Nuclear Phase-out and Climate Policy in Switzerland: An Integrated Top-down Bottom-up Assessment

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Abstract

We examine the economic effects of a nuclear phase-out under climate policy constraints in Switzerland in a model that integrates a top-down dynamic general-equilibrium model with a detailed bottom-up description of the Swiss electricity sector. The electricity-sector model features perfect foresight, exhibits a high level of technological and temporal resolution, is parametrized to represent resource potentials for renewable energy sources in Switzerland, and takes into account electricity trade between Switzerland and its neighboring countries. Consistently linking the electricity model to an economy-wide general equilibrium framework allows us to assess different policy options in terms of sound economic cost metrics while being able to explore the implications of alternative technology pathways.

1 Introduction

Over the last decade the energy debate in Switzerland has been dominated by climate change. Thus, decarbonization and energy conservation were pillars of the modern Swiss energy policy ever since the "Energy 2000" program has been introduced. Since electricity in Switzerland is produced virtually carbon neutral, electrification seemed to push Switzerland towards carbon neutrality. However, after the disaster at Fukushima Daiichi in March 2011 the perception of the whole situation changed drastically in many Western countries, including Switzerland. After the shock the Swiss federal council opted for a nuclear phase-out. Existing plants ought to be

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used until they expire and no new plants will be built. This proposal is equivalent to a gradual nuclear phase-out until 2034 based on a reactor life span of 50 years. This current development has confronted the Swiss energy policy with new challenges. If nuclear power will be phased-out, short falling capacities will raise prices of electricity. Although this will lead to decreased demand compared to a business-as-usual, increasing electrification will still likely lead to at least stable demand for electricity. This means that abandoned supply capacities have to be replaced in one way or the other.

While the simplest way of securing electricity supply would be via increased imports, decreased exports or gas-fired plants, all three options have major disadvantages. Additional imports would stem either from nuclear plants in France or coal-fired plants in Germany.[1] Decreasing exports may be very costly, since Swiss electricity producers are making profits from arbitrage by buying and storing cheap base load electricity and selling at expensive peak load. Additionally, having a negative annual net balance on electricity trade may be politically undesirable. Another option for replacing nuclear electricity would be generation from renewables including wind and solar.[2] However, they are associated with disadvantages via two channels: First, the technologies have high levelized average lifetime cost and second, the huge variance in electricity supply from those sources may use more of the storage capacity of the hydro plants which will hinder their use for trade gains on the european markets. A third renewable technology option is a large-scale geothermal power plant. While engineers think that geothermal generation could replace nuclear base load power at low cost, hardly calculable risks of earthquakes and their monetary consequences may make this option unattractive for potential investors.[3]

To shed light on the mechanics that drive the cost of Swiss electricity production and to pro-

[1] Both options may be viewed as critical: Replacing nuclear plants with foreign nuclear plants is useless since nuclear disasters strike huge regions and many french plants are build close to the Swiss border. Substituting nuclear plants with fossil fuel plants in Germany or Switzerland would put more stress on Swiss climate policy.

[2] There are several technologies that use solar power to produce energy or energy services. If we are referring to solar power we mean photovoltaic solar cells producing electricity throughout the paper, since we are interested only in electricity generation. Other solar technologies as for example solar collectors for heating up water, or concentrated solar power in large scale power plants, are not considered.

[3] A prominent case is the incident in Basel in 2006, where drillings produced an earthquake and subsequent legal issues.

vide an estimate of the additional cost imposed by a nuclear phase-out in a climate-constrained world, this paper develops a hybrid energy economic model of the Swiss economy. The model we propose in this paper builds on the decomposition technique developed by Böhringer and Rutherford (2009) as applied by Lanz and Rausch (2011). We integrate a copperplate bottom-up model of Switzerland's electricity generation, capacity expansion and trade into a top-down computable general equilibrium (CGE) model that represents Switzerland as a small open economy. However, we improve the literature in two ways. On the one hand no full grown hybrid model has yet been used to analyze the energy transition in Switzerland, and second, the hybrid modeling literature restricted itself to static or recursive-dynamic models so far. Since in both our submodels agents exhibit perfect foresight, the resulting integrated model exhibits perfect foresight as well.

Several papers exist that study nuclear phase-outs. Nakata (2002) studies a nuclear phase-out in Japan using an annual partial equilibrium model. However, an annual model of electricity markets seems to be inadequate since electricity supply and demand have to be balanced in every instant to prevent black-outs and other systemic instabilities. A study for Switzerland (Böhringer, Müller, and Wickart 2003), uses a general equilibrium model with an activity analysis. Such a model is suitable to compute economy-wide cost of a certain policy, but systemic stability and the operation of storage facilities cannot be taken into account as well. Bretschger, Ramer, and Zhang (2012) apply the CITE model, an endogenous growth CGE model. The incorporated learning-by-doing effects help to get better estimates of the cost of adopting new technologies, as future cost for different electricity generation technologies may be much lower. However, one important shortcoming of this study is that their model does not exhibit any intra-annual, temporal detail necessary to represent load, renewable resource profiles, and issues related to cross-country electricity trade in a meaningful manner. Also, the technology mix is exogenous following a prescribed profile.

Kunz, Hirschhausen, Möst, and Weigt (2011) use a bottom-up partial equilibrium model to compute short-term reactions of the german and the european power market to a german phase-out. They are modeling the dispatch on a single day of winter. However, all those energy economic models have short-comings in their time resolution. Either they compute long-run decisions or short-time dispatch, but no model links the different decisions. Another branch of research focuses on electricity dispatch models with high time resolutions (e.g. Ulbig, Koch, and Andersson 2012) which can represent dispatch and storage decisions sufficiently. However, their focus is on computation of optimal dispatch decisions given available data and given uncertainties.

Our analysis is also germane to the literature on integrating “top-down” and “bottom-up” models to overcome the shortcomings of the top-down and the bottom-up approach. Böhringer and Rutherford (2008) provides an overview of hybrid modeling efforts in energy policy evaluation. Their are basically three ways of synthesis between the two model types. The first way to integrate the two model types is a so called “soft link”. This means that two, potentially independently developed, models are used to access the same scenarios. The strength of this approach is that one can apply fully developed models. On the other hand one may run into problems of coherence. Models may apply inconsistent behavioral assumptions or different accounting. Examples are Drouet, Haurie, Labriet, Thalmann, Vielle, and Viguier (2005) or Schäfer and Jacoby (2006). The second approach is to use either a fully developed top-down or bottom-up model and integrate a “reduced form” of the other into one single optimization framework. An example for this is MERGE (Manne, Mendelsohn, and Richels 2006), where a fully grown bottom-up energy system model is linked with a highly aggregated one sector macro-economic model. Other examples are Bahn, Kypreos, Büeler, and Luethi (1999), Messner and Schrattenholzer (2000), Bosetti, Carraro, Galeotti, Massetti, and Tavoni (2006) or Strachan and Kannan (2008). The third class of hybrid models are completely integrated models sometimes referred to as “hard-linked”. Those models directly embed discrete representations of different technologies into a top-down model (Böhringer 1998, Böhringer and Rutherford 2008, Sue Wing 2006). While this approach is the most detailed one, at the same time this full representation of both model parts leads to high dimensionality and thus to high computational costs and constraints (Lanz and Rausch 2011). To overcome this shortcoming of the last approach Böhringer and Rutherford (2009) introduce an algorithm that can solve such a model by decomposing the two parts and solve them iteratively via a "soft-link" again. Examples are Tuladhar, Yuan, Bernstein, Montgomery, and Smith (2009) and Lanz and Rausch (2011). An often used approach to answer energy economic policy questions is to integrate a model of the electricity sector into a fully grown top-down CGE model.

The key innovation of this paper is that electric-sector optimization is fully consistent with the equilibrium response of the economy including endogenously determined electricity demand, fuel prices, and goods and factor prices. Fully integrating the electricity model with an economy-wide general equilibrium framework allows us to assess different policy options in terms of sound economic cost metrics while being able to explore the implications of alternative technology pathways.

The remainder of this paper is structured as follows. Section 2 presents the modeling framework. Section 4 presents our scenarios and simulation results. Section 5 concludes.

2 Analytical Framework

In order to analyze the economic impacts of the transition of Switzerland's electricity and energy sector, we embed a bottom-up copperplate model of the electricity sector into a top-down CGE representation of Switzerland as a small open economy. Both submodels are intertemporal dynamic, meaning that the agents in the resulting hybrid model exhibit perfect foresight. The following subsections will describe the submodels and our approach of integration.

2.1 Top-Down Economy-wide Model

As the top-down component of our hybrid model we employ a dynamic version of the CEPE GE model (Imhof 2011, Imhof 2012). The model has been developed as a contribution to Stanford's EMF (Energy Modeling Forum). CEPE is a multi-commodity energy economic GE model that has a rich representation of energy and fuel goods.

The version of the model we employ is of the classical Ramsey-type with endogenous depreciation and capital adjustment costs as developed in Imhof (2011). Firms have perfect foresight and maximize their present value profit over the whole model horizon. The employed version of the model includes 10 sectors producing 17 goods. The output can be exported or used domestically. Production for domestic use is combined with imports using the Armington assumption (Armington 1969). The Armington composite can be used as an intermediate input in production or in final demand. There are two demand-side agents. The representative consumer, who maximizes his discounted utility over the whole model horizon such that his budget constraint holds with equality, and the government, which buys a fixed bundle of goods and adjusts lump-sum transfers such that its budget is balanced period-by-period in all scenarios.

2.1.1 Data

CEPE is calibrated to the Swiss 2005 Input-Output table. This table was originally developed by the ETH in collaboration with Ecoplan Bern (Nathani and Wickart 2006, Nathani, Wickart, and van Nieuwkoop 2008). A second important data input are the elasticities of substitution. In the 2005 IO table energy goods are rather rough aggregates. CEPE exploits a database containing data on sectoral energy goods usage in physical units and sectoral energy prices to disaggregate the energy goods further. This allows the representation of sectoral energy use in the model and, thus, sectoral carbon emissions from fossil fuel combustion.

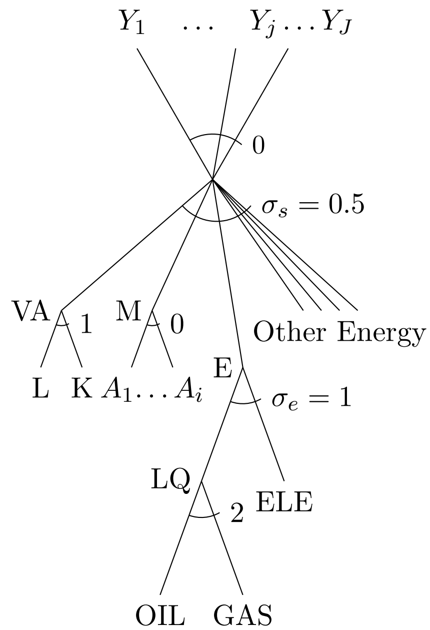
2.1.2 Energy Supply, Demand and Substitution Possibilities

CEPE-D covers 7 intermediate energy goods: Fuel oil, natural gas, coal, electricity, gasoline, diesel and kerosene. Switzerland is not endowed with any primary energy resources and has to import crude oil, coal, natural gas and uranium. While about half of Switzerlands demand for refined oil products is met by imports, the other half is produced from crude in the oil processing sector. Natural gas and coal are fully imported and the model's electricity sector is exogenously to the top-down model, determined by the bottom-up sub model.

The nested CES production function, common to all sectors but the electricity sector[4], and associated elasticities of substitution are illustrated in Figure 1. On the top nest less important

[4]While Imhof (2011) applies the same function to the electricity sector as well, we threat the electricity sector as exogenous to the GE model and use the bottom-up model to simulate its production function instead.

Figure 1: Production function nesting applied to all sectors



energy sources such as coal[5] and motor fuels[6] are substituted with a value added composite, intermediate goods and an energy aggregate with an elasticity of substitution of 0.5. The energy aggregate is produced in a Cobb-Douglas nest from electricity and fossil fuels, which combine fuel oil and natural gas inputs, substitutable with a constant elasticity of 2.

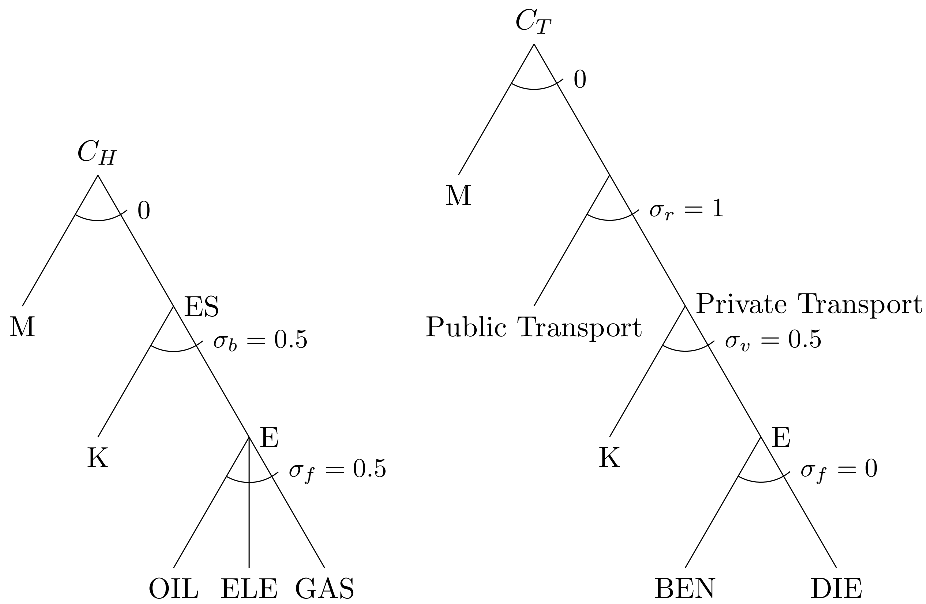
While final government demand for energy is fixed, the representative consumer has additional substitution possibilities. His one-period utility function combines consumption of non-energy activities with housing and transport services in the top nest. He can trade-off different activities with an elasticity of substitution of 0.5. Non-energy-related consumption goods are purchased with fixed budget shares.

Figure 2 demonstrates the substitution possibilities for the energy consuming activities of the consumer. In the lowest nest of the housing activity, fuel oil (OIL), natural gas (GAS) and electricity (ELE) are substituted with a constant elasticity of 0.5. The energy aggregate then trades-off with capital services representing improvements in furnaces, insolation or appliances.

[5]Coal plays a minor role in the Swiss economy. Coal accounts for less than one percent of total primary energy supply.

[6]Transport fuels covered are gasoline, diesel and kerosene. Kerosene is only used in the air transport sector and industrial demand for gasoline and diesel is minor.

Figure 2: Production function for housing and transportation services



To meet his transportation needs, the consumer purchases gasoline (BEN) and diesel (DIE) in fixed proportions. He can invest in higher fuel efficiency by substituting transport fuels with capital at a rate of 0.5. Finally, he spends fixed shares of his budget for public and private transportation.

2.2 Bottom-up Electricity Sector Model: Swissele

Our model of electricity dispatch maximizes the total surplus in the electricity market given some physical, economic and political conditions. The model takes the consumer surplus of the foreign consumer (the buyer of exports) into account to represent the fact that Switzerland is a small open economy, that acts as a price taker, but nevertheless its export decisions may influence the market price. Compared to other electricity dispatch models, an important feature of our model is the handling of trade in electricity. While most dispatch models do not pay major attention to trade issues, for Switzerland foreign electricity trade is very important, and thus an adequate electricity model for Switzerland has to take foreign trade into account. While imports are modeled to be perfectly elastic, we model export demand using a linear demand function calibrated to an elasticity of demand of 0.5 at 2010 prices and quantities. The model represents four load segments per day (night, morning, midday and evening) for each day of the 365 days in every modeled year, making a total of 1460 load segments per year. In what follows, we state the model algebraically and then in turn discuss each of the constraints. Sets, variables, and parameters are defined accordingly in the tables below.

$$
\begin{aligned}
\max \quad & \sum_t \beta^t \Bigg\{ p_t^{ele} p_0^{ele} AC_t \left(1 + \frac{2ac_t^0 - AC_t}{2\epsilon^D ac_t^0}\right) + \sum_s \theta_s \Big[p_0^X E_{s,t} \left(1 + 1/\epsilon^X \left(1 - \frac{E_{s,t}}{2e^0}\right)\right) \\
& - p_s^w I_{s,t} - \sum_j \left(p_t^a vc_j + p_t^{CO_2} \kappa_j^{CO_2} + p_t^{GAS} p_{ref}^{GAS} \kappa_j^{GAS} \right) G_{j,s,t} \Big] \\
& + \sum_j rk_t \big((\delta_j + r_j) kc_j + om_j \big) G_{j,t}^N \\
& + \sum_p rk_t \left(\delta_p + r_p\right) dc_p H_{p,t}^N + \sum_d rk_t \left(\delta_d + r_d\right) dc_d Q_{d,t}^N \Bigg\} \qquad (1)
\end{aligned}
$$

$$
s.t. \quad I_{s,t} + \sum_j G_{j,s,t} \geq c_{s,t} + E_{s,t} + \sum_p P_{p,s,t} \quad \forall s,t \qquad (2)
$$

$$
C(s,t) = c^0 s,t / ac_t^0 AC_t \qquad (3)
$$

$$
H_{s+1,t} = H_{s,t} + \theta_s \sum_p \left(\eta_p \cdot P_{p,s} - G_{p,s,t}\right) + \phi_s - RH_{s,t} \quad \forall s,t \qquad (4)
$$

$$
Q_{d,m+1,t} = Q_{d,m,t} - \sum_{s \in m} \theta_s \cdot G_{d,s,t} + \phi_{d,m} - RQ_{d,m,t} \quad \forall d,m,t \qquad (5)
$$

$$
\sum_s \theta_s \cdot E_{s,t} \geq \sum_s \theta_s \cdot I_{s,t} \quad \forall t \qquad (6)
$$

$$
0 \leq G_{j,s,t} \leq \alpha_{j,s} \cdot \left(cap_{j,t} + G_{j,t}^N\right) \quad \forall j,s,t \qquad (7)
$$

$$
0 \leq G_{j,t}^N \leq (1 - \delta_j) G_{j,t+1}^N \qquad (8)
$$

$$
0 \leq H_{s,t} \leq reservoir^H + \sum_p H_{p,t}^N \quad \forall p,s,t \qquad (9)
$$

$$
0 \leq H_{p,t}^N \leq (1 - \delta_p) H_{p,t}^N \qquad (10)
$$

$$
0 \leq Q_{d,m,t} \leq reservoir_d^Q + Q_{d,t}^N \quad \forall m,t \qquad (11)
$$

$$
0 \leq Q_{d,t}^N \leq (1 - \delta_d) Q_{d,t}^N \qquad (12)
$$

$$
0 \leq E_{s,t} \quad \forall s,t, \quad 0 \leq I_{s,t} \quad \forall s,t, \quad 0 \leq P_{p,s,t} \quad \forall s,t \qquad (13)
$$

$$
0 \leq RH_{s,t} \quad \forall s,t, \quad 0 \leq RQ_{d,m,t} \quad \forall s,m,t \qquad (14)
$$

The model accounts for variable cost of electricity generation as well as fixed operations & maintenance cost and fixed capital cost. The model maximizes total surplus subject to the market clearing condition (2) for every segment s of each year t. (3) distributes the annual

Table 1: Sets.

j	Technologies
p	Pump-and-storage plants (Subset of j)
d	Storage plants (Subset of j)
m	Months
s	Load segments
t	Years

Table 2: Variables.

$G_{j,s,t}$	Power generated by technology j in segment s [MW]
$G_{j,t}^N$	New vintage generation capacity [MW]
$I_{s,t}$	Imports in segment s [MW]
$E_{s,t}$	Exports in segment s [MW]
$P_{s,t}$	Pumping activity in segment s [MW]
$H_{p,s,t}$	Head in pump-and-storage reservoirs [MWh]
$H_{p,t}^N$	New vintage PHS reservoir capacity [MWh]
$RH_{s,t}$	Spill of water in pump-and-storage reservoirs [MWh]
$Q_{m,t}$	Head in storage reservoirs [MWh]
$Q_{p,t}^N$	New vintage seasonal reservoir capacity [MWh]
$RQ_{m,t}$	Spill of water in storage reservoirs [MWh]

domestic demand for electricity to the various load segments proportionally to what is reported by Swissgrid for 2010[7]. Equations (4) and (5) are updating the storage head of the short-term and the seasonal storage, respectively.

Equations (9) and (11) make sure that storage heads stay non-negative. While we have a separate storage equation for all new hydro storage technologies, we assume, that the pump-and-storage hydro facilities use the same reservoir. All those projects are built on existing lakes and dams and no new independent reservoirs are being built.

Constraint (7) restricts generation from all technologies to be non-negative and below the capacity limits taking into account availability in every specific segment. Since our representation of investment in new technologies is based on annual renting cost of capital (and annual fixed O&M expenditures), we need equations (8), (10) and (12) to ensure that capacities extend in a smooth way, and must not decrease by more than their exogenously given depreciation rate.

Equation (6) is a political constraint that requires annual imports to be balanced with

[7]See Figure 5a in the appendix.

Table 3: Parameters.

θ_s	Hours in load segment s [h]
vc_j	Variable cost [CHF/MWh]
δ_j	Linear depreciation rate of technology j
r_j	Return to investment including risk premium
p_s^w	Import price of electricity [CHF/MWh]
c_s	Consumption in load segment s [MW]
η_p	Efficiency of pumping [MW/MW]
$\kappa_j^{CO_2}$	Carbon intensity of technology j [t CO_2/MWh]
κ_j^{GAS}	Gas inputs for technology j [PJ/MWh]
$\phi_{p,s}^H$	Natural inflow to pump-and-storage reservoirs [MWh]
$\phi_{d,m}^Q$	Natural inflow to storage reservoirs [MWh]
cap_j	Installed capacity of technology j [MW]
$\alpha_{j,s}$	Availability of technology j in segment s
$reservoir_p^H$	Pump-and-storage reservoir capacity in [MWh]
$reservoir_d^Q$	Storage reservoir capacity in [MWh]
e_{ref}	Average export load in 2010 year [MW]
px_{ref}	Annual average export price [CHF/MWh]
ϵ^D	Price elasticity of domestic demand
ϵ^X	Price elasticity for exports

annual exports. Of course this self-sufficiency policy is costly and the stability of the system hinges critically on the ability of the system to trade electricity. However, the federal authorities are keen to maintain annual autarky of electricity supply. Dropping this constraint allows for an assessment of the additional cost implied by this virtual autarky.

2.3 Combining Bottom-up and Top-down

In principle, a bottom-up representation of the electricity sector can be integrated directly within a GE framework by solving Kuhn-Tucker equilibrium conditions that arise from the bottom up cost-minimization problem, along with general equilibrium conditions describing the top-down model (Böhringer and Rutherford 2008). In applied work, this approach may be infeasible due to the large dimensionality of the bottom-up problem. Moreover, the bottom-up model involves a large number of bounds on decision variables, and the explicit representation of associated income effects becomes intractable if directly solved within a GE framework (Böhringer and Rutherford 2009).

Our computational strategy is to use a block decomposition algorithm put forward by

Böhringer and Rutherford (2009) that involves an iterative procedure between both submodels solving for a consistent general equilibrium response in both models. The first step for implementing the decomposition procedure in an applied large-scale setting is the calibration of the two submodels to a consistent benchmark point. Initial agreement in the base year is achieved if bottom-up electricity sector outputs and inputs for all regions and generators are consistent with the aggregate representation of the electric sector in the Social Accounting Matrix (SAM) data.[8] To produce a micro-consistent SAM, a benchmarking routine was developed for a no environmental policy BAU wherein Swissele was solved with historical (fixed) prices for capital, labor, and fuel as well as fixed electricity demands.[9] Given Swissele electricity supplies and inputs demands, optimization techniques to estimate a new SAM holding fixed the (simulated) electric sector data. Our benchmarking routine implies that, in absence of a policy shock, the integrated model is fully converged for a BAU scenario.

Each iteration in the solution algorithm comprises two steps. Step 1 solves a version of the CEPE model with exogenous electricity production where electricity sector outputs and input demands for fuels, capital, labor, and other materials, are parametrized based on the last available solution of the Swissele model. The subsequent solution of the Swissele model in Step 2 is based on a locally calibrated demand function for electricity and a vector of candidate equilibrium prices for fuels, capital, labor, and materials. The key insight from Böhringer and Rutherford (2009) is that a Marshallian demand approximation in the electricity sector provides a good local representation of general equilibrium demand, and that rapid convergence is observed as the electricity sector is small relative to the rest of the economy.[10]

For all other commodities, CEPE simply passes commodity prices to Swissele, and Swissele treats these prices as parameters for a given iteration. Both submodels are intertemporal

[8] This step is necessary to ensure that in the absence of a policy shock iterating between both submodels always returns the no-policy benchmark equilibrium. Violation of this initial condition means that any simulated policy effects would be confounded with adjustments due to initial data inconsistencies between the two submodels

[9] Wholesale electricity is an output of the Swissele model, and remained so for the benchmarking routine. Electricity price distribution markups were estimated to be about one third of the benchmark wholesale electricity price.

[10] In our simulations, rapid convergence is observedusually eleven to thirteen iterations are neededas the electricity sector is small relative to the rest of the economy. The Swiss electric sector represents less than 5% of GDP.

dynamic implying that convergence between both submodels has to be established for all time periods in one shot.

A consistent integration of both models needs to capture all profits earned by sub-marginal generators in the electric sector. Profits or rents arise because of capacity, transmission and resource constraints. In Swissele the producer surplus represents the sub-marginal profits of technologies/generators that produce electricity at a cost that is smaller than the cost of the marginal generator and sell it at the market price which in equilibrium is equal to the marginal cost. We can calculate total sub-marginal profits as the difference between the value of electricity output and the value of inputs used to produce electricity.

Finally, implementing an economy-wide carbon policy in the integrated model requires iterating on the price of carbon and the demand for CO_2 emissions permits. We thus pass a candidate carbon price from CEPE to Swissele, and the subsequent solution of CEPE then calculates a new estimate for the equilibrium carbon price based on demands for emissions permits by the electricity and non-electricity sectors.

2.4 Data and Assumptions

This section (1) provides an overview of electricity generation and trade in Switzerland, (2) describes the data and sources we use to parametrize the model, and (3) discusses some of the key assumptions underlying our numerical simulations.

2.4.1 Electricity Generation and Trade in Switzerland

In 2010, Switzerland had a gross domestic electricity consumption of 64.2 TWh. End use net of transmission and other losses had been 59.8 TWh. At the same time generation had been 66.3 TWh, where 37.5 TWh (56.5%) stemmed from hydro power (The two dominating hydro power technologies are run-of-river facilities, which accounted for 16.0 TWh and storage facilities, which had a gross production of 21.5 TWh and a pump demand of 2.6 GWh.), nuclear accounted for 25.2 TWh (38.1%) and conventional thermic and other technologies generated 3.6

Table 4: Power Generation in Switzerland

	capacity [MW]	average availability [%]	generation in 2010 [TWh]
Nuclear	3253	88.5	25.2
Run-of-river	3768	48.6	16.0
Storage hydro	8073	-	(17.4)
+Pump-and-storage	2139	-	(+1.6) = 21.4
-pump		-	2.5
Conventional thermic	490	81.1	3.5
Wind	42	(28)	0.04
Photovoltaic	111	(12)	0.08
Total generation	15779	47.9	66.3
Imports			66.8
Exports			66.3
Losses & Waste			4.5

Source: SFOE (2011b, 2011c, 2012a)

TWh (5.4%).[11]

Figure 3 shows the load profile of the Swiss electricity network for the whole year as well as for the month of June 2010 based on data provided by Swissgrid for 2010 available for a resolution of 15 minutes time slices.[12] Notably, electricity trade with surrounding countries plays a huge role for Switzerland. In 2010 Switzerland imported electricity of 66.8 TWh and exported 66.3 TWh, resulting in a small net import balance of 0.5 TWh. This trade is due to the geographic location of Switzerland, as well as the economic incentive to do arbitrage on the european markets using the highly flexible hydro storage devices to store energy when prices are low and provide power when prices are high. Third, the generation profile of Switzerland is such that due to the run-of-river hydro plants more electricity is produced during summer months, which can be exported, and less during winter, when demand is higher and Switzerland, thus, relies on imports. Figure 4 illustrates the net trade flows in 2010.

3 Swissgrid Data

Figure 5a displays the load curve for 2010 in 15 minute resolution as published by Swissgrid. Since our model represents 4 time slices per day, we aggregate the 15 minute time steps to 1460

[11] Other technologies include electricity generated from wind (27 GWh) and photovoltaic (80 GWh), while conventional thermic sources account for the major share.

[12] Available online at http://www.swissgrid.ch/swissgrid/de/home/experts/topics/energy_data_ch.html

Figure 3: Load Curves for 2010

(a) 2010 Real Data from Swissgrid (b) 2010 Real Data for June

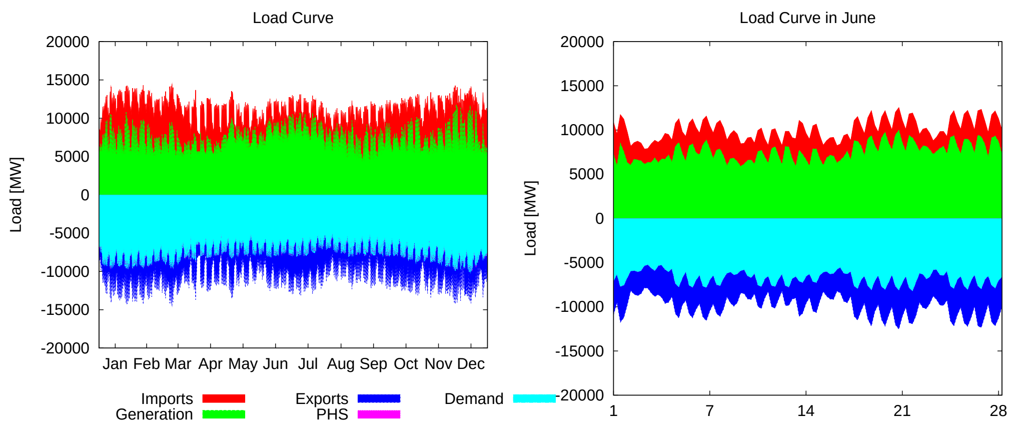
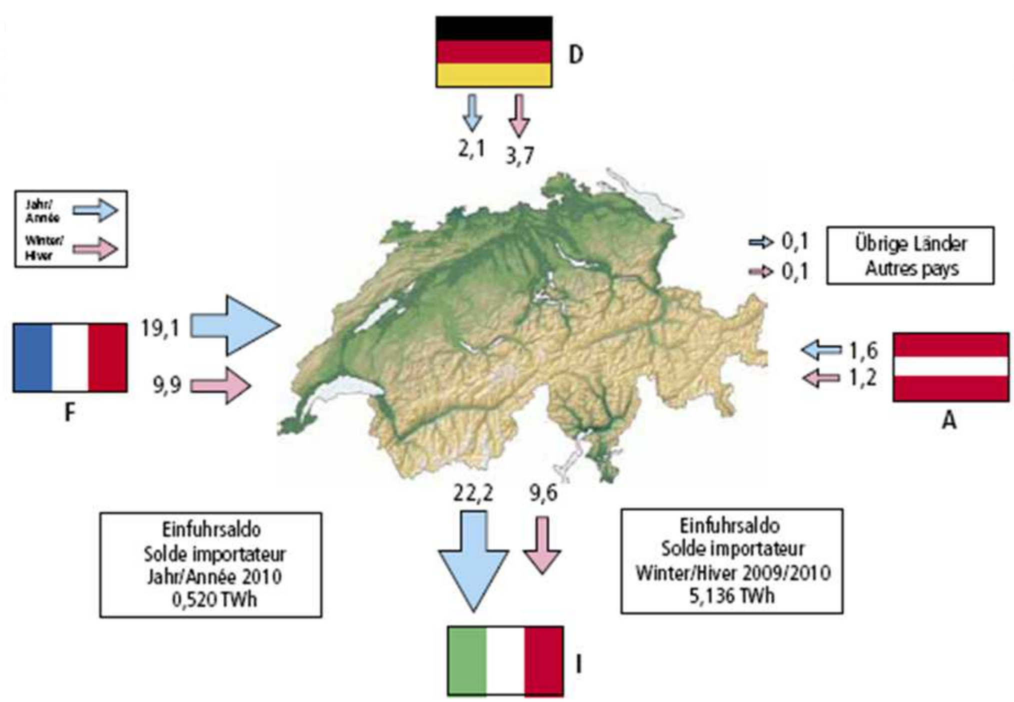
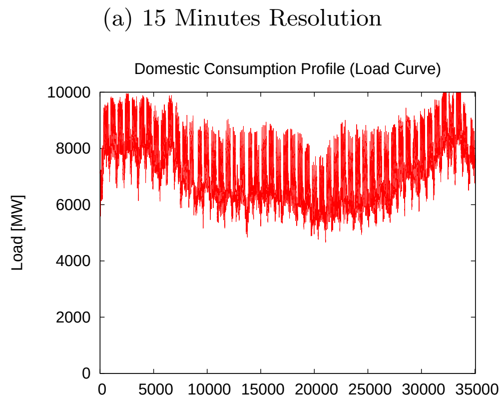


Figure 4: Electricity Trade in 2010



Source: SFOE (2011b).

Figure 5: Load Curves for 2010



load segments over the year. The corresponding load curve is displayed in Figure 5b.

As the two curves show, the generated load curve with four load segments per day results in a very similar load curve than the high resolved curve from the 15 minutes data. We also tested the bottom-up model and run it for a single year with 15 minutes time slices and results do not largely differ.

3.0.1 Nuclear Phase-out

The five existing nuclear reactors in Switzerland are Beznau I and II, Mühleberg, Gösgen and Leibstadt. Table 5 displays some important facts. The federal council decided to phase-out electricity gradually until 2034 by not extending expiration dates of existing plants and not building any new ones. This leaves the power sector with a relatively long time to plan a future without nuclear technologies. However, the load to replace is large and sums up to a total of 3253 MW operated at a availability rate of around 90 %. If a large fraction of the existing generation capacity is laid idle, the question arises how to substitute for short-falling capacities. Potential alternatives are discussed in the following subsections.

3.0.2 Imports

Imports could provide a simple means of providing electricity. However, there are two important short-comings of this option. First, importing electricity may be viewed as being critical, since,

Table 5: Nuclear power plants in Switzerland

Reactor	Capacity [net MW_e]	Utilization rate in 2010 [%]	Average rate between 2001 and 2010 [%]	Generation in 2010 [TWh]	Year of Expiration
Beznau I	365	83.1	92.4	2.6	2019
Beznau II	365	88.6	90.5	2.8	2021
Mühleberg	373	91.1	91.5	3.0	2022
Gösgen	985	93.1	93.6	8.0	2029
Leibstadt	1165	86.1	86.7	8.8	2034
Total	3253	88.7	90.4	25.2	-

Source: SFOE (2011b) Table 17 and own calculations

imported power would mainly stem from nuclear plants or fossil fuel combusting technologies. Second, it may be politically infeasible to become dependent from net imports on an annual basis.

While increased electricity trade over the last decades has helped to increase systemic stability and to raise revenues, politicians and voters may still feel obliged to have a net balanced electricity trade at the end of the year. The exogenously given spot market prices are taken from SWISSIX for 2010. The resulting import prices are displayed in Figure 6.

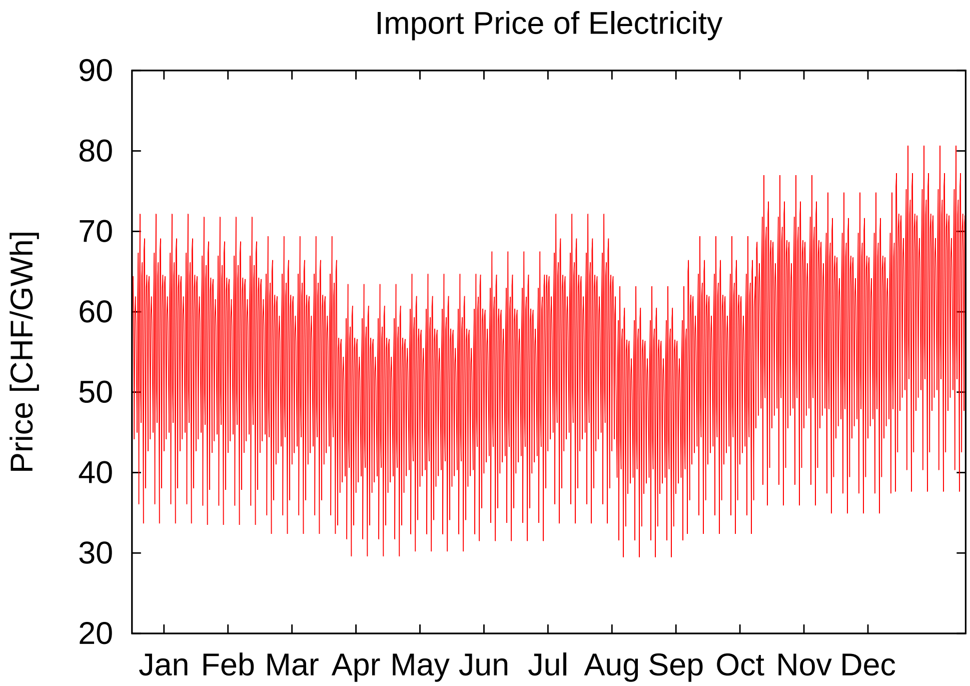
3.0.3 Natural Gas

Natural Gas may provide electricity when needed. Short planning and building times may be helpful to overcome temporary leaks in supply and the potential to provide electricity is hardly bounded. However, high marginal cost and associated CO_2 emissions may be undesirable. Three different technologies are considered in the model. Gas plants can be built either as conventional or advanced combined cycle plants or as advanced combined cycle with carbon capture and storage (CCS). We take the price structure for natural gas-fired plants from EIA (2012)'s estimates as reported in Table **??**.

3.0.4 Hydro Power

We used Laufer, Grötzinger, Peter, and Schmutz (2004) as a source of potential water power improvements. Later studies used this data source and applied several other issues to it. However,

Figure 6: Import prices in 2010



the newest study (SFOE 2012b)[13] implies that potentials may be much smaller due to several reasons. Instead of a potential increase of 7.57 TWh only increases of 4.56 TWh are reported.

Figure 7 shows the location of existing and potential pump-and-storage plants in Switzerland. Green circles represent existing capacities of 1400 MW, orange facilities are built at the moment and account for 2140 MW, blue spots mark projects for another 1630 MW, which are waiting for a construction license and gray circles denote early project ideas. Table 7 reports main characteristics of the projects.[14]

The existing sites are included in the benchmark replication already and we explicitly model all orange and blue projects as investment possibilities.

[13]Based on SFOE (2011a) and Laufer, Grötzinger, Peter, and Schmutz (2004)

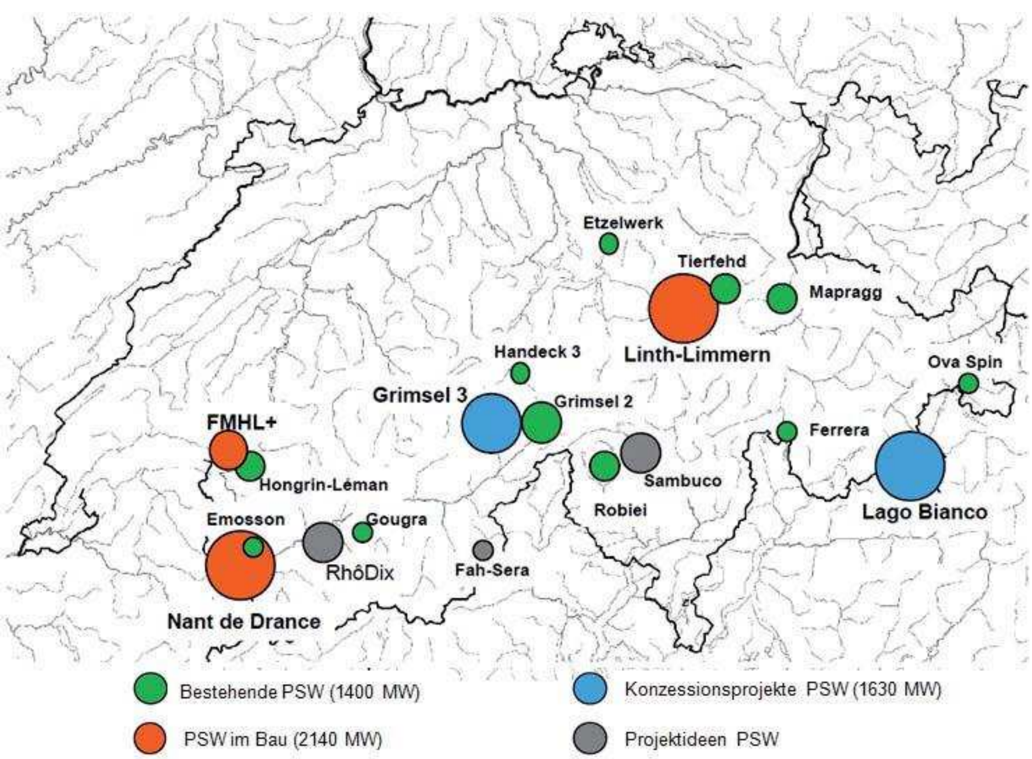
[14]Despite the fact that new pump-and-storage plants are built, no model run can support profitability of such devices. The prospect of buying future new renewable power from Germany may provide a case, but Hildmann, Ulbig, and Andersson (2011) detect economic risks for storage capacities in those scenarios.

Table 6: Capacity Improvement for Hydro Power

Type of improvement	Annual (GWh)	Power (MW)	Investment CHF/kW
Equipment high pressure Run-of-river	390	210	318
Delta Q high pressure Run-of-river	220	200	1100
Delta Height low-pressure Run-of-river	200	35	3429
Retrofit low-pressure Run-of-river	540	150	6480
New high-pressure Run-of-river	1200	500	4440
New low-pressure Run-of-river	1900	420	8143
Total Run-of-River	4450	1515	
Equipment storage hydro	360	120	300
Retrofit storage hydro	400	230	3130
New storage hydro	2360	1200	6883
Total Storage Hydro	3120	1550	

Source: Laufer, Grötzinger, Peter, and Schmutz (2004) Table A1-1

Figure 7: Pump-and-storage Locations and Capacity of new and existing Facilities



Source: Stettler (2011).

Table 7: Data of New Pump-and-Storage (Cost in billion CHF)

	Project	Investment Cost [million CHF]	Increased Storage [GWh]	Generation [MW]	Year of Completion
hyd-pum	Existing			1400	existing
PHS1	Hongrin-Leman	330	0	240	2015
PHS2	Linth-Limmern	2100	0	1000	2015
PHS3	Nant de Drance	1800	192	900	2017
PHS4	Grimsel 3	700	0	630	projected
PHS5	Lago Bianco	1500	0	1000	projected

Source: Own Survey based on project related publications by energy providers.

Table 8: Solar and Wind Power Potentials in Switzerland

Technology	Investment [CHF/kW]	Capacity [MW]	Average availability [%]	Generation [TWh]	Source
Wind		2000	22.8	4	[1]
	1700	-	9.1 - 22.8	-	[2]
		-	-	13	[3]
Photovoltaic	8000 - 2830	12000	11.4	12	[4]
		-	-	13	[3]

Source: EOLE (2012) [1], SFOE, FOEN, and ARE (2004) [2], VSE (2012) [3] and Swissolar (2012) [4].

3.0.5 Wind and Photovoltaic

Often discussed are new renewables as photovoltaic and wind power. However, the potential for those technologies in Switzerland is limited. Positive estimates on the potential capacities report 12 TWh of photovoltaic and 4 TWh of wind electricity (even though VSE reports up to 13 TWh each.). However, those estimates are very enthusiastic and more conservative numbers may be appropriate.

While annual production of wind and photovoltaic is relatively well predictable, the hourly and daily outputs are uncertain. This causes additional cost as peak load generating units may be activated to cover short-falling generation from new renewables. On the other hand, photovoltaic produces electricity especially during summer, when, traditionally electricity production is high from run-of-river hydro plants and demand is low. This would harden the systemic inefficiency of the annual Swiss electricity production schedule. Wind, which has a much lower potential in Switzerland, would be cheaper and would produce relatively more energy in winter months. This would be desirable and thus wind power seems to be a good complement to run-of-river hydro

Table 9: Model Input for Wind and Photovoltaic Technologies

Site	Average availability [%]	Capacity [MW]	Expected [GWh]	Investment cost [CHF/kW]
		Wind		
existing	28	30	74	0
wind 1	23	397	800	1700
wind 2	20	457	800	1700
wind 3	17	537	800	1700
wind 4	14	652	800	1700
wind 5	10	913	800	1700
		Photovoltaic		
existing	12	152	160	0
PV 1	10	2740	2400	3000
PV 2	9	3044	2400	3000
PV 3	8	3425	2400	3000
PV 4	7	3914	2400	3000
PV 5	6	4566	2400	3000

power. Finally Hildmann, Ulbig, and Andersson (2011) point out, that photovoltaic panels produce their output mainly around noon, when demand is highest during the day. However, evidence suggests that those peak loads have become smaller over the last decade. Both effects may drive price spreads to become smaller and thus may prevent storage technologies from becoming profitable. Table 9 shows the photovoltaic and wind technologies in the model. We assume that potential production increase is split over 5 type of sites with different capacity factors.

3.0.6 Geothermal

The technological potential for electricity generation from geothermal sources is estimated to be 17 TWh (Axpo, 2007). Geothermal is characterized by high upfront investment cost of the drilling, that accounts for about 65 75% of the investment cost with a 10-20% risk of failure. Failure could occur, as after drilling may be discovered that the underground is not ideal for electricity generation or seismic activities and associated damages may occur. Once a plant is built it produces base load electricity at very low marginal cost. Geothermal electricity has thus the potential to replace nuclear plants with a similar production schedule at comparable cost.

Table 10: Marginal Cost of Generation

	variable O&M [CHF/MWh]	fixed O&M [CHF/kW]	Investment Cost [CHF/kW]
Nuclear	11.7	43	9500
Conventional	24.0	40	6181
Run-of-River Hydro	6.3	17	6710
Pump-and-Storage	0.0	17	5500
Storage Hydro	0.0	17	5500
Gas-ccc	45.6	21	1320
Gas-acc	42.1	21	1352
Gas-ccs	49.6	21	2556
Wind	0.0	9	1700
Photovoltaic	0.0	9	3000
Geothermal	9.5	13	8800

Source: EIA (2012), Severance (2009), Ströbel, Pfaffenberger, and Heuterkes (2012) and IEA (2003).

3.1 Marginal Cost of Production

Table 10 reports marginal cost of production, fixed operation and maintenance cost and investment cost.

4 Scenarios and Results

4.1 Scenarios

In all scenarios we assume that Switzerland adopts a stringent carbon policy that is in line with the European targets as well as the proposals in the *Energiestrategie 2050.* The target is a reduction of carbon emissions by 20% below 1990 levels in 2020, and a reduction of 80% in 2050. We assume a linear reduction path that reduces emissions by 2 percentage points every year until 2050, where it will remain at 80% thereafter. To achieve this reduction target we implement a CO_2 tax which revenues are redistributed back to consumers lump-sum, leaving the tax reform to be revenue neutral.

While the business-as-usual scenario has only a CO_2 target and no restrictions on the electricity generation, we compute phase-out policies in the counterfactual. In those counterfactuals we assume that no new nuclear plants will be build, and that the existing ones will be put to rest at the end of a 50 years life-span. Thus, we compute scenarios where the power sector has

Table 11: Scenarios

Name	Description
CO2_BAU	Climate policy target
CO2_PO	Besides the climate policy target, nuclear power is phased-out
CO2_PO_GEO	We assume that large-scale geothermal plants can be built for a capacity of up to 2000 MW
CO2_PO_Gas	We assume that gas prices are 20% higher than assumed in the other scenarios

to deal with a short-fall of up to 3253 MW of its benchmark capacity, which has been operated at a high and stable availability of around 90%. We compare counterfactuals which differ with respect of the technologies allowed. We compute the phase-out scenario for counterfactuals where geothermal plants can penetrate the market or gas prices may be 20% higher then the benchmark predictions. The scenarios are summarized in Table 11.

4.2 Results

to be written

5 Conclusions

To shed light on the mechanics that drive the cost of Swiss electricity production and to provide an estimate of the additional cost imposed by a nuclear phase-out in a climate-constrained world, this paper develops a hybrid energy economic model of the Swiss economy. The model we propose builds on the decomposition technique developed by Böhringer and Rutherford (2009) as applied by Lanz and Rausch (2011). We integrate a copperplate bottom-up model of Switzerland's electricity generation, capacity expansion and trade into a top-down computable general equilibrium (CGE) model that represents Switzerland as a small open economy. However, we improve the literature in two ways. On the one hand no full grown hybrid model has yet been used to analyze the energy transition in Switzerland, and second, the hybrid modeling literature restricted itself to static or recursive-dynamic models so far. Since in both our submodels agents exhibit perfect foresight, the resulting integrated model exhibits perfect foresight as well.

Preliminary results suggest that a nuclear phase-out policy that forbids to build new plants and restricts the lifespan of the existing nuclear plants to 50 years does not add much additional cost in a low carbon future. However, availability of cheap alternatives, as large scale geothermal generation units or carbon capture and storage technologies could decrease the cost considerably. We find that conventional gas powered plants may well serve as a 'bridge' technology, but are likely to be too expensive once a severe carbon tax is put in place.

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