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

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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

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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. A prominent example is the building of the Olkiluoto plant in Finland.[4] 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,[5] 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[6], a higher dependence on foreign energy, or a possible conflict with climate targets if nuclear is replaced by gas or coal fired plants[7]. 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

[4]In 2005, costs were estimated to be around 3 bn. Euro. In 2011, this estimate has more than doubled (6.6 bn. Euro, see Prognos 2011), and the commissioning deadline has been delayed further.

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

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

[7]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.

energy demand but also bring about general growth impacts in the medium and long run.

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 Hådén (1997) and Nyström and Wene (1999) investigated the case of Sweden[8], Hoster (1998), Welsch (1998), Welsch and Ochsen (2001), and Böhringer, Hoffmann and Vögele (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). Böhringer, Wickart and Müller (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[9].

[8]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.

[9]The two proposals were "Strom ohne Atom" ("electricity without nuclear energy") and "Mora-

Our paper differs from these contributions in several respects. First, most of these papers restrict their attention to the impacts at the technology level[10]. 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.

We find that the phase-out can be achieved at moderate cost. Welfare losses amount 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 CITE model, the new 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 concludes.

2 The 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,

torium 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.

[10]The exceptions are Welsch (1998), Welsch and Ochsen (2001) and Böhringer, Wickart and Müller (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. Böhringer et al. report long-term GDP reductions between 0.01% and 0.38%. Out of these three studies, only Böhringer et al. make restrictions on carbon emissions.

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; a graphical representation of the nested production functions is given in the Appendix.

Production of each non-energy sector, which we call "regular" sector, is represented by a three-stage nested CES-function, see Figure 8 in the Appendix. The crucial model element is the intermediate composite good on the second stage, combining the accumulable capital with the other inputs. Investments into new capital varieties enhance the sectoral capital stocks. 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 and the sectoral inter-linkages are reflected in the usual way.

For the present paper analysis, 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. 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. Below, we present the extended set-up of the energy sector in detail.

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 whose market price P_{egy} is given by:

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

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:

$$P_{ele} = \left[\mu P_{gen}^{1-\sigma_{ele}} + (1-\mu) P_{dist}^{1-\sigma_{ele}}\right]^{\frac{1}{1-\sigma_{ele}}} , \tag{2}$$

with μ as share parameter and P_{gen} and P_{dist} denoting prices of total electricity generation and electricity transmission and distribution, respectively. 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 (Sue Wing *et al.* 2011). We set σ_{ele} to 0.5 (as in Sue Wing 2006). *dist* is a subsector that 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).

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:

$$P_{gen} = (\sum_h \delta_h P_{y_h}^{1-\sigma_h})^{\frac{1}{1-\sigma_h}}, \quad (3)$$

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[11]. 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 take 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. Lower values of σ_h is assigned for sensitivity analysis to capture the sunk cost that invested 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%

We then use information on levelized cost of different technologies resources (EIA 2012) to set up the individual cost functions for new renewables. The cost functions are assumed to have the following form:

$$P_h = \sum_f (\beta_f P_f) + P_{cap,h}, \quad (4)$$

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

[11] 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.

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.

Table 2: Share of factors for power generation across technologies

Technology	Labor	Non-accumulative capital	Accumulative 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 accumulative capital is calibrated to 0.25 in benchmark according to Bretschger, Ramer and Schwark (2010).

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 (see equation 1). 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 Cobb-Douglas fashion and the price index reads:

$$P_{fos} = P_{oil}^{\xi_{oil}} P_{gas}^{\xi_{gas}} P_{dhe}^{\xi_{dhe}}, \tag{5}$$

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).[12] 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

$$U = \left[\sum_{t=0}^{\infty} \left(\frac{1}{1+\rho} \right)^t C_t^{1-\theta} \right]^{\frac{1}{1-\theta}}, \tag{6}$$

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

$$C = \left[\zeta C_y^{\frac{\sigma_C - 1}{\sigma_C}} + (1-\zeta) C_e^{\frac{\sigma_C - 1}{\sigma_C}} \right]^{\frac{\sigma_C}{\sigma_C - 1}}. \tag{7}$$

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

$$C_e = \left[\phi C_{ele}^{\frac{\sigma_{ce} - 1}{\sigma_{ce}}} + (1-\phi) C_{fos}^{\frac{\sigma_{ce} - 1}{\sigma_{ce}}} \right]^{\frac{\sigma_{ce}}{\sigma_{ce} - 1}}. \tag{8}$$

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 (Böhringer and Rutherford 2005). However, as indicated above, good substitutability seems more valid for the analysis conducted here. We therefore set σ_{ce} to 1.5. This implies that the compensated price elasticity of electricity demand for consumption in the long run is about -1. We also test different substitution elastcities to allow the price elasticity ranges between -0.54 and -1.5. Figure 10 gives a graphical overview of the consumption nesting.

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

Additionally, since the share of fossil fuels and share of electricity use are different between consumption and intermediate production, the prices of energies are differenciated 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 limit computational complexity. The IOT includes more than 40 regular production sectors. We have aggregated it to 10. 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 3) and three fossil fuel catagories. Table 3 provides an overview of all sectors and technologies.

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.[13] 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, this reference growth rate is 1.33%/year. This rate refers to the economy without

[13] 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.

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

any policy. 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. Specifically, we assume a reduction of carbon emissions of 65% relative to the initial period until the year 2050. 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. 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, we assume for the BAU that the shares of the individual technologies of total electricity and fossil energy production 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 all variables grow at a constant annual rate of 1.28%. The time horizon for the simulation is 38 years (2012-2050).

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 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.

Table 5: Market shares in scenario $PO - CC$ (Source: Prognos 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

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 m 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 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 adjusted Scenario IV in Prognos 2011) 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 0.1% for $PO-FM$ and 0.4% for $PO-CC$, respectively.

Table 6: Average annual consumption growth rates and welfare losses

Scenario	**Consumption growth rate**	**Welfare loss (in % change versus *BAU*)**
PO-FM	1.27%	0.1%
PO-CC	1.26%	0.4%

These results show that the aggregate effects of a nuclear phase-out policy are not negligible, but relatively moderate. There are multiple explanations for this result. First of all, the tax rate on fossil energy can be significantly reduced if there is a target in the electricity sector complementing climate policy. This increases the incentives to substitute away from energy goods, leading to an accelerated reduction of fossil energy use and thus a lower tax rate for the specified target. Another important factor is planning reliability for investors. Second, 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 adaption 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). 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.

To test the robustness of our findings we now 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) obviously plays a crucial role. We had set these elasticities (σ_{egy} and σ_{ce}) to 1.5. We consider two alternative assumptions. First, we substantially 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.

Welfare change in the column 1 and 3 of Table 7 dues to the changes in elasticity values and implementation of technology policies. All of them are compared to the BAU with $\sigma_{egy} = \sigma_{ce} = 1.5$. 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 increases 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.

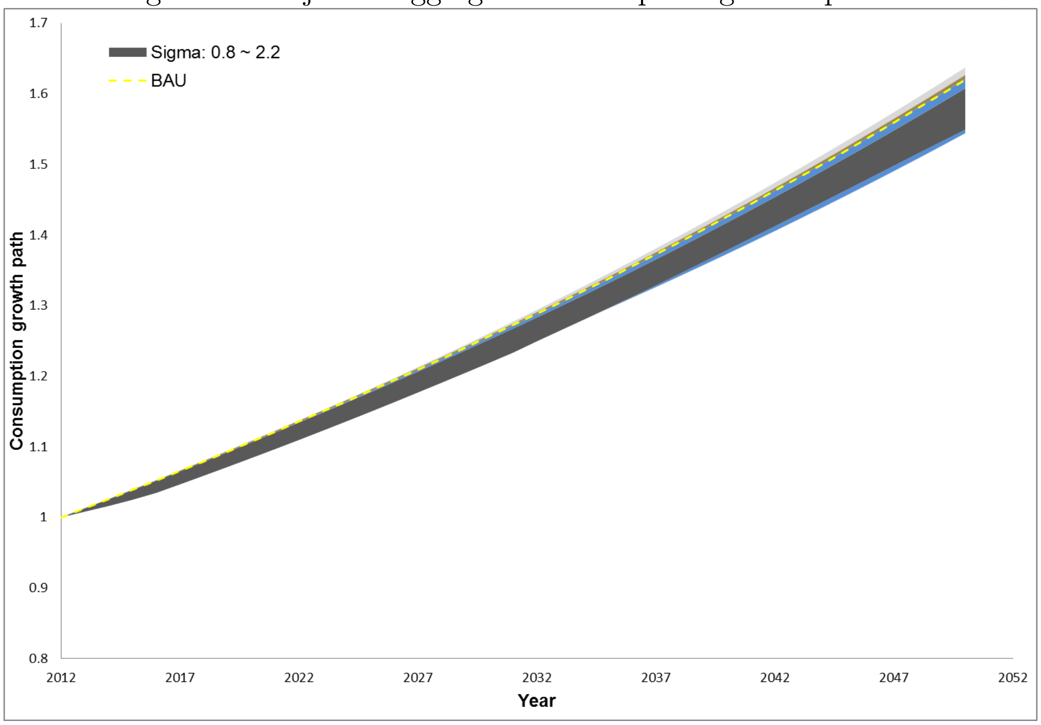
Table 7: Annual consumption growth rates and welfare losses under different assumptions for σ_{egy} and σ_{ce}

	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%

Note: welfare loss is compared to BAU with $\sigma = 1.5$.

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 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, especially for higher values. The growth rate can reach up to 1.31% in the most favorable case. Moreover, optimistic perception of better substitution between generation technologies lead to lower subsidies to expand renewable energies. Since 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), the result of a moderate impact in 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 also electricity use is 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.

The effects are stronger in $PO-CC$ for any 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. The welfare impacts discussed above show that these benefits come at very little additional cost.

Figures 2 to 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

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%

insignificant. 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 explanation for the low additional cost in welfare terms discussed above. Hence, even though new renewables have to be subsidized in order to gain the projected market shares, the reduced attractiveness of the established technologies facilitates the transition to an electricity sector that is increasingly dominated by new renewable technologies.

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

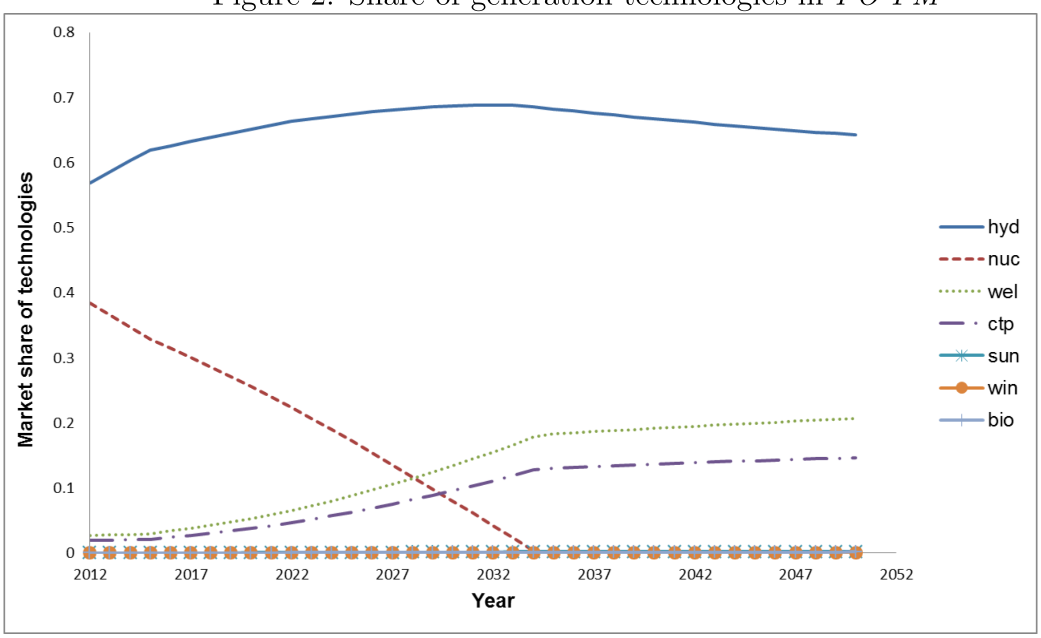
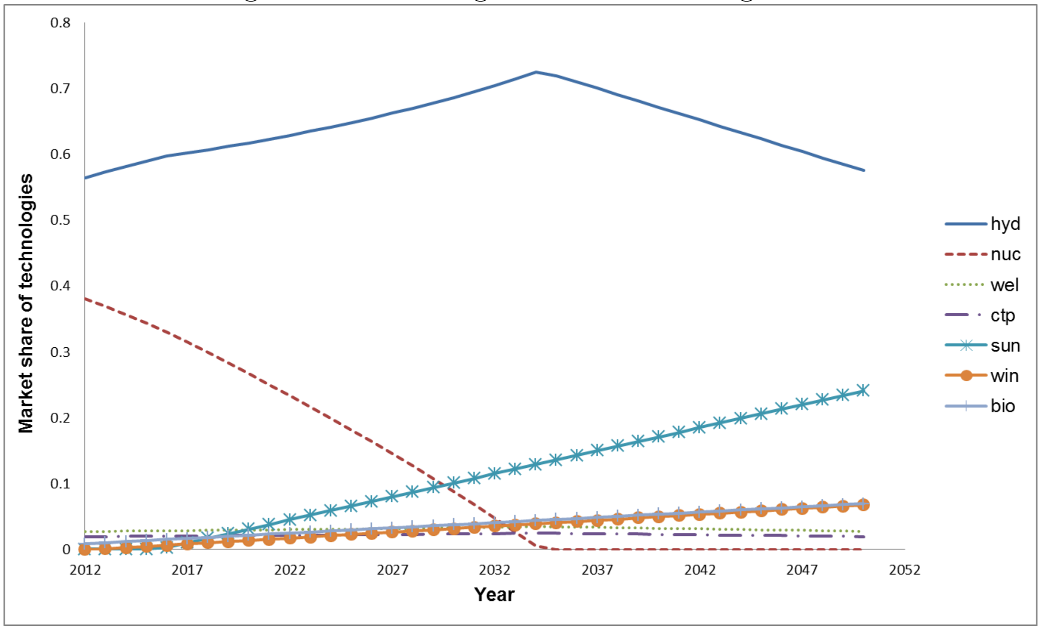


Figure 4 illustrates the total electricity generation in different scenarios. The average annual growth rate of electricity generation in *BAU* is calibrated to be 1.28%, which means the total electricity generation in 2050 is about 1.6 times the level in

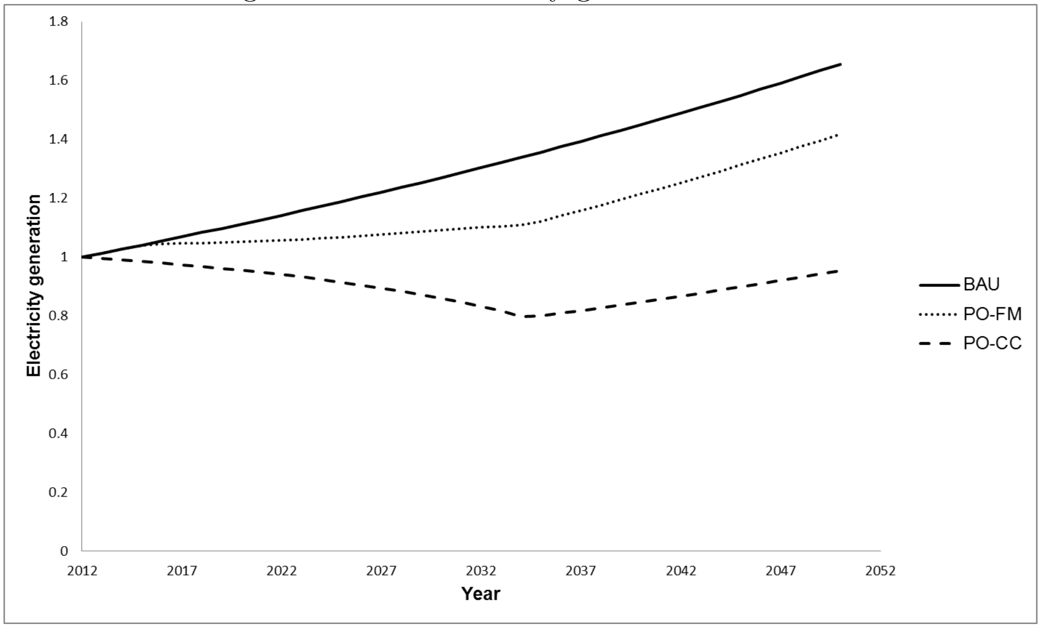
Figure 3: Share of generation technologies in *PO-CC*



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 2). 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 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 $PO - CC$.

Figure 4: Total electricity generation across scenarios



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

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%	0.97%
chm	1.51%	1.59%
mch	1.52%	1.65%
oin	0.95%	0.89%
con	1.32%	1.30%
trn	1.11%	1.07%
bnk	1.34%	1.33%
ins	1.45%	1.42%
hea	1.33%	1.32%
ose	1.32%	1.31%
oil	-1.94%	-1.97%
gas	-1.46%	-1.48%
het	-1.79%	-1.78%

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

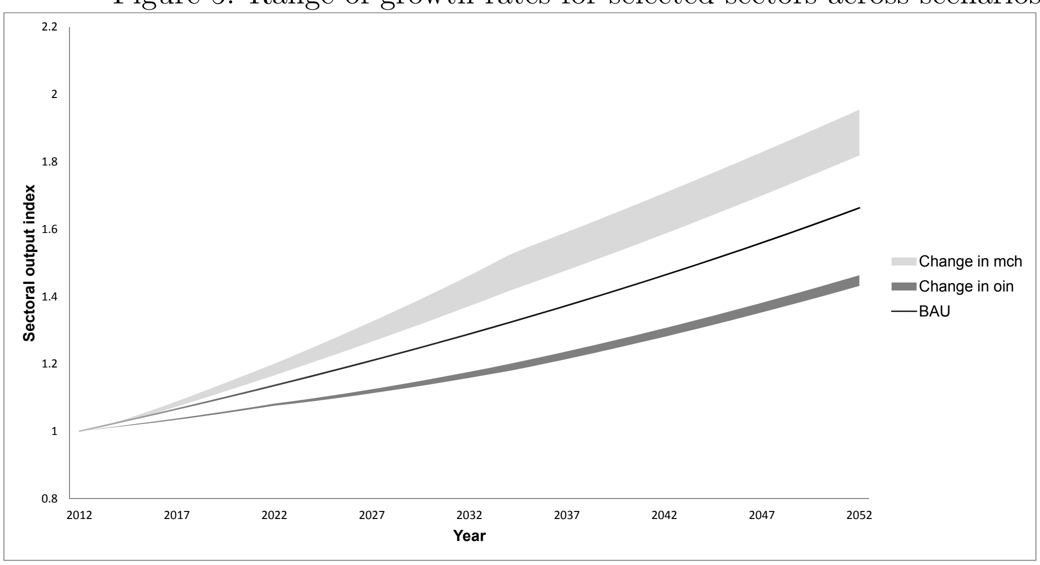
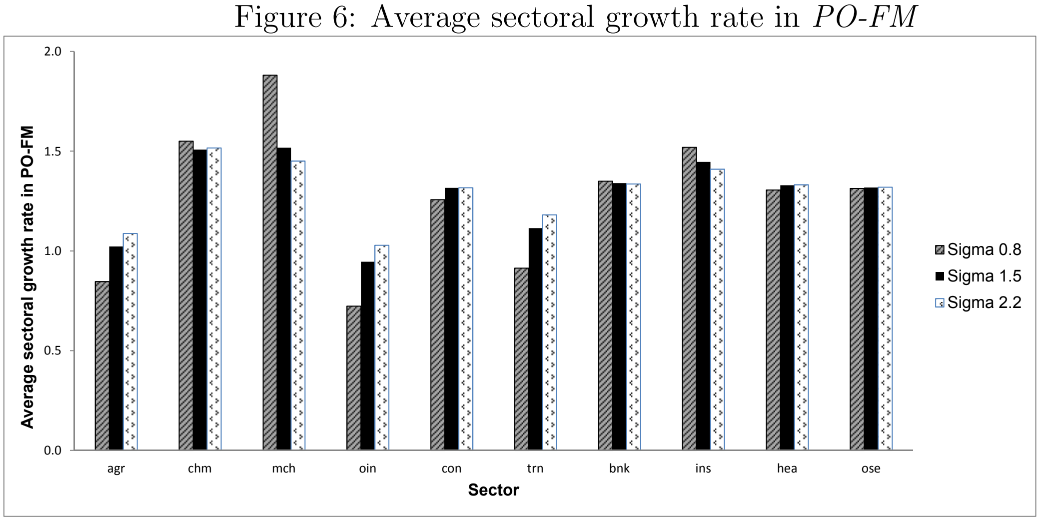


Figure 5 illustrates the differences in the two scenarios and the impacts on the degree of structural change. Figure 5 shows the growth paths of two selected sectors in the two phase-out scenarios. *mch*, a particularly innovative sector, benefits the most in both scenarios. *oin* on the other hand experiences 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.

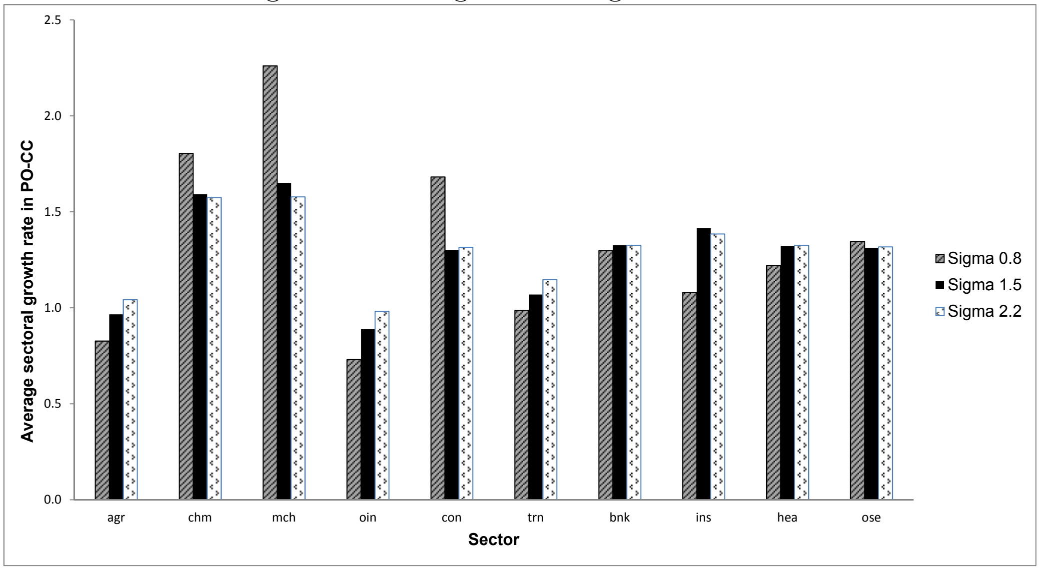
Again, we want to test the reliability of the results in terms of a sensitivity analysis. On the sectoral level, poor substitutability between the two energy sources amplifies the structural change. Figures 6 and 7 illustrate the intensified structural change in both scenarios when reducing the elasticities 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.

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



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

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



substitutability. 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 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 the CITE model, 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 leads to moderate impacts on welfare and 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 an almost negligible cost in welfare terms 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 moderately from 0.1% to 0.4%. These benefits can be achieved at relatively low additional cost. It should be noted that we do not include any external costs in the analysis, because they are hard to measure. But 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 incur 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 might underestimate the cost in a system that phase-out nuclear and moves towards high shares of renewables. All these aspects are left for future research.

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A Appendix: Tables and Figures

Table 10: 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 (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 (F) and non-energy goods (D) in consumption	0.5
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

Figure 8: Nested production function of regular sectors

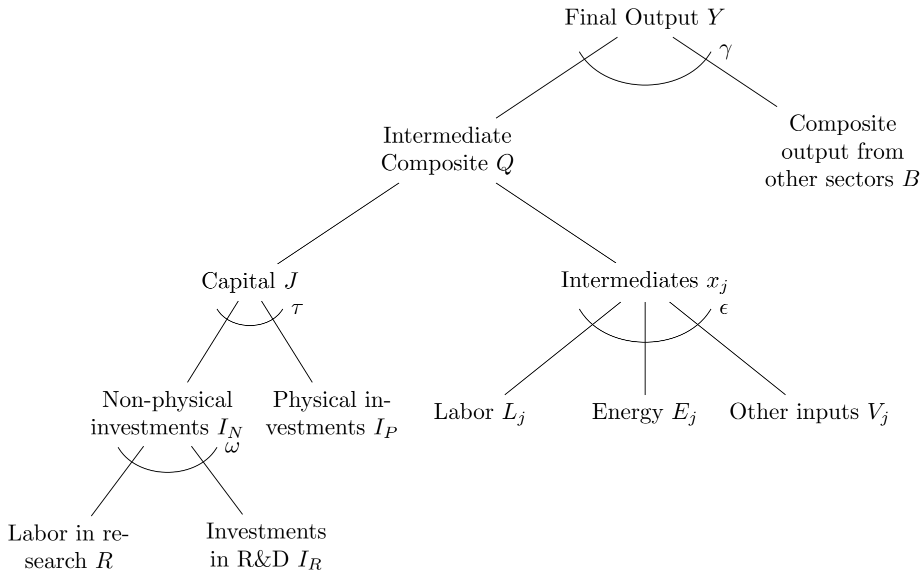

Figure 9: Nested production function of the energy sector

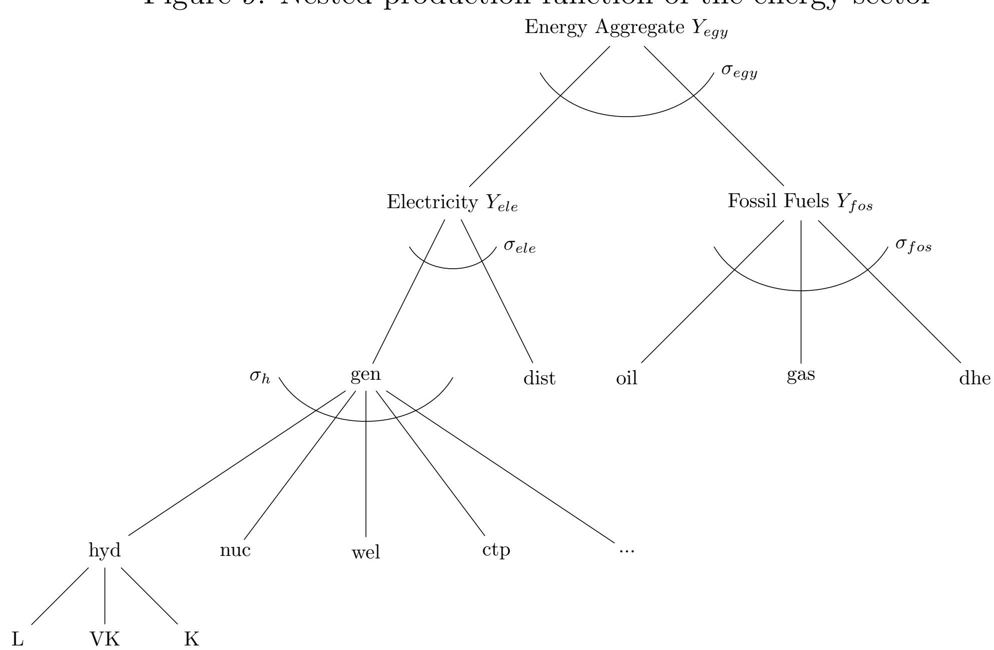

Figure 10: Nested consumption function