world[2], this implies, considering our formulation of environmental policy, that foreign countries set lower taxes on CO2-emissions than Switzerland. Thus, there is a higher premium on the prices of fossil fuels in Switzerland than abroad, which means that foreign goods are relatively cheaper compared to domestically produced goods. This increases the incentives to import goods rather than producing them in Switzerland. In terms of model

[2]Due to the one-country assumption, there is no further differentiation of foreign countries. As the differences are expressed through the trade elasticities, one may think of the most important trading partners of Switzerland, such as the European Union. But for simplification, we can also readily refer to the other countries as the rest of the world

parameters, this means that the Armington elasticities rise, as there is an increased preference for foreign goods. At the same time, Swiss goods become less attractive for foreign consumers, as they are relatively more expensive because of the higher tax. Demand for exports decreases, which is reflected by a lower value of the elasticity of transformation. The opposite holds if we assume that Switzerland implements a less stringent CO2-tax regime than foreign countries. The premium on the fossil fuels is smaller in Switzerland, and thus Swiss goods become more attractive for foreign countries, and export demand rises. Correspondingly, the elasticity of transformation also rises. Foreign goods on the other hand are now relatively more expensive and therefore less attractive for domestic consumers, implying that domestically produced goods cannot be readily replaced with foreign goods. Therefore the Armington elasticities decrease. In both scenarios, the domestic reduction target is the same as in sections 5.2.1 and 5.2.2, i.e. Switzerland reduces its energy use by 37.5%. If foreign policy is more stringent, this means the rest of the world sets an even more ambitious target. If it is less stringent, then the reductions abroad are below 37.5%.

6.1 More stringent policy abroad

First, we assume that Switzerland does not follow the rest of the world and implements a comparably loose energy policy regime. The underlying assumption is that the rest of the world sets a higher tax rate than Switzerland, which corresponds to a more ambitious reduction target. To model this, we reduce all Armington elasticities by 1 and double the elasticity of transformation. The results are shown in Figures 12 to 14.

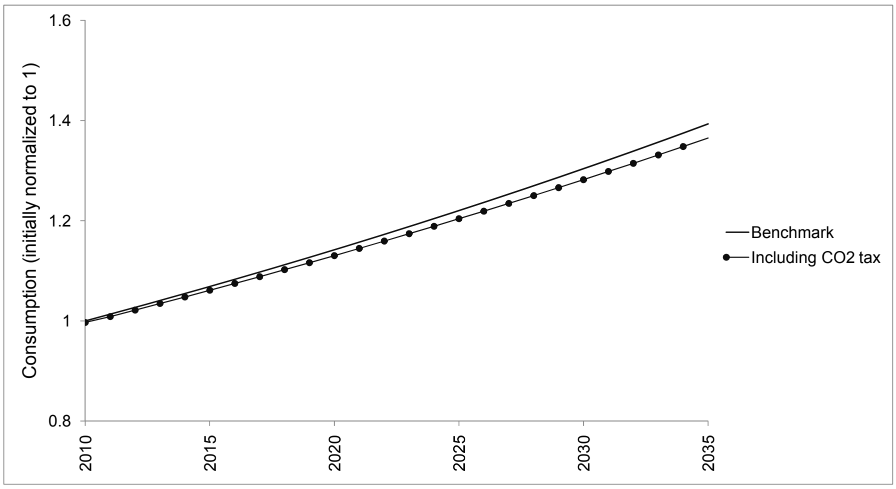

Figure 12: Growth paths of consumption when foreign policy is more stringent

In welfare terms, implementing a less stringent tax regime does not lead to significant changes in the results. The decrease is again about 1.2% and thus is at a similar magnitude as in the case with similar policies. This implies that consumption over time evolves in almost the same way. An important difference is that we need a higher tax rate (or a higher growth rate of the tax rate) to reach the reduction target. The tax profile of the base scenario would not lead to the requested decrease in energy use under these circumstances, indicating that the incentives to cut down energy use are smaller when foreign policy is more stringent.

Compared to the results derived with the standard values for the Armington elasticities and the elasticity of transformation, the range of percentage changes in sectoral output gets smaller. The reactions to the tax are less pronounced than in the case with similar policies. Due to the fact that domestic goods (that are affected by the tax in Switzerland) cannot be readily replaced by foreign goods, the policy has a smaller overall effect and leads to smaller adjustments, both on the positive and on the negative side. One possibility to react to the tax, namely substituting domestic for foreign goods, becomes unattractive in this scenario, because the foreign goods are relatively more expensive.

An interesting observation is that the machinery industry (a relatively trade intensive industry) is no longer the biggest winner in this scenario. Relying heavily on imports, the decrease in the corresponding Armington elasticity affects the machinery industry negatively. Insurances, a sector with comparably

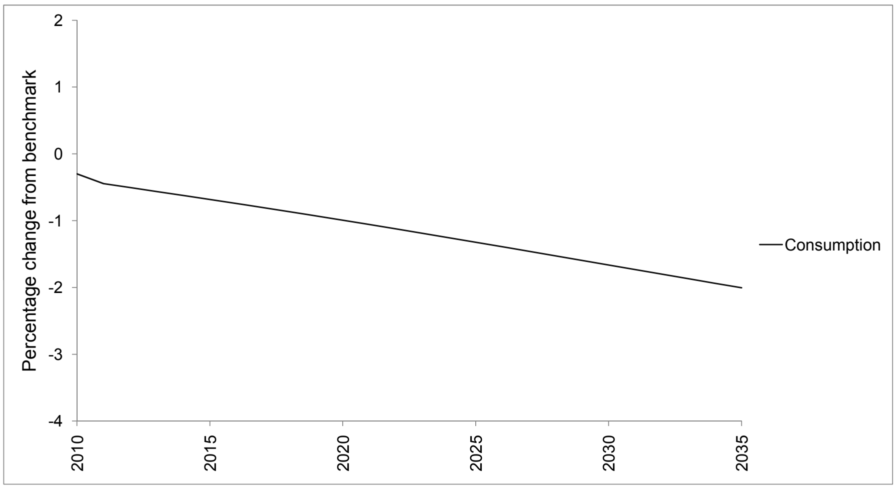

Figure 13: Aggregate consumption when foreign policy is more stringent

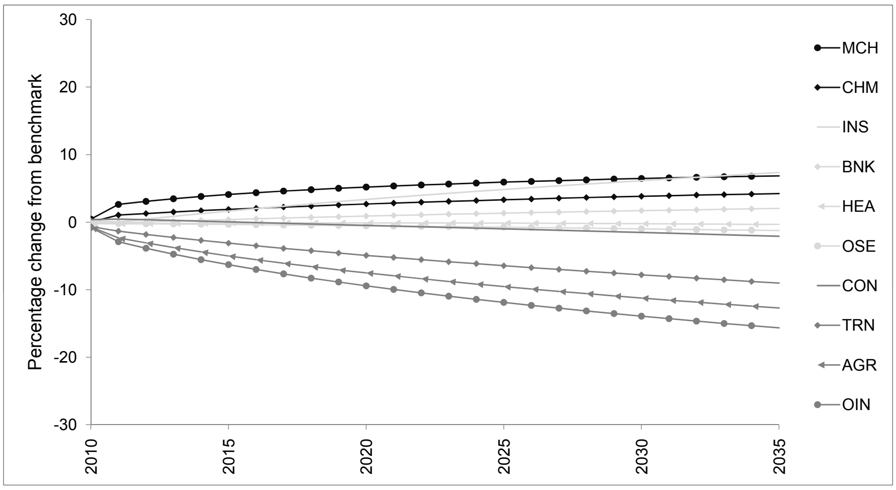

Figure 14: Sectoral outputs when foreign policy is more stringent

little trade activity, benefits the most from the circumstances. Banking and financial services are also among the winners in this scenario. This sector benefits from the increased elasticity of transformation due to its high export share. Other than that, structural change is similar in direction, but less pronounced in magnitude compared to Section 5.2.1. The energy-intensive sectors perform marginally better in this scenario, which leads to a smaller range of effect. Generally, adjustments are much smaller in this setup. If we implemented the tax profile from section 5.2.1, the reduction target would be missed. Domestic reduction incentives are thus considerably smaller when foreign policy is more ambitious.

6.2 Less stringent policy abroad

The contrary assumption that the rest of the world implements a less stringent policy than Switzerland is modeled in the opposite way compared to the case above. All Armington elasticities are increased by 1, and the elasticity of transformation is halved. Figures 15 to 17 show the results.

Given that the rest of the world implements a less stringent policy, the reduction target in Switzerland can be met with a lower tax (compared to the BAU scenario), which is just the opposite compared to the case discussed in the previous section. Welfare is now reduced by almost 1.3%, and consumption over time decreases a bit more. If we implemented the same tax profile as in the base scenario, the decrease in welfare would rise considerably, and energy use would be reduced by more than the requested 37.5%. Thus, in this case, the reactions to the tax are much more pronounced. Foreign goods are

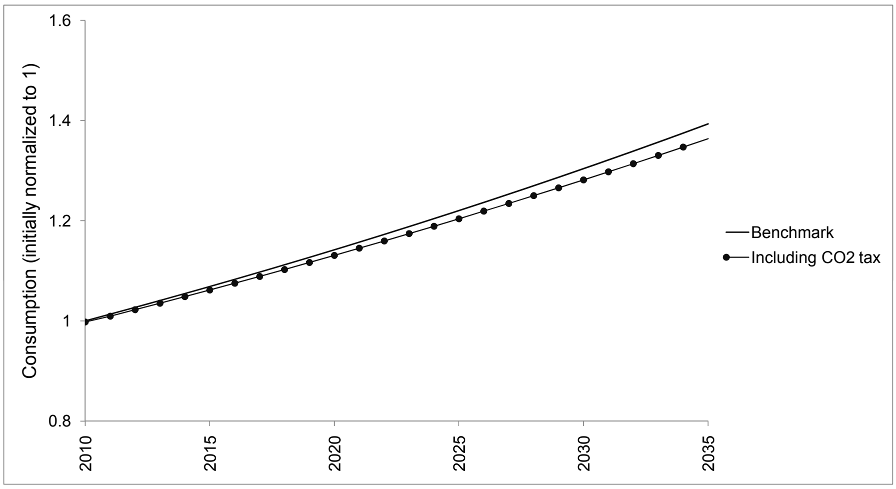

Figure 15: Growth paths of consumption when foreign policy is less stringent

now relatively cheaper than domestic goods, which translates to higher Armington elasticities. This is primarily beneficial for the industries with high import shares, such as the machinery industry and the chemical industry. The machinery industry accordingly increases its output significantly in this scenario. The chemical industry also increases its output by more than 5%.

Banking and financial services on the other hand, which were winners in the scenario with a more stringent policy abroad, now reduce their output, as the elasticity of transformation is lower. The three most energy-intensive sectors (transports, agriculture and other industries) suffer even larger losses than in the original case with similar policies. Thus, there are much more pronounced adjustments in this case, with a clearer shift towards a less energy-intensive economy.

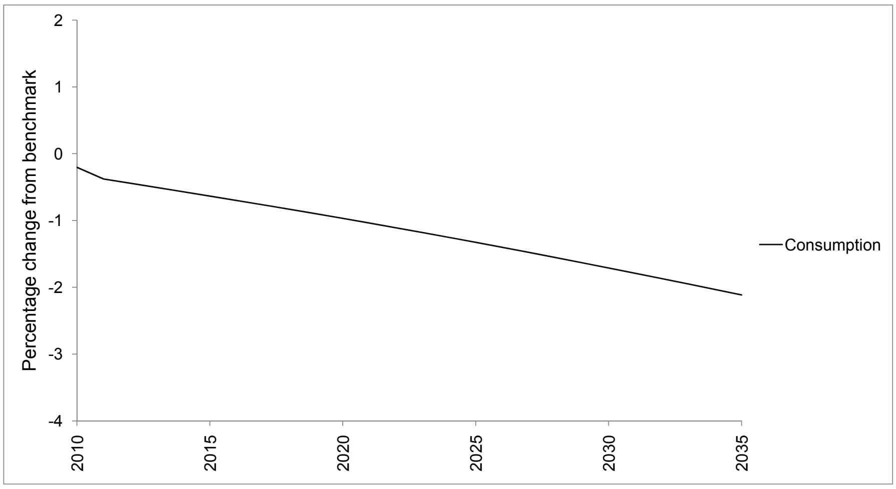

Figure 16: Aggregate consumption when foreign policy is less stringent

From these two scenarios, it becomes apparent that the policy of the rest of the world has a pronounced influence on the Swiss economy, both at the sectoral and the aggregate level. If Switzerland implements stronger regulations than the rest of the world, welfare loss increases, albeit on a very small scale. In this setting, a first-mover strategy in the sense of implementing strict regulations, no matter what the rest of the world does, is not beneficial, as welfare reductions are slightly higher than in the case with similar policies. A first-mover policy could have positive effects if learning effects were included in the model. Setting comparably stringent reduction targets necessitates an increased use of new, less energy-intensive technologies. If the use of these technologies entails learning effects, it may be beneficial in the long run if these technologies are used in production earlier than abroad. The corresponding cost reductions due

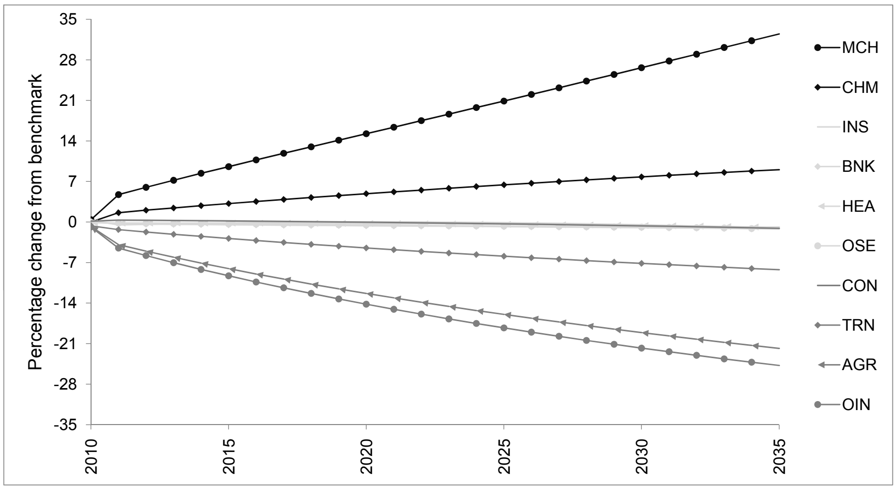

Figure 17: Sectoral outputs when foreign policy is less stringent

to learning-by-doing may lead to considerable comparative advantages. As this effect is excluded in this analysis, the negative effects of the first-mover strategy prevail and welfare is slightly lower than in the case with similar policies.

This analysis is obviously highly simplified, because the policies in the rest of the world cannot be modeled explicitly. The central assumption, that the different policies affect the substitutability of domestic and foreign goods, irrespective of the quantitative differences of the taxes applied, should be valid nonetheless. The results derived here may thus still give an indication of the possible effects of diverging policies.

7 Conclusions

This paper analyzes the effects of long-term energy policy in Switzerland within the framework of the CITE model. In contrast to other models used in similar studies, the CITE model features an endogenous growth mechanism that explicitly takes into account the inter-linkages between investments into sectoral capital stocks and the sectoral growth rates. We simulate two base scenarios. The first one implements a long-term policy with two intermediate targets. The second one is closely related to scenario IV of the Energy Perspectives. The key policy instrument is a CO2 tax that is levied on the two fossil fuels, oil and gas. The tax is set so that the reduction target is exactly met.

We find that even ambitious targets can be reached at a relatively low cost. Both welfare and consumption decline only at a small scale. On the production side, the tax predominantly affects the energy-intensive sectors negatively, while the energy-extensive sectors show only small reactions or even benefit from the introduction of the tax. The energy-extensive sectors also attract considerably more investments. There is a reallocation of capital in the sense that investments in energy-intensive sectors are reduced in favor of the energy-extensive sectors. In an alternative scenario, we change the redistribution mechanism of the tax revenues. Instead of redistributing them back to the household, they are used as a subsidy to non-physical investments. This mechanism leads to a higher welfare loss in the short term, but to less negative effects in almost all sectors. Welfare loss eventually becomes smaller if the time horizon is extended. Thus, it seems to make sense to use the tax revenues purposefully rather than uniformly redistributing them back to the household.

In the scenarios that aim at reducing energy use by 37.5% until 2035, the relatively small welfare losses result also because of the assumption that no further reduction targets have been put in place after 2035. In order to go further towards a 2000-Watt society, it is clear that additional reductions are necessary. This will of course also have effects on welfare and would influence the relatively positive results we found here. If no additional policy measures are introduced (i.e. if the CO2 tax remains the main instrument) and the tax is further augmented to trigger additional reductions in energy use, the structural change towards the energy-extensive sectors would go on and would be even more pronounced. The scenarios including the 80%-target prove this point and show at the same time that even with a longer time horizon for policy, overall reductions are relatively low.

As the focus of the CITE model is on the inclusion of the endogenous growth mechanism and the macro-effects of the energy policies, the energy sector is not represented in a very detailed way. There is for example no further differentiation of non-fossil energy sources. As the CITE model has essentially a top-down approach and focuses on the effects at the macro-level, these assumptions can be readily defended. However, we can for example not model subsidies for renewable energy, which may also be a straightforward way to use the tax revenues, and which is also an option that is up for discussion. It will therefore be a natural step to extend the CITE model in this respect. Alternatively, one could think of coupling the CITE model with an existing bottom-up model to include developments on a technological level. Similarly, the labor market is also modeled in a fairly rudimental way. A more sophisticated representation in this respect is therefore another possible extension.

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9 Appendix

9.1 Nestings

The following figures describe the production structure of the sectors used in the model (Figures 18 to 20) and the nestings of consumption (Figure 21) and of investments (Figure 22).

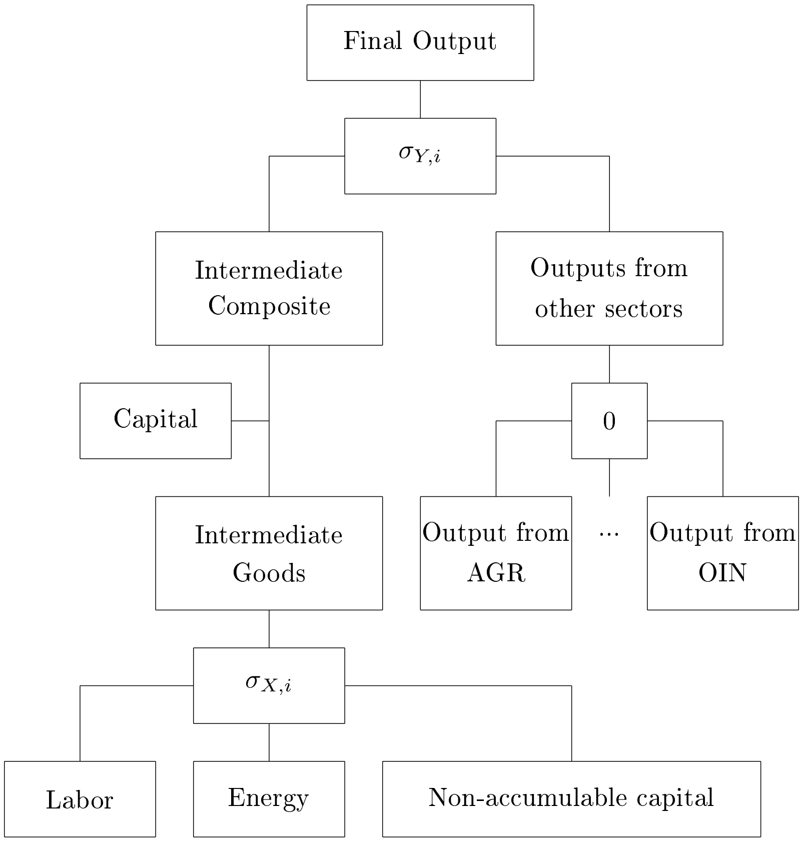

Figure 18: Nested production function of output sectors (except energy and oil)

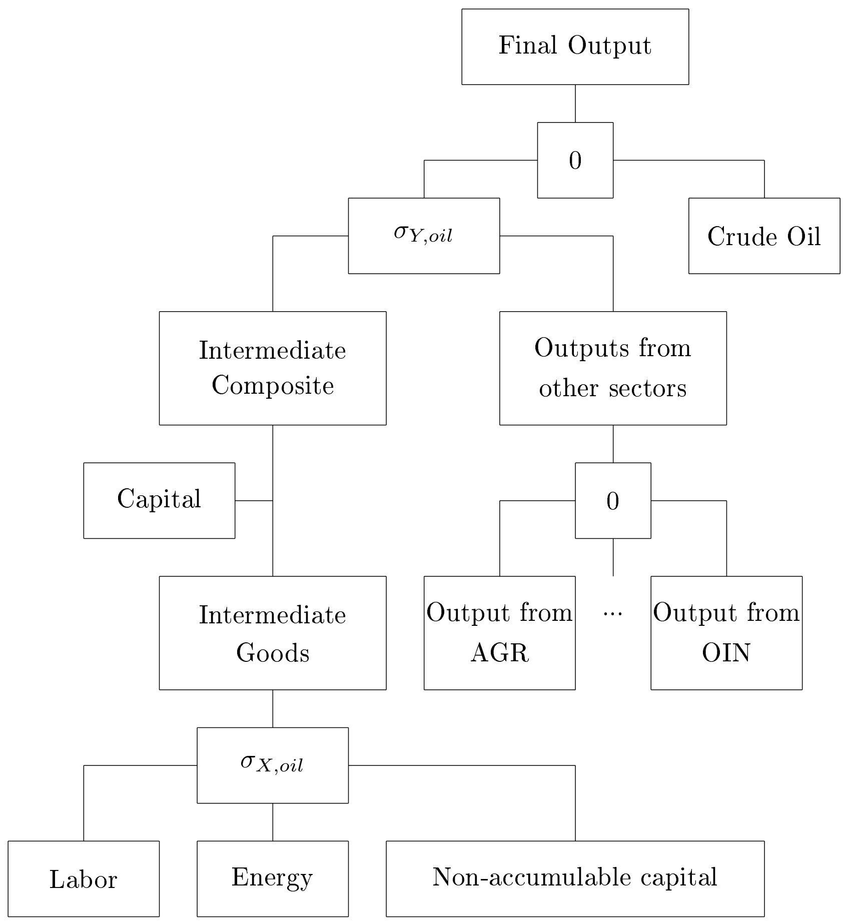

Figure 19: Nested production function for the oil sector

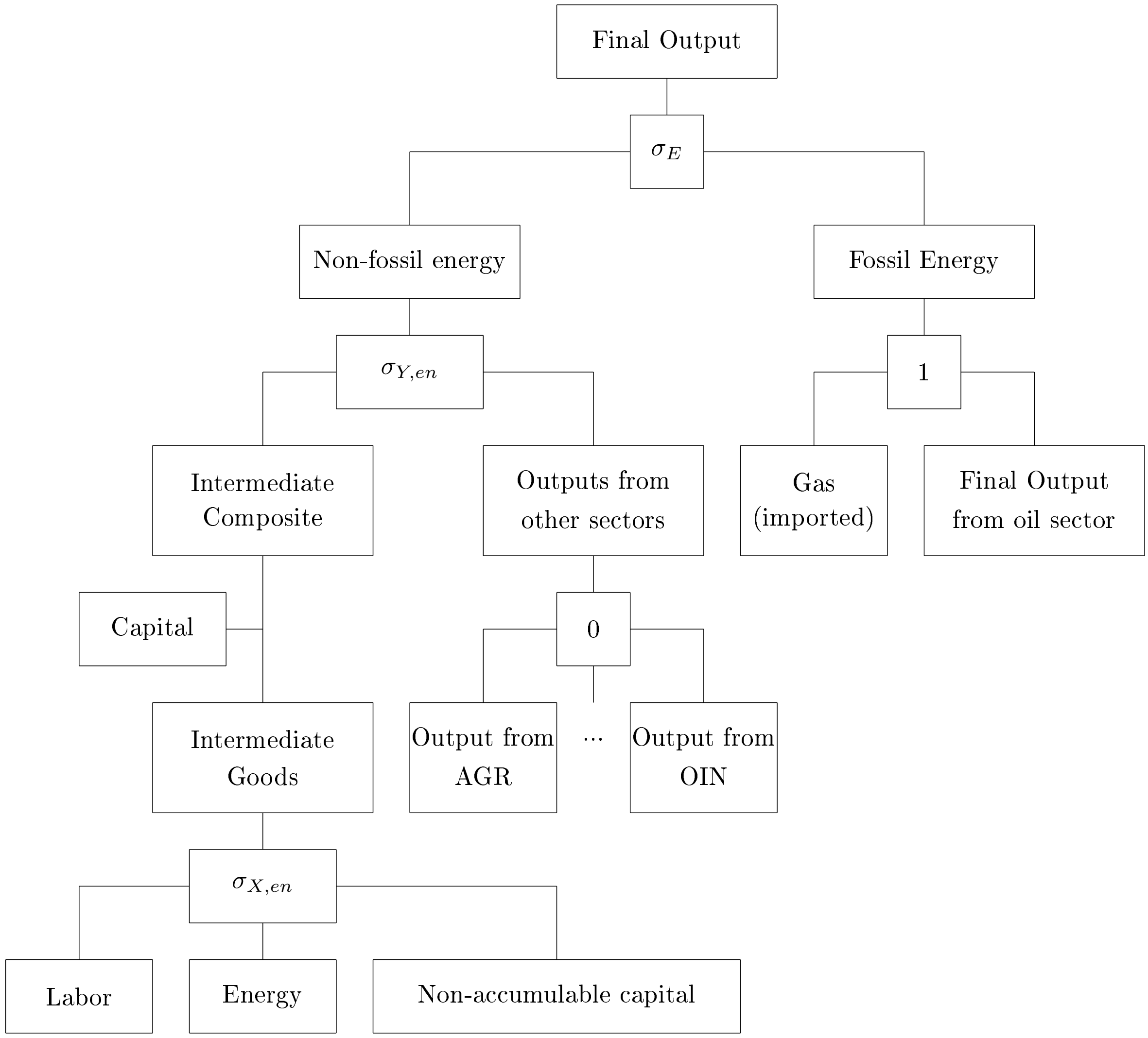

Figure 20: Nested production function for the energy sector

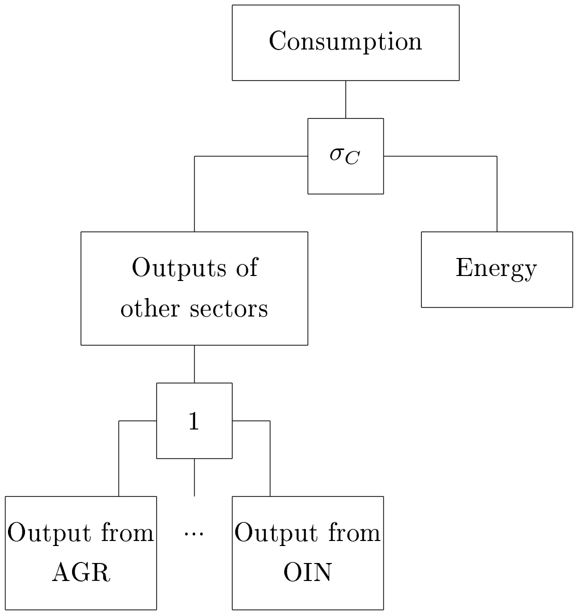

Figure 21: Nested consumption function

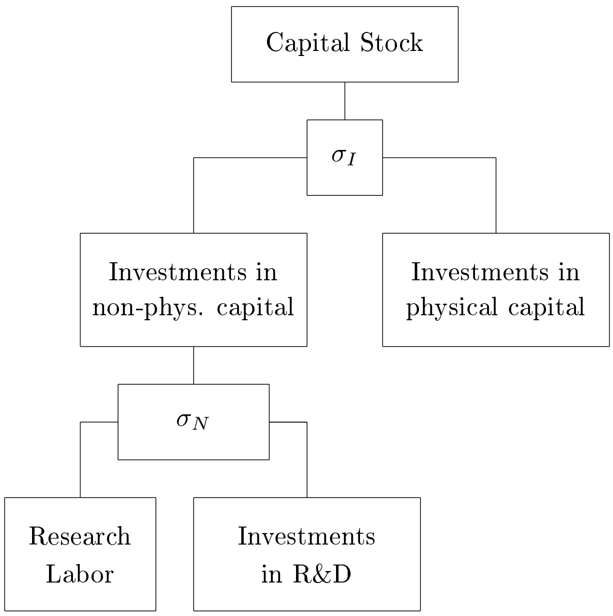

Figure 22: Nested investment function (equal for all sectors)

Sector	Energy Intensity
Agriculture (AGR)	0.101
Chemical Industry (CHM)	0.044
Machinery and Equipment (MCH)	0.027
Construction (CON)	0.047
Transport (TRN)	0.132
Banking and Financial Services (BNK)	0.006
Insurances (INS)	0.011
Health (HEA)	0.021
Other Services (OSE)	0.026
Other Industries (OIN)	0.084

Table 2: Energy intensities of regular sectors