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Exploring the Limits in Dynamic Energy Modelling

Bottom-up framework, uncertainty, and multi-regional setup using the CITE model approach

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Executive Summary in German

Das Forschungsprojekt "CITE - Weiterentwicklungen" umfasst eine Reihe von wichtigen Arbeiten am "CITE" Simulationsmodell (Computable Induced Technical change and Energy model), einem CGE Modell mit vollständig endogenem Wachstum. Die Weiterentwicklungen dienen der vollständigeren Erfassung von Energiepolitik und deren makroökonomischen Auswirkungen. Der erste Projektteil beschäftigt sich mit der Verfeinerung des Energie-Nestings, d.h. der differenzierten Unterscheidung verschiedener Energieträger (Kohle, Oel, Gas, Wasserkraft, Wind, Solar/Photovoltaik, Abfall, Biomasse, Kernenergie, Geothermie, Biogas) und deren Charakteristiken im CITE Modell. Ein zweiter Schwerpunkt ist die Implementierung neuer Energiedaten mit der Verwendung der neuen Energie-IOT (Nathani et al. 2011) als Datengrundlage für die Erweiterung des Energiesektors. Weiter untersuchen wir als dritten Schwerpunkt den Einfluss der Unsicherheit über verschiedene Sensitivitätsanalysen in den Bereichen Benchmark-Wachstum, Diskontrate und Innovationskraft. Ein vierter Schwerpunkt ist der Ausbau des bestehenden Einländermodells zu einem Mehrländermodell und die damit verbundene Beschaffung und Aufbereitung von Daten, insbesondere der internationalen Input-Output Tabellen. Dabei war es notwendig, zur internationalen Einbettung des bestehenden Modells für die Schweiz das gesamten CITE-Modell von MCP in MPSGE Programmiersprache umzukodieren. Weiter beschäftigen wir uns mit einer geeigneten Aufbereitung der internationalen Daten zu den Investitionen, die in der Logik des CITE Modells eine zentrale Rolle spielen, sowie der Entwicklung und CGE-Implementierung eines neuen und innovativen Ansatzes zur internationalen Wissensdiffusion, die den Wachstumsverlauf und die Kosten von Klima- und Energiepolitik zentral beeinflussen. Schliesslich zeigen wir in der Implementierung des erweiterten CITE Modells Simulationen und Analysen von verschiedenen Politikmassnahmen im Energiebereich.

Mit Blick auf die relevanten langfristigen Effekte der politischen Massnahmen im Zusammenhang mit der Energiewende interessieren wir uns insbesondere für die induzierten Innovationen (sowohl auf sektoraler, als auch auf aggregierter Ebene) und die Veränderungen in der strukturellen Zusammensetzung der Wirtschaft. In der vorliegenden Studie kombinieren wir den "top-down" Ansatz des dynamischen makroökonomischen Modells mit einer detaillierten Darstellung des Elektrizitätssektors ("bottom-up"), um zukünftige Technologieentwicklungen optimal darstellen zu können. Die Resultate zeigen, inwiefern die Schweiz das Potential hat, ambitiöse Umweltziele zu erreichen, selbst wenn der Energiesektor (starken) Restriktionen unterstellt ist. Dabei wird ersichtlich, dass Reformen hin zu einem Strommix mit deutlich mehr neuen erneuerbaren Energieformen ökonomisch verkraftbar sind. Eine wichtige Modellannahme dabei ist aber die der perfekten Voraussicht der Investoren über laufende und zukünftige Politikentscheidungen. Beachtet man die Langfristigkeit dieser Politikentscheidungen im Energiebereich betonen die Resultate die Wichtigkeit einer transparenten, kohärenten Kommunikation und die Verfolgung energiepolitischer Ziele über einen ausreichend langen Zeithorizont.

Um der Unsicherheit der langfristigen Entwicklung der Schweizer Wirtschaft explizit miteinbeziehen zu können, betrachten wir die Veränderungen im Energiebereich unter verschiedenen makroökonomischen Voraussetzungen. Ausserdem zeigen wir die sektoralen Wachstumsmöglichkeiten und die soziale Wohlfahrt unter verschiedenen Annahmen für die intertemporale Diskontrate für den projizierten Zeitraum mit den angenommenen Politikmassnahmen. Des Weiteren untersuchen wir den Einfluss der generellen Innovationstätigkeit und Kapitalinvestitionen auf die sektorale Entwicklung.

In einem letzten Schritt konstruieren wir eine voll funktionsfähige multi-regionale Version des CITE Modells. Darin wird der endogene Wachstumsmechanismus auf mehrere Weltregionen ausgeweitet. Zusätzlich wird, basierend auf empirischen Studien, ein Mechanismus eingefügt, der die internationale Innovationsverbreitung spezifiziert. Wir können somit zeigen, wie eine Innovation in einer Region sich auf die anderen Regionen ausbreiten kann, und wie dadurch die Wohlfahrt des regionalen Konsumenten verändert wird. Diese Analyse zeigt, inwiefern internationale Technologietransfers das Wachstum der Schweizer Wirtschaft fördern und gleichzeitig die Kosten von Politikmassnahmen senken können.

Executive Summary in English

The research project ”CITE - developments” includes a number of important works on the ”CITE” simulation model (Computable Induced Technical change and Energy model), a CGE model with fully endogenous growth. The general aim is a more complete and accurate characterization of energy policy and its macroeconomic impacts. The first part of the project deals with the refinement of the energy-nesting, i.e. the distinction between different energy sources (coal, oil, gas, hydro, wind, solar / photovoltaic, waste, biomass, nuclear, geothermal, biogas) and their characteristics in the CITE model. A second focus is the implementation of new energy data with the use of the new energy-IOT (Nathani et al. 2011) as a data base for the representation of the energy sector. Next we examine with the third focus in sensitivity analyzes the influence of uncertainty about various issues like benchmark growth, discount rate and innovativeness. A fourth focus is the expansion of the existing one-country setup to a multi-country model and the associated procurement and processing of data, in particular the international input-output tables. For the international integration of the existing model for Switzerland it was necessary to recode the entire CITE model of MCP into MPSGE programming language. Next we deal with a suitable preparation of international data on investment, which play a central role in the logic of the CITE model, and with the development and CGE implementation of a new and innovative approach to international knowledge diffusion, which crucially affects growth and the costs of climate and energy policy. Finally, we show in the implementation of the extended CITE model, simulations and analyzes of various policy measures in the energy sector.

Looking at the long-run effects of policy measures related to the energy revolution we are especially interested in induced innovations (both sectoral as well as at the aggregate level) and the changes in the structural composition of the economy. In the present study, we combine the ‘top-down ’approach of dynamic macroeconomic model with a detailed representation of the electricity sector (‘ bottom-up’) to represent future technology developments optimally. The results show the extent to which Switzerland has the potential and the capacity to achieve ambitious environmental goals, even if the energy sector is subject to (strong) restrictions. It becomes evident that reforms towards a mix with much more new renewable energies are economically feasible. But an important model assumption is that of perfect foresight of investors about current and future policy decisions. If one considers the long-term nature of these policy decisions in the energy sector the importance of a transparent, coherent communication and tracking of energy policy objectives over a sufficiently long time horizon has to be stressed.

To explicitly involve the uncertainty about the long-term development of the Swiss economy we consider the changes in the energy sector under different macroeconomic conditions, which determine the growth potential of the economy. We also show the sectoral growth opportunities and social welfare under different assumptions for the intertemporal discount rate for the projected period with the adopted policy measures. Furthermore, we investigate the influence of general innovation and capital investment on sectoral development.

In a last step, we construct a fully functional multi-regional version of the CITE model. Here, the endogenous growth mechanism is extended to several regions of the world. Additionally, based on empirical studies, a mechanism that specifies the international diffusion of innovations and knowledge is implemented. We can thus show how an innovation in one region can spread to the other regions, and how thereby the welfare of local consumers is changed. This analysis shows how international technology transfer foster the growth of the Swiss economy while reducing the costs of policy measures.

Chapter 1

Introduction

1.1 Long-run perspective of the Swiss energy policy

The "Energie Strategie 2050" formulates the relevant boundary conditions for an economically and environmentally sustainable transition of the energy system to ensure the country's needs, reducing the reliance on fossil fuels and nuclear energy. The necessary reduction of GHG emissions to reach global climate targets force a shift in the energy mix away from fossil fuels. Combined with the announcement of the federal council and the parliament about the gradual exit of nuclear power production, this challenges the current Swiss energy market.

In the following study, we show how fiscal and political support can contribute to a smooth transition without encumbering massive negative impacts on the Swiss industry. To develop a deeper understanding of the challenges and difficulties of such long-term energy strategies an economy will face in the future, we need a sound quantitative analysis from the perspective of economic growth and structural change.

After the Fukushima disaster in Japan, Switzerland elaborated its "Energie Strategie 2050" concerning nuclear energy and the economic consequences of a possible accident. Until recently nuclear energy has contributed a considerable share to total electricity generation, for example in 2012 around 36% (Elektrizitaetsstatistik 2012)[1] of electricity generation came from nuclear energy generation. Now the discussion on the external costs of nuclear energy has led to a considerable tightening of the security standards leading to higher investment and infrastructure costs of existing and new reactors. Moreover, the problem of how and where to store nuclear waste still exists. Consequently, not only the Swiss government perceives nuclear energy as problematic and hence reconsiders the current energy mix. The German government recently decided to phase-out nuclear completely. Germany and Switzerland both have relatively high shares of nuclear in their recent energy mix and the envisaged schedule for the phase-out, major changes for the economy result.[2]

Climate policy in Switzerland and relevant foreign countries restricts the use of fossil fuels to replace nuclear energy and also the expansion potential of hydro energy in Switzerland

[1] `http://www.bfe.admin.ch/themen/00526/00541/00542/00630/index.html?lang=de&dossier_id=00768`

[2] For example Nestle (2012) discusses the issue of rising energy prices due to reduced supply of nuclear energy and a resulting switch to more expensive energy sources.

is relatively limited.[3] Hence, even under the assumption of a paradigm shift towards an increased acceptance of the expansion of hydropower and a corresponding change of the legal framework, the amount of additional capacities is modest. Energy from new renewables, such as solar and wind, are necessary to fill the upcoming gap in electricity generation from nuclear phase out. The positive effect from this enforced change in the energy system are increased innovation and higher investments in renewable energy sources and technologies, induced by the nuclear phase-out. This can not only reduce the overall energy demand but also bring about general growth impacts in the medium and long run.

The needed transformation of the energy system to ensure a sustainable, secure and relatively independent energy supply requires support from research in new technologies, changes in the political environment and the determining factors of the energy market to include external costs, to ensure highest possible cost reflectiveness. When additionally the long run strategy of the federal government is known and consistent with the targets to reach, then the positive effects from induced innovations can more than outweigh the negative impacts from higher energy prices.

1.2 Energy transition in CGE models

Several papers have studied the costs and the economic impacts of nuclear phase-out policies in general equilibrium frameworks. Nordhaus (1995), Andersson and Haden (1997) and Nystrom and Wene (1999) investigated the case of Sweden[4], Hoster (1998), Welsch (1998), Welsch and Ochsen (2001), and Boehringer, Hoffmann and Voegele (2002) provide analysis for Germany. The costs of the phase-out policies depend on the number of available substitutes (and hence the degree of detail of the energy sector) and their capabilities, on the regulation scheme of the phase-out, and on the limitations imposed on carbon emissions. If no limit is imposed on the use of fossil fuels as a replacement for nuclear energy, a phase-out tends to raise carbon emissions substantially (see also Nakata (2002) and his study on Japan). Boehringer, Wickart and Mueller (2001) investigate the economic impacts of two

[3] See BFE (2012) or Andersson et al. (2011).

[4] Following the nuclear accident in the US power plant Three Mile Island 2 in 1979, the Swedish government decided to phase out nuclear energy until the year 2000. Later on, this deadline was moved to 2010, and in 2009, the phase-out plans were completely abandoned. Today, nuclear energy still has a share of about 38% on total electricity production in Sweden.

policy proposals that aimed at restricting the use of nuclear energy in Switzerland. They find non-negligible phase-out costs for the more stringent case, mainly because this proposal administered the use of non-competitive sources as substitutes.[5] Bauer et al. (2012) study nuclear and climate policy from the global perspective concluding that the nuclear phase-out has minor effects on macroeconomic development.[6] Marcucci and Turton (2012) use a bottom-up approach with endogenous technology learning to show that the decision to stop nuclear in Switzerland results in losses of 0.7 percent of GDP in 2030 and 0.5 percent in 2100 compared to the scenario with nuclear.[7]

There are also some papers which have studied the long-run effects of energy transition from different perspectives. Kemp et al. (2007) describe the Dutch energy transition model and highlight the success of reflexive governance on achieving sustainability goals. Recent research of Bretschger et al. (2012) indicates the complete nuclear phase-out can be achieved with relatively low costs if renewable technologies are used as a substitute. This is in line with the results of Welsch (1998), and Boehringer, Wickart and Mueller (2001).

1.3 Content of the project

The present project continues the work of BFE-Project 153007/101953. In this project, we first analyze the economic consequences of a gradual nuclear power phase-out policy in Switzerland. Given the relatively high share of nuclear energy, the limited potential for additional hydropower and the political aim not to increase foreign dependency, the Swiss policy can be viewed as an ambitious and challenging project with effects on many levels of the economy. Looking at the relevant long-run impact, we are particularly interested in the induced innovation effects (both on the sectoral and on the aggregate level) and the structural changes in the economy. We apply a model especially designed for that purpose, the

[5] The two proposals were "Strom ohne Atom" ("electricity without nuclear energy") and "Moratorium plus". The former postulated a limitation of the operational lifetime of powerplants to 20-30 years, and nuclear energy was requested to be replaced with combined heat and power. The latter was less restrictive and limited operation time to a maximum of 40 years. Both proposals were put to vote in 2003, and they were both turned down.

[6] They use the ReMIND-R model to explicitly reflect the adjustment costs due to acceleration of capacity build-up and resource extraction. Their analysis show that the GDP loss of climate policy is 2.1% in 2050, the incremental costs of a nuclear phase-out is about 0.2% in 2050.

[7] As we do in this report, climate policies are given in both with- and without- nuclear scenarios in their analysis.

Computable Induced Technical change and Energy (CITE) model, see Bretschger, Ramer and Schwark (2011), which is a CGE model with fully endogenous growth.

For the present study, the original CITE model has been extended with a bottom-up model to include a broad range of different technologies in the electricity sector. This enables us to explicitly show the effects and requirements on the technological level and the underlying substitution potentials. Our analysis differs from the contributions described in the section in several respects. First, most of these papers restrict their attention to the impacts at the technology level. The focus of our investigation is on the macroeconomic consequences of the policy, which largely determines whether the policy is desirable. Second, existing studies either use pure energy system models or models where economic growth is treated as an exogenous variable. We use a CGE model with endogenous growth in all sectors. Specifically, we show how the nuclear phase-out affects long-term growth at the aggregate and at the sectoral level and how the structure of the economy changes over time. The main transmission mechanism under study are sectoral innovation and investment decisions. Finally, we combine our top-down approach of the dynamic macroeconomy with a detailed bottom-up model of the electricity sector, to exploit the technical information on future technology development in an optimal way.

Addressing long-run uncertainty in the Swiss economy, we investigate the impacts of the energy transition under different macroeconomic environments, which largely determine the potential growth of an economy. Moreover, we also show how the sectoral growth and social welfare are affected by the intertemporal discount rate when the energy transition is imposed along the projection periods. We further corroborate our analysis by investigating the impact of innovativeness, to exploit how the sectoral growth is dependent on innovation and capital investment.

Finally, we successfully construct the multi-regional version of the CITE model. The new model generation extends the endogenous growth mechanism to other regions of the world. Moreover, based on the empirical studies in literature, a new module for international knowledge spillover is specified. We illustrate how knowledge in one region can be spread to other regions through different channels, and how such spillover changes the welfare of regional consumers. Hence, our analysis provides more liable results for policy-makers in

Switzerland.

This report is structured as follows. Chapter 2 explains the extension of the CITE model regarding the energy sector. Chapter 3 describes the scenarios and presents the results. In chapter 4, the multi-regional model framework and effects of knowledge spillover are explained and illustrated. Chapter 5 provides conclusion from the apsects of academic research and policy making. In the appendix, three papers are attached with regard to detailed model description, sensitivity analysis, and further data calibration issues.

Chapter 2

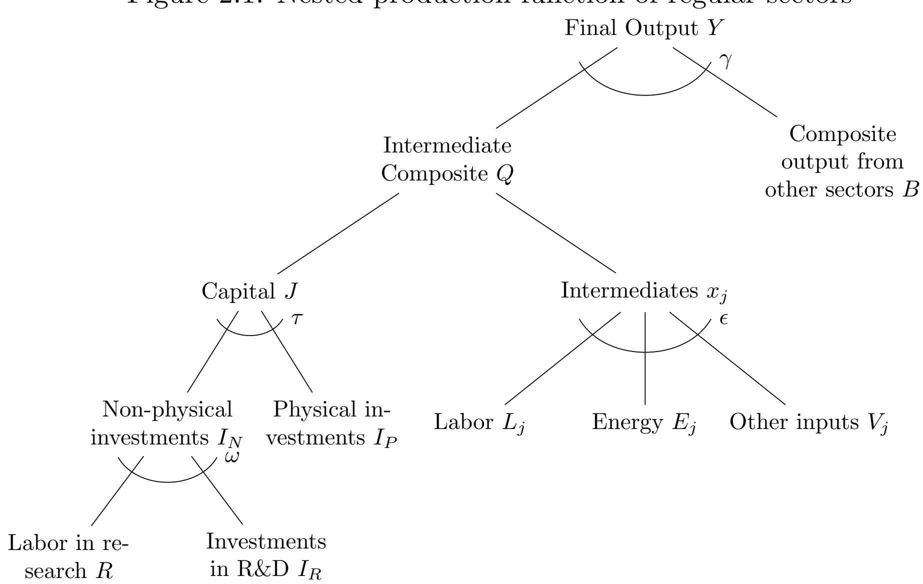
Extension of the CITE model

2.1 Aggregate economy

The CITE model is a multi-sectoral CGE model with fully endogenous growth. Growth in the different sectors is driven by an expansion-in-varieties mechanism, based on the seminal contribution of Romer (1990). Investments in capital and knowledge extend the number of capital varieties, which foster factor productivity. The formal structure and the main features of the basic model are presented in detail in Bretschger, Ramer and Schwark (2011). Here, we include a brief non-technical description of the macroeconomic part with an emphasis on the model extension to show the energy sector.

Production in each non-energy sector, which we call "regular" sector, is represented by a three-stage nested CES-function, see Figure 2.1. The crucial model element is the intermediate composite good on the second stage, combining the accumulable capital with labor, energy and the other inputs. Investments into new capital varieties enhance the sectoral capital stocks (J). The accumulation of sectoral capital has a positive effect on sectoral productivity and hence on sectoral growth. The endogenous determination of sectoral growth is the main model feature. The rest of the production function is quite standard. Factor inputs enter at the level of the production of the capital varieties (J) and the sectoral inter-linkages are reflected in the usual way.

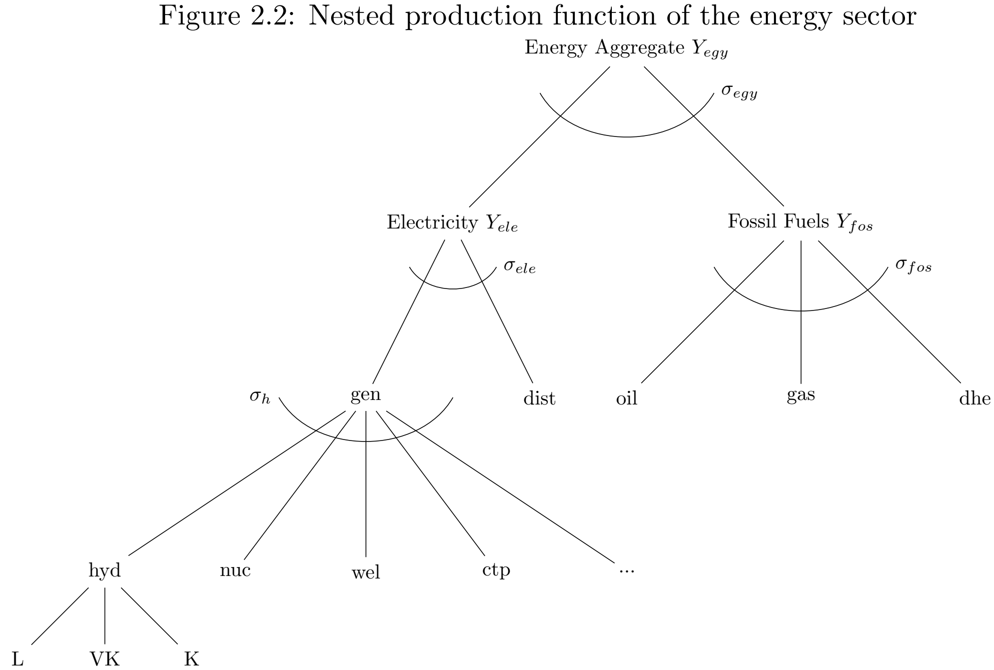
Figure 2.1: Nested production function of regular sectors



2.2 The energy sector

For the present analysis in this report, we have extended the energy sector of the original CITE model to represent the Swiss energy mix in greater detail. Notably, we refine the modeling of the electricity sector by using a detailed bottom-up approach for the cost functions of the different technologies. The bottom-up model of the electricity sector is then combined with the macroeconomic top-down part. In the energy sector, both electric and non-electric (mostly fossil energies) are used for intermediate production and consumption. We include seven different technologies that are available to produce electricity. Below, we present the extended set-up of the energy sector in detail. A graphical overview of the energy sector can be found in Figure 2.2.

Figure 2.2: Nested production function of the energy sector



The optimization problems for energy suppliers are presented in the form of cost minimization, which is the dual-form problem of usual profit maximization. Assuming perfect competition, in the optimum, the market price equals marginal costs.

The electricity sector includes two activities: electricity generation on the one hand and electricity transmission and distribution on the other. They trade off in the second nesting. Finally, electricity is generated using seven technologies: Hydro (*hyd*), nuclear (*nuc*), waste (*wel*), conventional thermal plants (*ctp*), solar (*sun*), wind (*win*) and biomass (*bio*). The aggregation of output from these technologies captures two features: it (i) allows for different marginal costs for technologies and (ii) represents multiple types of generation technologies that are simultaneously dispatched by assuring positive activity levels. The shares in the benchmark year 2005 are listed below in Table 2.1.[1]

Table 2.1: Electricity technologies and their production in 2005

Technology	**Production in GWh**	**Share**
Hydro	32800	56.60%
Nuclear	22020	38.00%
Conventional Thermal Plants	2100	3.62%
Waste / Sewage Plants	968	1.67%
Biomass	43	0.07%
Solar Energy / Photovoltaics	20	0.03%
Wind	9	0.01%

We then use information on levelized cost of different technologies resources (EIA 2012) to set up the individual cost functions for new renewables. In general, the endogenous growth mechanism also applies to the electricity sector in the top nesting. Investment in capital varieties helps to improve the efficiency and productivity of delivering electricity. For generation technologies, they compete with each other in terms of cost to gain factors (labor, capital) for capacity expansion.

The second major element of the energy sector is fossil energy. As indicated, in the Swiss case, electricity is assumed to be (almost entirely) carbon-free, with the exception of some electricity produced in conventional thermal plants. Fossil fuels are used primarily for heating and transport. This is why we strictly differentiate between electricity and fossil energy. Total fossil energy Y_{fos} is produced using three technologies: Oil (*oil*), gas (*gas*) and district heating (*dhe*). These three technologies are assumed to trade off in a Cobb-Douglas fashion. Gas is fully imported, but distribution requires some domestic inputs as well, which is why it is treated as a regular sector similar to the other technologies. We assume that crude oil (also fully imported) enters the production function of Y_{oil} at the top level.

The usage of fossil fuels produces carbon emissions. The three technologies differ in their carbon intensities (i.e. in the amount of carbon emitted per unit). We assume that oil has the highest carbon intensity, followed by gas and district heat. These carbon intensities

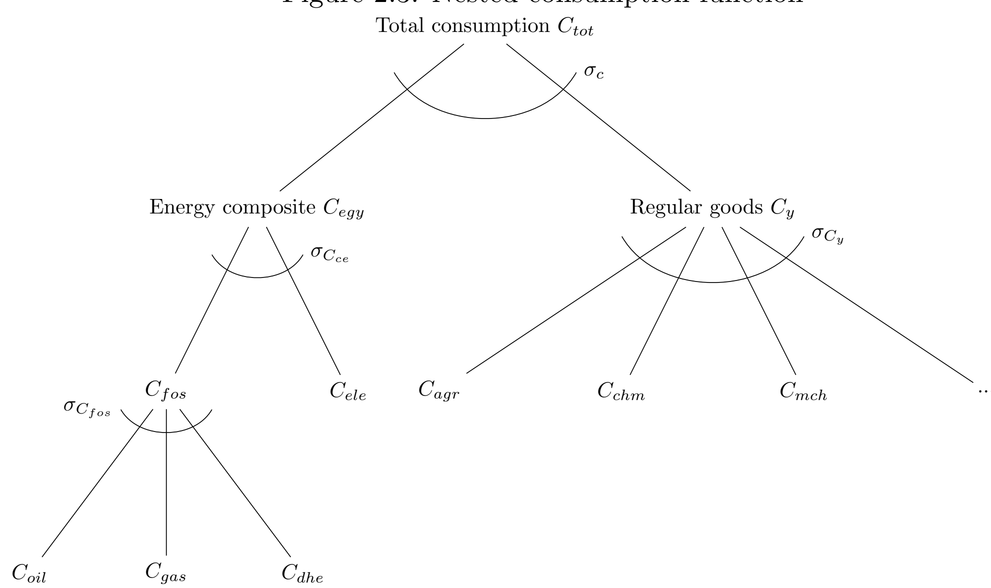
[1] Sources for data on electricity production are the Swiss Electricity Statistics (SFOE 2006) and the Swiss Statistics of Renewable Energy (SFOE 2006) for the year 2005.

are relevant for the effective tax rates imposed on fossil fuels later on.

2.3 Consumers

As in the original model version, we assume that a representative, infinitely lived household allocates its factor income between consumption and investments under perfect foresight and in accordance with intertemporal utility maximization. Figure 2.3 gives a graphical overview of the consumption nesting.

Figure 2.3: Nested consumption function



C represents an aggregate of different goods, consisting of consumption of a regular sector output composite C_y and an energy aggregate C_{egy}. As a new feature, we further disaggregate the energy composite C_{egy}. It is assumed to consist of electricity consumption C_{ele} and the consumption of fossil fuels C_{fos}. Additionally, since the share of fossil fuels and share of electricity use are different between consumption and intermediate production, the prices of energies are differentiated based on their final use.

2.4 Data and parameters

The model builds on data from the Swiss energy input-output table (IOT) for the year 2005 (Nathani et al. 2011).[2] In addition to the information on intermediate and factor inputs of more than 40 industries and service sectors, this table also includes detailed information on the production structure of various energy sources. This allows us to use this IOT to calibrate the cost functions of the different electricity technologies. It also holds detailed descriptions of household consumption of regular sector output and energy goods, and it includes data on physical and non-physical investments.

We have reduced the number of regular sectors to limit computational complexity. The IOT includes more than 40 regular production sectors, which we aggregated into 10 sectors. On the other hand, we have extended the table to include a larger variety of electricity sources, using data from the Swiss Electricity Statistics. In total, the model differentiates between seven technologies for electricity generation and three fossil fuel categories. Table 2.2 provides an overview of all sectors and technologies.

Table 2.2: Overview of the sectors and technologies used in the model

Sector/Technology	**Abbreviation**
Agriculture	agr
Chemical Industry	chm
Machinery and Equipment	mch
Construction	con
Transport	trn
Banking and Financial Services	bnk
Insurances	ins
Health	hea
Other Services	ose
Other Industries	oin
Delivered Electricity	ele
Hydro Energy	hyd
Nuclear Energy	nuc
Electricity from Waste	wel
Conventional Thermal Plants	ctp
Solar Energy	sun
Wind	win
Biomass	bio
Refined Oil Products	oil
Gas	gas
District Heat	dhe

The chosen parameter values are mostly identical to the original model version, they

[2]We implemented some preliminary checks on the new data set of 2008. The main results stay the same as using 2005 data. However, to keep consistent with the papers attached to the report, the analysis presented in the report is based on 2005 data.

are presented in Table 2.3. We again assume relatively low elasticities in most cases to prevent overly optimistic model results due to unrealistic substitution potentials. Whenever possible and available, the values are taken from existing studies.[3] Together with the share parameters α, which we calculate directly from the IOT, the elasticities of substitution are the basis for the calibration of the model. As it is common in CGE modeling, the model is calibrated such that it reflects the base-year data given in the IOT. As in the original model, we use the capital share to calculate a reference growth rate that is equal for all sectors. So that the structure of the economy stays the same through the benchmark scenario. This growth rate gives the benchmark path that can be used to evaluate the policy effects. Given the capital shares in the IOT, this reference growth rate is 1.33% per year. This rate refers to an economy without any policy. Further details on calibration are explained in Bretschger, Ramer and Schwark (2010, 2011).

[3] See van der Werf (2007) and Okagawa and Ban (2008) for estimations of elasticities related to the production process, Hasanov (2007) for estimations of the intertemporal elasticity of substitution in consumption, and Donnelly et al. (2004) for the Armington elasticities. Sue Wing et al.(2011) and Acemoglu et al. (2012) for elasticity of substitution of energies. Mueller and Mohler (2012) for elasticity of substitution in Manufacturing.

Table 2.3: Parameter values for regular sectors and consumption

Parameter	**Description**	**Value**
γ	Elasticity of substitution between Q and inputs from other sectors B	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)
ε	Elasticity of substitution between the three inputs (Energy E, labor L and other inputs V)	0.7 (agr, oil, chm, egy) 0.8 (mch) 0.52 (con) 0.82 (oin) 0.4 (rest)
τ	Elasticity of substitution between physical investments (I_P) and non-physical capital (I_N)	0.3
ω	Elasticity of substitution between investments in R&D (I_R) and research labor R	0.3
σ_{egy}	Elasticity of substitution between electricity and fossil fuels (F) in intermediate production	1.5
σ_C	Elasticity of substitution between energy (F) and non-energy goods (D) in consumption	0.5
σ_{ce}	Elasticity of substitution between electricity and fossil fuels (F) in consumption	1.5
θ	Inter-temporal elasticity of substitution in the welfare function	0.6
η	Trade (”Armington ”) elasticities	3.2 (agr) 4.6 (mas) 3.8 (egy, oin) 2.9 (rest)
χ	Elasticity of transformation	1
υ	Elasticity of substitution between sectoral outputs for the input B	0

Chapter 3

Policy scenarios and results

3.1 Description of scenarios

The aim of this project is to investigate the economic effects of long-run energy policies in Switzerland considering technology availability and substitutability, uncertainty, and other economic and political shocks. Four main scenarios are constructed in order to answer such questions in a complete format.

3.1.1 Business as usual

BAU: Business as usual scenario with climate policy. In Switzerland, a reduction of 20% (compared to 1990) until 2020 has already been decided upon and longer-term targets will most possibly follow in the context of an international framework. The analysis of any other energy policy should take these targets into account, given their importance for the energy sector. We can assume that the climate targets will have to be met in any case, i.e. irrespective of the plans concerning nuclear energy and construct a benchmark scenario (BAU) that includes a long-term emissions reduction target which is compatible with international climate targets. Specifically, we suggest to assume a reduction of carbon emissions of 65% relative to the initial period until the year 2050. This reduction target is compatible with international climate targets, in particular the target of an average temperature increase of maximum 2°C. Calculating the world carbon budget that is compatible with this temperature increase and requiring Switzerland to converge to a world average per capita carbon emission by 2050, the country will have to reduce its emission from 40 MtCO2 in 2010 to 14 MtCO2 in 2050, which is a reduction of carbon emissions by 65%.

3.1.2 Nuclear phase-out scenario

PO-FM: Nuclear phase-out scenario. We assume a smooth, gradual phase-out of nuclear energy until the year 2034, reflecting the currently envisaged operation time of 50 years for all existing nuclear power plants. First, we simulate a scenario ($PO - FM$) where no quantitative constraints on the future electricity mix are made. The results of this scenario are derived under free market (FM) conditions where only demand and supply determine the outcome and no constraints on the use of any technology, except for nuclear, or of total electricity are prescribed. An exception is hydropower: a recent report of the Federal Office of Energy (2012) shows that, even under idealized conditions, the expansion potential for hydro energy is relatively small in Switzerland. Hence, even under the assumption of a paradigm shift in energy policy towards an increasing political acceptance of the expansion of hydro energy and a corresponding change of the legal framework, the amount of additional capacities is strictly limited. Accordingly, we assume a maximal expansion of hydro energy of 10% relative to the base year level in all scenarios. Apart from this restriction, $PO-FM$ abstracts from any other limitations. $PO-FM$ thus shows a phase-out policy and the resulting electricity mix without assuming any political preferences or support for any specific combination of generation technologies.

3.1.3 Scenario on new renewables

PO-CC New renewable energies scenario according to Prognos (2011). The second policy scenario ($PO-CC$) implements concrete projections for individual technologies, based on the Energy Strategy 2050 of the Swiss Government (see Prognos 2011), which serves as a policy guideline for a nuclear phase-out. Prognos (2011) provides detailed projections on the shares of new renewable technologies and on the future electricity mix following the governmental strategy. It also assumes a limited potential for the expansion of hydro energy and imposes an upper limit for electricity from conventional thermal plants and from waste. As a result, the share of new renewable energy, most notably of solar energy, increases significantly. Given the low shares of new renewable energy on current electricity production and the relatively high marginal costs, it appears evident that these sources have to be supported by policy so that the requested gains in market shares can be achieved. We use a subsidy (which is technology- and time- specific) to promote renewable energy sources in this scenario.

The exact target shares for individual technologies (following the adjusted Scenario IV in Prognos 2011) are presented in Table 3.1. The resulting capacity rents are recycled in lump-sum fashion to the representative household.

Table 3.1: Market shares in scenario $PO - CC$ (Source: Prognos 2011, Table 4-11)

Year	**hyd**	**nuc**	**ctp**	**wel**	**sun**	**win**	**bio**
2010	0.57	0.39	0.03	0.01	0	0	0
2020	0.64	0.26	0.03	0.01	0.020	0.015	0.025
2035	0.69	0	0.10	0.03	0.095	0.035	0.060
2050	0.52	0	0.06	0.02	0.270	0.070	0.060

3.1.4 Scenario on uncertain future

UNC: Future uncertainty and people's concern on equality are important issues in evaluating the cost of energy policies. First, it would be interesting to investigate how the economy reacts when the macroeconomic environment for investment changes. Switzerland has experienced a steady growth of capital in the past decades. Due to the global economic crisis, Switzerland as a country is booming due to the "safe haven" perception and vast inflows of foreign capital. This can change the investors' investment strategy and thus the growth potential of sectors in the economy. We can elaborate our analysis by incorporating these new results in order to reflect the uncertainty on future economic environment as a whole.

Second, in growth theory or in the context of sustainable development, we use a discount rate to reflect the welfare of future generations (or future time periods) in the preferences of the present generation. However, there is no consensus on which value should be used for discounting. The controversial debate on discount rate has led to two opposite opinions on it. On the one hand, some environmental economists are in favor of a low discount rate. One famous example is Stern (2006), who applies the discount rate of 1.4% for his work "Review on the Economics of Climate Change". Ramsey (1928) also argues that the discount rate should be set close (if not equal) to zero which is "ethically indefensible" for the government to do so. On the other hand, high rates of discount rate are used, typically in the analysis of financial markets. Zeldes (1989) has demonstrated that "patience" in consumption is positively correlated with income. In the model, high income is the result of high capital growth. Hence, consumers are more patient when the capital market is booming, and "patient" implies a low discount rate for future incomes. This interpretation allows us to raise the discount rate if a low income level (growth of capital) is assumed in our model. The choice of an "appropriate" discounting rate to estimate the cost for energy polices has long been a complex decision. For a complete analysis we can consider two alternatives besides the value derived from Energy IOT (which is 0.74%), which are zero discounting and 4% discounting.

Table 3.2 summarizes the policies and assumptions on technology development in all scenarios.

Table 3.2: Summary of scenarios

Scenario	**Climate Target**	**Nuclear Phase-Out**	**Capacity Constraints**
BAU	yes (-65%)	no	no
$PO-FM$	yes (-65%)	yes	no
$PO-CC$	yes (-65%)	yes	yes
UNC	yes (-65%)	yes	yes

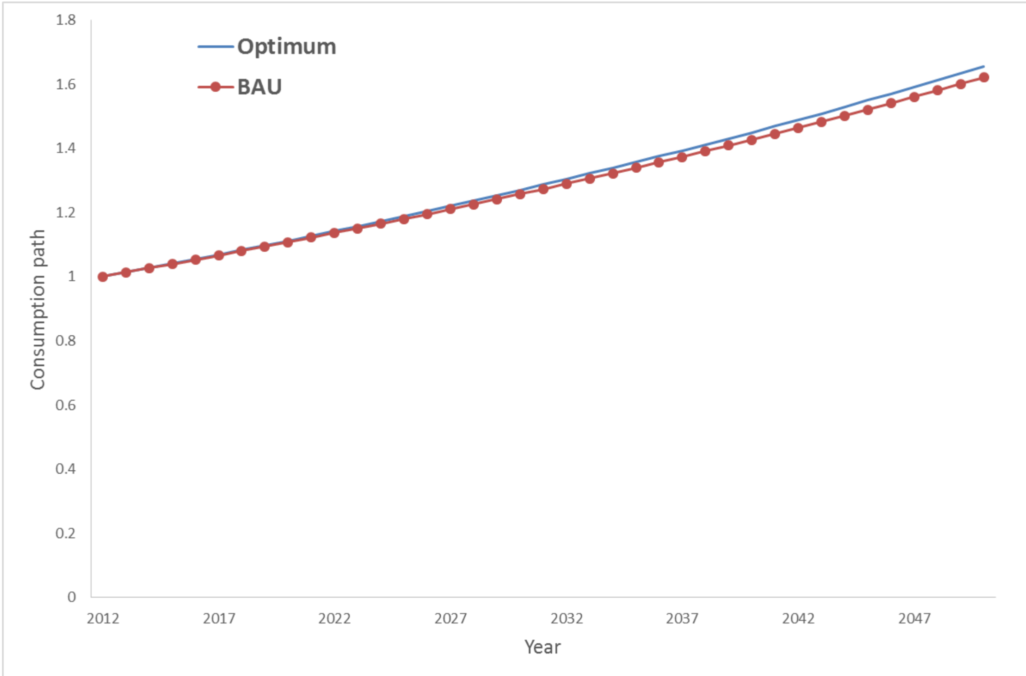
3.2 Results and analysis

3.2.1 BAU

We calibrate the endogenous growth mechanisms according to the characteristics of the BAU, which exhibits a very moderate growth rate. The assumed capital growth rate relies on long-run capital development. If there are no policies implemented, which we might call the "optimum" (if there is not yet an impact of climate change) we have a balanced growth path (BGP) where all the sectors grow at a rate of 1.33% per year. For our business-as-usual scenario we include the targeted climate policy, which results in growth of 1.28% per year. The discounted accumulative welfare loss (compared to the optimum) due to the climate target is 1.2%, which is the initial distance from the optimum and is much larger than the one for nuclear phase-out policy. Because we study the effects of nuclear policy only, the cost of climate policy is assumed to be already absorbed by the economy. Figure 3.1 describes such effects of climate policy in BAU.

In the absence of any additional incentives and policies in the BAU, the market shares of the individual technologies in total electricity generation remain constant at their initial levels. This implies that nuclear energy contributes to electricity supply for the entire time horizon. The benchmark scenario is calibrated so that the economy grows at a constant annual rate of 1.28%, with a welfare loss of 1.2% compared to the economy under the optimum growth rate of 1.33% absent of any policy shocks.

Figure 3.1: Consumption growth is lowered in BAU when considering climate policy



3.2.2 PO-FM

Given the drastic changes evoked by the nuclear phase-out one might expect significant changes for future development. On the other hand, the counteracting forces of rising renewable energies and induced innovations and capital investment might mitigate the original negative effects. As the nuclear plants are shut down, the supply of electricity decreases which leads to an increase in electricity price. Firms' reaction to the increasnig price of electricity (as well as energy) is the substitution effects between energy and other factor inputs, between energy and capital. Firms attract more capital and invest for innovation to improve the productivity. Indeed, this is what the results of our model suggest. In the $PO-FM$ scenario, the annual growth rate is 1.27%. The associated welfare loss (measured by the decrease in total aggregated discounted consumption) is 0.10%, and the discounted accumulative GDP loss is 0.12%.

These results show that the aggregate effects of a nuclear phase-out policy are not negligible, but not as large as shown in other studies (see e.g. Marcucci and Turton 2012). There are multiple explanations for this result. First of all, the stringent climate target (65% of emission reduction) has already imposed strong impacts on the economy. Carbon taxes increase the production cost for firms of all sectors (where energy aggregate is one of the essential inputs) and thus reduce the demand of fossil energies. This gives incentive for firms to seek ways to improve their technology efficiency on one hand, and enforce the substitution between energy and other factor inputs on the other hand. This type of substitution has indeed reduced the demand for electricity as well because firms use energy aggregate as a whole to produce intermediate goods. Nuclear phase-out works as a complementing policy for emission mitigation, which makes it much easier to reach both climate and nuclear target in the same time. Another important factor is planning reliability for investors. The phase-out increases the incentives to invest in alternative electricity technologies, which leads to a reduction in the cost of these technologies and a smoother and less costly adoption of the economy. In a setting where innovation and growth are directly interrelated, these additional investment incentives contribute significantly to lowering the cost of the phase-out. Third and related to that, investments in all parts of the economy are fostered, because capital becomes cheaper relative to energy. Note, however, we assume that the phase-out policy (like the carbon policy) is announced at the beginning and the phase-out pattern is known to all actors in the economy.

More sensitivity analysis on the values of substitution elasticities used in the model can be found in the Appendix B. These additional studies confirm our results are stable and do not largely deviate much from the results shown in the above.

In the energy sector, both fossil fuels and electricity are used in the production of intermediate goods and for consumption. Let $egyi$ and $egyc$ denote aggregate energy use (i.e. the use of electricity and fossil fuels) in intermediate production and consumption respectively. Table 3.3 shows that the nuclear phase-out leads to a significant decrease in energy use, most notably in intermediate goods production. Producers substitute away from energy as an input, and the energy efficiency of the economy as a whole increases. We can also observe that the nuclear phase-out leads to an additional reduction in fossil energy use, both in intermediate goods production ($fosi$) and in consumption ($fosc$). This confirms the intuition that a combination of a climate target and a reform of the electricity sector facilitates the reduction of emissions, because it induces both producers and consumers to lower their demand for energy goods. Finally, the last two rows of Table 3.3 indicate that electricity use is also reduced significantly. This can be explained by the fact that the BAU scenario assumes only a climate target, which leads to an increased electrification of the economy. This trend is reversed to some extent in the two phase-out scenarios.

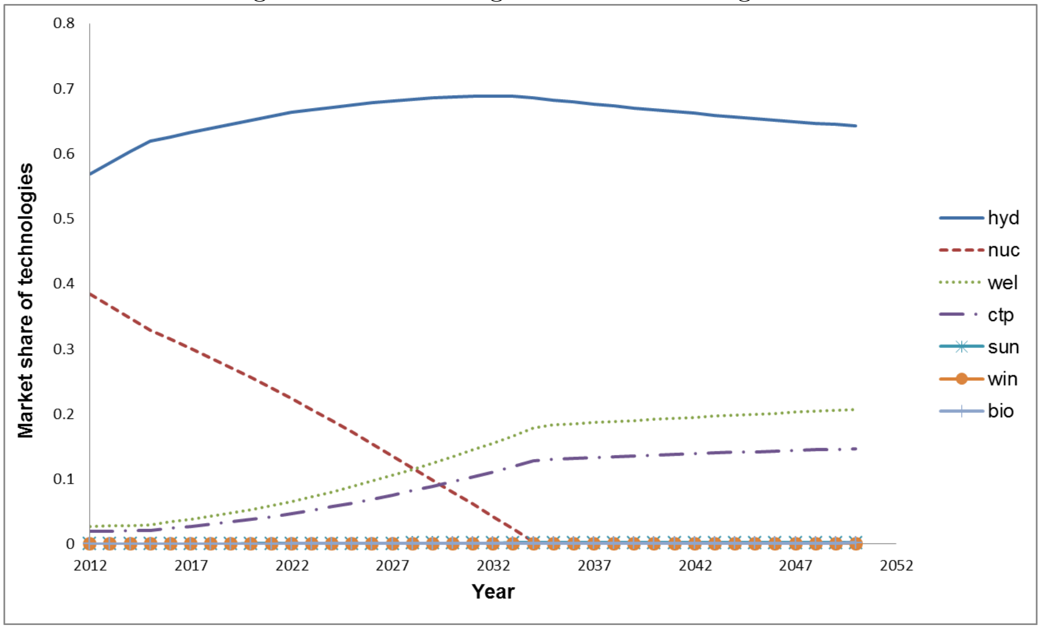
Table 3.3: Use of aggregated energy, fossil energy and electricity (% change vs. BAU)

Variable	**Scenario**	**2020**	**2035**	**2050**
$egyi$	*PO-FM*	-2.50%	-8.34%	-7.04%
	PO-CC	-6.52%	-20.2%	-21.1%
$egyc$	*PO-FM*	-0.28%	-0.81%	-0.94%
	PO-CC	-1.49%	-6.59%	-8.27%
$fosi$	*PO-FM*	-0.40%	-1.86%	-1.87%
	PO-CC	-1.12%	-4.91%	-5.73%
$fosc$	*PO-FM*	0.69%	1.03%	-0.16%
	PO-CC	1.76%	1.86%	-0.20%
ele	*PO-FM*	-3.63%	-10.5%	-8.07%
	PO-CC	-9.40%	-24.9%	-24.1%
Y_{ele}	*PO-FM*	-5.44%	-17.3%	-14.3%
	PO-CC	-14.1%	-41.1%	-42.4%

As for the market share of electricity generation technologies, under the free market scenario ($PO-FM$), when nuclear phases out, electricity generation from hydro will increase first rather than other technologies. The renewables increase with a small value since they are less than 1% in the beginning. This is because all technologies are competing through price/cost mechanism to replace nuclear. As hydro is currently in large-scale use, it is less costly to expand the capacity for higher output. While for new renewables, new facilities for larger capacity requires substantial investment, related infrastructures are also needed. Such fixed cost investments make them less competitive compared to other established technologies. Figure 3.2 shows the development of market share of technologies over time in $PO-FM$.

Using a less complex version of the CITE model, Bretschger et al. (2011) show that climate policy will induce a certain structural change of the economy. These findings are strengthened by the results derived from the policies simulated in the present paper. Highly innovative sectors and/or sectors with a relatively low dependency on electricity (chm, mch and most of the service sectors) become relatively more important and gain higher market shares. On the other hand, energy-intensive sectors such as trn or oin (which includes all the heavy industries) grow at lower rates compared to the BAU scenario and therefore contribute less to total output of the economy. (See the abbreviations of the sectors in Table 2.2.)

Figure 3.2: Share of generation technologies in *PO-FM*



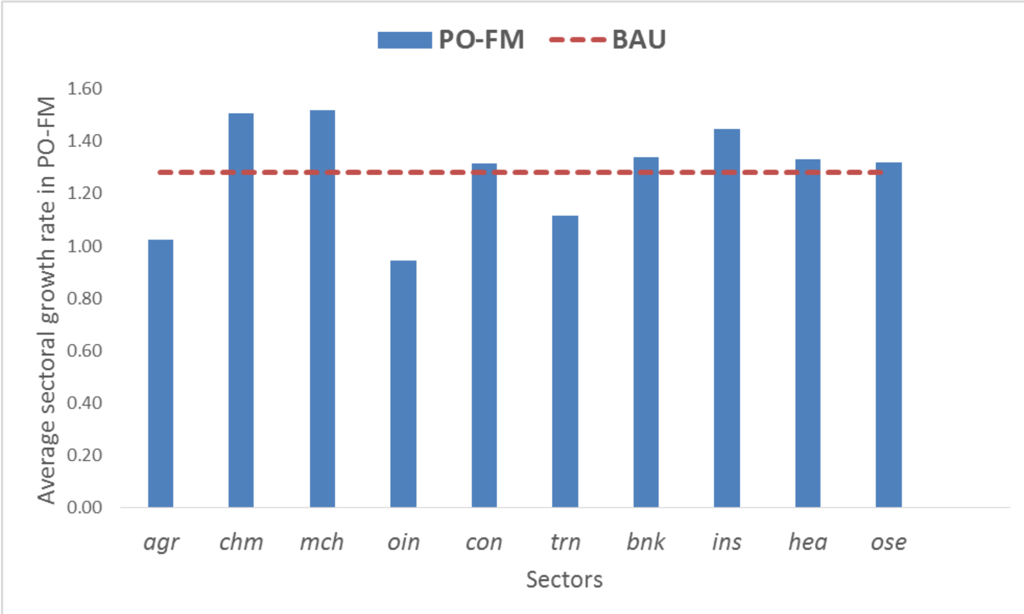
3.2.3 PO-CC

The aggregate effect in $PO-CC$ is relatively larger than in $PO-FM$. The consumption growth rate is declined to 1.26%. The associated welfare loss is 0.40%, with 0.53% loss of the discounted accumulative GDP.

The differences between the two policy scenarios can be explained by the assumptions on technology restrictions. In $PO-FM$, aggregated costs are lower because no subsidies have to be paid for less competitive technologies, which means that lower cost technologies gain larger market shares and new renewables continue to contribute relatively little to electricity generation (see below). Fading input of fossil fuels is to a large part compensated by increasing capital and its productivity. On the other hand, $PO-CC$ shows that the promotion of new renewables does not impose a significant drag on the growth rate of the economy. On the contrary, it highlights that a substantial increase of renewable electricity generation is possible at relatively low cost. Compared to $PO-FM$, there is more substitution of decreasing fossil fuels within the energy sector in the case of $PO-CC$.

To meet the requirements of climate policy we posit a continuously rising carbon tax over time. In 2050, the carbon tax in $PO-CC$ is 7.1% higher compared to the tax in $PO-FM$, while the carbon tax in $PO-FM$ is about 3.7% higher compared to the tax in BAU. In absolute term, the carbon tax in BAU in 2050 has to be 2504 Swiss Francs

Figure 3.3: Average sectoral growth rate in $PO - FM$



per ton of CO2 in order to reach the reduction of emissbion by 65%. The tax rate will rise up to 2500 Swiss Francs per ton of CO2 in $PO - CC$. Due to the low initial market share of solar, a huge expansion of capacity is needed in order for solar energy to take up more than 20% of the electricity market in $PO - CC$ from current share of less than 1%. To achieve the market share target, the capacity expansion in generation and back-up has to be partly financed by subsidies. This cost is the sunk cost incurred before producing electricity. Subsidies are endogenously determined by the model in order to achieve the market share target. From our simulation results, the cost for 1KWh electricity produced from solar is about 0.10 Swiss Francs with the subsidy of 0.04 Swiss Francs in 2035, the year after the nuclear plants are completely shut down; In 2050, the costs decrease to 0.06 Swiss Franc per KWh. However, new capacities' increase in the last 15 years of the simulation are twice the size of the increase between 2012 and 2034; hence, consumers still have to pay 0.03 Swiss Francs as a subsidy to compensate for new capacities in 2050.

The energy sector is strongly affected in $PO - CC$, which can be observed from Table 3.3. The free choice of the electricity mix and the absence of any political or technological constraints (with the exception of hydro energy) in $PO - FM$ allow for a less costly transition to a nuclear-free electricity sector. This leads to a less significant reduction of energy use, to less substitution for other inputs and consequently to a less pronounced shift to a less energy dependent economy. The results for scenario $PO - CC$ show that combining the phase-out plan with supportive measures for new renewable energy sources also leads to a faster reduction of emissions and to more energy efficient production in general.

Moreover, the market share of new renewables in the electricity market needs to be significantly increased in $PO - CC$. This is hardly possible without government subsidy on new renewable technologies such as solar and wind. The government subsidy drives down the cost of producing electricity using such technologies, making them competitive compared to the established technologies. It also helps to attract new investments, and hence capital stock increases and helps renewable technologies to build up their capacities for large scale production in order to meet the policy target. These reasons explain why solar faces a drastic increase in the $PO - CC$ scenario. Without any support for new renewables, they will not be able to gain a significant market share, because the market mechanism will choose to produce electricity from technologies with large market shares in the benchmark. Large market shares in the benchmark means that a technology is more profitable than others.

Figure 3.4: Share of generation technologies in PO-CC

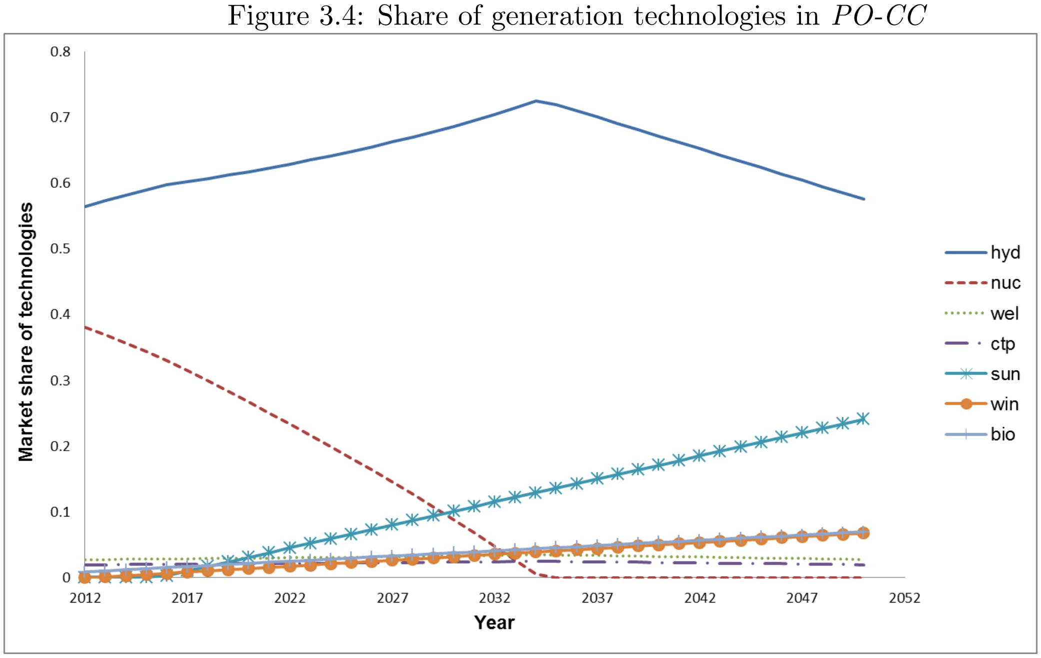
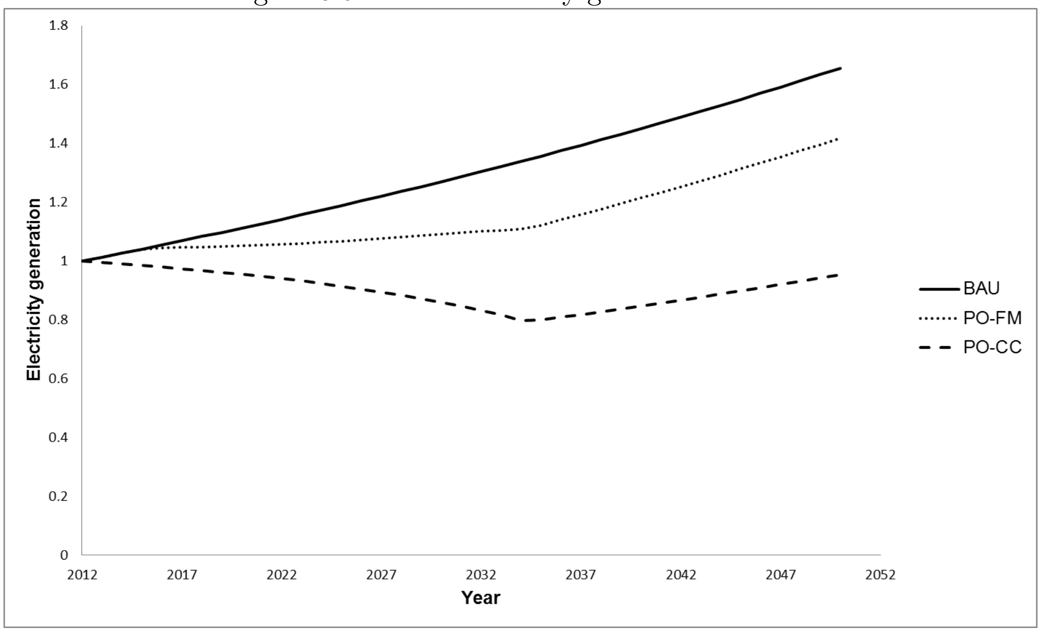


Figure 3.5 illustrates the total electricity generation in different scenarios. Assuming the BAU as the sub-optimal path for the balanced growth of Swiss economy, all sector grow at the same rate as the consumption growth. Hence, the average annual growth

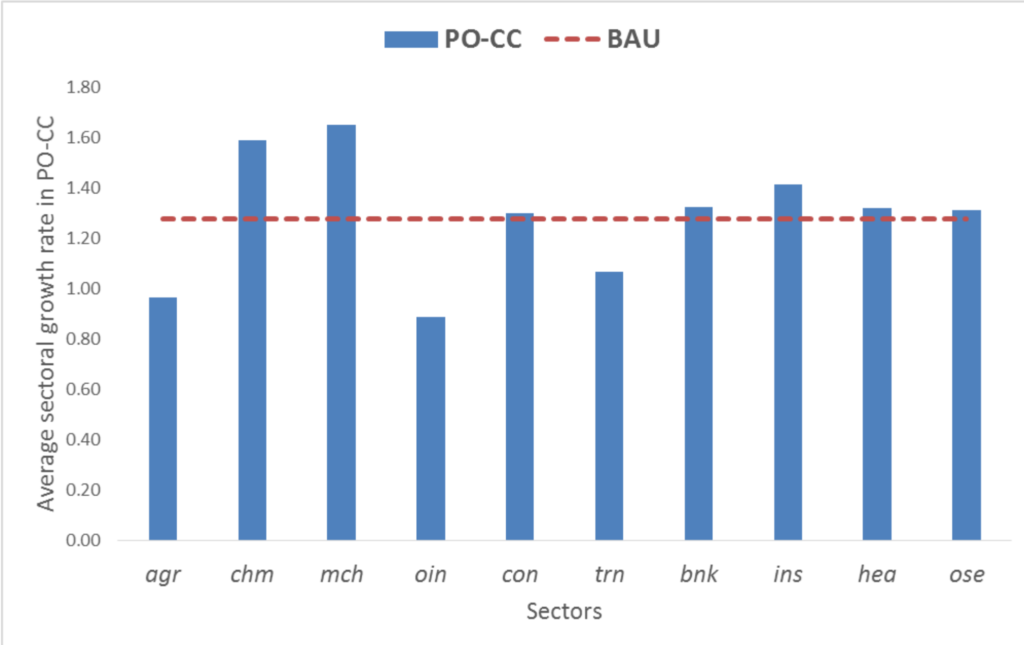
rate of electricity generation in BAU is calibrated to be 1.28%. With such growth rate, total electricity generation in 2050 is about 1.6 times the level in 2012. In *PO-FM*, the total electricity generation declines by 14.3% in 2050 compared to BAU, which is about 1.4 times the level in 2012. The output from electricity sector in 2050 further decreases to approximately the level of Year 2012 in *PO-CC*.

Figure 3.5: Total electricity generation across scenarios



There are some differences for the impacts on the degree of structural change between $PO-FM$ and $PO-CC$. Figure 3.6 shows the growth rate of sectors in $PO-CC$. mch, a particularly innovative sector, benefits the most in both scenarios. oin (e.g. cement, pulp and paper) on the other hand experiences the highest drop compared to BAU, both in scenario $PO-FM$ and $PO-CC$. Hence, the difference in sectoral output in 2050 will be substantially larger in scenario $PO-CC$. The (politically desired) shift to an electricity sector dominated by new renewable generation technologies is thus accompanied by a "greening" process in the economy where energy intensive sectors become less important. The shaded areas illustrate that the assumptions on technology expansion have a pronounced impact on individual growth rates. Given that more restrictions tend to lead to a higher divergence of sectoral growth rates, scenario $PO-FM$ indicates the minimum (or the bottom limit) of structural change that can be expected to result from a phase-out policy under the given conditions.

Figure 3.6: Average sectoral growth rate in $PO - CC$



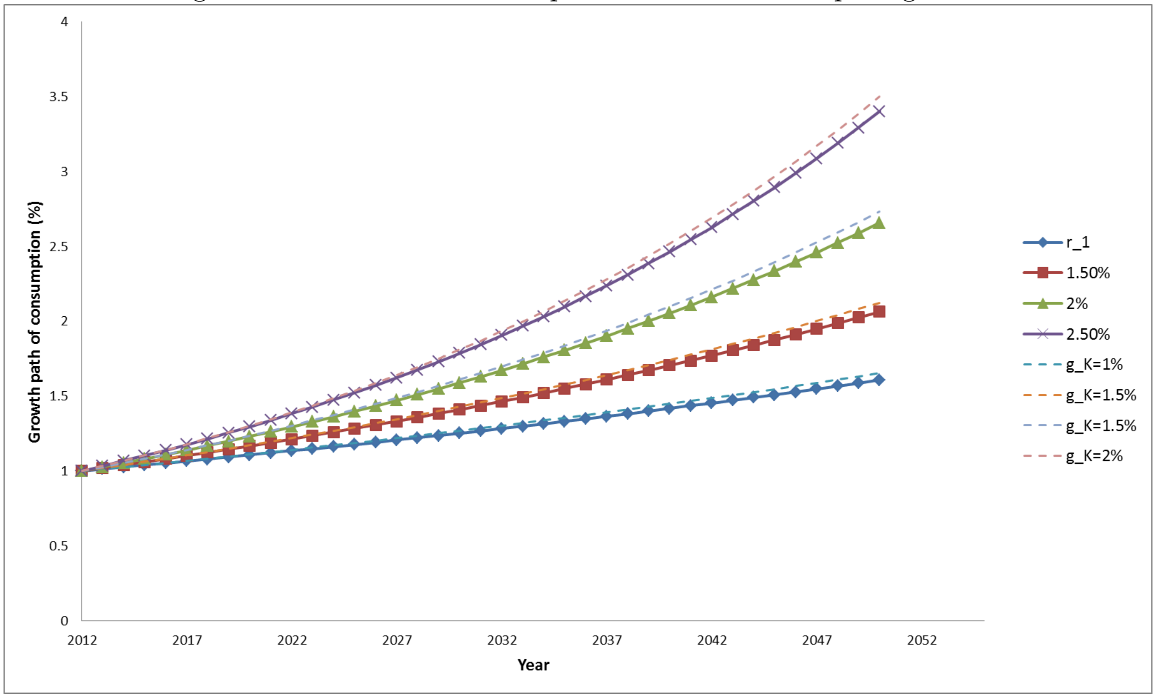
3.2.4 UNC

Uncertain future reflected by capital growth

One challenging issue for economic analysis is the uncertainty of future development for an economy. Many factors such as domestic deficit, global crisis can affect the macroeconomic environment for investment and consumption decisions, and hence the overall growth of an economy. Various growth trajectories and outliers are necessary to be taken into consideration for a complete analysis.

In the original model of Bretschger et al. (2011), the capital growth is assumed to be 1 %, which corresponds to the growth of the economy at the rate of 1.33%. This is consistent with a simple average of historical growth rates. However, OECD (2012) estimates that the average growth rate in GDP for Switzerland between 2011-2060 will be 2.1%. Even in per capita level, the growth rate is 1.7%. Rudolf and Zurlinden (2009) estimate the growth rate of capital to be between 1.90% and 2.38% in the period 1990-2005 based on different definitions. Data from Swiss Federal Statistical Office also show that the average growth rate of capital between 1990 and 2005 is about 2.5%. The growth rate of capital between 1990-2010 is about 1.98% (nominal) and 1.58% (real), calculated based on data from Swiss Federal Statistical Office. These estimations are all far above the value used in the previous

Figure 3.7: Growth of consumption with different capital growth



analysis (which is 1%). Hence, we define various growth rates (1.5%, 2% and 2.5%) for capital to further the CGE analysis so as to incorporate information on the new estimates.

When setting the capital growth rate to be 1%, the growth of consumption in the energy package scenario is approximately 1.26%, which is lower than the growth rate of GDP when no energy policies are implemented (which is 1.34%). The 0.07 percentage point loss follows from the energy policy shocks, resulting in 1.7% welfare loss compared to the baseline without energy policies.

As shown in above, the growth rate of capital used in the model is underestimated. We elaborate our analysis by incorporating these new results in order to reflect the true effects on the economy. Intuitively, raising the capital growth rate will contribute to higher growth of sectoral outputs and hence of the whole economy. As we can see from Figure 3.7, the dashed lines indicate the baseline scenarios where the energy policies are absent, while the colored lines show the scenarios when energy policies are taking place. All colored lines are underneath the dashed lines, showing that energy policies indeed negatively effect the economy.

From theory we know that one percentage growth of factor input will results in more than one percentage growth of output due to endogenous innovation and productivity increase.[1] According to our data calibration, in the case of Switzerland, each additional percentage point of growth in capital can produce 1.34 additional percentage points of output growth, the same is true for aggregate consumption. The growth rates of aggregate consumption in higher capital growth scenarios are 1.93% for capital growth rate of 1.5%, 2.60% for 2.0%, 3.27% for 2.5%, respectively, confirming our intuition from theory. The welfare loss compared to their respective baseline scenarios are the same, which is approximately a decline of 1.7%.[2] However, higher capital growth leads to higher output growth. That means, with the same share of welfare loss, the economy in absolute terms suffers more severely with high capital growth than with low capital growth. The increasing gap in Figure 3.7 between baseline growth path and respective growth path under policy illustrates this feature.

The sectoral effects under different capital growth rates are similar to the effect on aggregate consumption. The incremental for each of the sector's growth due to the rise of capital growth is 0.67% for additional 0.5% of capital growth. Put differently, the aggregate increase in capital stock is not proportionately distributed across sectors. For example, sector A in the beginning grows at the rate of 1%, 0.5% incremental of sectoral growth means it grows at the rate of 1.5% now, which is a 50% increase; while if sector B grows at the rate of 2%, 0.5% incremental raises the growth rate to 2.5%, however the growth rate increases by 25% only. In the end, sectors with a lower growth rate can speed up with booming capital investment in the future, and reduce difference in sectoral output values. The change of sectoral share of GDP will finally adjust the structure of the economy towards an equal development. In contrary, low future capital investments can lead to specialization of the economy towards innovative and energy-extensive sectors where the return on capital is much higher.

The above analysis also suggests that securing the sustainable capital market can help an economy to develop an unbiased economic structure instead of investing in some sectors which can produce high output while dragging other sectors into the mire. In the context of global competition, foreign direct investment will play an important role as a major source

[1]See Appendix A equation 2 for more information.

[2]As indicated in Figure 3.7, the 1.7% welfare loss is due to the lower value of the colored lines compared to the respective dashed lines lying just above it.

of capital investment.

Uncertain perceptions on future generations

Another crucial factor which affects the future cost of energy policies is the inter-temporal discount rate ρ. In growth theory or in the context of sustainable development, the discount rate is used to reflect the welfare of future generations (or future time periods) in the preferences of the present generation. However, there is no consensus on which value should be used for discounting. The controversial debate on discount rate has led to two opposite opinions. On the one hand, some environmental economists are in favor of low discount rate. One famous example is that Stern (2006) applies the discount rate of 1.4% for his work "Review on the Economics of Climate Change". Ramsey (1928) also argues that the discount rate should be set close (if not equal) to zero which is "ethically indefensible" for the government to do so. On the other hand, high discount rate are used, typically in the analysis of financial market. Zeldes (1989) has demonstrated that "patience" in consumption is positively correlated with income. In the model, high income is the result of high capital growth. Hence, consumers are more patient when the capital market is booming, and "patient" implies low discount rate for the future. This interpretation allows us to raise the discount rate if low income level (growth of capital) is assumed in our model. Moreover, Weitzman (2001) proposes the so-called gamma discounting, indicating the declining value of discount rate from around 4% per year for the immediate future to around zero for the far-distant future.

The choice of an "appropriate" discount rate to estimate the cost of energy polices has long been a complex decision. In the original model, the discount rate is implicitly set to be 0.74% by the model system. Although Stern (2007) prefers the discount rate to be close to zero, Nordhaus (2007) points out that near-zero discounting implies current generations having an unrealistically high willingness-to-pay for reducing damages, which gives problematic results for model simulations with long time horizons (Ramer 2011). Including a time-variant discounting rate will increase the complexity of the model significantly and there will be no balanced growth path in the end. To address this issue, we have to test various constant discount rates to see the deviation of the model results. For a complete

Table 3.4: Aggregate effects of discounting rates on the whole economy

ρ	r	Welfare loss	Aggregate consumption growth rate
0%	0.67%	1.8%	1.256%
0.74%	1.41%	1.7%	1.259%
4%	4.69%	1.1%	1.263%

Note: Welfare loss is compared with the baseline scenario where the growth rate of capital is 1% and β is 0.75, and absent of energy policies.

analysis we consider two outliers besides the value derived from the Energy IOT (which is 0.74%).

Table 3.4 gives message on how welfare loss and aggregate consumption growth are affected by the change of the discount rate. 0.74% is the implied discount rate derived from the original energy IOT.[3] If no energy policy is applied to the economy, the aggregate consumption would grow at the rate of 1.33% per year. Under pre-designed energy policy package, it will suffer from a welfare loss of 1.7% with a lower growth rate of consumption. If we increase the discount rate, the present value of future generations' consumption is lower than before, because later periods have a lower weight in the total welfare. The total welfare loss should thus be considerably lower than before. With a discount rate of 4%, the welfare loss is only 1.1%. The effects on the overall welfare are mitigated with a higher discount rate. However, with the same carbon tax profile, we are not able to reach the emission reduction target of 65%. A higher tax is required in the future to achieve the same emission target, which means the policy cost for achieving the same target is higher with a larger discount rate. On the contrary, zero discounting means that we treat all generations equally. The welfare loss becomes larger due to heavier weights for future generations.

In general, the effects on aggregate consumption are surprisingly small even though the discount rate varies from 4% to 0. However, the growth rate of aggregate consumption is positively correlated with the discount rate. Lower discount rate contributes to lower growth of consumption, while higher discount rate encourages consumptions. This is because lower discount rate also implies lower interest rate which reduces the return on capital. Hence, it reduces the incentives to invest for new capital varieties, and thus lower output and consumption. Moreover, zero discount rate implies future consumptions have the same

[3]See Appendix B equation 5 for the evaluation of discount rate.

weight as the current consumption, this will amplify the long run effects on consumption and limit the growth of consumption.

The results are similar for different discount rates on the sectoral level. The whole structure of the economy will not be affected significantly. With higher discount rate, energy intensive sectors tend to shrink, and energy extensive sectors grow a little faster compared to scenarios with low discount rate. As discussed before, a higher discount rate requires higher tax rate to remain the same climate target. This will increase the price of energy goods and hence reduce the demand for it. Energy intensive sectors will reduce the use of energy goods and hence the output of these sectors will decline compared to before; while energy extensive sectors are now much more beneficial than energy intensive sectors. More inputs flow into energy extensive sectors and make it even cheaper to produce. Lower price will increase the demand for energy extensive goods as well. In the end, the growth rate of energy extensive sectors increases compared to the case when the discount rate is relatively low. Within the energy sectors, the change in growth rates is the same. We assume that the carbon content of *oil* is much higher than that of *gas* and *dhe*. To reach the same level of emission reduction, the reduction in oil consumption is higher than in other energy sectors. Therefore, *oil* sector further decreases and the others raises their outputs.

Appendix gives more detailed analysis on the discussion of uncertainty issues.

Chapter 4

Multi-regional framework and knowledge spillover

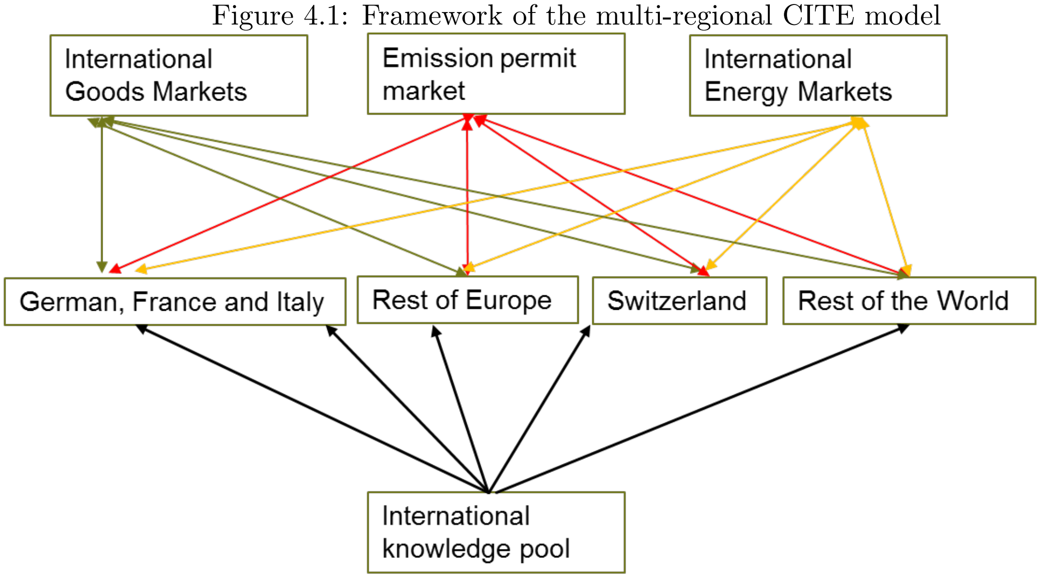
4.1 Multi-regional setting of the CITE model

The CITE model is a one-country multi-sector model with endogenous growth. It is solved with inter-temporal optimization, and hence it avoids the problems existing in recursive dynamic models, where the intertemporal substitution possibilities are neglected and the optimization behavior of agents between the static and the dynamic equilibrium are inconsistent. To exploit growth effects of various energy policies with international context, we develop the international version of the CITE model.

To analyze the effects of neighboring countries' energy policies on the economic growth of Switzerland, we distinguish the three major players for the Swiss economy (CHE), which are one region combining Germany, France and Italy (GFI), one region for the rest of Europe (ROE), and all the other regions, which are aggregated into the region called "Rest of the World" (ROW). In total, the model simulates four regions. For each of the regions, the growth engine follows the same rules as described in the one-region version of the CITE model. The regions are connected through international trade, capital flow, and their current account balance.

There are three international markets playing roles for the global economy: the international goods markets which trade "regular goods" between regions, the international energy markets which deal with energy goods, and the emission permit market which take into account both local and international emission reduction targets. In addition, we consider

Figure 4.1: Framework of the multi-regional CITE model



the effects of knowledge spillovers on economic development. To facilitate such analysis, the so called "international knowledge pool" is constructed for the flow of knowledge between regions and sectors.

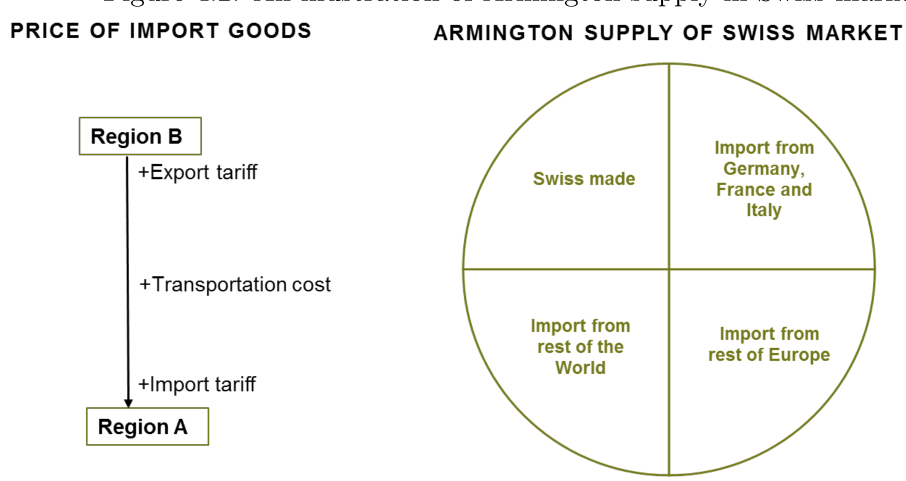
The multi-regional version CITE model is coded by following the mathematical programming system for general equilibrium analysis (MPSGE)[1] routine.

4.1.1 Armington supply and trade

We use the Armington assumption to differentiate domestically produced goods and foreign goods in the CITE model. This assumption still holds within the multi-regional setting. One advantage to assume Armington goods is that all goods can be identified by the original regions of production. Hence, we can describe the international trade patterns among countries explicitly.

Furthermore, the price of imported goods includes export/import tariff, transportation cost, and the production cost of the exporting country. As illustrated in Figure 4.2, the goods used for Swiss demand comes from four sources in general, the domestically produced goods and imported goods from the three foreign regions. Of course, one or more of the sources can be irrelevant in some sectors or regions due to the trade regulation or other factors.

Figure 4.2: An illustration of Armington supply in Swiss market



[1] More information can be found in `http://www.gams.com/solvers/mpsge/index.htm`.

4.1.2 Current account

The equilibrium condition of the model requires that the present value of consumption to equal the present value of income over the entire time horizon. This is the budget constraint which must hold. However, a region is able to borrow or lend money in a given time period t, which is the so-called current account surplus or deficit. As stated in Carbone et al. (2003), the closure of financial flows within the model needs an additional constraint on current account deficit for the whole world. That is, for any given time period, the "global" current account deficit has to be zero.

Springer (1999) and Rutherford (2003) define the current account of a region as the trade deficit, which means if one country imports more than its exports (in terms of value), it will result in a current account deficit. Since in the model the balance of trade deficit or surplus holds for any given time,[2] the balance of current account deficit or surplus holds automatically by such definition.

4.1.3 Spillover

Griliches's contribution (1979) is one of the first papers addressing two types of spillovers: the embodied knowledge spillover and dis-embodied knowledge spillover. The embodied knowledge spillover is what he called "rent spillover", which is due to the fact that purchase prices of imported goods do not reflect their "full quality price" including the opportunity cost of R&D of foreign innovation. The dis-embodied knowledge spillover refers to borrowing ideas by industry i from the research results of industry j. Usually this types of knowledge augments the domestic knowledge stock while the learning cost is lower than the original R&D cost.

Embodied knowledge spillover has its origin from the empirical work of Coe and Helpman (1995). This paper indicates that knowledge spillover is embodied in the flow of physical commodities transactions through the channels of trade and FDI.

The seminal work of Rivera-Batiz and Romer (1991) suggests that economic integration increases the worldwide stock of ideas, and hence contributes to growth. This provides root for the so-called dis-embodied knowledge spillover.

[2]The total value of export equals the total value of import for the whole world.

Knowledge itself, particularly tacit knowledge, is unmeasurable, and its flows are invisible (Krugman 1991). This means that studying knowledge spillovers quantitatively one has to rely on crude proxy variables. In general, the knowledge spillovers are a function of the total available knowledge and the spillover coefficient.[3]

By distinguish the sourcing sectors of spillover, we can identify four kinds of spillovers: intra-industry spillovers domestic, inter-industry spillovers domestic, intra-industry spillovers foreign[4], inter-industry spillover foreign[5]

The one-region CITE model has already illustrated the intra-industry spillovers through the endogenous growth mechanism. In the one-country version CITE model, there is no explicit modeling of inter-industry spillovers. This is because we assume the economy is exempted from externalities. Intra-industry spillover is due to the existence of monopolistic competition. However, inter-industry spillover is public goods which are free. Hence the market condition can not be fulfilled if this is included. Hence, in the multi-regional model version, the total spillovers used for variety-expansion of one sector is a combination of self-generated knowledge spillover and spillovers from the other three sources. Knowledge generated from outside of the industry and region is also partly available to the domestic industry. Such public knowledge is treated as public goods which can be used for further innovation. Hence, domestic firms do research and innovation not only based on the knowledge stemmed from themselves, but also external knowledge. All spillovers together contribute to the increase in varieties in the respective sector. Then the usual mechanism for endogenous growth takes place.

4.2 Data

The dataset used for the model is GTAP 8, and we follow the rules developed by Rutherford (GTAPinGAMS model) for aggregation before used for calibration in the model. GTAP 8 Data Base[6] is used in this chapter to analyze the effects of foreign policies on economic

[3]It is a form of absorptive capacity, however, we will use the term "absorptive capacity" for something really related to "absorption". Hence, we define the term "spillover coefficient" here instead.

[4]Knowledge spillovers from foreign countries of the same industry.

[5]Knowledge spillovers from foreign countries of other industries.

[6]More information on this data set can be found on the web-page: `https://www.gtap.agecon.purdue.edu/databases/v8/`.

growth of Switzerland.

The highly disaggregated sectors in GTAP8 are aggregated into 10 sectors as described in Table 4.1, for the sake of reducing computational complexity. However, all the key sectors which play important roles for growth and/or have an impact on energy policies are highlighted. We argue that this simplified version of multi-regional CITE model can produce rich results regarding the impact of knowledge diffusion.

Table 4.1: Overview of the sectors used in the multi-regional CITE model

Sector	**Abbreviation**
Agriculture	agr
Manufactured and Processed Goods	man
Services	ser
Transport	trn
Other energy intensive sectors	eis
Coal	col
Electricity	ele
Refined Oil Products	oil
Crude oil	cru
Natural Gas	gas

There is no empirical estimation on the intensity of spillovers over regions and (or) across sectors.[7] We provide illustrative examples and show how large the spillover would be and how strong it will impact the economy as a whole and the structure among respective sectors by assuming some arbitrary values for the spillover intensity coefficients. The parameter values used in the model to simulate spillovers are described in Table 4.2. We choose these values based on our preliminary estimations and consult previous studies in literature to ensure the assumptions are not largely deviated from the real value. The three elasticities illustrate the substitutability between various channels of knowledge spillover and the self-created knowledge. The spillover intensity coefficients tell how much of outside knowledge is accessible or useful.

Table 4.2: Parameters used for modeling spillovers

Parameter	**Meaning**	**Value**
σ^I	elasticity of international spillover from the same sector	0.20
σ^{JI}	elasticity of international spillover from different sector	0.05
σ^{JH}	elasticity of domestic spillover from different sector	0.05
β^I	spillover intensity coefficient from the same sector in foreign region	0.10
β^{JI}	spillover intensity coefficient from different sector in foreign region	0.01
β^{JH}	spillover intensity coefficient from different sector in the same region	0.02

[7]We are now conducting empirical study to estimate the intensity coefficient using patent and citation data from OECD.

4.3 Scenarios

The multi-regional version of the CITE model is now constructed and can be used to model the knowledge spillover from all four channels. We first study how the positive externalities change the regional welfare. In scenario $SP - ref$, the channels for spillovers are active and foreign knowledge flows freely to Switzerland, which potentially increases the stock of knowledge for the creation of new blueprints for new varieties. The effects of knowledge spillover on economic growth is illustrated in this scenario. Later on, the climate policy is re-modeled with inclusion of spillovers for the economies (scenario $SP - 65 - ref$).[8] Moreover, we construct sensitivity analysis to test for the parameters and elasticities we use for modeling spillovers (scenario $SP - 65 - high$ and $SP - 65 - low$).

Table 4.3: Summary of scenarios in the multi-regional CITE model

Scenario	**CHE**		**GFI**		**ROE**		**ROW**	
	Emission	*Spillover*	*Emission*	*Spillover*	*Emission*	*Spillover*	*Emission*	*Spillover*
benchmark	-	-	-	-	-	-	-	-
$SP - ref$	-	SP-ref	-	SP-ref	-	SP-ref	-	SP-ref
$SP - 65 - ref$	-65%	SP-ref	-65%	SP-ref	-65%	SP-ref	-	SP-ref
$SP - 65 - high$	-65%	SP-high	-65%	SP-high	-65%	SP-high	-	SP-high
$SP - 65 - low$	-65%	SP-low	-65%	SP-low	-65%	SP-low	-	SP-low

4.4 Results

4.4.1 The impact of knowledge spillover

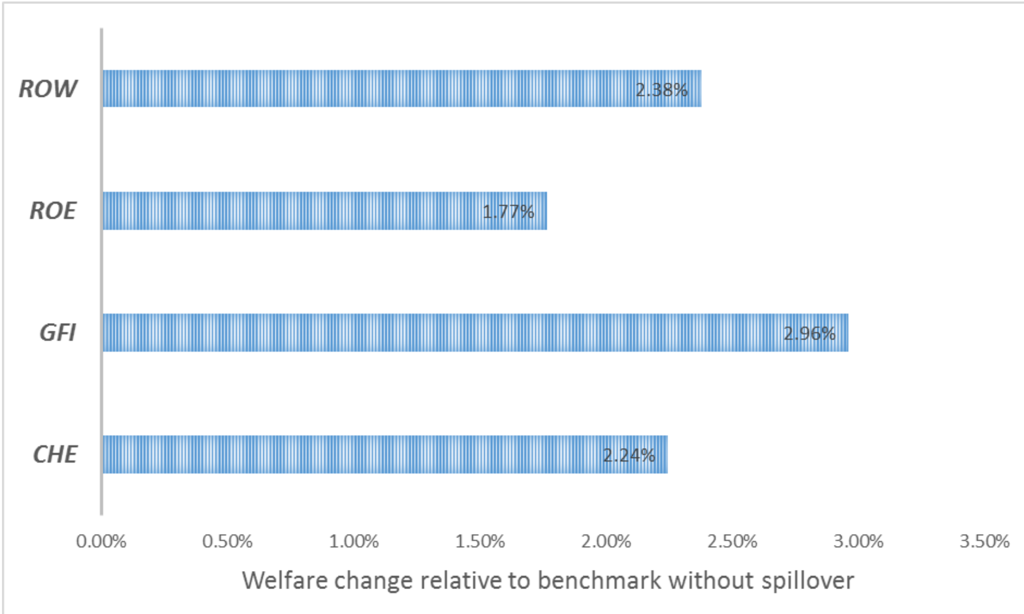
Figure 4.3 shows the change of regional welfare compared to the benchmark in which knowledge spillover is absent.[9] The results are in line with our perceptions. Knowledge spillovers contribute positively with welfare and economic growth. Knowledge inflow increases the welfare of Swiss consumers by 2.24%. The region GFI has a relative higher welfare increase, reaching up to around 3%. ROW has a welfare increase similar to Switzerland. ROE shows the lowest increase in welfare level (1.77%).

In the sectoral level, sectors react differently with respect to the knowledge inflow. The results are summarized in Table 4.4. In the balanced growth path without knowledge

[8] We do not simulate various spillover channels separately. This is because once spillovers are being taken into account, they are simultaneously treated as parts of the world knowledge pool. It makes no sense to consider one aspect while ignoring the other aspects.

[9] However, intra-industry spillover is always included in the model no matter which scenarios are implemented. This is due to the fact that intra-industry spillover is the result of endogenous growth mechanism.

Figure 4.3: Regional welfare increase due to knowledge spillover



spillover, all sectors in all regions grow at a rate of 1.33%. In the world with knowledge flow, all sectors and all regions receive knowledge bonus from diffusion. In particular, capital-intensive sectors have higher potential to gain extra incentive for higher growth. This is because new knowledge can be directly transfered into productivity, and hence capital-intensive sectors can substantially reduce their fixed cost which are used to cover the research expenses. In Switzerland, the growth rate of manufacturing (man) increases to 1.38% followed by service (ser) and transport (trn). The energy-intensive sector (eis) increases slightly from 1.33% to 1.35%.

Table 4.4: The average growth rate of regional non-energy sectors in a world with inflow and outflow knowledge

Sectors	CHE	GFI	ROE	ROW
agr	1.39%	1.40%	1.39%	1.38%
eis	1.35%	1.37%	1.40%	1.38%
man	1.38%	1.38%	1.39%	1.38%
ser	1.37%	1.37%	1.37%	1.37%
trn	1.37%	1.39%	1.39%	1.38%

To compare between regions, it shows that Switzerland has relatively lower gain relative to for example GFI. In sector eis, GFI region grows at a rate of 1.37%. One explanation is that Switzerland is more capital-intensive than GFI, the positive effects of knowledge on productivity have be exploited in the benchmark scenario without spillovers. On top of that, when spillovers are considered, the share of inflow knowledge to the capital stock of its own is lower in Switzerland compared to GFI. This limits the possibilities to profit from international knowledge transfer. Hence, the result shows CHE grows lower than GFI when knowledge spillover is allowed. It is also worthy of noting that we calibrate the model to a steady state where all regions and sectors grow at the same rate. All the values in Table 4.4 are compared to such a baseline. But in reality, sectors between regions grow at different rates. This implies that with knowledge spillover *eis* sector in Switzerland may expand at a higher rate compared to GFI.

Last, it is interesting to note that the agricultural sector (*agr*) grow at the highest rate compared to other sectors in both CHE and GFI. We believe several reasons attributed to this. First, the positive contribution of knowledge inflow of other sectors. Second, *agr* requires more inputs from other sectors while not the other way around. The positive effects of other sectors can spread to *agr* through the use of other sector's goods as inputs in the production. Third, international trade in *agr* is small compared to other sectors, which implies that knowledge spillovers into *agr* can be interpreted as a positive shock to the sector. More goods are produced and much of the goods are consumed in domestic market since export is limited. This also contributes to its growth.

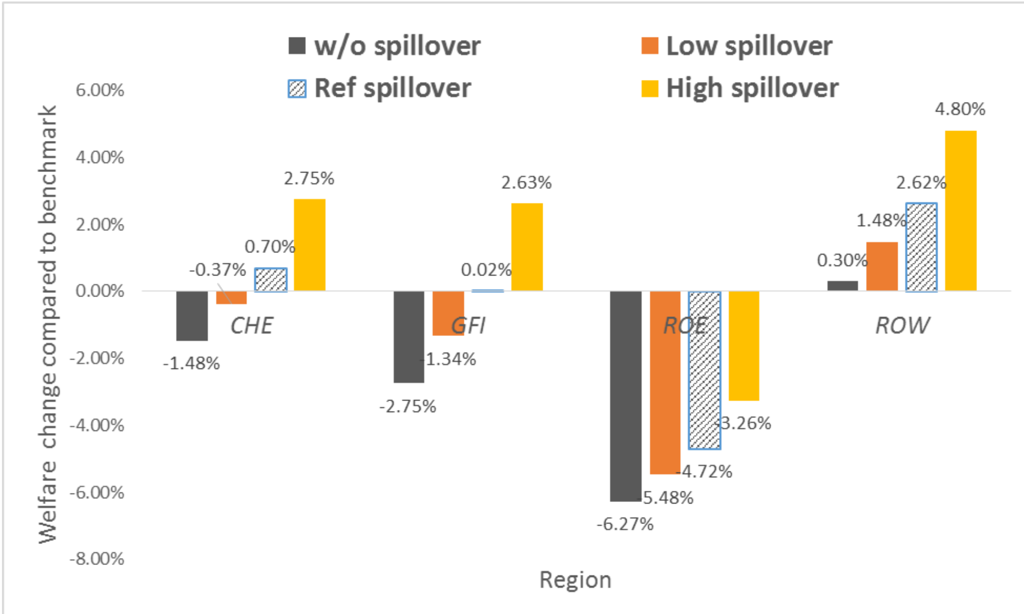
4.4.2 Climate policy in regions with knowledge diffusion

In this section, we discuss the possible outcome when climate policy is implemented in a world with knowledge diffusion in aggregate level because we know the parameters and elasticities used in the knowledge spillover module will drive the results largely.

Figure 4.4 shows the welfare changes of climate policy (65% emission reduction in 2050) in a world with and without knowledge diffusions.[10] Comparing the results between without spillover and with reference spillover (first and second bars in each region in Figure 4.4), we can see that all regions have a welfare increase due to the externalities of spillover. Switzerland gains in welfare level by 0.7%, compared to a loss of 1.48%. GFI is now able to cover its cost of climate policy through knowledge spillover. ROE reduces its cost by one third with the increased knowledge from outside.

[10]The estimated welfare changes are relative to the benchmark where there is no climate policy and no spillover.

Figure 4.4: Regional welfare change when carbon policy is implemented in a world with knowledge spillover



It is true that the results are very sensitive to the spillover intensity coefficients we assume in the model. By varying the coefficients the welfare level changes significantly across regions. If we lower the coefficients to half of the assumed value, both CHE and GFI still suffer from a welfare loss. On the contrary, doubling the coefficient value substantially increases the welfare level of all regions. However, the direction of how the spillovers affect the regional welfare is stable.

In this illustrative study we assume that the spillover intensity coefficients are the same for regions and between sectors. This is a very strong assumption which does not hold in reality. To investigate and estimate the knowledge diffusion effects quantitatively, we first have to obtain a precise estimation of such knowledge diffusion coefficients by sectors and by regions. Another issue is how the spillover can be proxied accordingly. There is no direct statistic on spillovers. In literature patent and citation data are often used as an approximation of knowledge spillovers. Data missing in regions and differentiated definition and accounting methods on these figures will largely affect the estimation results.

To sum up, knowledge spillovers contribute positively to regional growth. In the case of Switzerland, knowledge spillovers will also reduce the policy cost for emission reduction. If foreign regions implement more stringent carbon policies, the price of foreign goods will increase and this gives incentive to consume more domestic products. Given that foreign and domestic products are only imperfect substitutes, the increasing input cost in production will give domestic firms incentives to replace energy input and the input of energy intensive goods. Furthermore, higher energy prices in foreign regions will stimulate foreign innovation activities. One result of this is an increased variety in the world knowledge stock. As innovation is the process of standing on the shoulder of giants, a larger world knowledge stock means Swiss firms can benefit more from international knowledge spillovers, which further increases their productivity.

Finally, knowledge spillovers reduce the cost of carbon policies and decrease the CO2 taxes if innovation is directed at productivity improvement of energy use. As for renewable energies, a substantial decline in production cost is expected. This is not only the result of self-investment and innovation; knowledge spillovers from other countries are another crucial driver for the cost reduction. Hence, the subsidies for renewables may not necessarily have to be as large as some expect if taking into account the spillover effects.

Chapter 5

Conclusions

5.1 Academic conclusion

This project includes three parts: (I) the analysis of Swiss energy policy using detailed description of technologies; (II) the impact of uncertainty to the policy cost estimation; (III) the effect of knowledge spillover on the growth of Swiss economy and the cost of climate policy in a multi-regional framework. The first two parts are conducted using the one-country CITE model, a CGE model with endogenous growth. We extend the model with a rich representation of electricity generation technologies. We find that a gradual phase-out of nuclear energy until the year 2035 combined with a longer-term emissions reduction target results in up to 0.4% of welfare loss until 2050. It also leads to structural adjustments in the economy. The magnitude of these impacts depends on the assumptions and the restrictions on the expansion and the capacities of replacement technologies. In the free market scenario $PO - FM$, the phase-out can be achieved at the cost of 0.1% welfare loss and with only moderate adjustments in the structural composition of the economy. Imposing capacity limits for established technologies and target shares for new renewable electricity sources (as in scenario $PO - CC$) increases the welfare loss from 0.1% to 0.4%. Evidently, the planned reorganization of energy supply aims at substantially decreasing external costs of energy use, which raises welfare for the consumers. The studied policies also accelerate the greening process of the economy by redirecting more resources and investments towards innovative industries, energy-extensive sectors and new renewable technologies.

We elaborate our analysis in consideration of future uncertainties, mainly focusing on macroeconomic environment and ethical concerns. Historical data and recent studies imply that the capital market of Switzerland is growing steadily at a higher speed than previously assumed. Starting from this point, we include different growth numbers of capital as a driver to describe different macroeconomic environments for Switzerland. The results show that higher capital growth rate can diminish the discrepancy between sectors. This is because any additional percentage point of growth in total capital will result in the same percentage point of growth in output for all sectors. Hence, the impact of growth rate difference becomes less and less important with higher capital growth. Moreover, higher capital growth triggers more investment and innovation which can lead to further growth of the economy. The analysis of historical data shows strong evidence supporting high growth of the economy in the long run. This confirms the robustness of our analysis.

The discount rate presents different views on future generations. Under a mild growth of capital (1%), we find that in general the sectoral growth effects depending on how you treat later periods are moderate. However, lower discount rate will result in higher welfare loss because future periods which are heavily shocked by policies, have higher weights in welfare. In general, the effects of discounting in dynamic models for analysis of the long-run are not as big as one expects. However, such effects can be much stronger for countries with a large share of fossil energy use. For example, China and the US are the two largest emitters using plenty of fossil energies, if substantial emission pledged by the governments, the effects on the economy will be huge. The value of discount rate in such cases can play a significant role in estimating the cost for carbon mitigation.

Finally we construct a multi-regional model with the fully endogenous growth mechanism to be applied to all regions and sectors. Furthermore, knowledge spillover is included in the model as an new module with explicit description of knowledge diffusion from various channels. Our results confirm the positive externality of knowledge diffusion to regional welfare and economic growth. However, the impacts among sectors in different regions varies. Finally, we derive from an illustrative example with international spillover that the cost of emission cut can be partly or fully compensated through knowledge diffusion.

5.2 Conclusion for policy

The results highlight that Switzerland has the potential and the capacities to achieve ambitious environmental targets with restrictions in the electricity sector, and that a reform towards an electricity generation sector dominated by new renewables is economically feasible. An important model assumption concerns the perfect information of investors on current and future policies. Given the long time horizon of energy policy, the results highlight that the innovative potential of the economy can only be fully exploited if the regulatory frameworks are announced at an early stage and the corresponding targets receive political support over a sufficiently long time period.

In general, these results highlight the importance of innovation for the stability of the economy. An energy reform towards expansion in renewables is feasible to achieve at moderate social cost in an innovation economy. In the case of Switzerland, the cost of shifting from nuclear to renewable energies is about 0.4% welfare loss. However, this is the results under a full information market where consumers and investors have perfect foresight. Departing from this assumption, energy transition may raise the policy cost significantly. This also implies that the government has to create the legal conditions to support the market in the first place, for instance, announcing the policy at an early stage, designing appropriate regulations with regard to the emission standard and criteria for evaluation, in order to solve or partly dissolve the consequence coming from "market failure" which is the common view existing in climate and environmental problems. Otherwise we have to pay for an expensive failure in the future.

To extend these findings to other countries, the government should consider policies to attract capital for sustainable investment if the aim is to sustain the economic structure in the background of energy transition. Otherwise, deep reform of energy sectors can result in dramatic structural change of the economy. Moreover, any policy analysis from perspective of welfare economics should be more careful in picking the discounting values. It is very important for policy makers to have a more precise understanding of the economic cost of long-term energy policies in particular.

Finally, by including the knowledge spillover effects into the model, we find that, as Switzerland is an economy with high degree of innovation, additional policies from the perspective of promoting knowledge exchange between regions are also beneficial to the Swiss economy.

5.3 Extensions and questions for further research

The analysis could be extended in various respects. An important aspect excluded in this paper are the external costs of nuclear and new renewbles such as solar, wind, biomass. These costs are, however, hard to quantify, and the existing estimates vary significantly. Additionally, secondary benefits of reduced emissions (in the form of a positive impact on productivity, health and/or welfare) could also be included. Both of these extensions would most probably contribute to a further reduction of the policy costs derived in this paper. However, there are other factors which may lead to an underestimation of the welfare loss. Capital invested in electricity sectors is technology specific. It exhibits a slow rate of turnover and a high degree of sunkness. This will lead to additional cost to retrofit or scarp plants. Furthermore, new renewable energy requires back-up capacity to secure the stable power supply. The higher the penetration of renewables in the system, the more back-up capacity is needed.

It would also be interesting to study the issue in the context of varied degree of innovation across sectors. For the current version of the model, the degree of innovation is unique for all sectors which assures all sectors to grow at the same rate in the benchmark absent of policies. This is what growth theory tells us. But, the real world is much more complicated as described in theory. Market structures are different, and the possibility of innovation varies across sectors. Assuming different rates of innovation can allow us to return to a more realistic world scenario. However, this will increase significantly the problem of model calibration. Additional data are also required to describe the real situation in specific sectors, which may not be easy to obtain.

In the multi-regional version of the CITE model, a higher degree of disaggregation of regions and sectors may bring in more insightful discussions for current policy. A precise estimation of knowledge diffusion effects requires both advancement in econometric analysis of data and computational construction of the knowledge production function. However, all above will increase the model complexity exponentially, and they are left for the future research.

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Appendix A: Economic effects of a nuclear phase-out policy: A CGE analysis

Economic effects of a nuclear phase-out policy: A CGE analysis

Abstract

The paper investigates the long-run consequences of a phase-out of nuclear energy for the Swiss economy. We apply the CITE model, a CGE model with fully endogenous growth, and complement it with a bottom-up model. We find that the nuclear phase-out can be achieved at relatively low costs, even when the expansion capacities of other technologies are limited. Consumer welfare decreases by 0.4% at the maximum compared to business as usual. Our results show that an economy can cope well with ambitious energy policies through sufficient innovation. Economic growth is not slowed down significantly. The phase-out policy contributes to a structural shift in favor of innovative, energy-extensive sectors. It does not work against the climate policy goals but rather accelerates the transition to a less energy-dependent economy.

Keywords: Energy and growth, nuclear phase out, CGE model, induced innovation

JEL Classification: Q43, C68, Q48, O41

1 Introduction

In past decades, nuclear energy has contributed a considerable share to total electricity generation, notably in Europe, the U.S. , Japan and South Korea. In 2010, 19 European countries had at least one nuclear power plant in operation and many relied substantially on nuclear energy, like the UK (nuclear share 15.7%), Germany (28.4%), Switzerland (38.0%) or France (74.1%). Also, emerging economies like China and India are planning to increase nuclear (IAEA 2011, Table 1). In 2011, the IEA projected that "the share of nuclear in global primary energy supply increases from 6% in 2008 to 7% in 2035" (IEA 2011, p.20).

However, the attractiveness of nuclear energy has decreased significantly with the recent catastrophic nuclear accident in Fukushima, highlighting the vulnerability of nuclear power plants and the economic consequences of an accident. This event has refueled the discussions on the external costs of nuclear energy and led to considerable tightening of security standards. Higher security standards and input prices have raised investment and infrastructure costs for new reactors.[1] Moreover, the problem of how and where to store nuclear waste is still unsolved. As a consequence, nuclear energy is increasingly viewed as a problematic technology for energy generation, which has led several countries to reconsider their electricity mix. Recently, Germany and Switzerland have decided to phase-out nuclear completely. Considering the shares of nuclear energy in these two countries and the envisaged time frames for the phase-out,[2] it entails major changes in the involved economies. The scope of possible consequences includes rising energy prices due to reduced supply, a switch to more expensive energy sources[3], a higher dependence on foreign energy, or a possible conflict with climate targets if nuclear is replaced by gas or coal fired plants[4]. On the positive side, increased innovation and higher investments in renewable energy sources and technologies, which are induced by nuclear phase-out, could not only help to reduce energy demand but also bring about general growth impacts in the medium and long run.

[1] Examples are the Olkiluoto plant in Finland and the Flamanville plant in France.

[2] Germany plans to shut down the last plant in 2022, Switzerland in 2034.

[3] See Nestle (2012) for a recent discussion of these issues.

[4] van der Zwaan (2002) provides a detailed discussion of this issue. He shows that a significant expansion of nuclear energy could greatly contribute to a reduction of global emissions. However, he also shows that these benefits could easily be outweighed by the corresponding increases in nuclear waste, security issues and increased proliferation.

In this paper, we analyze the economic consequences of a gradual nuclear power phase-out policy, using the example of Switzerland. Given the relatively high share of nuclear energy, the limited potential for additional hydropower and the political aim not to increase foreign dependency, the Swiss policy can be viewed as an ambitious and challenging project with effects on many levels of the economy. Looking at the relevant long-run impact, we are particularly interested in the induced innovation effects (both on the sectoral and on the aggregate level) and the structural changes in the economy. We apply a model especially designed for that purpose, the Computable Induced Technical change and Energy (CITE) model, see Bretschger, Ramer and Schwark (2011), which is a CGE model with fully endogenous growth. For the present study, the original CITE model has been extended with a bottom-up model to include a broad range of different technologies in the electricity sector. This enables us to explicitly show the effects and requirements on the technological level and the underlying substitution potentials.

Several papers have studied the costs and the economic impacts of nuclear phase-out policies in general equilibrium frameworks. Nordhaus (1995), Andersson and Haden (1997) and Nystrom and Wene (1999) investigated the case of Sweden[5], Hoster (1998), Welsch (1998), Welsch and Ochsen (2001), and Boehringer, Hoffmann and Voegele (2002) provide analysis for Germany. The costs of the phase-out policies depend on the number of available substitutes (and hence the degree of detail of the energy sector) and their capabilities, on the regulation scheme of the phase-out, and on the limitations imposed on carbon emissions. If no limit is imposed on the use of fossil fuels as a replacement for nuclear energy, a phase-out tends to raise carbon emissions substantially (see also Nakata (2002) and his study on Japan). Boehringer, Wickart and Mueller (2001) investigate the economic impacts of two policy proposals that aimed at restricting the use of nuclear energy in Switzerland. They find non-negligible phase-out costs for the more stringent case, mainly because this proposal administered the use of non-competitive sources as substitutes[6]. Bauer et al. (2012)

[5]Following the nuclear accident in the US power plant Three Mile Island 2 in 1979, the Swedish government decided to phase out nuclear energy until the year 2000. Later on, this deadline was moved to 2010, and in 2009, the phase-out plans were completely abandoned. Today, nuclear energy still has a share of about 38% on total electricity production in Sweden.

[6]The two proposals were "Strom ohne Atom" ("electricity without nuclear energy") and "Moratorium plus". The former postulated a limitation of the operational lifetime of powerplants to 20-30 years, and nuclear energy was requested to be replaced with combined heat and power. The latter was less restrictive and limited operation time to a maximum of 40 years. Both proposals were put

study nuclear and climate policy from the global perspective concluding that the nuclear phase-out has minor effects on macroeconomic development[7]. Marcucci and Turton (2012) use a bottom-up approach with endogenous technology learning to show that the decision to stop nuclear in Switzerland results in losses of 0.7 percent of GDP in 2030 and 0.5 percent in 2100 compared to the scenario with nuclear.[8]

Our paper differs from these contributions in several respects. First, most of these papers restrict their attention to the impacts at the technology level[9]. The focus of our investigation is on the macroeconomic consequences of the policy, which largely determine whether the policy is desirable. Second, existing studies either use pure energy system models or models where economic growth is treated as an exogenous variable. We use a CGE model with endogenous growth in all sectors. Specifically, we show how the nuclear phase-out affects long-term growth at the aggregate and at the sectoral level and how the structure of the economy changes over time. The main transmission mechanism under study are sectoral innovation and investment decisions. Finally, we combine our top-down approach of the dynamic macroeconomy with a detailed bottom-up model of the electricity sector, to exploit the technical information on future technology development in an optimal way.

We find that the phase-out can be achieved with welfare losses amounting to a maximum of 0.4% compared to a scenario where only a climate target is included. Moreover, we show that the phase-out leads to structural adjustments in favor of innovative and energy-extensive sectors. There is no conflict between climate policy targets and the phase-out policy. On the contrary, the phase-out of nuclear energy can even contribute to a greening process in the economy.

The paper is structured as follows. Section 2 introduces the model features and the data. Section 3 presents the simulated policy scenarios. The results of the simulations and associated sensitivity analysis are discussed in Section 4. Section 5

to vote in 2003, and they were both turned down.

[7]They use the ReMIND-R model to explicitly reflect the adjustment costs due to acceleration of capacity build-up and resource extraction. Their analysis show that the GDP loss of climate policy is 2.1% in 2050, the incremental costs of a nuclear phase-out is about 0.2% in 2050.

[8]As we do in this paper, climate policies are given in both with- and without- nuclear scenarios in their analysis.

[9]The exceptions are Welsch (1998), Welsch and Ochsen (2001) and Boehringer, Wickart and Mueller (2001). The two German studies find GDP decreases in the range of 0.01% to 0.3%, depending on the time frame of the phase out. Boehringer et al. report long-term GDP reductions between 0.01% and 0.38%. Out of these three studies, only Boehringer et al. make restrictions on carbon emissions.

concludes.

2 The model

2.1 Aggregate economy

The model we use is a multi-sectoral CGE model with fully endogenous growth. Growth in the different sectors is driven by an expansion-in-varieties mechanism, based on the seminal contribution of Romer (1990). Investments in capital and knowledge extend the number of capital varieties, which foster factor productivity. A graphical representation of the nested production functions is given in the Appendix.

Production of each non-energy sector i, which we call a "regular" sector, is represented by a multi-stage nested CES-function, see Figure 8 in the Appendix. Final sectoral output Y_i is produced under the conditions of CES production function, according to

$$Y_i = [\alpha_i Q_i^{\frac{\sigma_Y - 1}{\sigma_Y}} + (1-\alpha_i) B_i^{\frac{\sigma_Y - 1}{\sigma_Y}}]^{\frac{\sigma_Y}{\sigma_Y - 1}} \tag{1}$$

where the two inputs are the intermediate composite good, Q_i , and composite output from the other sectors, B_i; σ_Y is the elasticity of substitution between the inputs; α_i and $1-\alpha_i$ are the value shares.[10] The crucial model element is the determination of the intermediate composite good Q_i, which reads

$$Q_i = [\int_{j_i=0}^{J_i} x_{j_i}^{\kappa} dj_i]^{1/\kappa} \tag{2}$$

with $0 < \kappa < 1$ and x_{j_i} denoting the quantity of the jth type of specialized intermediate good. J_i is the number of intermediates available in a sector at each point in time. κ reflects the substitutability between the intermediate goods and, at the same time, measures the gains from diversification, i.e. the productivity increase of the economy when using a larger variety of intermediate goods. Expression (2) shows that Q_i can be increased by either raising intermediate goods quantity, x_{j_i}, or an expansion in varieties, J_i, which is achieved by investments into new varieties. Taking the two points in time t and $t+1$, investments in physical capital, I_{Pi}, and non-physical investments, I_{Ni}, determine the stock of sectoral varieties in period $t+1$ according to

$$J_{i,t+1} = [\gamma_i I_{Pi,t}^{\frac{\tau-1}{\tau}} + (1-\gamma_i) I_{Ni,t}^{\frac{\tau-1}{\tau}}]^{\frac{\tau}{\tau-1}} + (1-\delta_t) J_{i,t} \tag{3}$$

[10] The optimization programs of the different firms are presented in Bretschger, Ramer and Schwark (2011).

where τ is the elasticity of substitution between the two investment types, γ_i and $1-\gamma_i$ are the value shares, and δ_t is the depreciation rate.

Based on new growth theory, research output depends on research labor and other specific inputs used in the research labs; moreover, research efforts are supported by positive learning spillovers which are proportional to the number of already developed varieties, J_i. Accordingly, non-physical investments, I_{Ni}, are determined by labor in research, R_i, non-labor inputs in R&D, I_{Ri}, and the number of intermediate goods, J_i, according to

$$I_{Ni} = [\beta_i(\frac{J_i}{z_i} \cdot R_i)^{\frac{\omega-1}{\omega}} + (1-\beta_i)I_{Ri}^{\frac{\omega-1}{\omega}}]^{\frac{\omega}{\omega-1}} \tag{4}$$

with β_i and $1-\beta_i$ labelling the share parameters, ω representing the elasticity of substitution between the inputs, and $1/z_i > 0$ denoting the spillover intensity. Total research labor, R, is assumed to be constant. It can be reallocated between sectors and its productivity in each sector increases with the factor $\frac{J_i}{z_i}$, i.e. with the number of existing varieties and with spillover intensity, reflecting the intensity of the learning effects in the research lab. By determining the decisions for research investments within the model, all the factor productivities are endogenously derived by the model equations.

For the present paper analysis, we aim at representing the Swiss energy mix in great detail. Notably, we use a detailed bottom-up approach for the cost functions of the different technologies. We include seven different technologies that are available to produce electricity. The bottom-up model of the electricity sector is then combined with the macroeconomic top-down part.

2.2 The energy sector

The optimization problems for energy suppliers are presented in the form of cost minimization, which is the dual-form problem of usual profit maximization. Assuming perfect competition, in the optimum the market price equals marginal costs. Accordingly, the following price equations fully reflect the underlying cost and production functions. We use P to denote prices in general and assume that both consumers and producers use an energy aggregate consisting of electricity and fossil energy. In Switzerland, electricity is mainly generated by carbon-free technologies, so electricity and fossil energy are strictly differentiated in the model[11]. The market price P_{egy} of energy aggregate is given by:

$$P_{egy} = \left[\alpha P_{ele}^{1-\sigma_{egy}} + (1-\alpha) P_{fos}^{1-\sigma_{egy}}\right]^{\frac{1}{1-\sigma_{egy}}} , \tag{5}$$

where P_{ele} is the price of total electricity (produced in the electricity sector) and P_{fos} the price of total fossil energy. α is a share parameter and σ_{egy} denotes the elasticity of substitution between electricity and fossil energy. The variance of values for σ_{egy} used in the literature is large, ranging from poor substitutability, see e.g. Goulder and Schneider (1999), to values considerably above unity, see Gerlagh and van der Zwaan (2003) or Acemoglu et al. (2012). Given the long time horizon of our study (38 years), we consider the assumption of good substitutability to be the relevant case for our analysis. We therefore use a value of 1.5 as a main calibration value but test deviations from this assumption in the sensitivity analysis.

The electricity sector includes two activities: electricity generation on the one hand and electricity transmission and distribution on the other. They trade off according to:

$$P_{ele} = \left[\mu P_{gen}^{1-\sigma_{ele}} + (1-\mu) P_{dist}^{1-\sigma_{ele}}\right]^{\frac{1}{1-\sigma_{ele}}} , \tag{6}$$

with μ as share parameter and P_{gen} and P_{dist} denoting prices of total electricity generation and electricity transmission and distribution, respectively. The used energy input-output table captures electricity transmission and distribution as one single sector independent of fuel choices. Hence we assume that electricity generated from all sources are dispatched through this unique grids network. The underlying production function assumes that there is a substitutability (denoted by σ_{ele}) between the generation and the distribution of electricity. The literature typically assumes low values for σ_{ele}, ranging from perfect complementarity (Rausch and Lanz 2011) to 0.7 with a possibility to substitute (Sue Wing *et al.* 2011). Sue Wing (2006) assumes that the elasticity of substitution between these two activities is 0.5. We follow this assumption and set σ_{ele} equal to 0.5. The subsector *dist* produces infrastructure to transmit and distribute electricity. We assume the same production structure for *dist* as for normal production sectors (see Figure 8 in the Appendix).

[11] This assumption is also valid for countries where renewable technologies are highly appreciated, for example in Sweden the use of fossil energy for electricity generation is extremely small, taking up less than 3% of total production.

Finally, electricity is generated using seven technologies: Hydro (*hyd*), nuclear (*nuc*), waste (*wel*), conventional thermal plants (*ctp*), solar (*sun*), wind (*win*) and biomass (*bio*). The aggregation of output from these technologies captures two features: it (i) allows for different marginal costs for technologies and (ii) represents multiple types of generation technologies that are simultaneously dispatched by assuring positive activity levels. P_{gen} denotes the price of a composite consisting of electricity produced by the seven technologies and is given by the CES formulation:

$$P_{gen} = (\sum_h \delta_h P_{y_h}^{1-\sigma_h})^{\frac{1}{1-\sigma_h}}, \tag{7}$$

where the subscript h denotes the active technologies; δ_h indicates the share of technology *tech* of total electricity generation ($\sum_h \delta_h = 1$). The shares in the benchmark year 2005 are listed below in Table 1[12]. Given the topic of the paper, the parameter σ_h plays an important role, because it determines to what degree the other technologies can substitute for nuclear energy. It must be calibrated in a way that "strikes a balance between the homogeneity of electric power as a commodity and the considerable variation in the characteristics of the technologies employed in its generation" (Sue Wing 2006, p. 3852). We assume that the individual technologies are good but not perfect substitutes and set $\sigma_h = 10$ as in Sue Wing (2006). However, the rate of capital stock turnover in the electricity sector is relatively slow. Hence, in the sensitivity analysis we also test lower values of σ_h to capture the sunk costs associated with investments in different technologies.

Table 1: Electricity technologies and their production in 2005

Technology	**Production in GWh**	**Share**
Hydro	32800	56.60%
Nuclear	22020	38.00%
Conventional Thermal Plants	2100	3.62%
Waste / Sewage Plants	968	1.67%
Biomass	43	0.07%
Solar Energy / Photovoltaics	20	0.03%
Wind	9	0.01%

The endogenous determination of factor productivities, see Section 2.1, equally applies to the energy sector. In analogy to the rest of the economy, efficiency depends on three different factors (see Figure 8 in the Appendix): (i) endogenous

[12] Sources for data on electricity production are the Swiss Electricity Statistics (SFOE 2006) and the Swiss Statistics of Renewable Energy (SFOE 2006) for the year 2005.

capital build-up and sectoral capital inflow, (ii) investments in energy research, and (iii) research labor used for developing innovations in the energy sector. When energy becomes relatively expensive compared to the other inputs, substituting for the relatively expensive input entails energy efficiency improvements. The endogenous growth mechanism of the other model sectors equally applies to the electricity sector.

Electricity generation *gen* and electricity transmission *dist* (see the second level nesting in Figure 9 in the Appendix) are determined by a process according to the production of regular sectors (see the top level nesting in Figure 8). The different electricity generation technologies (see lowest level in Figure 9) compete in terms of production cost to gain mobile factors for capacity expansion.

We use information on levelized cost of different energy technologies resources (EIA 2012) to set up the individual cost functions for new renewables. Cost functions for other technologies are derived from the Energy IOT. In general, The cost functions are assumed to have the following form:

$$P_h = \sum_f (\beta_f P_f) + P_{cap,h}, \tag{8}$$

where P_h denotes the price of technology h, β is a share parameter, P_f the cost of production factors (labor L, capital K, and other inputs V) and $P_{cap,h}$ denotes the capacity rent of technology h, which becomes positive when the supply of this technology is restricted and demand exceeds supply. In the benchmark scenario, we assume that all technologies operate at full capacity, so that $P_{cap,h} = 0$ for all technologies. The capacity rent becomes relevant when quantity restrictions (which are exogenously given) are imposed upon technologies in the policy scenarios. Table 2 describes the cost structure of different technologies.

The second major element of the energy sector is fossil energy. As indicated, in the Swiss case, electricity is assumed to be (almost entirely) carbon-free, with the exception of some electricity produced in conventional thermal plants. Fossil fuels are used primarily for heating and transport. This is why we strictly differentiate between electricity and fossil energy (see equation 5). Total fossil energy Y_{fos} is produced using three technologies: Oil (*oil*), gas (*gas*) and district heating (*dhe*). In Switzerland, district heating refers to utilization of waste heat from large energy and waste incineration plants for heating purposes. District heating is produced in central facilities and then supplied to consumers via a pipeline network in the form of

Table 2: Share of factors for power generation across technologies

Technology	**Labor**	**Other inputs**	**Capital**
hyd	0.20	0.55	0.25
nuc	0.15	0.60	0.25
wel	0.35	0.40	0.25
ctp	0.20	0.55	0.25
sun	0.08	0.67	0.25
win	0.09	0.66	0.25
bio	0.13	0.62	0.25

Note: factor shares of *hyd, nuc, wel, ctp* are estimated from Energy IOT (Nathani *et al.* 2011); the levelized capital cost in EIA (2012) is used to estimate the capital share of new renewables (*sun, win, bio*). The capital is calibrated to 0.25 in the benchmark scenario according to Bretschger, Ramer and Schwark (2010).

hot water for heating and hot-water supply. Hence, this is one form of technology for fossil energy use. These three technologies are assumed to trade off in Cobb-Douglas fashion and the price index reads:

$$P_{fos} = P_{oil}^{\xi_{oil}} P_{gas}^{\xi_{gas}} P_{dhe}^{\xi_{dhe}}, \tag{9}$$

with $\xi_{oil} + \xi_{gas} + \xi_{dhe} = 1$. Gas is fully imported, but distribution requires some domestic inputs as well, which is why it is treated as a regular sector similar to the other technologies. We assume that crude oil (also fully imported) enters the production function of Y_{oil} at the top level. A graphical overview of the energy sector can be found in the Appendix (see Figure 9).

The usage of fossil fuels produces carbon emissions. The three technologies differ in their carbon intensities (i.e. in the amount of carbon emitted per unit).[13] We assume that oil has the highest carbon intensity, followed by gas and district heat. These carbon intensities are relevant for the effective tax rates imposed on fossil fuels later on.

2.3 Consumers

As in the original model version, we assume that a representative, infinitely lived household allocates its factor income between consumption and investments under perfect foresight and in accordance with intertemporal utility maximization. Utility is derived from consumption according to

[13]Carbon intensities in the model are 1.35 for *oil*, 1.01 for *gas* and 1 for *dhe*.

$$U = \left[\sum_{t=0}^{\infty}\left(\frac{1}{1+\rho}\right)^{t} C_t^{1-\theta}\right]^{\frac{1}{1-\theta}}, \tag{10}$$

with ρ denoting the utility discount rate and θ denoting the intertemporal elasticity of substitution. C represents an aggregate of different goods, consisting of consumption of a regular sector output composite C_y and an energy aggregate C_e. C_y and C_e are linked as follows

$$C = \left[\zeta C_y^{\frac{\sigma_C - 1}{\sigma_C}} + (1-\zeta) C_e^{\frac{\sigma_C - 1}{\sigma_C}}\right]^{\frac{\sigma_C}{\sigma_C - 1}}. \tag{11}$$

The elasticity of substitution σ_C is set to 0.5. As a new feature, we further disaggregate the energy composite C_e. It is assumed to consist of electricity consumption C_{ele} and the consumption of fossil fuels C_{fos}, as

$$C_e = \left[\phi C_{ele}^{\frac{\sigma_{ce} - 1}{\sigma_{ce}}} + (1-\phi) C_{fos}^{\frac{\sigma_{ce} - 1}{\sigma_{ce}}}\right]^{\frac{\sigma_{ce}}{\sigma_{ce} - 1}}. \tag{12}$$

Like in the production part of the model, oil, gas, and heating are aggregated to fossil energy consumption, since all of them use primary fossil fuels for production and emit greenhouse gases. Moreover, as mentioned above, we distinguish energy consumption between electricity and non-electricity energies due to the fact that electricity in Switzerland is basically carbon free. The literature provides mixed estimates for the elasticity of substitution σ_{ce}. Static studies typically assume a high degree of complementarity with values between 0 (Koschel 2000) and 0.5 (Boehringer and Rutherford 2005). However, as indicated above, good substitutability with the substitution elasticity of 1.5 seems more valid for the analysis conducted here. We therefore set this value for our analysis. This implies that the compensated price elasticity of electricity demand for consumption in the long run is about -1. We also test different substitution elasticities to allow the price elasticity ranges between -0.54 (which corresponds to $\sigma_{ce} = 0.8$) and -1.5 (which corresponds to $\sigma_{ce} = 2.2$). Figure 10 gives a graphical overview of the consumption nesting. Additionally, since the share of fossil fuels and share of electricity use are different between consumption and intermediate production, the prices of energies are differentiated based on their final use.

2.4 Data

The model builds on data from the Swiss energy input-output table (IOT) for the year 2005 (Nathani et al. 2011). In addition to the information on intermediate and factor inputs of more than 40 industries and service sectors, this table also includes detailed information on the production structure of various energy sources. This allows us to use this IOT to calibrate the cost functions of the different electricity technologies. It also holds detailed descriptions of household consumption of regular sector output and energy goods, and it includes data on physical and non-physical investments.

We have reduced the number of regular sectors to 10 to limit computational complexity. On the other hand, we have extended the table to include a larger variety of electricity sources using data from the Swiss Electricity Statistics. In total, the model differentiates between seven technologies for electricity generation (as indicated in Equation 7) and three fossil fuel categories. Table 3 provides an overview of all sectors and technologies.

Table 3: Overview of the sectors and technologies used in the model

Sector/Technology	**Abbreviation**
Agriculture	agr
Chemical Industry	chm
Machinery and Equipment	mch
Construction	con
Transport	trn
Banking and Financial Services	bnk
Insurances	ins
Health	hea
Other Services	ose
Other Industries	oin
Delivered Electricity	ele
Hydro Energy	hyd
Nuclear Energy	nuc
Electricity from Waste	wel
Conventional Thermal Plants	ctp
Solar Energy	sun
Wind	win
Biomass	bio
Refined Oil Products	oil
Gas	gas
District Heat	dhe

Parameter values are mostly identical to the original model version, they are presented in Table 10. We again assume relatively low elasticities in most cases to prevent overly optimistic model results due to unrealistic substitution potentials. Whenever possible and available, the values are taken from existing studies.[14] Together with the share parameters α which can be calculated directly from the IOT, the elasticities of substitution are the basis for the calibration of the model. As it is common in CGE modeling, the model is calibrated such that it reflects the base-year data given in the IOT. As in the original model, we use the capital share to calculate a reference growth rate that is equal for all sectors. This growth rate gives the benchmark path that can be used to evaluate the policy effects. Given the capital shares in the IOT, the optimum growth rate of the economy in the long-run without any policy is 1.33% per year. Further details on calibration are explained in Bretschger, Ramer and Schwark (2010, 2011).

3 Scenarios

The aim of this paper is to investigate the economic effects of a nuclear phase-out policy. The task runs parallel to another big challenge for energy policy, which is the drastic reduction of carbon emissions over the next decades. In Switzerland, a reduction of 20% (compared to 1990) until 2020 has already been decided upon and longer-term targets will follow in the context of an international framework. The analysis of a phase-out policy should take these targets into account, because they obviously affect the incentives and the possible reactions following a shut-down of nuclear energy.

We assume that the climate targets will have to be met in any case, i.e. irrespective of the plans concerning nuclear energy. We therefore construct a benchmark scenario (BAU) that includes a long-term emissions reduction target which is compatible with international climate targets, in particular the target of an average temperature increase of maximum 2° C. Calculating the world carbon budget that is compatible with this temperature increase and requiring Switzerland to converge to a world average per capita carbon emission by 2050, the country will have to reduce its emission from 40 MtCO2 in 2010 to 14 MtCO2 in 2050, which is a reduction of carbon emissions by 65%. Accordingly, this emission reduction target is part of our

[14] See van der Werf (2007) and Okagawa and Ban (2008) for estimations of elasticities related to the production process, Hasanov (2007) for estimations of the intertemporal elasticity of substitution in consumption, and Donnelly et al. (2004) for the Armington elasticities.

BAU. In the model, the target is achieved using a carbon tax that is levied on the use of fossil energy and whose revenues are redistributed to the representative household as a lump-sum transfer. The carbon taxes increase over time and are adjusted across scenarios in order to ensure the climate target is the same for all scenarios.[15] Considering the very small share of fossil fuels in electricity production in Switzerland, we assume that the carbon tax does not affect electricity generation. However, we include carbon emissions and carbon taxes where the electricity is distributed and transmitted to end use. Other than that, the benchmark scenario can be viewed as a business-as-usual scenario that does not include any other policy measures. In the energy sector, the carbon tax affects the use of fossil energies and hence the fossil energy production declines. Accordingly, the share of fossil energy in total energy aggregate decreases and more electricity is used as a substitute for fossils. In the absence of any additional incentives and policies in the BAU, the market shares of the individual technologies in total electricity generation remain constant at their initial levels. This implies that nuclear energy contributes to electricity supply for the entire time horizon. The benchmark scenario is calibrated so that the economy grows at a constant annual rate of 1.28%, with a welfare loss of 1.2% compared to the economy under the optimum growth rate of 1.33% absent of any policy shocks. The time horizon for the simulation is 38 years (2012-2050), and the time step for the simulation is one year.

Table 4: Summary of scenarios

Scenario	**Climate Target**	**Nuclear Phase-Out**	**Capacity Constraints**
BAU	yes (-65%)	no	no
$PO-FM$	yes (-65%)	yes	no
$PO-CC$	yes (-65%)	yes	yes

The phase-out plan is simulated in two policy scenarios. In both cases, we assume a smooth, gradual phase-out of nuclear energy until the year 2034, reflecting the currently envisaged operation time of 50 years for all existing nuclear power plants. The policy scenarios differ with respect to their treatment of future development of the non-nuclear electricity technologies and the assumptions on capacity limits. First, we simulate a scenario ($PO-FM$) where no quantitative constraints on the future elec-

[15] With climate policies, the sectoral capital stocks exhibit a similar pattern like sectoral output, so that that capital is shifted to the non-energy intensive and capital-intensive sectors, see Bretschger, Ramer and Schwark (2011, p. 975/6).

tricity mix are made. The results of this scenario are derived under free market (FM) conditions where only demand and supply determine the outcome and no constraints on the use of any technology, except for nuclear, or of total electricity are imposed. An exception is hydropower: a recent report of the Federal Office of Energy (2012) shows that, even under idealized conditions, the expansion potential for hydro energy is relatively small in Switzerland. Hence, even under the assumption of a paradigm shift in energy policy towards an increasing political acceptance of the expansion of hydro energy and a corresponding change of the legal framework, the amount of additional capacities is strictly limited. Accordingly, we assume a maximal expansion of hydro energy of 10% relative to the base year level in all scenarios. Apart from this restriction, $PO-FM$ abstracts from any other limitations. Various technologies compete for marginal cost to gain market share. Technologies with lower cost are able to replace nuclear energy when it is phased out. New renewables (solar, wind, etc.) are expensive compared to other established technologies. $PO-FM$ thus shows a phase-out policy and the resulting electricity mix without assuming any political preferences or support for any specific combination of generation technologies.

Table 5: Market shares in scenario $PO-CC$ (Source: Prognos 2012, Table 4-9)

Year	**hyd**	**nuc**	**ctp**	**wel**	**sun**	**win**	**bio**
2010	0.57	0.39	0.03	0.01	0	0	0
2020	0.64	0.26	0.03	0.01	0.020	0.015	0.025
2035	0.69	0	0.10	0.03	0.095	0.035	0.060
2050	0.52	0	0.06	0.02	0.270	0.070	0.060

The second policy scenario ($PO-CC$) implements concrete projections for individual technologies, based on the Energy Strategy 2050 of the Swiss Government (see Prognos 2012), which serves as a policy guideline for a nuclear phase-out. Prognos (2012) provides detailed projections on the shares of new renewable technologies and on the future electricity mix following the governmental strategy, which reflects technical, environmental, and societal conditions for electricity generation. It also assumes a limited potential for the expansion of hydro energy and imposes an upper limit for electricity from conventional thermal plants and from waste. The share of new renewable energy, most notably of solar energy, increases significantly. Given the low shares of new renewable energy of current electricity production and their relatively high marginal costs, it appears evident that these energy sources have to be supported by policy; only then the requested gains in market shares can be achieved.

We therefore add a subsidy (which is technology- and time- specific) for renewable energy sources in this scenario. Table 4 summarizes the policies and assumptions on technology development in the three scenarios. The exact target shares for individual technologies (following the "NEP" scenario, i.e. the New Energy Policy in Prognos 2012) are presented in Table 5. The resulting capacity rents are recycled in lump-sum fashion to the representative household.

4 Results

4.1 Aggregate consumption and welfare

In the BAU scenario, aggregate consumption grows at an annual rate of approximately 1.28% on average during the simulation time horizon. Given the drastic changes evoked by the nuclear phase-out one might expect significant changes for future development. On the other hand, the counteracting forces of rising renewable energies and induced innovations and capital investment might mitigate the original effects. Indeed, this is what the results of our model suggest. As can be seen from Table 6, the consumption growth rates in the two phase-out scenarios are only marginally lower than in the BAU. In the $PO-FM$ scenario, the annual growth rate is 1.27%, and in the $PO-CC$ scenario, the rate is 1.26%. The associated welfare losses (measured by the decrease in total aggregated discounted consumption) are 0.10% for $PO-FM$ and 0.40% for $PO-CC$, respectively. The discounted accumulative GDP losses are 0.12% for $PO-FM$ and 0.53% for $PO-CC$.

Table 6: Average annual consumption growth rates, welfare and GDP losses

Scenario	**Consumption growth rate**	**Welfare loss**	**GDP loss**
PO-FM	1.27%	0.10%	0.12%
PO-CC	1.26%	0.40%	0.53%

Note: Welfare loss and GDP loss is calculated in % change versus BAU.

These results show that the aggregate effects of a nuclear phase-out policy are not negligible, but not as large as shown in other studies (see e.g. Marcucci and Turton 2012). There are multiple explanations for this result. First of all, the stringent climate target (65% of emission reduction) has already imposed strong impacts on the economy. Carbon taxes increase the production cost for firms of all sectors (where energy aggregate is one of the essential inputs) and thus reduce the demand of fossil energies. This gives incentive for firms to seek ways to improve their technology efficiency on one hand, and enforce the substitution between energy and other factor inputs on the other hand. This type of substitution has indeed reduced the demand for electricity as well because firms use energy aggregate as a whole to produce intermediate goods. Nuclear phase-out works as a complementing policy for emission mitigation, which makes it much easier to reach both climate and nuclear target in the same time. Another important factor is planning reliability for investors. The phase-out increases the incentives to invest in alternative electricity technologies, which leads to a reduction in the cost of these technologies and a smoother and less costly adoption of the economy. In a setting where innovation and growth are directly interrelated, these additional investment incentives contribute significantly to lowering the cost of the phase-out. Third and related to that, investments in all parts of the economy are fostered, because capital becomes cheaper relative to energy. Note, however, that we assume that the phase-out policy (like the carbon policy) is announced at the beginning and the phase-out pattern is known to all actors in the economy.

The differences between the two policy scenarios can be explained by the assumptions on technology restrictions. In $PO-FM$, aggregated costs are lower because no subsidies have to be paid for less competitive technologies, which means that lower cost technologies gain larger market shares and new renewables continue to contribute relatively little to electricity generation (see below). Fading input of fossil fuels is to a large part compensated by increasing capital and its productivity. On the other hand, $PO-CC$ shows that the promotion of new renewables does not impose a significant drag on the growth rate of the economy. On the contrary, it highlights that a substantial increase of renewable electricity generation is possible at relatively low cost. Compared to $PO-FM$, there is more substitution of decreasing fossil fuels within the energy sector in the case of $PO-CC$.

To meet the requirements of climate policy we posit a continuously rising carbon tax over time. In 2050, the carbon tax in $PO-CC$ is 7.1% higher compared to the tax in $PO-FM$, while the carbon tax in $PO-FM$ is about 3.7% higher compared to the tax in BAU. Due to the low initial market share of solar, a huge expansion of capacity is needed in order for solar energy to take up more than 20% of the electricity market in $PO-CC$ from current share of less than 1%. To achieve the market share target, the capacity expansion in generation and back-up has to be partly financed by subsidies. This cost is the sunk cost incurred before producing electricity. Subsidies are endogenously determined by the model in order to achieve the market share target. From our simulation results, the cost for 1KWh electricity produced from solar is about 0.10 Swiss Francs with the subsidy of 0.04 Swiss Francs in 2035, the year after the nuclear plants are completely shut down; In 2050, the costs decrease to 0.06 Swiss Franc per KWh. However, new capacities' increase in the last 15 years of the simulation are twice the size of the increase between 2012 and 2034; hence, consumers still have to pay 0.03 Swiss Francs as a subsidy to compensate for new capacities in 2050.

To test the robustness of our findings we perform a sensitivity analysis and vary important model parameters. Given the research question of this paper, the elasticity of substitution between electricity and fossil energy (both in production and in consumption) plays a crucial role. We had set these elasticities (σ_{egy} and σ_{ce}) to 1.5. We consider two alternative assumptions. First, we reduce the values to 0.8 (Sue Wing *et al.* 2011) and thus (pessimistically) assume poor substitution between the two energy sources. This restriction limits the possibilities for further reduction of carbon emissions and a quicker development of new renewables. As a second variation, we increase the values of the elasticities to 2.2, which implies a higher substitution potential.

The resulting effects on welfare are shown in columns 1 and 3 of Table 7. As can be seen from Table 7, the assumption of poor substitutability has quite a strong impact on consumption growth and welfare, especially in scenario $PO - CC$. In this case, substitution within the energy sector is aggravated, and impacts on the rest of the economy are stronger. Additionally, higher carbon taxes are necessary to reach the climate target, and new renewables have to be subsidized at a higher rate. This decreases real income of households and leads to a significant drop in consumption growth. On the other hand, under ideal conditions (i.e. a minimal degree of restrictions in technology expansion and a high degree of substitutability between the two energy sources), even a welfare gain compared to BAU is possible. Generally, better substitutability lowers the cost in welfare terms of the phase-out policy and leads to higher growth rates for consumption.

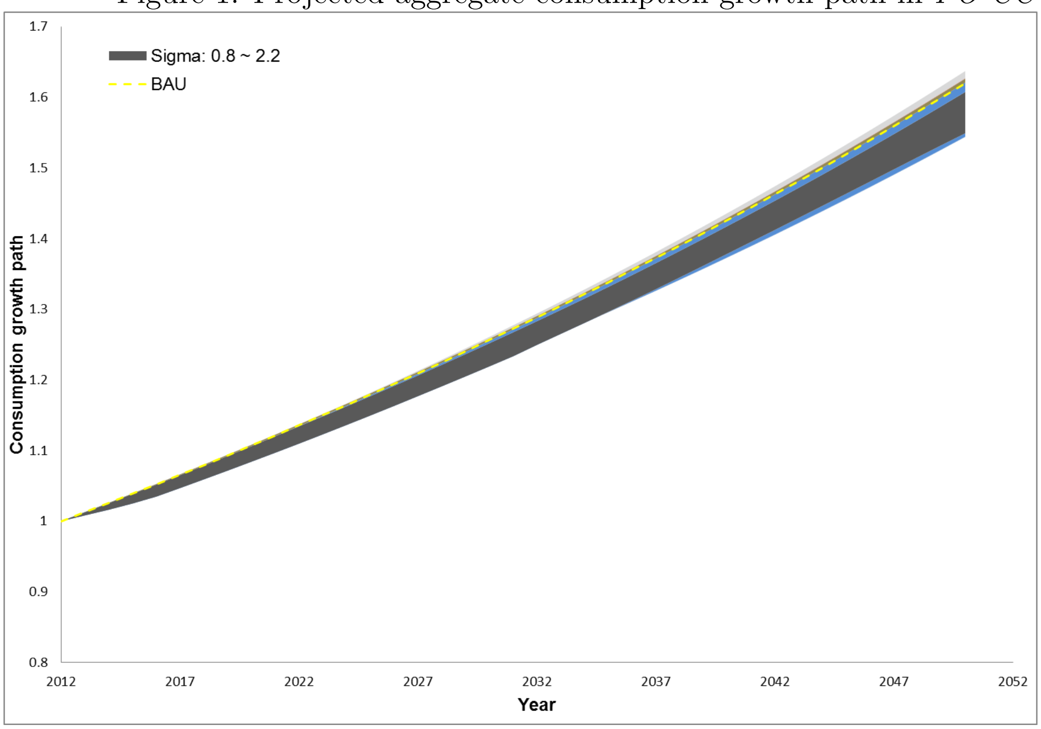
Figure 1 shows the range of consumption growth rates under different values for σ_{egy} and σ_{ce} in the *PO-CC* scenario. The core range (grey area in Figure 1) goes from

Table 7: Annual consumption growth rates and welfare losses under different assumptions for σ_{egy} and σ_{ce}

	0.8	1.5	2.2
PO-FM			
Growth rate of consumption	1.22%	1.27%	1.29%
Welfare loss	0.6%	0.1%	-0.2%
PO-CC			
Growth rate of consumption	1.16%	1.26%	1.28%
Welfare loss	2.5%	0.4%	0.2%

a rate of 1.16% for $\sigma_{egy} = \sigma_{ce} = 0.8$ to a rate of 1.28% for $\sigma_{egy} = \sigma_{ce} = 2.2$. The dashed line shows the BAU case (with $\sigma_{egy} = \sigma_{ce} = 1.5$). The variations in consumption growth can be further affected by the elasticity values. Lower elasticities depress the aggregate consumption growth, while higher elasticity values give more room for substitution between energy sources and thus increase consumption.

Figure 1: Projected aggregate consumption growth path in *PO-CC*



We also check other elasticities of substitution which may have impacts on aggregate consumption. Trade elasticities (η) affect the aggregate consumption, however, the effects are relatively insignificant. Lower trade elasticities encourage domestic production and increase consumption while higher values decrease consumption. Technology substitution elasticity (σ_h) has relatively large impacts on consumption compared to the trade elasticities. A lower elasticity of substitution between technologies means that it is much difficult to replace one technology with the other. Because there is no cost incurred in the model when replacing nuclear with other technologies, we use a lower value to implicitly capture the sunk cost that invested in different technologies in order to expand capacity or to build storage facilities. Holding other parameters the same as in PO-CC, we find that the growth rate of consumption decreases to 1.25% in the case $\sigma_h = 5$, with a welfare loss of 0.51%. On the other hand, a higher value for the elasticity of substitution ($\sigma_h = 20$) reduces the barriers for substitution between technologies. Doubling the value of σ_h to 20 will increase the growth rate of consumption to 1.264% with a welfare loss of 0.3%. The growth rate can reach up to 1.31% in the most favorable case[16]. Moreover, better substitution between generation technologies lead to lower subsidies to expand renewable energies. Consumption rates outside of the core range are derived under extreme assumptions. if we restrict our attention to more realistic cases (most notably values above unity for the two elasticities), aggregate effects on consumption and welfare is robust, and the uncertainty on the magnitude of the aggregated effects can be reduced significantly.

4.2 Energy use and electricity generation

Both fossil fuels and electricity are used in the production of intermediate goods and for consumption. Let *egyi* and *egyc* denote aggregate energy use (i.e. the use of electricity and fossil fuels) in intermediates production and consumption respectively. Table 8 shows that the nuclear phase-out leads to a significant decrease in energy use, most notably in intermediate goods production. Producers substitute away from energy as an input, and the energy efficiency of the economy as a whole increases. We can also observe that the nuclear phase-out leads to an additional reduction in fossil energy use, both in intermediate goods production ($fosi$) and in consumption ($fosc$). This confirms the intuition that a combination of a climate target and a reform of the electricity sector facilitates the reduction of emissions, because it induces both producers and consumers to lower their demand for energy goods. Finally, the last two rows of Table 8 indicate that electricity use is also reduced significantly. This can be explained by the fact that the *BAU* scenario assumes only a climate target, which leads to an increased electrification of the economy. This trend is reversed to

[16] This is the PO-CC scenario with higher values elasticity of substitution where $\sigma_{egy} = \sigma_{ce} = 3$ and $\sigma_h = 20$.

some extent in the two phase-out scenarios.

The effects are stronger in $PO-CC$ for all of the variables in Table 8. The free choice of the electricity mix and the absence of any political or technological constraints (with the exception of hydro energy) in $PO-FM$ allow for a less costly transition to a nuclear-free electricity sector. This leads to a less significant reduction of energy use, to less substitution for other inputs and consequently to a less pronounced shift to a less energy dependent economy. The results for scenario $PO-CC$ show that combining the phase-out plan with supportive measures for new renewable energy sources also leads to a faster reduction of emissions and to more energy efficient production in general.

Table 8: Use of aggregated energy, fossil energy and electricity (% change vs. BAU)

Variable	**Scenario**	**2020**	**2035**	**2050**
$egyi$	*PO-FM*	-2.50%	-8.34%	-7.04%
	PO-CC	-6.52%	-20.2%	-21.1%
$egyc$	*PO-FM*	-0.28%	-0.81%	-0.94%
	PO-CC	-1.49%	-6.59%	-8.27%
$fosi$	*PO-FM*	-0.40%	-1.86%	-1.87%
	PO-CC	-1.12%	-4.91%	-5.73%
$fosc$	*PO-FM*	0.69%	1.03%	-0.16%
	PO-CC	1.76%	1.86%	-0.20%
ele	*PO-FM*	-3.63%	-10.5%	-8.07%
	PO-CC	-9.40%	-24.9%	-24.1%
Y_{ele}	*PO-FM*	-5.44%	-17.3%	-14.3%
	PO-CC	-14.1%	-41.1%	-42.4%

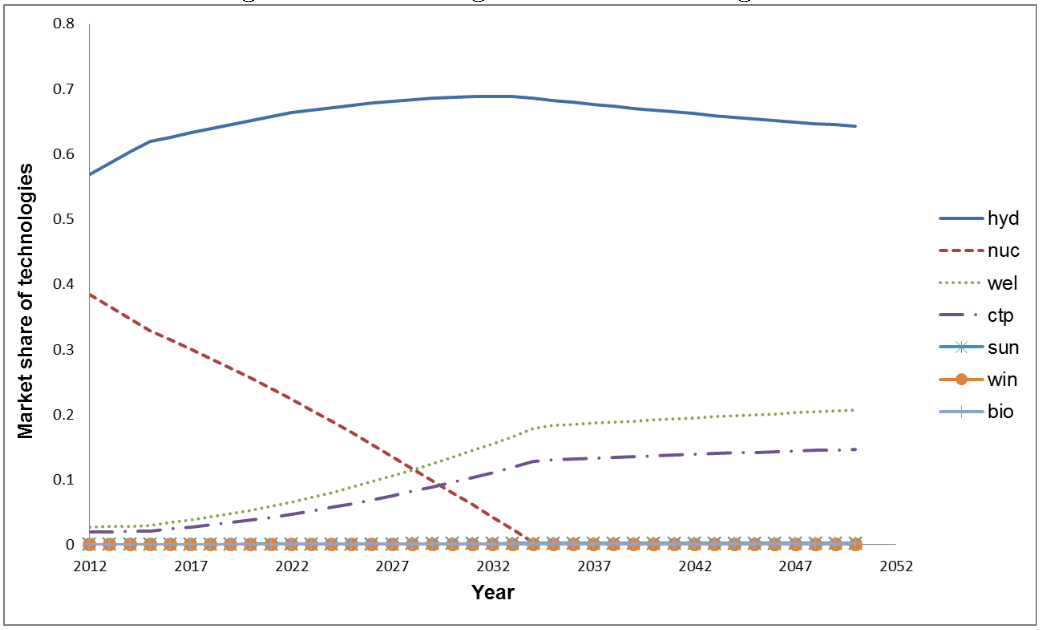
Figures 2 and 3 show the shares of different electricity generation technologies on total electricity generation in the scenarios $PO-FM$ and $PO-CC$. Figure 3 replicates the target shares from Table 5, while Figures 2 and shows the shares derived under free market conditions in scenario $PO-FM$. The Figures show that in the absence of significant constraints and support for new renewables, it is mostly the established technologies that replace nuclear energy. The new renewables on the other hand do not gain sufficiently high market shares and remain almost insignificant. Since there are no constraints for technologies expect for hydro, technologies with lower marginal cost are able to gain market share, replacing the nuclear energy. New renewables (solar, wind, etc.) are expensive compared to other established technologies. Moreover, current capacities of new renewables are very small. It requires heavy investment to increase their capacities. We do not distinguish fixed cost and marginal cost in the model, so that the cost of producing one more unit of electricity out of the capacity is larger for new renewables. In $PO - CC$, the assumed physical limitations for hyd, ctp and wel lead to an increase in the cost of these established technologies. This is an additional explanation for the low additional cost in welfare terms discussed above. The reduced attractiveness of the established technologies facilitates the transition to an electricity sector that is increasingly dominated by new renewable technologies.

Moreover, the market share of new renewables in the electricity market needs to be significantly increased in $PO - CC$. This is hardly possible without government subsidy on new renewable technologies such as solar, wind. The government subsidy drives down the cost of producing electricity using such technologies, making them competitive compared to the established technologies. It also helps to attract new investments, and hence capital stock increases and helps renewable technologies to build up their capacities for large scale production in order to meet the policy target. These reasons explain why solar faces a drastic increase in the $PO - CC$ scenario. Without any support for new renewables, they will not be able to gain a significant market share, because the market mechanism will choose to produce electricity from technologies with large market shares in the benchmark because large market share in the benchmark means that technology is more profitable to produce than others. So under the free market scenario ($PO - FM$), when nuclear phases out, electricity generation from hydro will increase first rather than other technologies. The renewables increase with a small value since they are less than 1% in the beginning.

Figure 4 illustrates the total electricity generation in different scenarios. The average annual growth rate of electricity generation in BAU is calibrated to be 1.28%, which means the total electricity generation in 2050 is about 1.6 times the level in 2012. In *PO-FM*, the total electricity generation declines by 14.3% in 2050 compared to BAU, which is about 1.4 times the level in 2012. The output from electricity sector in 2050 further decreases to approximately the level of today in *PO-CC*.

Finally, even though the CITE model is a one-country model, we can also draw some conclusions on the impacts on electricity imports and hence on foreign dependency. y_{ele} in Table 8 indicates domestic production of electricity (or the total output of the electricity sector as described by Equation 6). Compared to ele (which in fact describes the change in the use of the corresponding Armington good), Y_{ele} decreases more, which indicates an increasing difference in domestic electricity use

Figure 2: Share of generation technologies in *PO-FM*

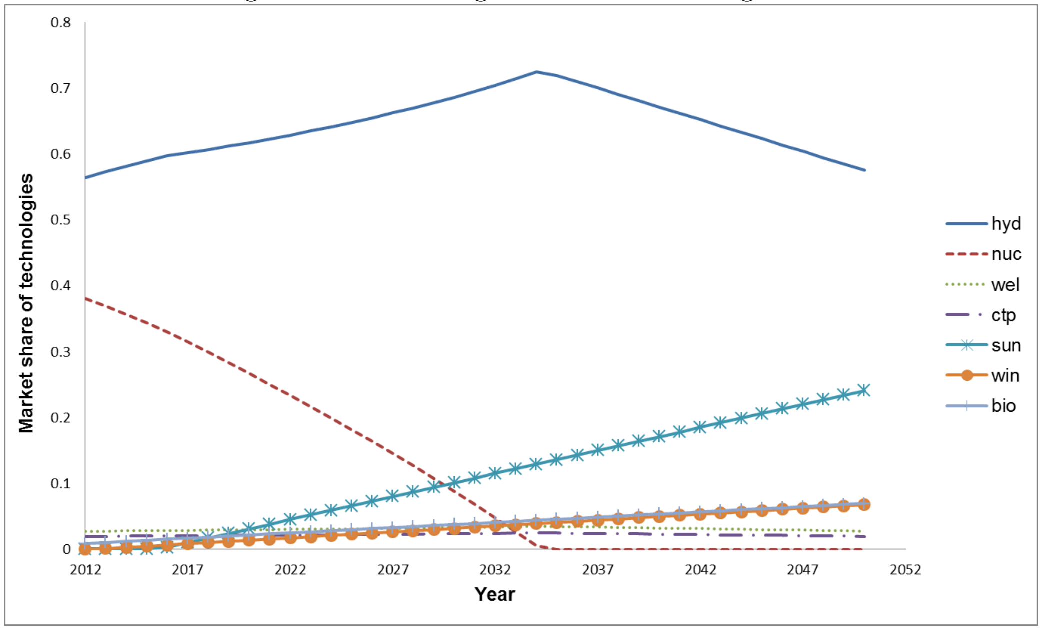


and domestic electricity production and hence an increase in imports. In scenario $PO-CC$, the decrease in Y_{ele} relative to BAU is about 40%. In absolute terms, this means that domestic electricity generation remains more or less at the level of today. However, electricity use decreases only by about 24%. Again measured in absolute terms, this figure implies an increase relative to the initial level and hence an increasing need for imports. The differences between the two scenarios can again be explained by the more restrictive assumptions on technology expansion in scenario $PO-CC$. These results are in line with Marcucci and Turton (2012) who abstract from endogenous capital formation and therefore obtain losses which are higher than those of our calculations.

4.3 Sectoral output

Using a less complex version of the CITE model, Bretschger, Ramer and Schwark (2011) show that climate policy will induce a certain structural change of the economy. These findings are strengthened by the results derived from the policies simulated in the present paper. Highly innovative sectors and/or sectors with a relatively low dependency on electricity (*chm*, *mch* and most of the service sectors) become relatively more important and gain higher market shares. On the other hand, energy-intensive sectors such as *trn* or *oin* (which includes all the heavy industries) grow

Figure 3: Share of generation technologies in *PO-CC*



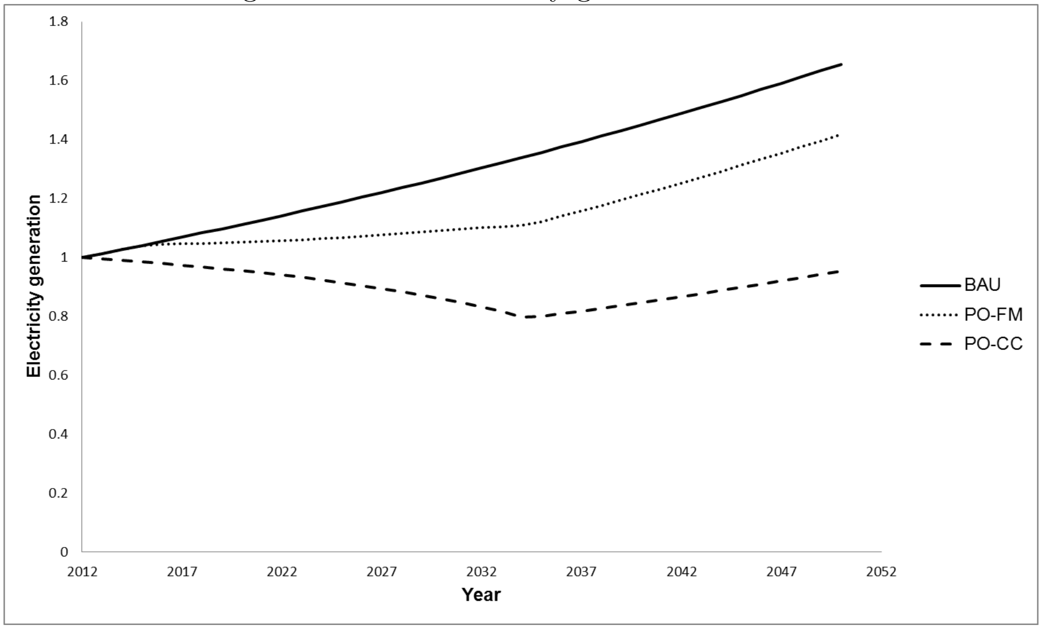
at lower rates compared to the *BAU* scenario and therefore contribute less to total output of the economy. Fossil energy production sectors exhibit negative growth rates, indicating an increased shift away from fossil energy use in the two phase-out scenarios. The results derived here are similar in direction compared to Bretschger, Ramer and Schwark (2011), but slightly larger in magnitude due to the extension of political intervention to the electricity sector.

Table 9: Annual growth rates of regular sectors and fossil energy sectors in the phase-out scenarios

Sector	*PO-FM*	*PO-CC*
agr	1.02%	0.95%
chm	1.53%	1.61%
mch	1.52%	1.67%
oin	0.94%	0.87%
con	1.32%	1.31%
trn	1.11%	1.07%
bnk	1.34%	1.33%
ins	1.45%	1.43%
hea	1.33%	1.33%
ose	1.32%	1.32%
oil	-1.93%	-1.95%
gas	-1.45%	-1.45%
het	-1.72%	-1.69%

Table 9 summarizes the sectoral growth rates. As already indicated above, structural change is clearly directed towards innovative sectors (*mch* and *chm*) and sectors

Figure 4: Total electricity generation across scenarios



with low energy intensities (*ins*, *bnk*, *hea*, *ose*). Structural change is amplified in scenario $PO - CC$. Under more restrictive conditions and the resulting higher costs of the phase-out, resources are increasingly reallocated to innovative and less energy-dependent sectors. This leads to a higher divergence of sectoral growth rates and a larger degree of structural change.

Figure 5: Range of growth rates for selected sectors across scenarios

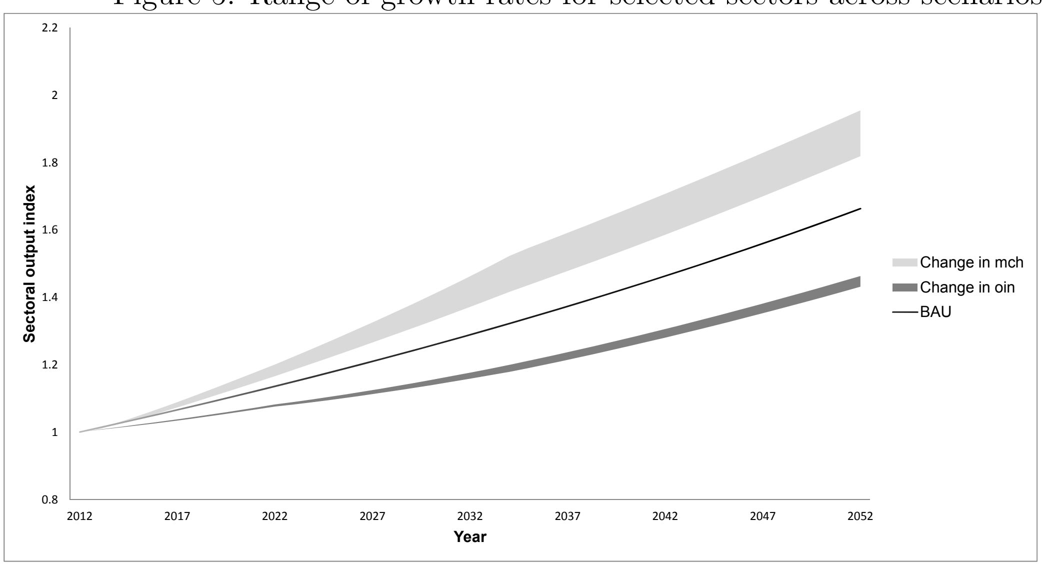


Figure 5 illustrates the differences in the two scenarios and the impacts on the degree of structural change. Figure 5 shows the growth paths of two selected sectors in the two phase-out scenarios. mch, a particularly innovative sector, benefits the most in both scenarios. oin (e.g. cement, pulp and paper) on the other hand experiences the highest drop compared to BAU both in scenario $PO - FM$ and $PO - CC$. As can be seen, the difference in output in 2050 is substantially larger in scenario $PO - CC$. The (politically desired) shift to an electricity sector dominated by new renewable generation technologies is thus accompanied by a "greening" process in the economy where energy intensive sectors become less important. The shaded areas illustrate that the assumptions on technology expansion have a pronounced impact on individual growth rates. Given that more restrictions tend to lead to a higher divergence of sectoral growth rates, scenario $PO - FM$ indicates the minimum (or the bottom limit) of structural change that can be expected to result from a phase-out policy under the given conditions.

Again, we want to test the reliability of the results in terms of a sensitivity analysis. On the sectoral level, poor substitutability between the two energy sources amplifies the structural change. Figures 6 and 7 illustrate the intensified structural change in both scenarios when reducing the elasticities to $\sigma_{egy} = \sigma_{ce} = 0.8$. As indicated above, poor substitutability in the energy sector leads to larger impacts on the rest of the economy, to a more pronounced reallocation of resources and investments to innovative and less energy dependent sectors and thus to larger structural adjustments. These effects are significantly stronger in scenario $PO - CC$. In this scenario, the costs of the phase-out are higher in any case, and the assumption of poor substitutability leads to an even more pronounced change of the structure of the economy. The opposite holds under better substitutability. However, the effects of these adjustments are much weaker in this case. Nonetheless, Figures 6 and 7 indicate that higher values for σ_{egy} and σ_{ce} mitigate the structural changes and lead to a lower difference in sectoral growth rates.

These sensitivity checks show that the main results of our study continue to hold under varying model assumptions. But the costs of the phase-out depend crucially on whether we presume relative complementarity (i.e. values below unity) or good substitutability between energy sources. However, if we focus only on cases where both σ_{egy} and σ_{ce} are set above unity, the variation in the magnitude of the observed effects is reduced considerably. We consider this to be the relevant case, and therefore conclude that our results are robust under realistic assumptions, both in direction

Figure 6: Average sectoral growth rate in *PO-FM*

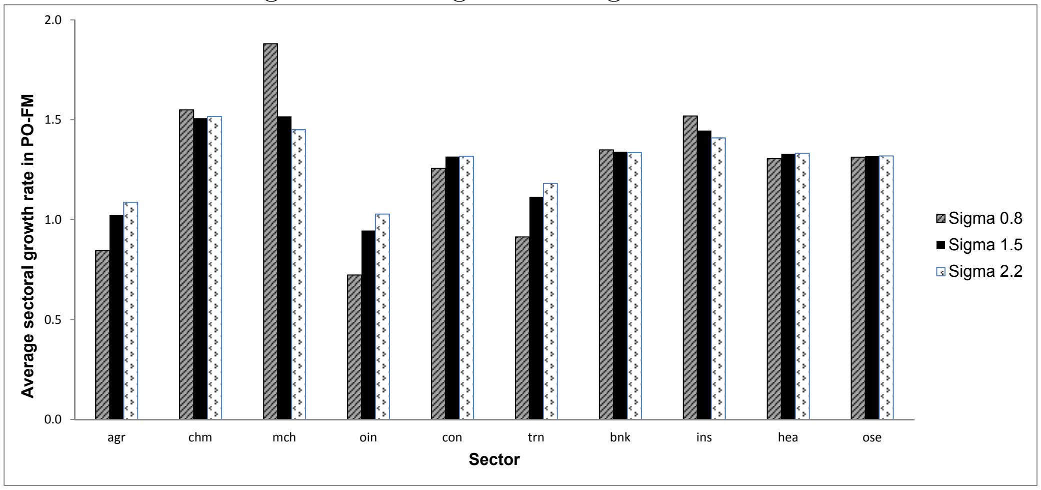
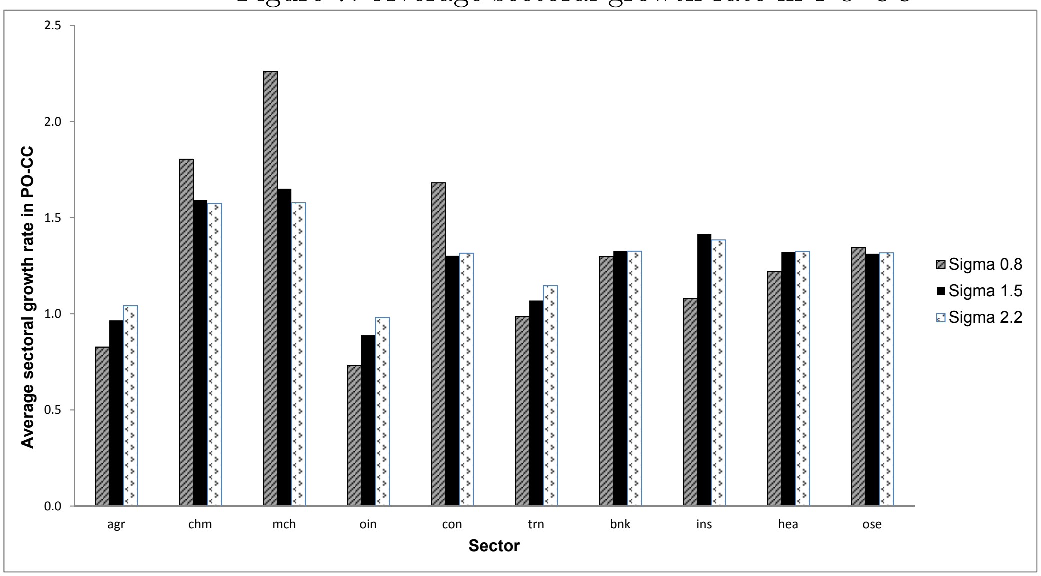


Figure 7: Average sectoral growth rate in *PO-CC*



and magnitude.

5 Conclusions

In this paper, we analyze the economic effects of a gradual nuclear phase-out policy in Switzerland. Due to its relatively high current share of nuclear energy of total electricity generation, its high investment rates and its significant research activity, Switzerland is a good case to study the implications of such a policy in an innovative, developed economy. The analysis is conducted using a CGE model with endogenous growth and a detailed representation of the Swiss electricity sector. We find that a gradual phase-out of nuclear energy until the year 2035 combined with a longer-term emissions reduction target results in up to 0.4% of welfare loss. It also leads to structural adjustments in the economy. The magnitude of these impacts depends on the assumptions and the restrictions on the expansion and the capacities of replacement technologies. In the free market scenario $PO - FM$, the phase-out can be achieved at the cost of 0.1% welfare loss and with only moderate adjustments in the structural composition of the economy. Imposing capacity limits for established technologies and target shares for new renewable electricity sources (as in scenario $PO - CC$) increases the welfare loss from 0.1% to 0.4%. Evidently, the planned reorganization of energy supply aims at substantially decreasing external costs of energy use, which raises welfare of the consumers. The studied policies also accelerate the greening process of the economy by redirecting more resources and investments towards innovative industries, energy-extensive sectors and new renewable technologies.

The results highlight that innovative economies have the potential and the capacities to achieve ambitious targets in the electricity sector, and that a reform towards an electricity generation sector dominated by new renewables is economically feasible. An important model assumption concerns the perfect information of investors on current and future policies. Given the long horizon of energy policy, the results highlight that the innovative potential of the economy can only be fully exploited if the regulatory frameworks are announced at an early stage and the corresponding targets receive political support over a sufficiently long time period.

The analysis could be extended in various respects. An important aspect excluded in this paper are the external costs of nuclear energy. These costs are, however, hard to quantify, and the existing estimates vary significantly. Additionally, secondary benefits of reduced emissions (in the form of a positive impact on productivity and/or welfare) could also be included. Both of these extensions would most probably contribute to a further reduction of the policy costs derived in this paper. However, there are other factors may lead to underestimate the welfare loss. Capital invested in electricity sectors is technology specific. It exhibits a slow rate of turnover and a high degree of sunkness. This will lead to additional cost to retrofit or scarp plants. Furthermore, new renewable energy requires back-up capacity to secure the stable power supply. The higher the penetration of renewables in the system, the more back-up capacity is needed. This is not considered in this paper. All these aspects are left for future research.

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A Appendix: Tables and Figures

Figure 8: Nested production function of regular sectors

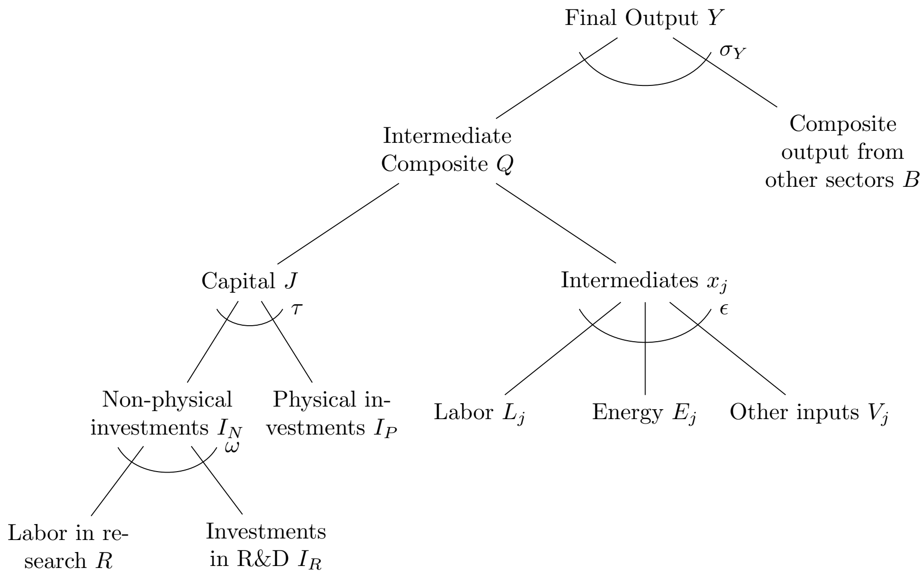


Figure 9: Nested production function of the energy sector

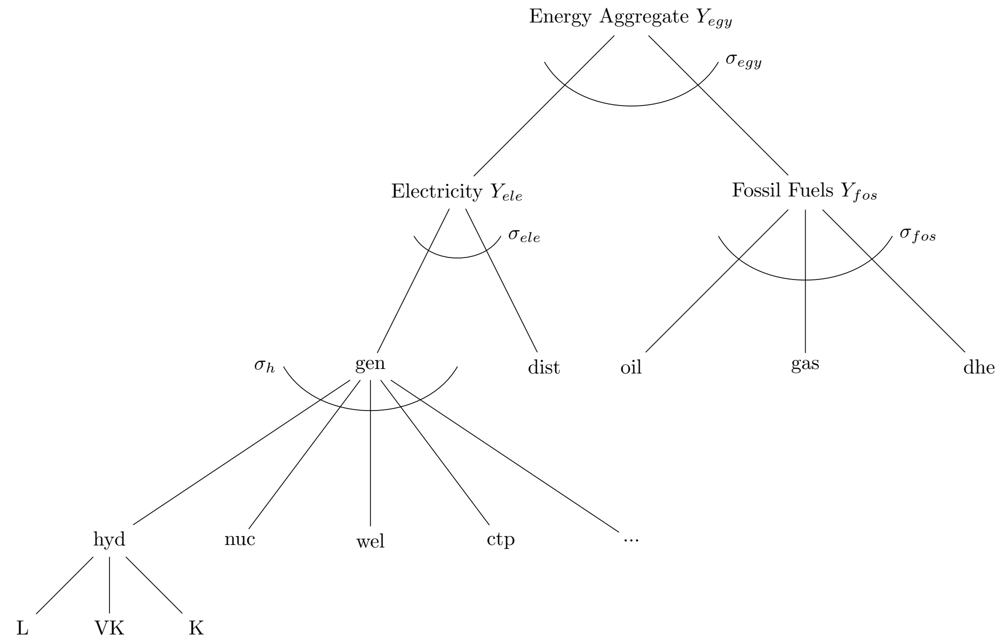


Figure 10: Nested consumption function

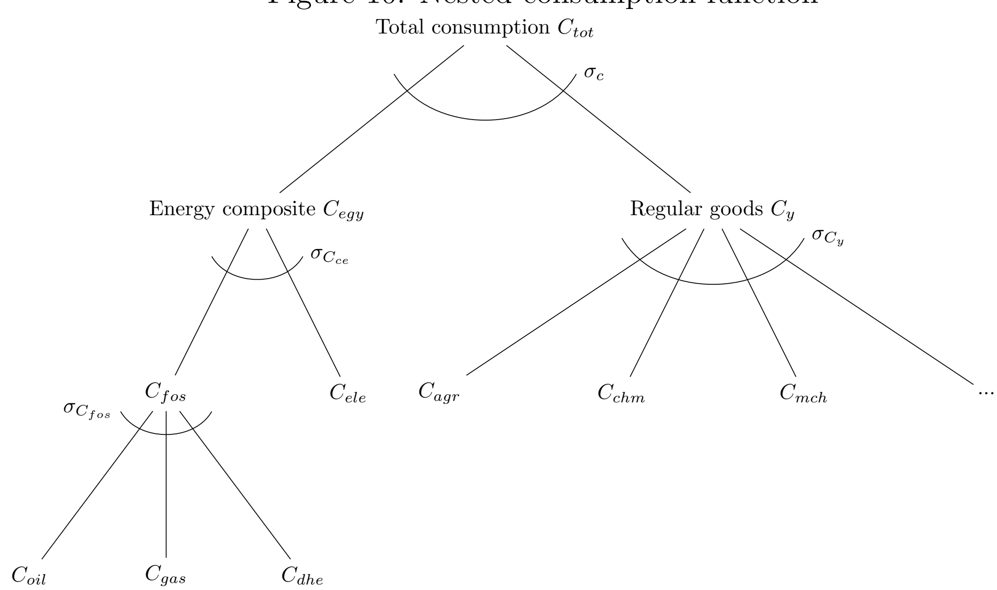


Table 10: Parameter values for regular sectors and consumption

Parameter	Description	Value
σ_Y	Elasticity of substitution between Q and inputs from other sectors B	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)
ε	Elasticity of substitution between the three inputs (Energy E, labor L and other inputs V)	0.7 (arg, oil, chm, egy) 0.8 (mch) 0.52 (con) 0.82 (oin) 0.4 (rest)
τ	Elasticity of substitution between physical investments (I_P) and non-physical capital (I_N)	0.3
ω	Elasticity of substitution between investments in R&D (I_R) and research labor R	0.3
σ_C	Elasticity of substitution between energy (C_y) and non-energy goods (C_e) in consumption	0.5
σ_{egy}	Elasticity of substitution between electricity and fossil fuels in intermediate production	1.5
σ_{ce}	Elasticity of substitution between electricity and fossil fuels in consumption	1.5
σ_{ele}	Elasticity of substitution between electricity electricity generation and distribution	0.5
σ_h	Elasticity of substitution between different generation technologies	10
θ	Inter-temporal elasticity of substitution in the welfare function	1.666
η	Trade ("Armington ") elasticities	3.2 (agr) 4.6 (mas) 3.8 (egy, oin) 2.9 (rest)
χ	Elasticity of transformation	1
υ	Elasticity of substitution between sectoral outputs for the input B	0

Appendix B: Estimating social cost of energy transition within the endogenous growth framework

Evaluating social cost of energy transition within the endogeneous growth framework

Abstract

The paper employs the expansion-in-varieties model to investigate the social cost of energy transition towards renewable energies in the future, taking Switzerland as an example. I study three important and frequently debatable assumptions that may significantly affect the policy cost: the capital growth rate and the innovativeness of an economy, as well as the intertemporal discount rate. By incorporating new results from recent empirical studies, I find that deviations from previous assumptions can result in large changes in estimation results. This study shows that the energy transition can be achieved with relatively small welfare loss. However, future investment environment can impact the sectoral growth differently, leading to significant change of the economic structure. Discounting rate has only mild effects on sectoral growth in a dynamic setting. In the sectoral level, knowledge intensive sectors suffer drastically if the economy is less innovative and lower innovation can result in negative effects on substituting fossil energies.

Keywords: Climate policy, energy transition, endogenous growth, CGE

JEL Classification: C68, Q43, Q48, O41

1 Introduction

Energy transition can be seen as a process of technical innovation and resource substitution into a stage of sustainable energy use. It usually takes time to accomplish, and the greater the degree of reliance on a particular energy source, the more widespread the prevailing uses and conversions, the longer their substitutions will take (Smil 2010). However, this is also one of the most pressing challenges for the whole world in order to achieve the internationally agreed on two-degree climate target. Many countries have initiated their own energy transition profiles in the long run. Germany published a policy document outlining the energy transition it will face until 2050, including aspects such as greenhouse gas reduction of 80%-95% by 2050 and renewable energy taking up to 60% share by 2050. Its final goal is the phase-out of coal and other non-renewable energy sources (FME 2012). France, which is heavily dependent on nuclear power, has launched a national debate on the governmen's proposals for an energy transition involving reduction of nuclear power and the development of more renewable dependent system. Switzerland has the so-called "Energy Strategy 2050" regarding energy transition to offer an economically and environmentally sustainable energy supply for the country's needs. This strategy focuses on three priorities: boosting energy efficiency, increasing the share of renewable energy, and meeting any remaining requirements through imports or electricity production from gas.

The transition toward a low-carbon economy is not free. It is for sure that Switzerland will face many challenges to cut CO2 emissions while also phasing out its use of nuclear power. Possible consequences include rising energy prices, switching to more expensive energy sources, or a higher dependence on foreign supply. However, if the government is in favor of the development of renewable resources, providing both fiscal and political support, some of the challenges can be tackled without incurring additional cost. Countries like Switzerland, having few or no indigenous fossil fuel resources are unsurprisingly at the forefront of the solar revolution. Moreover, the Swiss Energy Foundation (SES) has shown in a study that the energy transition in Switzerland may create 85,000 new jobs by 2035, if the country taps the potential for increasing energy efficiency and expanding renewable energy.[1]

To develop a deeper understanding of the social cost of energy transition an

[1]http://www.energiestiftung.ch/energiethemen/energiepolitik/energiewende/85000-jobs/

economy will face in the future, I use the Swiss economy as a case study, together with an endogenous growth model to investigate three critical assumptions which can affect the potential social cost of energy transition. Combining the Swiss government strategy and the latest studies of Prognos (2012), an energy package is designed to illustrate the energy transition strategy of Switzerland, which includes 65% of greenhouse gas emission reduction by 2050, complete nuclear phase-out until 2034, and a quick expansion in renewable resources, particularly for solar energy. Given this energy policy, I follow a stepwise strategy to answer three research questions in order to give a complete answer on the estimation of energy transition cost for an economy.

My first question is how the economy reacts when the macroeconomic environment for investment changes. This question is due to the concerns about uncertain future development. Switzerland has experienced a steady growth of capital in the past decades. Due to the global economic crisis, Switzerland is booming due to the "safe haven" perception and vast inflows of foreign capital. This can change the investors' investment strategy and thus the growth potential of sectors in the economy.

As a long-term process, energy transition can affect the future generations as well. Hence, the second question appears is how to value future generations? This is one of the environmental economists' major concerns for life-cycle analysis. It is common to assume a social discount rate to estimate the present value of future periods. What is an appropriate value for this discount rate? If it retards the investment and private entrepreneurship needed to innovate, certain generations may be impoverished, leading to a distortion in social welfare.

The third issue to be investigated is: can the society provide sustainable innovation for the growth in the long run? Innovation triggers further growth. The degree of innovativeness of the economy is decided by the capital share in production. Since new knowledge is the results of capital investment, failure to support innovation may cause serious consequences for the growth of knowledge intensive sectors, which can be passed on to other sectors through the inter-linkage between sectors.

Several papers have studied parts of the three questions raised above. Nordhaus (1992) finds the net economic costs can be modest if the transition follows the optimal path. Kemp et al. (2007) describe the Dutch energy transition model and highlight the success of reflexive governance on achieving sustainability goals. Stern (2007) points out that low discount rate may augment the cost of climate change to a loss of GDP per capita up to 35% in 2200 if no political actions take place. Stephan and Mueller-Fuerstenberger (1998) find that higher discount rate leads to significantly lower emission reductions. Recent research by Bretschger et al. (2012) indicate the complete nuclear phase-out can be achieved with relatively low costs if renewable technologies are used as a substitute. This is in line with the results of Welsch (1998), and Boehringer, Wickart and Mueller (2001).

This paper contributes to the literature for providing a better understanding the factors that impact the long-term estimation of energy policy cost. First, I investigate the impacts of the energy transition under different macroeconomic environments which largely determines the potential growth of an economy. Second, I corroborate my analysis by investigating the impact of innovativeness, to exploit how the sectoral growth is dependent on innovation and capital investment in production. Finally, I show how the sectoral growth and social welfare are affected by the inter-temporal discount rate in a dynamic setting.

I find that energy transition can be achieved at moderate cost in general. Higher capital growth will push the economic structure toward diversification instead of specialization. The effects of innovativeness on sectoral growth are determined by several forces. Knowledge dependent sectors grow at a lower rate compared to labor intensive sectors. Less productive use of capital for innovation can also produce negative effects on substituting fossil energies. Discounting of future generations has only mild effects on sectoral growth in a dynamic world. However, people have to pay more when lowering the discount rate.

The remainder of the paper is organized as follows. Section 2 gives a brief introduction of the general equilibrium model with endogenous growth. Section 3 describes the data and scenarios used for computational analysis. Section 4 presents the results and discusses the findings. Section 5 includes sensitivity analysis on different energy transition paths. Finally, section 6 concludes.

2 The methodology of CITE model

The CITE model is a multi-sectoral CGE model with fully endogenous growth mechanism. The growth is described in an expansion-in-varieties fashion based on Romer (1990). I use the latest version of the CITE model to analyze how the Swiss economy accommodates with energy transition policies. In particular, I investigate circumstances where the renewable energies are supported by the government to replace fossils and nuclear, under different growth trajectories.

The macroeconomic structure is described in Bretschger et al. (2011). The bottom-up representation of the energy sector is presented in Bretschger et al. (2012). I include a brief description of the model settings here and highlight several crucial components only. A graphical representation of the model nesting in production and consumption is given in the Appendix.

Production in each non-energy sector, which we call "regular" sector, is represented by a three-stage nested CES function, see Figure 9 in the Appendix. In the first nesting, both intermediate composite (Q) and regular output composite (B) are used for the production of final goods (Y). In the second stage, the intermediate composite goods (Q) are produced by combining the accumulable capital (J) with other inputs (X_j). Investment is distinguished into physical investment and non-physical investment. Outputs from regular sectors (NE) are used for physical investment. Non-physical investment requires research labor together with research in R&D as inputs. The capital accumulation and investment decision process are formulated in an usual way. In the bottom nesting, factor inputs and energy are used as essential inputs to produce intermediate goods (X_j). The final goods (Y) producer's problem and the intermediate composite producer's problem in each sector can be formulated as:

Final goods produer:

$$\max_{Q,B} p_Y Y - p_Q Q - p_B B \tag{1a}$$

Intermediate composite producer:

$$\max_{X_j} p_Q Q - \int_{j=0}^{J} p_X X_j dj \tag{1b}$$

$$\max_{NE} p_B B - \sum_{ne} p_{ne} NE \tag{1c}$$

where p_Y, p_Q, p_B, p_X, p_{ne} are the price of final good Y, price of intermediate composite Q, price of output composite B, price of intermediate good X, and price of regular goods ne. And the production of intermediate goods X_j can be written as:

$$X_j = J[\phi L_j^{\frac{\epsilon-1}{\epsilon}} + \eta E_j^{\frac{\epsilon-1}{\epsilon}} + (1-\phi-\eta) V_j^{\frac{\epsilon-1}{\epsilon}}]^{\frac{\epsilon}{\epsilon-1}} \tag{2}$$

where L is labor, E is energy, and V is public capital; ϵ is the elasticity of sbustitution between three inputs; phi, η, and $1 - \phi - \eta$ are the share parameters.

The energy sector is constructed in a similar way (see Figure 10). It comprises two energy sources: fossil fuels and electricity, which is the top nesting of the energy production (See 3a). Three technologies are considered in the production of fossil fuels: oil(oil), gas(gas), and district heat(dhe). They are assembled by the Cobb-Douglas approach on the second stage. While electricity services are provided to end use by combining the pure electricity generation and electricity supply (transmission and distribution). In the lowest nesting, the electricity is generated in a bottom-up fashion. Utility companies choose the cheapest technologies according to the cost function to produce electricity. In the model, seven technologies can be used for electricity generation: hydro(hyd), nuclear(nuc), waste(wel), conventional thermal plants(ctp), solar(sun), wind(win), and biomass(bio).

$$E_j = [\alpha_{ele,j} ELE_j^{\frac{\sigma_{egy}-1}{\sigma_{egy}}} + (1 - \alpha_{ele,j}) FOS^{\frac{\sigma_{egy}-1}{\sigma_{egy}}}]^{\frac{\sigma_{egy}}{\sigma_{egy}-1}} \tag{3a}$$

$$ELE_j = [\alpha_{gen,j} GEN^{\frac{\sigma_{ele}-1}{\sigma_{ele}}} + (1 - \alpha_{gen,j}) DIS^{\frac{\sigma_{ele}-1}{\sigma_{ele}}}]^{\frac{\sigma_{ele}-1}{\sigma_{ele}}} \tag{3b}$$

where ELE is electricity aggregate, FOS is fossil energy aggegrate, GEN is the electricity genration, DIS is the electricity distribution and transmission. $\alpha_{ele,j}$ and $\alpha_{gen,j}$ are the share parameters and σ_{egy} and σ_{ele} the substitution elasticities.

For consumers, a representative, infinitely lived household allocates her factor income between consumption and investments under perfect foresight and in accordance with inter-temporal utility maximization. The agent consumes both regular goods and energy goods. In the lowest nesting, various regular goods are substitutable, fossil fuels and electricity also substitute with each other to a certain extent (See Figure 11). The household problem can be written as:

$$\max_{C_t} [\sum_{t=0}^{\infty} (\frac{1}{1+\rho})^t C_t^{1-\theta}]^{1/(1-\theta)} \tag{4a}$$

s.t.

$$p_{W,t+1} W_{t+1} = (1 + r_{t+1}) p_{W,t} W_t + \sum_f w_{f,t} F_t - p_{C,t} C_t \tag{4b}$$

where ρ is the intertemporal discount rate, θ represents intertemporal substitution, C_t is the consumption at time t, W_t is the assets of the household at time t, r is the interest rate, f denotes the factor inputs including worker labor, research labor, public capital, and $w_{f,t}$ is the respective prices, $p_{C,t}$ is the consumer price index. Hence equation 4b describes the budget constraint in each time period.

3 Data and scenarios

This study utilizes the data from the Swiss energy input-output table (IOT) of the year 2005 (Nathani *et al.* 2011) which provides detailed information on energy sources, intermediate and factor inputs for many sectors. Cost functions in the model are calibrated according to the information in IOT.

In the model, sectors in IOT are aggregated from more than 40 to 10 regular sectors, 7 sectors for electricity generation, one sector for electricity distribution and supply service, and 3 sectors for non-electricity energies (See Table 1 for details). Table 6 provides parameter values which are the same as used in Bretschger, Ramer and Zhang (2012). Whenever possible and available, the values of elasticities are taken from existing studies.[2] Cost shares derived from aggregated IOT and elasticities from previous studies together calibrated the base year economic structure in production, investment and consumption.

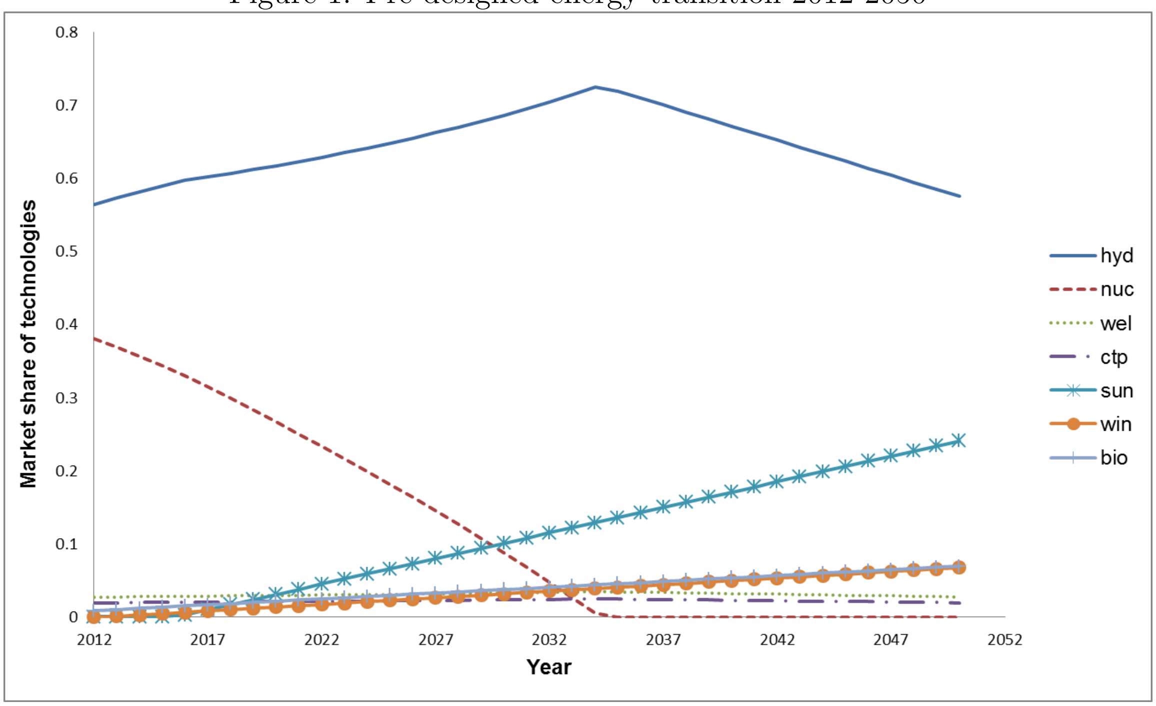
In order to reflect the energy transition during the simulation period, energy policies have to be included in the model. An energy policy package is considered to be binding, no matter how the economic situation is. This package includes three aspects: first, reducing carbon emissions by 65% relative to the intial period until 2050; second, the nuclear power plants have to be shut down completely until 2034 (reflecting 50 years of operation time for all existing nuclear power plants); third, the government supports the development of renewable energies in electricity generation industries. The expansion of different generating technologies follows the estimation of Prognos (2011) (See Figure 1 and Table 7).

[2]See van der Werf (2007) and Okagawa and Ban (2008) for estimations of elasticities related to the production process, Hasanov (2007) for estimations of the intertemporal elasticity of substitution in consumption, Donnelly et al. (2004) for the Armington elasticities, Sue Wing et al.(2011) and Acemoglu et al. (2012) for elasticity of substitution of energies.

Table 1: Overview of the sectors and technologies used in the model

Sector/Technology	Abbreviation
Agriculture	agr
Chemical Industry	chm
Machinery and Equipment	mch
Construction	con
Transport	trn
Banking and Financial Services	bnk
Insurances	ins
Health	hea
Other Services	ose
Other Industries	oin
Delivered Electricity	ele
Hydro Energy	hyd
Nuclear Energy	nuc
Electricity from Waste	wel
Conventional Thermal Plants	ctp
Solar Energy	sun
Wind	win
Biomass	bio
Refined Oil Products	oil
Gas	gas
District Heat	dhe

Figure 1: Pre-designed energy transition 2012-2050



4 Simulation results and analysis

4.1 Uncertain future reflected by capital growth

One challenging issue for economic analysis is the uncertainty of future development for an economy. Many factors such as domestic deficit, global crisis can affect the macroeconomic environment for investment and consumption decisions, and hence the overall growth of an economy. Various growth trajectories and outliers are necessary to be taken into consideration for a complete analysis.

In the orginal model of Bretschger et al. (2011), the capital growth is assumed to be 1 %, which corresponds to the growth of the economy at the rate of 1.33%. This is consistent with a simple average of historical growth rates. To be more precise, I use the so-called Markov Chain anlysis to estimate the possibilities of future growth convergence in the long run (Details in Appendix). The results show that we can expect the Swiss economy to experience a favorable growth between 0 and 1.5% with the probability of 33%, between 1.50% and 3.0% with the probability of 35%. This result is in agreement with that of OECD (2012) estimates which reports that the average growth rate in GDP for Switzerland between 2011-2060 will be 2.1%. Even in per capita level, the growth rate is 1.7%, falling into the steady growth group (growth rate between 1.5 and 3%) in my analysis.

Rudolf and Zurlinden (2009) estimate the growth rate of capital to be between 1.90% and 2.38% in the period 1990-2005 based on different definitions. Data from Swiss Federal Statistical Office also shows that the average growth rate of capital between 1990 and 2005 is about 2.5%.[3] These estimations are all far above the value used in the previous analysis (which is 1%). Hence, I define various growth rates (1.5%, 2% and 2.5%) for capital to further the CGE analysis so as to incorporate information on the new estimates.

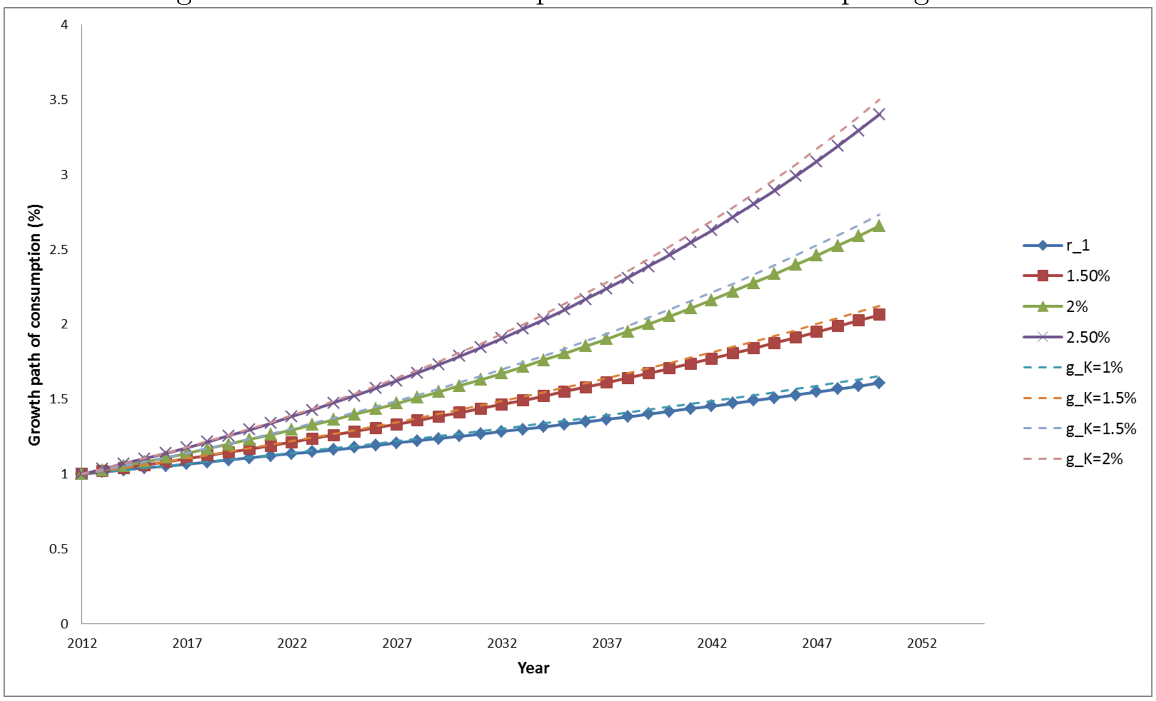
When setting the capital growth rate to be 1%, the growth of consumption in the energy package scenario is approximately 1.259%, which is lower than the growth rate of GDP when no energy policies are implemented (which is 1.34%). The 0.07 percentage point loss follows from the energy policy shocks, resulting in 1.7% welfare loss compared to the baseline without energy policies.

As recent studies show (Rudolf and Zurlinden, 2009), the growth rate of capital used in the model is underestimated. We elaborate our analysis by incorporating these new results in order to reflect the true effects on the economy. Intuitively, raising the capital growth rate will contribute to higher growth of sectoral outputs and hence of the whole economy. As we can see from Figure 2, the dashed lines indicate the baseline scenarios where the energy policies are absent, while the colored

[3]The growth rate of capital between 1990-2010 is about 1.98% (nominal) and 1.58% (real), calculated based on data from Swiss Federal Statistical Office.

lines show the scenarios when energy policies are taking place. All colored lines are underneath the dashed lines, showing that energy policies indeed negatively impact the economy.

Figure 2: Growth of consumption with different capital growth



Follow the BGP described by growth theory, each additional percentage point of growth in capital produces 1.34 additional percentage points of output growth, as well as aggregate consumption. The growth rates of aggregate consumption in higher capital growth scenarios are 1.93% for capital growth rate of 1.5%, 2.60% for 2.0%, 3.27% for 2.5%, respectively, confirming our intuition from theory. The welfare loss compared to their respective baseline scenarios are the same, which is approximately a decline of 1.7%.[4] However, higher capital growth leads to higher output growth. That means, with the same share of welfare loss, the economy in absolute terms suffers more severely in high capital growth case that that of low capital growth case. The increasing gap in Figure 2 between baseline growth path and respective growth path under policy illustrates this feature.

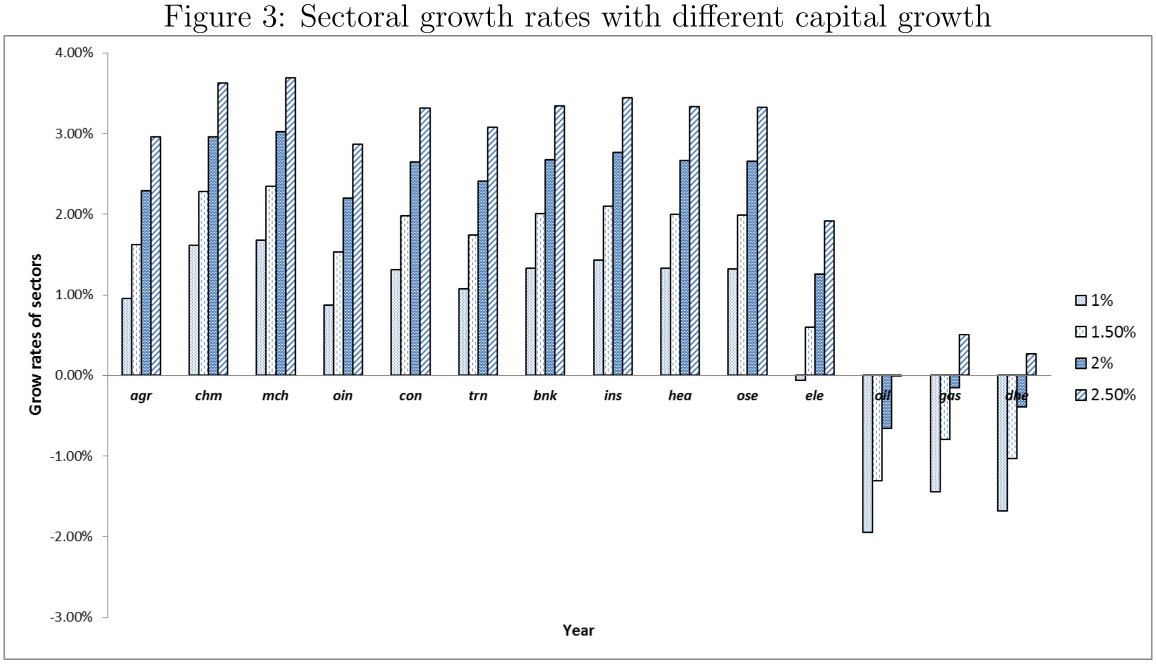
The sectoral effects under different capital growth rates are similar to the effect on aggregate consumption. The incremental for each of the sector's growth due

[4] As indicated in Figure 2, the 1.7% welfare loss is due to the lower value of the colored lines compared to the respective dashed lines lying just above it.

to the rise of capital growth is 0.67% for additional 0.5% of capital growth. Put differently, the aggregate increase in capital stock is not proportionately distributed across sectors. For example, sector A in the beginning grows at the rate of 1%, 0.5% incremental of sectoral growth means it grows at the rate of 1.5% now, which is 50% increase; while if sector B grows at the rate of 2%, 0.5% incremental raises the growth rate to 2.5%, however the growth rate increases by 25% only. In the end, sectors with a lower growth rate can speed up with booming capital investment in the future, and reduce difference in sectoral output values. The change of sectoral share of GDP will finally adjust the structure of the economy towards an equal development. In contrary, low capital investment in the future can lead to specialization of the economy towards innovative and energy-extensive sectors where the return on capital is much higher.

The above analysis also suggests that securing the sustainable capital market can help an economy to develop an economic structure of "autarky" type instead of investing in some sectors which can produce high output while dragging other sectors into the mire. This is particulary important if the strategy of an economy is to be self-sufficient. In the context of global competition, foreign direct investment will play an important role as a major source of capital investment. This is one of the many reasons why emerging economies put great efforts to attract outside money.

Figure 3: Sectoral growth rates with different capital growth



4.2 Uncertain innovativeness of an economy

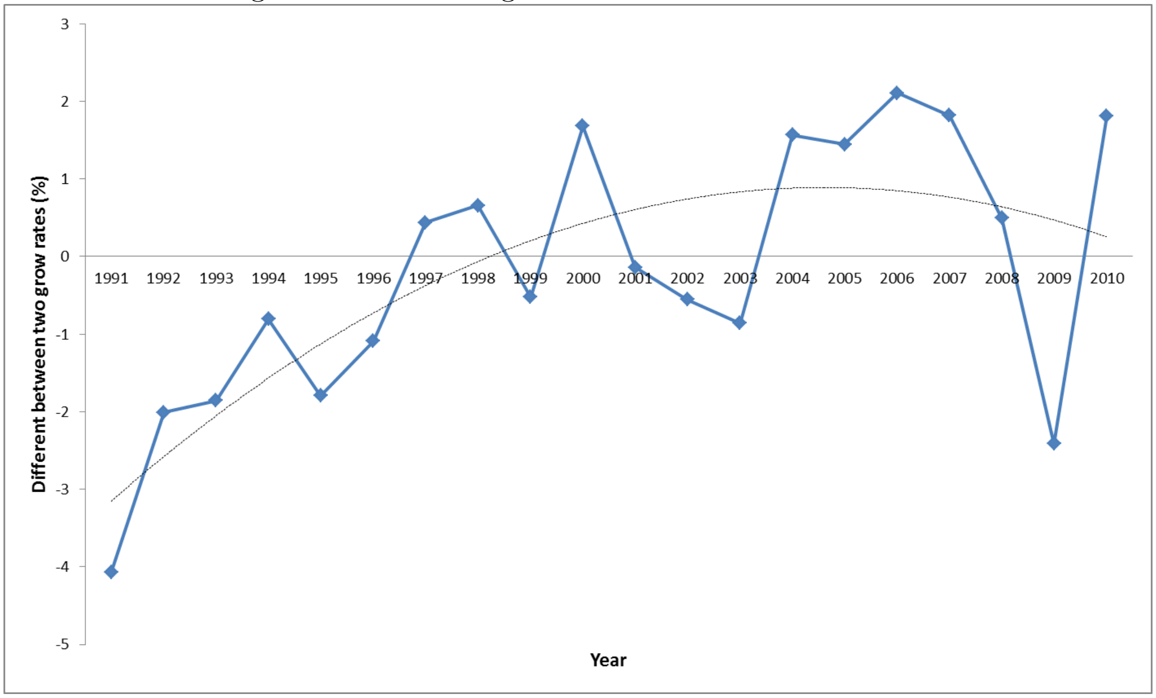
The focal point of the endogenous growth model is that innovation contributes to additional output. Innovation, or say creation of new capital variety, comes from knowledge, particularly from new knowledge. However, it is not plausible to expect innovation contributes to economic growth at the same rate over time. Human-initiated innovation, like energy consumption and population growth, is a process that naturally saturates with rising global income levels and technological intelligence (Huebner 2005). The model assumes that the capital share in production is about 25%.[5]

As from theory it is the innovation that makes the whole economy grow at a higher rate than the growth rate of capital. The difference between the growth rate of capital and the growth rate of GDP implies the contribution of innovation on economic growth. As illustrated in Figure 4, the data for Switzerland demonstrate that innovation has been playing an important role since 1990s, though its effects on growth have been declining from mid-2000s onwards. The impact of innovation peaked around the year 2005, the global financial crisis since 2008 has shocked the economy and depressed its development even though it is doing better in mastering the current economic crisis than its recession-hit European peers. However, with the continuous low growth of world's economy, it is of importance to study scenarios with lower productivity of capital. This can be done by varying the capital share in the model (through adjusting the parameter β).

Changing the capital share in production has several effects on growth. First, increasing the value for β lowers the market power of monopolies in production, and hence decreases the incentive for firms to invest for further innovation. In the long run, the growth of the economy is lowered since innovation is not encouraged. Second, a higher β implies lower gain from diversification (which is $\frac{1-\beta}{\beta}$). Namely, it lowers the additional growth coming from innovation, so the growth of output is depressed. Third, the economic structure will remain almost unchanged with high β, which is good and bad. It is good because consumers across generations are able to enjoy the same variety of products. It is bad for an open economy, particular for export-

[5]This is the value calibrated to replicate the average growth rate of capital and GDP in history. According to the aggregated Energy IOT, the lower bound for the share of capital in the energy and factor aggregation is about 26% (in sector *con* and *hea*), the accumulative capital used to cover innovation cost in intermediate production can not be larger than 26%.

Figure 4: Economic growth attributed to innovation



oriented economy, because lower innovation means less competitiveness on the global market. Capital can easily flow into countries where the return on capital is high. As shown in Table 2, the growth rate of output and consumption decreases with higher β.

Table 2: Aggregate effects of innovation on the whole economy with energy policies

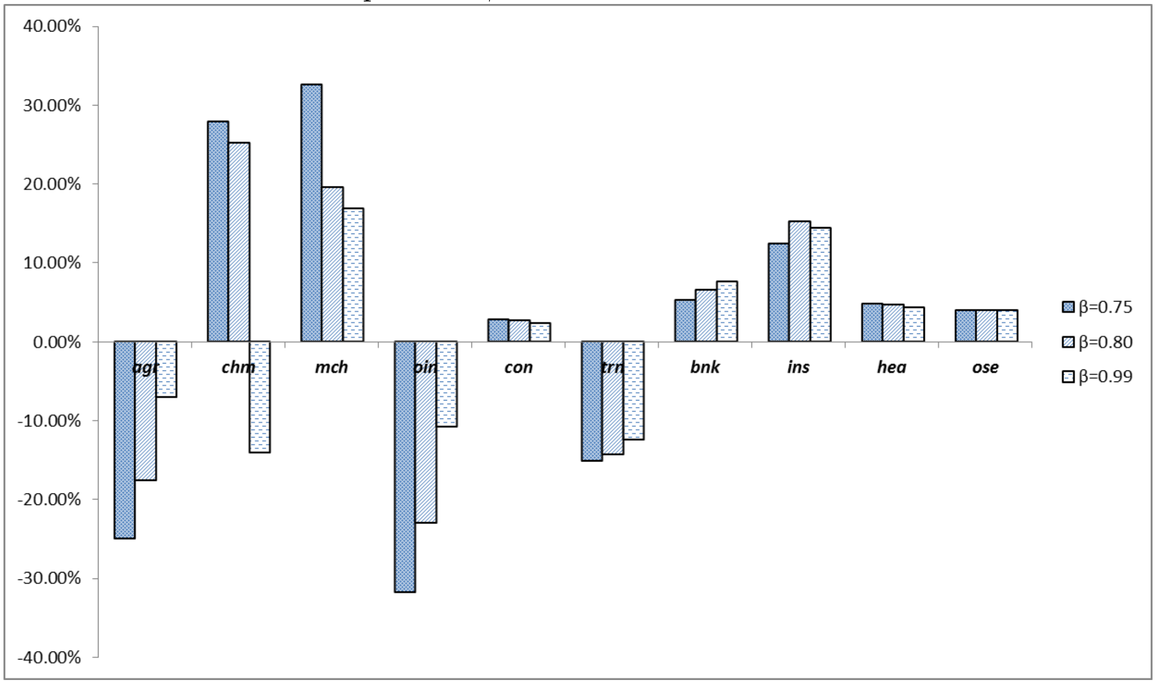
β	Reference growth	Aggregate consumption growth	Welfare loss
0.75	1.34%	1.26%	1.1%
0.90	1.25%	1.19%	0.9%
0.99	1.01%	0.97%	0.6%

Note: This table shows welfare loss if energy policies are implemented, compared to the respective baseline scenarios where the growth rate of capital is 1% and $\rho = 4\%$, and absent of energy policies. The only difference among baselines are various values for β.

We can observe significant structural change for the three scenarios from Figure 5. This figure shows the percentage change relative to respective aggregate consumption growth rate. If the value is positive, it means the growth rate of this sector is higher than the average growth rate of the economy, hence the sector is experiencing expansion; if the value is negative, it indicates the sector is shrinking compared to other sectors in terms of GDP share.

Sectors react differently. A drastic change happens in the sector *chm* when

Figure 5: Growth rates of regular sectors relative to aggregate consumption growth rate under different assumption on β



Note: This figure shows relative sectoral growth rates if energy policies are implemented. The respective baseline scenarios assume that the growth rate of capital is 1% and $\rho = 4\%$, and absent of energy policies. The only difference among baselines are various values for β.

$\beta = 0.99$. There is almost no contribution from innovation to the growth of output in this scenario ($\beta = 0.99$). Chemical industry turns from expansion to shrink as the value of β goes up. There are various reasons for this structural change. First, *chm* is an innovative sector which can benefit from substitution of capital for energy and thus the increase in investments. This capital and knowledge intensive feature supports its winning position when β is high, as can be seen in Figure 5 when β is 0.75 or 0.90, its growth rate relative to the overall growth rate is extremely high, showing its expanding share in GDP. The benefit from knowledge intensity is diminished when β is 0.99. Second, as the energy policies push forward deeply, the force coming from energy intensity starts to dominate. Energy intensive sectors decrease significantly when fossil fuel supply declines. We can observe this pattern from sectors such as *agr, oin*, and *trn*. The chemical sector requires both *oil* and *gas* for production. Hence, it will suffer from the decline in fossil fuels. Third, the energy package leads to a substitution between electricity and fossil fuels. The electricity sector expands much faster than in other scenarios. New grids and networks have to be supplemented for larger delivery and storage. The growth of Electricity Transformation and Distribution (ETD) sector demands inputs from other sectors. However, there is no need of input from *chm* according to the Energy IOT, while sectors such as *mch, con, bnk*, and *ose* contribute largely to the production of ETD (the output of ETD can be interpreted as the final delivered electricity). This results in a further decline of output of *chm*. Finally, the linkage between sectors also contributes to the structural change. The output of *chm* is mostly used in the sector *oin* which is also growing much slower in production compared to others. This reduces the demand for *chm*.

The sectoral innovation activity exhibits a similar information as output growth rate. Table 3 lists the sectoral innovation growth rate with β equal to 0.90 and 0.99 for five representitive sectors. There is a clear indication showing that *chm* turns from the most innovative sector to the least innovative one. This confirms the idea that capital intensity contributes largely to the high growth of this sector. When the innovation is limited due to the available capital, other effects dominate and result in low growth. This table also confirms that the robust growth of electricity sector in the scenario $\beta = 0.99$ where the substitution of capital for energy is restricted. More energy is demanded for growth, while the growth of fossil fuels is limited due to the emission target. This leads to further substitution between electricity and fossils because electricity in Switzerland is CO2 free. These forces together contribute to strong growth in the electricity sectors.

Table 3: Growth rate of sectoral innovation (in %)

β	agr	chm	mch	oin	ele
0.90	0.65	0.96	0.89	0.60	0.80
0.99	0.73	0.66	0.87	0.71	0.98

4.3 Uncertain perceptions on future generations

One frequently discussed factor which affects the future cost of energy policies is the inter-temporal discount rate ρ. In growth theory or in the context of sustainable development, the discount rate is used to reflect the welfare of future generations (or future time periods) in the preferences of the present generation. However, there is no consensus on which value should be used for discounting. The controversial debate on discount rate has led to two opposite opinions. On the one hand, some environmental economists are in favor of low discount rate. One famous example is that Stern (2006) applies the discount rate of 1.4% for his work "Review on the Economics of Climate Change". Ramsey (1928) also argues that the discount rate should be set close (if not equal) to zero which is "ethically indefensible" for the government to do so. On the other hand, high discount rate are used, typically in the analysis of financial market. Zeldes (1989) has demonstrated that "patience" in consumption is positively correlated with income. In the model, high income is the result of high capital growth. Hence, consumers are more patient when the capital market is booming, where "patient" implies low discount rate for the future. This interpretation allows us to raise the discount rate if low income level (growth of capital) is assumed in our model. Moreover, Weitzman (2001) proposes the so-called gamma discounting, indicating the declining value of discount rate from around 4% per year for the immediate future to around zero for the far-distant future.

The choice of an "appropriate" discount rate to estimate the cost of energy polices has long been a complex decision. In the original model, the discount rate is implicitly set to be 0.74% according to the equation 5.[6]

$$\rho = \frac{1+r}{(1+g_Q)^{1-\theta}} - 1. \tag{5}$$

where g_Q is the growth rate of output.

Although Stern (2007) prefers the discount rate to be close to zero, Nordhaus (2007) points out that near-zero discounting implies current generations having an unrealistically high willingness-to-pay for reducing damages. This gives problematic results for model simulations with long time horizons (Ramer 2011). Including a time-variant discounting rate will increase the complexity of the model significantly and there will be no BGP in the end. To address this issue, various constant discount rates are included to see the deviation of the model results. Specifically, two extreme values are used for the analysis.

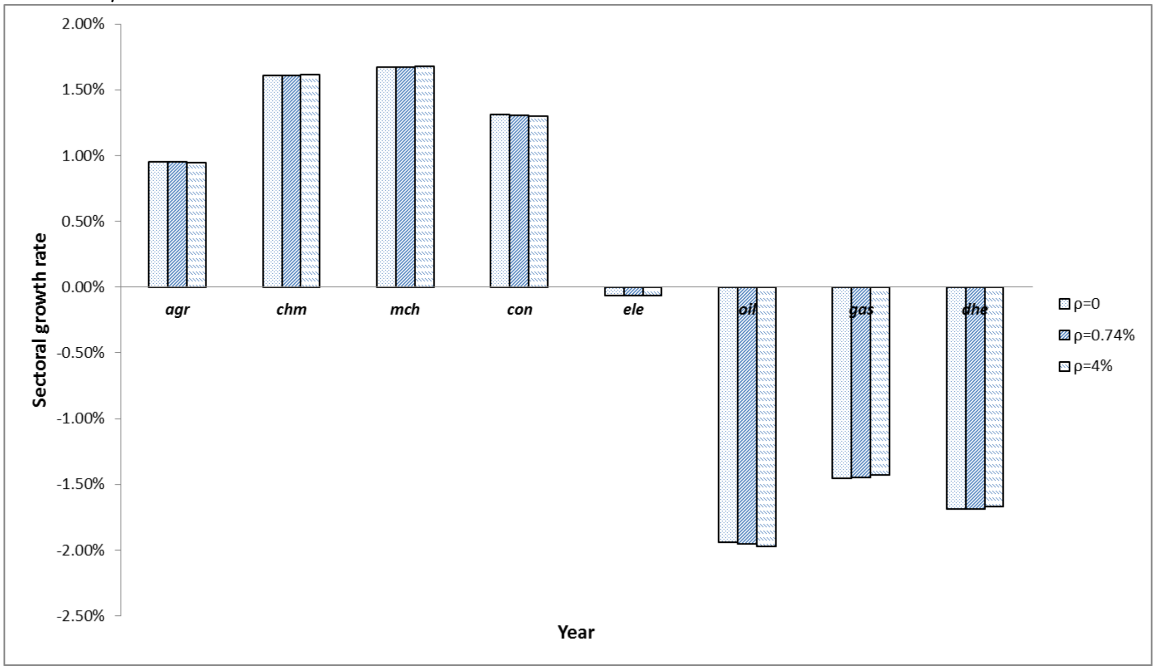
Using IO table with 0.74% discounting rate, the economy can grow at a rate of 1.33% per year when no energy policy is applied. With the shock of exogenous energy policy package, it will suffer from a welfare loss of 1.7% with a lower growth rate of consumption of 1.26%. If we increase the discount rate, the present value of future

[6]The implicit rate of inter-temporal pure time preference ρ can also be expressed equation 5 according to Rutherford (2004). In the base scenario and previous model version, g_K is equal to 1%, and θ is 0.5, the interest rate is determined to be 1.41% according to the Energy IOT, depreciation rate in the beginning is 4%. This results in a discount rate of 0.74% across generations.

generations' consumption is lower than before, because later periods have a lower weight in the total welfare. The total welfare loss should thus be considerably lower than before. With a discount rate of 4%, the welfare loss is only 1.1%. The effects on the overall welfare are mitigated with a higher discount rate. However, with the same carbon tax profile, it is not possible to reach the emission reduction target of 65%. A higher tax is required in the future to achieve such emission target, which means the policy cost for achieving the same target is higher with a larger discount rate. On the contrary, if we treat all generations equally, which means to set ρ equals 0, the welfare loss (1.8%) becomes slightly larger due to heavier weights for future generations. In general, the effects on welfare are surprisingly small even though the discount rate varies between 4% and 0. One explanation is that in a dynamic setting, changing discount rate in an economy will also change the interest rate which impacts the investing strategy of asset owners, and finnaly the output of the setctors.

As shown in Figure 6, the results are similar for different discount rates on the sectoral level. This figure includes two energy intensive sectors (*agr, con*), two energy extensive sectors (*chm, mch*) and four energy sectors (*ele, oil, gas, dhe*). There is only a slight change on the sectoral growth rates. The whole structure of the economy will not be affected significantly. With higher discount rate, energy intensive sectors tend to shrink, and energy extensive sectors grow a little faster compared to scenarios with low discount rate. As discussed before, a higher discount rate requires higher tax rate to remain the same climate target. This will increase the price of energy goods and hence reduce the demand for it. Energy intensive sectors will reduce the use of energy goods and hence the output of these sectors will decline compared to before; while energy extensive sectors are now much more beneficial than energy intensive sectors. More inputs flow into energy extensive sectors and make it even cheaper to produce. Finally, the growth rate of energy extensive sectors is higher than before when the discount rate is relatively low. Within the energy sectors, the change in growth rates is the same. The model assumes that the carbon content of *oil* is much higher than that of *gas* and *dhe*. To reach the same level of emission reduction, the reduction in oil consumption is higher than in other energy sectors. Therefore, *oil* sector further decreases and the others raises their outputs.

Figure 6: Growth rates of energy intensive and extensive sectors: scenarios with various ρ

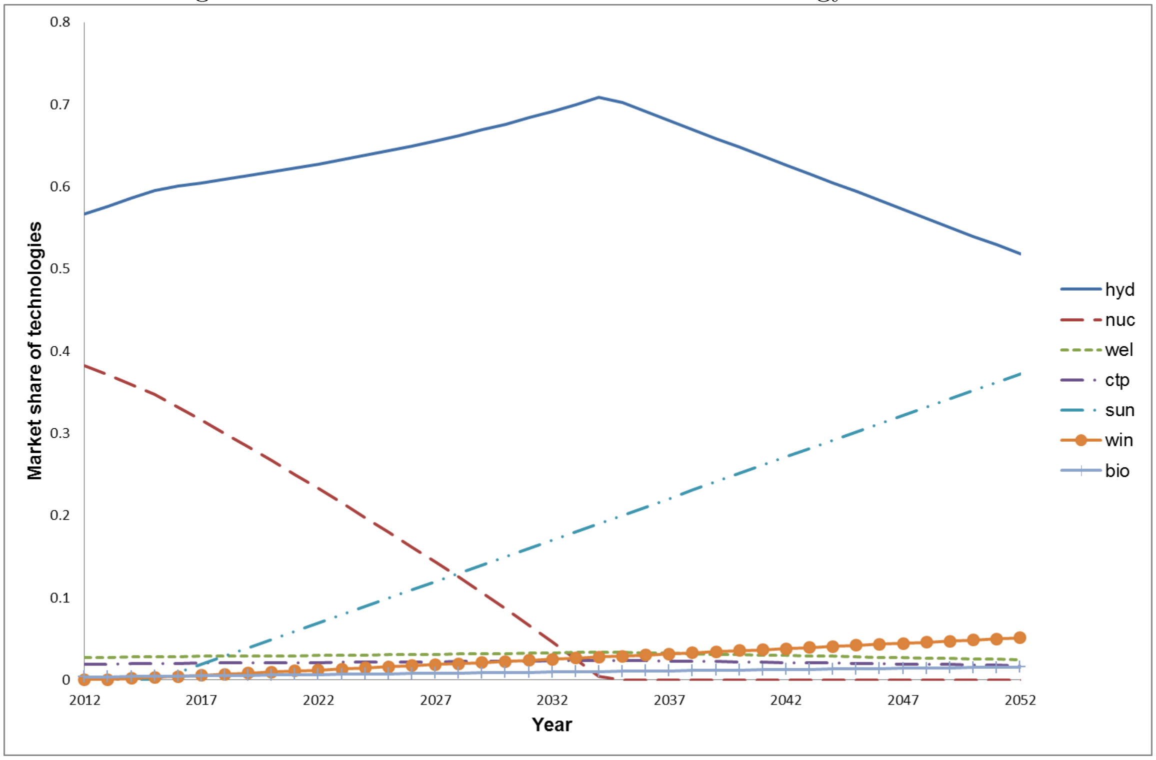


5 Sensitivity analysis

To add some robustness to our computations, a different energy transitions is considered. As estimated by Swiss Cleantech's research (2012), electricity generation from solar energy will double compared to the number reported by Prognos. Instead, other electricity sources contribute with lower market shares in order to keep the total electricity generation be the same level as in Prognos's report. Again, translating the quantity values into market share we obtain a new energy transition path for Switzerland. Figure 7 shows the strategy demonstrated by Swiss Cleantech (2012). Electricity generation from nuclear is again phased out gradually. The expansion of hydro technology is limited due to ecological concerns. Renewables are encouraged to develop, particularly the solar energy, it will make up for approximately 35% of the market share in the year 2050.

The aggregate consumption growth rate and welfare level are kept unchanged in the two scenarios. Electricity use grows at the same rate, which allows us to keep the electricity at the same level. Faster expansion in solar energy leads to substitution between electricity generation technologies. Solar is a capital intensive technology which will demand more capital input for production, compared to technologies such

Figure 7: Swiss Cleantech's view on future energy transition



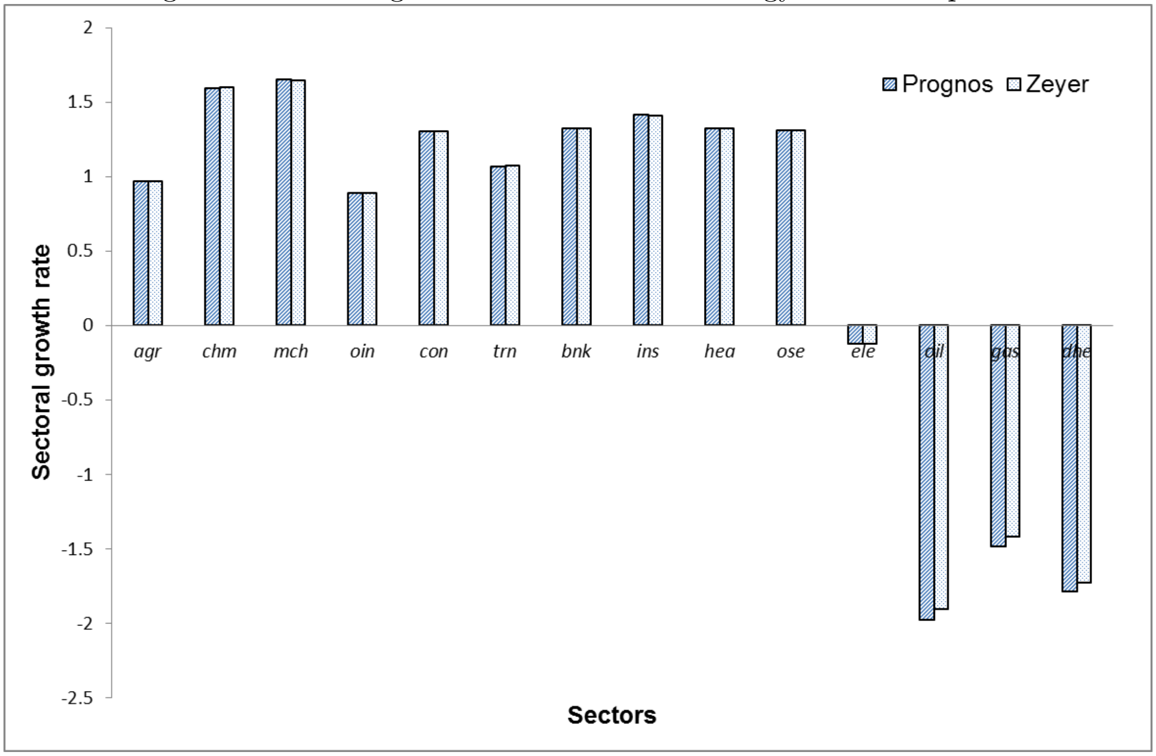
as *hyd, ctp, wel*. For the electricity sectors as a whole, it requires more capital and less labor or other inputs for production. This increases the relative price for capital and contributes to two effects: the substitution of fossil energy for electricity, and the substitution of labor and energy for capital. Regular sectors which are not capital intensive can gain more growth, for example *agr*, and *con*. All three fossil fuel sectors also have a slower decline due to the substitution effects (Figure 8). However, all these changes are marginal.

6 Conclusions

In this paper an extended version of the CITE model is used to analyze how an economy accommodates future energy transitions. The Swiss data is used as an illustrative example for a deeper comprehension of the sectoral effects. To answer this question, three aspects have been elaborated in this paper: macroeconomic environment, innovativeness of the whole economy, and discounting future generations.

Historical data and recent studies imply that the capital market of Switzerland is growing steadily at a higher speed than previously assumed. Starting from this

Figure 8: Sectoral growth under different energy transition paths



point, different growth rates of capital are studied as a driver to describe different macroeconomic environments for Switzerland. The results show that lower capital growth rate tends to develop an economy specialized in capital intensive sectors, while higher capital growth rate can diminish the discrepancy between sectors towards a self-sufficient structure. Moreover, higher capital growth triggers more investment and innovation which can lead to further growth of the economy. The analysis of historical data shows strong evidence supporting high growth of the economy in the long run. This confirms the robustness of our analysis. To extend these findings to other countries, the government should consider policies to attract capital for sustainable investment if the aim is to sustain the economic structure in the background of energy transition. Otherwise, deep reform of energy sectors can result in dramatic structural change of the economy.

The effects of innovativeness is more complicated because of several forces in play. I find that the chemical sector suffers drastically when innovation is absent. The main reason is that it is a capital and knowledge intensive sector, and benefits hugely from the growth in capital and investment, even though other factors depress its growth. When capital growth is not enough to support innovation, the negative growth effects cannot be offset. The electricity sector, which is not dependent on output from chemical sector, has no negative effects. Factor inputs flow into the electricity sector and contribute to its high growth. The linkage between sectors again pushes the growth of electricity intensive sectors.

The discount rate presents different views on future generations. Under a mild growth of capital (1%), we find that in general the sectoral growth effects depending on how you treat later periods are moderate. However, lower discount rate will result in higher welfare loss because future periods which are heavily shocked by policies have higher weights in welfare. In general, the effects of discounting in dynamic models for analysis in the long-run are not big as one expects. However, such effects can be much stronger of countries with large share of fossil energy uses. For example, China and the US are the two largest emitters using plenty of fossil energies, if substantial emission pledged by the governments, the effects on the economy will be huge. The value of discount rate in such cases can play a significant role in estimating the cost for carbon mitigation. Any policy analysis from such perspective hence should be more careful in picking the discounting values. This is also very important for policy makers to have a more precise understanding the economic cost of long-term energy policies in particular.

The model results are robust when more aggressive renewable expansion is implemented. Sectoral effects on different energy strategies are similar. In general, these results highlight the importance of innovation for the stability of the economy. A energy reform towards expansion in renewables is feasible to achieve with moderate social cost. However, this is the results under a perfect information market where consumers and investors have perfect foresight. Departing from this assumption, drastic energy transition may raise the policy cost significantly. This also illustrates that the government has to create the legal conditions to support a market in the first place, which can solve or partly dissolve the consequence coming from "market failure" which is the common view existing in climate and environmental problems. Otherwise we have to pay for an expensive failure in the future.

It would be interesting to study the issue in the context of varied degree of innovation across sectors. For the current version of the model, the degree of innovation is unique for all sectors which assures all sectors to grow at the same rate in the benchmark absent of policies. This is what growth theory tells us. However, the real world is much more complicated as described in theory. Market structure is different, and the possibility of innovation is varied across sectors. Assuming different rate for innovation can allow us to return to a more realistic world scenario. However, this will increase significantly the problem of model calibration. Moreover, additional data are required to describe the real situation in specific sectors, which may not be easy to obtain. In this regard, this is left for future research.

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7 Appendix

7.1 Capital, innovation, and growth

The crucial model element is the endogenous growth characterized by new capital varieties. Investment can enhance the capital stock by inventing new blueprints (new varieties). The accumulation of sectoral capital has a positive effect on sectoral productivity and hence on sectoral growth.

$$Q = [\int_0^J x_j^\beta dj]^{1/\beta} \tag{6}$$

where $0 < \beta < 1$ and J is the number of intermediate varieties. With symmetric intermediates $x_j = x$ it can be simplified into:

$$Q = J^{\frac{1-\beta}{\beta}} X \tag{7}$$

where $X = J \cdot x$ for the aggregate output of the J-firms. $\frac{1-\beta}{\beta}$ reflects the gains from diversification (Bretschger and Ramer 2012).

In the benchmark case, we assume the economy follows the balanced growth path (BGP). We also assume the growth rate of factors (g_K) is lower than the economic growth (GDP growth). The difference between the two different growth rates is the gain from specialization which is created by innovation. Innovation extends the possibilities of production and hence requires less inputs to reach the same level of output in later time period, compared to the starting point.

Differentiating logarithmically both sides of equation (7), we have:

$$g_Q = \frac{1-\beta}{\beta} \cdot g_J + g_X \tag{8}$$

where $g_J = \frac{\dot{J}}{J}$ is growth rate of varieties, $g_X = \frac{\dot{X}}{X}$ is the growth rate of intermediate production, and $g_Q = \frac{\dot{Q}}{Q}$ is the growth rate of output.

Creating new varieties requires new capital which is used to cover the costs spent during innovation. Hence the growth rate of varieties in one sector is proportional to the growth rate of capital accumulation. Intermediate production requires factor inputs and energy input. All inputs for intermediate production are assumed to be at a lower rate, which leads to a lower growth rate for intermediate production. From above, if we assume this lower growth rate for factors to be g_K, then $g_J = g_X = g_K$.

The equation 8[7] can be further simplified to

$$g_Q = \frac{1-\beta}{\beta} \cdot g_K + g_K = \frac{1}{\beta} g_K \tag{9}$$

7.2 Values for controled parameters

Based on the above mentioned analysis, we choose different capital growth rates and capital shares to reflects information from new studies. The rates of interest and discount are selected to present different views for the future cost of energy policies. The growth rate of GDP then can be derived from equation 9. In general, three groups of scenarios have designed to investigate the effects of energy transitions in the periods of 2012-2050: scenarios on capital growth (g_K), scenarios on innovation (β), scenarios on foresight (ρ). Details on the key parameters are illustrated in Table 4.

Table 4: Growth, innovation, interest and discount rate

g_K	$1-\beta$	g_Q	r	ρ
1%	0.25	1.33%	1.41%	0.74%
1%	0.25	1.33%	2.73%	2.05%
1%	0.15	1.18%	2.65%	2.05%
1.5%	0.25	2.00%	1.96%	0.95%
1.5%	0.25	2.00%	3.07%	2.05%
1.5%	0.15	1.77%	2.95%	2.05%
2%	0.25	2.68%	2.50%	1.16%
2%	0.25	2.68%	3.41%	2.05%
2%	0.15	2.36%	3.25%	2.05%
2.5%	0.25	3.35%	3.35%	1.66%
2.5%	0.25	3.35%	3.74%	2.05%
2.5%	0.15	2.95%	3.54%	2.05%

7.3 Markov chain analysis of long-run growth

In this section, I present some evidence to show the robustness of sustainable growth for the Swiss economy. One of the famous methodologies in dynamic analysis is the Markov chain analysis. A Markov analysis looks at a sequence of events and

[7]The model is simulated in discrete time periods, hence the equation used in the model calibration is different compared with the one derived from continuous time case. In discrete time, equation 7 can be expressed as follow: $Q_0(1+g_Q) = [J_0(1+g_K)]^{\frac{1-\beta}{\beta}} \cdot X_0(1+g_K)$. Rearrange it we can obtain the discrete version for the relationship between growth rates: $g_Q = (1+g_K)^{1/\beta} - 1$.

analyzes the tendency of one event followed by another. It has been implemented in many fields. The first financial model to use a Markov chain was from Prasad et al. in 1974. Stockey and Lucas (1989) use it to analyze industry investment under uncertainty. Quah (1993) introduces Markov chain into convergence analysis. We apply this methodology to the convergence of economic growth and provide insights on the sustainable growth using historical data.

If we denote g_t as the distribution of GDP growth at time t, we also assume that the distribution follows a homogeneous, stationary, first-order Markov chain process. The evolution of this discrete distribution can be written as follows:

$$g_{t+1} = M \cdot g_t \tag{10}$$

where M is the transition probability matrix which maps one distribution into another and tracks where in g_{t+1} points of g_t end up. This relationship reflects the economic growth of one period is only dependent on the last period, not how it was reached.[8]

Assuming that the transition probability matrix remains the same over time, the distribution after N periods can be obtained by iterating equation (10) N times, namely:

$$g_{t+N} = M^N \cdot g_t \tag{11}$$

As $N \to \infty$, the distribution converges to the ergodic distribution or the steady state distribution, g^{ss}, which can be characterized as:

$$g_{t+N} = M^N \cdot g_t \longrightarrow g^{ss} \tag{12}$$

Growth theory tells us there is a steady-state of an economy will converge to in the long-run. However, we do not know exactly what the level of steady-state growth rate will be. The ergodic distribution depicts the eventual long-run distribution of economic growth rate possibilities.

From data in IMF (2011), the average GDP growth of Switzerland since 1980 is about $\bar{g} = 1.50$. This value is larger than what we assumed in previous papers (Bretschger et al. 2011, 2012). Even though experienced global economic crisis since 2008, the average annual economic growth of Switzerland in the last five year is more than 2%.

We construct the economic growth into four states: depression (with $g < 0$), low growth ($0 \leq g < \bar{g}$), steady growth ($\bar{g} \leq g < 2\bar{g}$), and the peak ($g \geq 2\bar{g}$). By

[8]This is the propertity of Markov chain: memoryless

using above mentioned appoach we are able to find the Markov transition matrix described in Table 5. We find that when the economy experiences a depression, it is able to recover quickly and turn into low or steady growth with equal probability. Moreover, if the economy is in the state of low growth or steady growth, the probability of sustaining is high: 43% and 50%, respectively. In the long-run, the ergodic distribution shows that we can expect the Swiss economy to experience a favorite growth between 0 and 1.5% with the probability of 33%, between 1.50% and 3.0% with the probability of 35%. This result is in agreement with that of OECD (2012) estimate.[9] It also confirms that the scenarios we analyzed are plausible.

Table 5: Markov transition probabilities and ergodic distribution

State	$g < 0$	$0 \leq g < \bar{g}$	$\bar{g} \leq g < 2\bar{g}$	$g \geq 2\bar{g}$
$g < 0$	0	**0.50**	**0.50**	0
$0 \leq g < \bar{g}$	0.29	**0.43**	0.14	0.14
$\bar{g} \leq g < 2\bar{g}$	0.17	0.17	**0.50**	0.17
$g \geq 2\bar{g}$	0.25	0.25	0.25	0.25
ergodic	0.19	0.33	0.35	0.14

[9] OECD estimates that the average growth rate in GDP for Switzerland between 2011-2060 will be 2.1%. Even in per capital level, the growth rate is 1.7%, falling into the steady growth group in our analysis. OECD data are available in http://www.oecd.org/eco/outlook/lookingto2060.htm

Figure 9: Nested production function of regular sectors

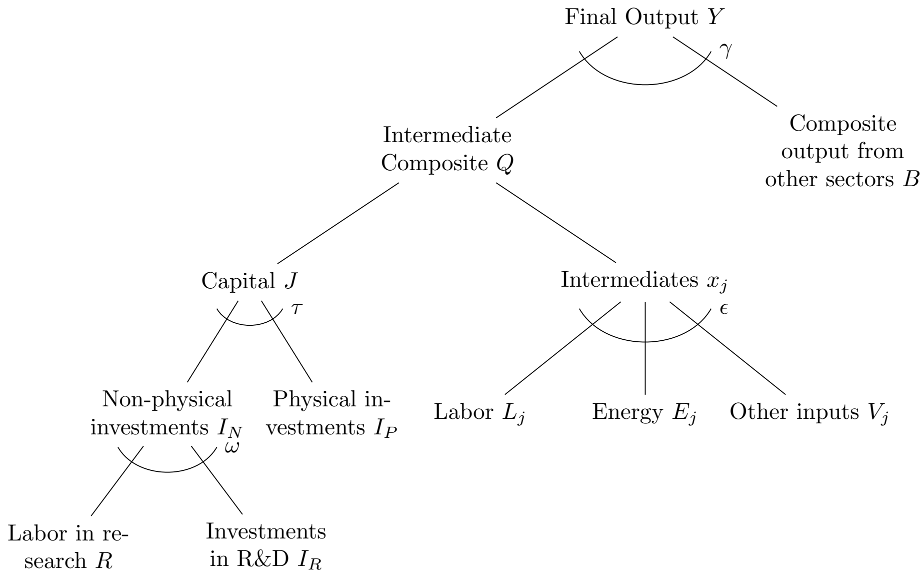

Figure 10: Nested production function of the energy sector

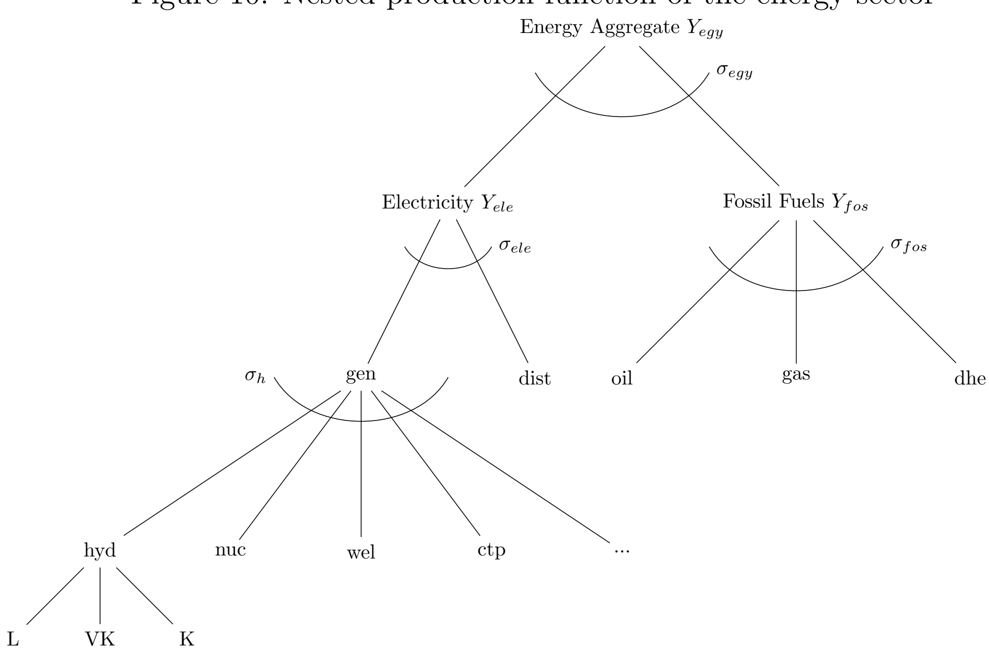

Figure 11: Nested consumption function

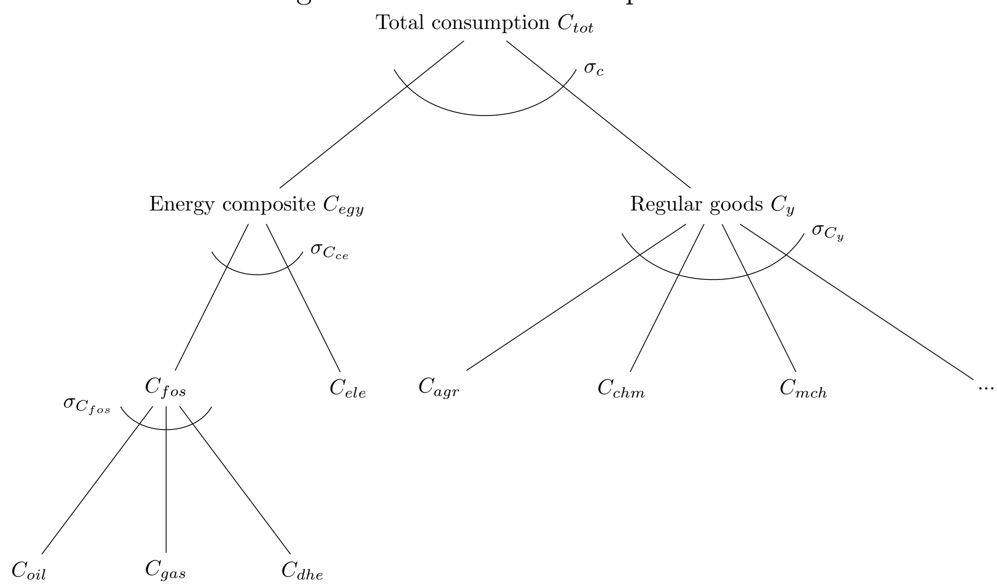

Table 6: Parameter values for regular sectors and consumption

Parameter	Description	Value
γ	Elasticity of substitution between Q and inputs from other sectors B	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)
ε	Elasticity of substitution between the three inputs (Energy E, labor L and other inputs V)	0.7 (agr, oil, chm, egy) 0.8 (mch) 0.52 (con) 0.82 (oin) 0.4 (rest)
τ	Elasticity of substitution between physical investments (I_P) and non-physical capital (I_N)	0.3
ω	Elasticity of substitution between investments in R&D (I_R) and research labor R	0.3
σ_{egy}	Elasticity of substitution between electricity and fossil fuels (F) in intermediate production	1.5
σ_C	Elasticity of substitution between energy (F) and non-energy goods (D) in consumption	0.5
σ_{ce}	Elasticity of substitution between electricity and fossil fuels (F) in consumption	1.5
θ	Inter-temporal elasticity of substitution in the welfare function	0.6
η	Trade ("Armington ") elasticities	3.2 (agr) 4.6 (mas) 3.8 (egy, oin) 2.9 (rest)
χ	Elasticity of transformation	1
υ	Elasticity of substitution between sectoral outputs for the input B	0

Table 7: Market shares derived from Prognos estimation (2011)

Year	hyd	nuc	ctp	wel	sun	win	bio
2010	0.57	0.39	0.03	0.01	0	0	0
2020	0.64	0.26	0.03	0.01	0.020	0.015	0.025
2035	0.69	0	0.10	0.03	0.095	0.035	0.060
2050	0.52	0	0.06	0.02	0.270	0.070	0.060

Appendix C: The description of the multi-regional CITE model

The description of the multi-regional CITE model

In this paper, we present our baseline model. This is a dynamic general equilibrium model where the whole world economy is composed by several regions. In each region of the model, the final output combines sectoral specific inputs using intermediate aggregates and general inputs. Capital, labor, energy and knowledge are used for intermediate aggregate production under monopolistic competition where individual firms earn positive profit to cover their fixed cost. Production is subject to taxes, so that profit-maximizing decision making firms will reallocate capital investments for improving productivity and alleviating the impacts of taxes. Research in the model is directed for the expansion in varieties which enable new firms to entry into production. Outside knowledge spilled over into the industry provides extra productivity increase for the whole sector. Such positive externality spreads to other sectors and regions through cross-sector interaction and international trade. We now describe each module of the model in turn.

1 Preferences and Endowments

In each region, the economy is populated by infinitely-lived households with the following CRRA preferences

$$U = \int_0^\infty \exp(-\rho t)\frac{C(t)^{1-\theta}-1}{1-\theta}dt \tag{1}$$

where $\rho > 0$ is the utility discount rate, θ the elasticity of inter-temporal substitution and $C(t)$ is the household consumption aggregate consisting of consumption of a regular sector output composite (C_y) and an energy aggregate (C_e) with an elasticity of substitution (σ_C):

$$C(t) = \left[\zeta C(t)_y^{\frac{\sigma_C-1}{\sigma_C}} + (1-\zeta)C(t)_e^{\frac{\sigma_C-1}{\sigma_C}}\right]^{\frac{\sigma_C}{\sigma_C-1}}. \tag{2}$$

The regular sector output composite (C_y) is given by a Cobb-Douglas function, according to:

$$C_y = \prod_{ne} C_{ne}^{\beta_{ne}}. \tag{3}$$

where subscript ne is a set containing many non-energy goods, β_{ne} shows the consumption shares of each goods respectively. We further disaggregate the energy composite into fossil aggregate and electricity consumption with an elasticity of substitution σ_{ce}:

$$C_e = \left[\iota C_{ele}^{\frac{\sigma_{ce}-1}{\sigma_{ce}}} + (1-\iota) C_{fos}^{\frac{\sigma_{ce}-1}{\sigma_{ce}}}\right]^{\frac{\sigma_{ce}}{\sigma_{ce}-1}}. \tag{4}$$

where ι is the value share of electricity consumption in total energy aggregate and the fossil aggregate (C_{fos}) is given by

$$C_{fos} = C_{coa}^{\alpha_{coa}} C_{oil}^{\alpha_{oil}} C_{gas}^{\alpha_{gas}} \tag{5}$$

where α_{coa}, α_{oil}, α_{gas} are the respective energy source consumption share in fossil aggregate with $\alpha_{coa} + \alpha_{oil} + \alpha_{gas} = 1$.

We assume that the representative household owns production labor L_U and research labor L_R, both of who will be fully employed in production and R&D activities. The representative household is the owner of all firms in the economy, who will face the problem of maximizing (1) subject to following budget constraint

$$w(t)^U L_U + w(t)^R L_R + \sum_f p(t)^f E_f + r(t)A(t) \geq C(t) + \dot{A(t)} + CA(t) \tag{6}$$

with transversality condition holds to avoid Ponzi game. Here $w(t)^U$ and $w(t)^R$ are the wage rates of production and research labor, $p(t)^f$ is the price of resources including natural resources and price of permits of carbon policies are implemented, E_f is the endowment of resource f, $r(t)$ is the equilibrium interest rate on assets $A(t)$. $CA(t)$ is the current account deficit in time t which will be discussed later. In following sections, time-indexes are omitted when this causes no confusion.

2 Final good technology and growth mechanics

The final output Y in each sector and region is produced with a sector specific intermediate composite Q and composite input from other sectors B:

$$Y = [\alpha_Q Q^{\frac{1-\gamma}{\gamma}} + (1-\alpha_Q) B^{\frac{1-\gamma}{\gamma}})]^{\frac{\gamma}{1-\gamma}} \tag{7}$$

where α_Q is a share parameter. Time, sector and region indices are omitted whenever there is no ambiguity. The final good (Y) producers maximize profits under perfect competition, i.e. they take prices of Q and B as given. The intermediate composite Q is manufactured based on Dixit and Stiglitz (1977), where q_j denotes the jth type of intermediate good and J is the total number of intermediate varieties available at a certain point of time, according to:

$$Q = [\int_{j=0}^{J} q_j^{\kappa} dj]^{\frac{1}{\kappa}} \tag{8}$$

with $0 < \kappa < 1$. If assuming symmetric intermediate goods, i.e. $q_j = q$, expression (8) can be simplified to:

$$Q = J^{1/\kappa - 1} X \tag{9}$$

where $X = J \cdot q$ measures aggregate input in the intermediate sector. The intermediate output Q can be increased through either by producing larger quantity per firm q, or by increasing the number of varieties (and the number of intermediate firms J. The term $J^{1/\kappa-1}$ measures the gains from diversification on the aggregate level of the whole industry (Dixit and Stiglitz 1977). Since each of the intermediate firm j operates under monopolistic competition, the term $1/\kappa - 1$ corresponds to the optimum markup in the intermediates' sector.

Furthermore, each intermediate good needs one capital unit in order to be produced.[1] Accordingly, J denotes the amount of capital used in the economy, $1 - \kappa$ represents the share of capital in production. With $g_J = \dot{J}/J$ being the growth rate of capital, g_X the growth rate of intermediate production and g_Q the growth rate of output, we have from (9):

$$g_Q = (\frac{1}{\kappa} - 1) g_J + g_X \tag{10}$$

The accumulation of capital is characterized through positive investments into new varieties ($I_J > 0$) and a time varying depreciation of δ_t.

$$J_{t+1} = I_t + (1 - \delta_t) J_t \tag{11}$$

where t is the time index. Investments depend on the input of research labor L_R[2]

[1]In Romer (1990), capital is knowledge capital in the form of blueprints. We generalize the assumption to broad capital because we want to capture not only investments into non-physical but also into physical capital in the numerical simulations below. The latter constitutes an important channel for the effects of carbon policies.

[2]This variable denotes a specific type of labor, which can be derived directly from the input/output table.

and on other investment specific inputs, B_{inv}, according to:

$$I = [\xi(zJ \cdot L_R)^{\frac{\omega-1}{\omega}} + (1-\xi)B_{inv}^{\frac{\omega-1}{\omega}}]^{\frac{\omega}{\omega-1}} \tag{12}$$

where ξ and $1-\xi$ are share parameters, ω is the elasticity of substitution, J represents the aggregate spillover to research labor productivity usually assumed in growth theory, and z the spillover intensity. Put differently, the invention of new goods varieties increases the stock of public knowledge which is a free input into investment activities of the next period. The knowledge spillover zJ raises research labor productivity, counteracting decreasing returns to labor in investment activities. This common mechanism of new growth theory will be present both in the benchmark scenario and the policy applications.

3 Intermediate good production and energy sector

Intermediate goods q_j are produced using three essential inputs: production labor L_U, energy E, and other input V which includes all the other materials contributing to the production of intermediate goods:

$$q_j = J[\phi(L_U)_j^{\frac{\epsilon-1}{\epsilon}} + \xi E_j^{\frac{\epsilon-1}{\epsilon}} + (1-\phi-\xi)V_j^{\frac{\epsilon-1}{\epsilon}}]^{\frac{\epsilon}{\epsilon-1}} \tag{13}$$

with ϕ, ξ, and $1-\phi-\xi$ being the share parameters and ϵ represents the substitution elasticity between the three inputs.[3] By multiplying the expression by J the production of intermediates is assumed to benefit from a knowledge spillover through capital accumulation. This is, output of intermediate goods increases over time with positive investments even when the quantity of the other inputs in (13) remains constant.[4]

For non-electricity sector, energy (E) used for intermediate production is a two-stage aggregate process. In the top, electricity E_{ele} and fossil fuels bundle E_{fos} are combined according to

$$E = [\delta E_{ele}^{\frac{1-\sigma_{egy}}{\sigma_{egy}}} + (1-\delta)E_{fos}^{\frac{1-\sigma_{egy}}{\sigma_{egy}}}]^{\frac{\sigma_{egy}}{1-\sigma_{egy}}} \tag{14}$$

where σ_{egy} is the elasticity of substitution and δ is a value share. In the bottom

[3]Since L_U is completely different from L_R in (12) so that there is no labor reallocation between these two labor types.

[4]The assumption is necessary for the calibration of the reference case (which is a balanced growth path) but not crucial for our policy evaluations, because the effect is present both in the benchmark and with the policies.

nesting, fossil fuels E_{fos} are further disaggregated into coal (coa), oil (oil), and gas (gas) through the production technology of CES function (omitted for the sake of brevity).

Energy aggregate used in the electricity sector has a slightly different structure where both electricity and three fossil fuels are assembled through CES technology in the same nesting.

4 Open economy and trade

We assume that trade between any pair of two regions are possible. In each region, the produced final goods are consumed by domestic household or exported to other regions through trade. Output composite B in (7) reflects inter-sectoral linkages through the input-output structure of the economy. Each region trades with the rest of the world (all the other regions abroad) on all markets for final goods Y. For simplicity Armington demand functions are employed to model trade, where goods of each sector are differentiated by the origin region of production. Markets for final goods are perfectly competitive and provide goods for domestic use (D) or exports (P):

$$Y = [\alpha_d D^{1+tr} + (1-\alpha_d) P^{1+tr}]^{\frac{tr}{1+tr}} \tag{15}$$

where α_d is the share of domestic use in total output Y and tr is the elasticity of substitution between D and P. Also, there is imperfect substitution between domestically produced goods Y and total imported foreign goods M:

$$A = [\nu M^{\frac{\eta-1}{\eta}} + (1-\nu) Y^{\frac{\eta-1}{\eta}}]^{\frac{\eta}{\eta-1}} \tag{16}$$

where ν and $1-\nu$ are the value shares and η is the elasticity of substitution. The total import in sector s of region b ($M_{s,b}$) is a CES aggregation of goods imported from all the other regions plus the transport margins

$$M_{s,b} = [\sum_{a,a\neq b} \psi_{s,a,b} (M_{s,a,b} + TN_{s,a,b})^{\frac{\sigma_M - 1}{\sigma_M}}]^{\frac{\sigma_M}{\sigma_M - 1}} \tag{17}$$

where $\psi_{s,a,b}$ is the share of import from a in total imports with $\sum_a \psi_{s,a,b} = 1$. $TN_{s,a,b}$ is the value of transportation services needed to transport goods $M_{s,a,b}$ from region a to region b.

The world goods trade is balanced in each period. In each sector, the market clearing condition requires that supply equals demand.

$$\sum_{a,b} p^M_{s,a,b} M_{s,a,b} = \sum_{a,b} [p^{EX}_{s,a,b}(1+t^{ex}_{s,a,b})EX_{s,a,b} + p^{TR}_{s,a,b} TN_{s,a,b}](1+t^M_{s,a,b}) \tag{18}$$

where $p^M_{s,a,b}$ is the price of import, $p^{EX}_{s,a,b}$ is export price net tariff, $p^{TR}_{s,a,b}$ is the unit cost of transportation service, $t^{ex}_{s,a,b}$ and $t^M_{s,a,b}$ are the export and import tariff.

5 Knowledge spillover

Griliches's contribution (1979) is one of the first papers addressing two types of spillovers: the embodied knowledge spillover[5] and dis-embodied knowledge spillover. The embodied knowledge spillover is what he called "rent spillover", which is due to the fact that purchase prices of imported goods do not reflect their "full quality price" including the opportunity cost of R&D of foreign innovation. Since during the production of intermediate goods the monopolistic competition characteristics of individual firms allows them to charge a price premium, we assume that part of the embodied knowledge spillover effects is absorbed through the mechanism and spreads to other regions and/or sectors with trade and inter-sectoral linkage. We consider the dis-embodied spillover only in this paper. The dis-embodied knowledge spillover refers to borrowing ideas by industry s from the research results of industry r. Usually this types of knowledge augments domestic knowledge stock while the learning cost is lower than the original R&D cost.

The seminal work of Rivera-Batiz and Romer (1991) suggests that economic integration increases the worldwide stock of ideas, and hence contributes to the growth. We borrow this idea for the construction of knowledge pool in our model. However, knowledge itself, particularly tacit knowledge, is unmeasurable, and its flows are invisible (Krugman 1991). This means that studying knowledge spillovers quantitatively have to rely on crude proxy variables. In general, new knowledge stock of sector a is a function of the existing knowledge stock $J_a(t)$ and the augmenting component due to spillover effects $\tilde{J_a}(t)$.

$$J_a(t+1) = J_a(t)\tilde{J_a}(t) \tag{19}$$

where $\tilde{J_a}(t)$ is defined by accessible knowledge from outside and presenting the "absorptive capacity" of specific sector φ_a and the production elasticity reflects the transformation of the absorbed knowledge into new varieties μ. If assuming

[5]Embodied knowledge spillover has its origin from the empirical work of Coe and Helpman (1995). This type of spillover is embodied in the flow of physical commodities transactions through the channels of trade and FDI

the world is consist of only two regions a and b, and each region has only one sector, the spillover effects of region a can be expressed as follow:

$$\tilde{J_a}(t) = [\sum_{b,b\neq a} \varphi_a J_b(t)]^{\mu}$$

Many factors can affect the size of φ_a, for instance, the cultural difference, geographic distance, trade treaties between regions, the level of knowledge in the world technology ladders. The size of knowledge stock at home country is one of the factors impacts the value of μ. Further discussion and estimation of the two will be discussed later.

To extend our analysis to multi-channels, we assume each of the regions has two sectors s and r. By distinguishing the sourcing sectors of spillover, we can identify four channels of spillovers: intra-industry spillovers domestic, inter-industry spillovers domestic, intra-industry spillovers foreign[6], inter-industry spillover foreign[7]. The "expansion-in-varieties" mechanism has already captured the intra-industry spillovers ($SPH1$). Hence, the total stock of knowledge used for variety-expansion of one sector is a combination of self-generated knowledge stock and spillovers from the other three sources. Hence, (19) can be further expanded as follows:

$$J_{s,a}(t+1) = J_{s,a}(t)[\tilde{J_{r(r\neq s),a}}(t)][\tilde{J_{s,b}}(t)][\tilde{J_{r(r\neq s),b}}(t)] \tag{20}$$

where $\tilde{J_{r(r\neq s),a}}(t)$ is the inter-sectoral spillover within the same region ($SPH2$); $\tilde{J_{s,b}}(t)$ is the intra-sectoral between regions ($SPF1$); $\tilde{J_{r(r\neq s),b}}(t)$ is the inter-sectoral spillover between regions ($SPF2$). More parameter estimations are required to capture the differences between channels using Eq. (20).

6 Current account balance

In the model, the equilibrium condition requires that the present value of consumption has to equal the present value of income over the entire time horizon. This is the budget constraint which has to be held. However, a region is able to borrow or lend money in a given time period t, which is the so-called current account surplus or deficit. As stated in Carbone et al. (2003), the closure of financial flows within the model needs an additional constraint on current account deficit for the whole world. That is, for any given time period, the "global" current

[6]Knowledge spillovers from foreign countries of the same industry.
[7]Knowledge spillovers from foreign countries of other industries.

account deficit has to be zero.

$$\sum_a CA_a(t) = 0 \tag{21}$$

Springer (1999) and Rutherford (2003) defines that the current account of a region as the trade deficit, which means if one country imports more than its exports (in terms of value), it will result in current account deficit.[8]

$$CA_a = \sum_{s,b} p^{EX}_{s,a,b} EX_{s,a,b} - \sum_{s,b} p^{M}_{s,b,a} M_{s,b,a} \tag{22}$$

The closure of financial flow is determined by fulfilling the budget constraint (6). This condition also closes our model.

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[8] Since in the model the balance of trade deficit or surplus holds for any given time, the total value of export equals the total value of import for the whole world. the world balance of current account (21) holds automatically by such definition.

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