Coupled energy economic model framework for analyzing Swiss electricity markets in changing policy environments

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Lausanne, August 17, 2016 Sophie Maire

Abstract

Energy policy needs to rely on the proper understanding of the interactions between policy instruments, consumer preferences, investment behavior, market structure, electricity supply, and the wider policy environment. This asks for appropriate modeling tools, able to represent precisely electricity supply options, model all types of energy and climate policies, as well as the reactions of the rest of the economy.

Chapter 2 describes the ELECTRA-CH framework, developed to analyze electricity markets in Switzerland. This framework is composed of two component models: (1) a dynamic electricity supply model, CROSSTEM-CH, and (2) a dynamic computable general equilibrium (CGE) model of the Swiss economy, GENESwIS. The two models are coupled through an iterative soft link.

Electricity market liberalization is altering pricing mechanisms in wholesale electricity markets, and thus the links between generation costs and user prices. This will affect the effectiveness of climate and energy policies. Models used to simulate such policies must be responsive to pricing rules. Chapter 3 shows how this can be done with the ELECTRA-CH framework and simulates a tightening of climate and energy policies. In the coupling procedure, the link between wholesale electricity prices (top-down) and generation costs (bottom-up) depends precisely on regulatory market assumptions: In the regulated market, wholesale electricity prices are "cost-plus", while they depend on marginal generation costs in the liberalized market. We show that, in Switzerland, an electricity tax is significantly more effective in reducing electricity demand in the liberalized than in the regulated market.

Technology restrictions are still widely used in energy policy. Concerns about security, climate, or jobs preservation induce political quasi-selections of electricity generation technologies. Instruments inherited from regulation, technology restrictions may have different impacts on the economy when markets are largely liberalized. In chapter 4, we analyze (1) a balanced-trade scenario in which Switzerland's annual electricity production must be equal to its consumption; and (2) a no-gas scenario that forbids gas-fired power plants, but accepts net electricity imports. For Switzerland, the prohibition of gas-fired power plants and relaxation of trade constraints lower average cost while increasing marginal cost. With marginal cost pricing in liberalized markets, this increases profits. Reduction in total system cost and increase in electricity price affect welfare in opposite ways. A pure bottom-up analysis would overestimate the benefits of technology restrictions.

Our framework's strength lies in the capacity of exploring interactions in a complex economic system, rather than in strict policy recommendations. Therefore, in this thesis, the emphasis is put on the understanding of mechanisms. At the end of this research, it has been shown that energy modelers must communicate and temper their results carefully. While much has been said about the impact of assumptions on substitution elasticities and exogenous costs projections on modeling results, this research adds to the awareness on the effects of market liberalization assumptions and choice of modeling framework on policy assessment.

Keywords: *energy policy, electricity markets, market liberalization, energy modeling, top-down model, bottom-up model, soft-link coupling, general equilibrium.*

Résumé

Une politique énergétique judicieuse s'appuie sur la compréhension des interactions entre les instruments politiques, les préférences des consommateurs, le comportement des investisseurs, l'offre en électricité, et l'environnement politique au sens large. Pour ceci, l'on a besoin de s'appuyer sur des outils de modélisation appropriés qui ont les capacités de représenter de manière précise et adéquate les options d'offre d'électricité, les instruments des politiques énergétique et climatique, ainsi que les réactions de l'économie en général.

Le chapitre 2 présente le modèle ELECTRA-CH, développé en vue d'analyser les marchés de l'électricité en Suisse. Il se compose de deux modèles : (1) un modèle dynamique d'offre de l'électricité - CROSSTEM-CH - et (2) un modèle dynamique d'équilibre général calculable de l'économie suisse - GENESwIS. Les deux modèles sont couplés à l'aide d'une méthode itérative d'échange de variables (soft-link).

La libéralisation des marchés de l'électricité change la façon dont les prix de gros de l'électricité sont déterminés, et par conséquent le lien entre les coûts de génération et le prix facturé à l'utilisateur final. Cela peut modifier l'efficience des politiques énergétiques et climatiques. Par conséquent, les modèles utilisés pour simuler ces politiques doivent prendre en compte la façon dont les prix sont déterminés, ce que nous proposons au chapitre 3 avec le modèle ELECTRA-CH. Lors du couplage des deux modèles, le lien entre les prix de gros de l'électricité (modèle top-down) et les coûts de générations (modèle bottom-up) dépend précisément des hypothèses sur la libéralisation du marché : pour un marché régulé, les prix de gros sont déterminés à prix coûtant majoré, alors qu'ils dépendent des coûts marginaux de production dans un marché libre. Nous simulons un durcissement des politiques climatiques et énergétiques pour deux hypothèses de libéralisation du marché et montrons que, pour la Suisse, une taxe sur l'électricité réduit la consommation d'électricité de manière plus significative dans un marché libre que dans un marché régulé.

Les restrictions technologiques sont omniprésentes en politique de l'énergie. En effet, de préoccupations concernant - entre autre - la sécurité, le climat, ou la protection de l'emploi, peuvent naitre des choix politiques en rapport avec les technologies de production de l'électricité. Communément utilisées sous régulation, les restrictions technologiques peuvent avoir un impact différent lorsque les marchés sont largement libéralisés. Au chapitre 4, nous analysons (1) un scénario dans lequel la production indigène et la demande d'électricité annuelle suisse doivent se compenser ; et (2) un scénario "sans gaz" qui interdit la construction de centrales électriques au gaz, mais accepte des importations annuelles nettes d'électricité. Pour la Suisse, l'interdiction de construire des centrales à gaz et la relaxation des contraintes sur les importations d'électricité baissent le coût moyen de l'électricité, tout en augmentant le coût marginal. Dans le cas d'un marché libéralisé - où le prix de gros dépend du coût marginal - cela augmente les profits. La diminution du coût total de production et l'augmentation du prix de l'électricité ont des effets opposés sur le bien-être. Une analyse se basant purement sur un modèle de type bottom-up surestimerait les bénéfices d'une telle politique.

La capacité d'explorer les interactions dans un système économique complexe fait la force de notre modèle. Ainsi, cette thèse se concentre sur la compréhension des mécanismes en jeux, et ne se lance pas dans des recommandations et prédictions par rapport aux politiques analysées. A l'aboutissement de cette recherche, il ressort qu'une communication minutieuse des résultats et particulièrement des modèles et hypothèses utilisés est cruciale. Alors que les impacts des choix liés aux élasticités de substitution et aux coûts exogènes sont bien connus, cette recherche souligne l'importance des hypothèses sur la libéralisation des marchés et du type de modèle utilisé pour l'évaluation des politiques étudiées.

Mots clefs: *politique énergétique, marchés de l'électricité, libéralisation des marchés, modélisation, modèle d'équilibre général calculable, modèle d'offre de l'électricité, couplage soft-link*

Declaration

This thesis is an account of research undertaken between November 2011 and May 2016 at the Laboratory of Environmental and Urban Economics (LEURE), École Polytechnique fédérale de Lausanne (EPFL), Lausanne, Switzerland, and the consulting firm Econability, Mühlethurnen, Switzerland.

Except where acknowledged in the customary manner, the material presented in this thesis is, to the best of my knowledge, original and has not been submitted in whole or part for a degree in any university.

This thesis work is born of the project *ELECTRA - Electricity markets and trade in Switzerland and its neighboring countries: Building a coupled techno-economic modeling framework* financed by the research program Energy-Economy-Society of the Swiss Federal Office of Energy. Three institutions were involved in the project: the consulting firm Econability, the Laboratory of Environmental and Urban Economics (LEURE) at EPFL, and the Energy Economics Group from Laboratory for Energy Systems Analysis (LEA) at Paul Scherrer Institute (PSI).

This thesis investigates the interplay between electricity markets and the rest of the economy in changing policy environments with the help of the ELECTRA-CH framework. My contribution in the creation of ELECTRA-CH involved the conception and implementation of the coupling procedure as well as further development of the existing GENESwIS model. The modifications of GENESwIS involved namely the introduction of the energy-disaggregated input-output table, further data collection and disaggregation of the input-output table, modification of nesting structures, modeling of 5-year steps putty-clay capital, implementation of climate and energy policies, and alterations related to the coupling procedure. The conception and implementation of the coupling procedure between GENESwIS and CROSSTEM-CH included - among others - the development of the coupling methodology, the liaison with the bottom-up modelers on the comprehension of their work and of how to harmonize and modify the models, the creation of an automated coupler, troubleshooting, and analysis of the results.

All developments of the CROSSTEM-CH model are the work of Rajesh Pattupara, Kannan Ramachandran and Hal Turton. Despite some model descriptions and results from CROSSTEM-CH appearing in this thesis for the sake of consistency and completeness, I do not claim any intellectual ownership on the bottom-up modeling.

The body of the thesis is composed of three articles. The three articles were written by myself, with valuable insight, discussions and corrections provided by my supervisors Philippe Thalmann and Frank Vöhringer.

Lausanne, August 17, 2016 Sophie Maire

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Chapter 1

Introduction

Energy policy transitions may be initiated by multiple drivers, ranging from concerns about energy supply security, reduction of energy intensity or pollution-related health issues, to political agreements to mitigate climate change.

Following the Fukushima nuclear disaster, the Swiss Government took the decision to redefine its energy policy. The Swiss Federal council put forward the Energy Strategy 2050, which aims for an energy supply for Switzerland that is cost-effective, respectful of the environment and safe.

In accordance with this strategy, nuclear power plants are to be decommissioned at the end of their "safe" operational lifetime and not replaced by new nuclear plants. It is yet unclear whether a time-limit will be set on the operation of nuclear plants, or if they will be allowed to run as long as safety standards are met. With the phase-out of nuclear, projected electricity supply options rely on renewables and, if necessary, gas-fired combined-cycle power plants and combined heat and power plants.

While the Swiss Energy Strategy 2050 plans to foster energy efficiency improvements and promote renewables, the nature of the policies to be put in place in this regard - namely the replacement from 2020 of the existing promotion system by incentive mechanisms - is still under discussion.

Also in transition and under discussion is the liberalization of Swiss electricity markets. Currently, Swiss electricity markets are partly liberalized: Large consumers (annual consumption > 100 MWh) can choose their supplier and decide to pay market prices instead of regulated tariffs. Full market liberalization has been postponed and will depend on the advancement of the legislative work on the Energy Strategy 2050, the situation of the electricity market, and the negotiations with the European Union regarding the full integration of the Swiss electricity market into the European electricity market, which are still ongoing.

Energy policy needs to rely on the proper understanding of the interactions between policy instruments, consumer preferences, investment behavior, market structure, electricity supply, and the wider policy environment. Gaining such an insight on the mechanisms at work helps taking into account the transient state of both policy landscape and energy markets, which is essential for designing adaptable policies that can be adequately modified to reach the objectives in changing policy environments.

The objective of this thesis is to investigate the interplay between the electricity market and the economy in changing policy environments. This asks for an appropriate modeling tool, able to represent precisely electricity supply options, model all types of energy and climate policies, as well as the reactions of the rest of the economy.

1.1 The choice of an appropriate modeling tool

Climate and energy policy analysis is mostly informed by two modeling approaches: bottom-up and top-down.

Bottom-up models are based on extensive technological detail and are very well suited to model technology choices. They are typically set as partial equilibrium models of the energy sector(s) and maximize total surplus, although some models - like the CROSSTEM model used in this work - take exogenous vertical demand functions and minimize total system cost. Bottom-up models therefore lack feedback from the economy, and particularly macro-economic reactions to policy shocks. Moreover, their optimization nature requires an efficient allocation of resources, which prevents them from taking into account inefficiencies such as initial tax distortions, income effects or market failures. Bottom-up models can implement precisely command-and-control policies as well as technological constraints. However, due to integrability constraints, ad-valorem taxes aren't implemented easily in mathematical programing (Böhringer and Rutherford, 2008).

Top-down models are aggregated, consistent macro-economic frameworks with micro-economic foundations that simulate the interactions between consumers, producers and the public sector. Typically, they display smooth production functions with elasticities of substitution, calibrated on benchmark values. Moreover, they are often written as mixed complementary problems (MCP) in which each constraint that is associated with an income effect must be linked to a shadow variable. The introduction of discrete technologies hence increases complexity and dimensionality very quickly (Böhringer and Rutherford, 2008, 2009). This prevents top-down models from adequately modeling discrete technologies, technical constraints and worlds very different from today's. These models are designed to assess market-based policies and very well suited to investigate second-best-world situations with initial tax distortions. However, they struggle to incorporate technology-specific or command-and-control policies adequately.

The combination of top-down and bottom-up models into a single framework (Hourcade et al., 2006) endeavors to incorporate the technological explicitness of bottom-up models with the micro-economic representation of agents' behavior in a general equilibrium of flexible markets provided by top-down models. A lot of effort has been devoted to developing and assessing coupling methods since the first coupling by Hoffman and Jorgenson (1977). Two main currents emerged: "hard linking", which encompasses the two model types into one single model, and "soft linking", which couples existing full-size models by exchange of variables (Wene, 1996).

The hard linking methodology may be implemented by enhancing one model with a reduced version of the other; whether by adding a highly aggregate representation of macro-economic reactions in a bottom-up optimization framework (Manne and Wene, 1992; Messner and Schrattenholzer, 2000; Bosetti et al., 2006; Kannan et al., 2008), or by embedding a set of discrete generation technologies into a dop-down model (Böhringer, 1998; Kombaroglu and Madlener, 2003; Sue Wing, 2006; Böhringer and Rutherford, 2008), or by writing a hybrid model directly as a mixed complementary problem (Böhringer and Rutherford, 2008; Frei et al., 2003). This methodological choice insures consistency within the model but does not permit a high level of detail in both technical specification and economic interactions.

The "soft link" coupling method (Drouet et al., 2005; Schäfer and Jacoby, 2005; Martinsen, 2011; Sceia et al., 2012; Riekkola et al., 2013; Fortes et al., 2014) involves keeping the models' full structure and complexity, exchanging a chosen set of variables and solving the models iteratively until convergence is reached on a given criterion. It has the advantage to permit the use of full-scale models with full dimensionally and complexity. However, Böhringer and Rutherford (2009) warn of the dangers of inter-model inconsistencies and convergence issues when soft-coupling models with fundamentally different logics. They decompose a mixed complementary problem hybrid model and solve it iteratively, proposing a more consistent way of soft-coupling models. This approach inspired implementations by Tuladhar et al. (2009), Lanz and Rausch (2011), and Rausch and Mowers (2014) - the latter with full-scale models.

The objective of this thesis is to investigate the interplay between the electricity market and the economy in changing policy environments. This goal influences the choice of coupling method. First, electricity is a specific commodity which cannot be easily stored. Supply and demand must balance at each moment to maintain the stability of the network. A careful and detailed modeling of time-periods, load-curves and technological potentials is crucial. Such technical precision requires a detailed electricity supply model. Second, we endeavor to analyze changing policy environments. This involves existing policies and their resulting distortions. Adding an aggregate representation of macro-economic reactions to a bottom-up optimization framework is therefore not optimal, as integrability constraints prevent these models from including distortionary taxes (Böhringer and Rutherford, 2008, 2009). Furthermore, electricity is a commodity that is used by all sectors and households. It is hence instructive to adequately model the electricity sector's interactions with the other economic actors with the help of a computable general equilibrium model (Schäfer and Jacoby, 2005). Finally, as energy and climate policies in Switzerland involve a wide spectrum of policy types, an appropriate implementation of both market policies and technological restrictions is required. We therefore choose to couple a bottom-up electricity supply model with a top-down computable general equilibrium model (CGE) through soft-link.

An obvious choice would have been to implement the soft-coupling methodology put forward by Böhringer and Rutherford (2009) with large scale models, as has been done by Rausch and Mowers (2014). However, this technique involves the implementation of a linear price-responsive demand function in the bottom-up model that is re-benchmarked at each iteration on a Marshallian demand approximation of the CGE model demand curve. This was not possible in our case for reasons of project organization[1]. The electricity supply model - CROSSTEM-CH - is based on the TIMES framework (Loulou et al., 2005). Electricity demand is a fixed exogenous input in the CROSSTEM-

[1]See section 1.4 p. 7

CH model, which minimizes total system cost[2]. Although the TIMES framework allows for the introduction of elastic demand functions, calibrated from a reference run and given constant own-price elasticities (Loulou et al., 2005), this is a delicate task for which our partners did not have the resources within this project. We therefore developed an alternative soft-link coupling method which can be implemented in cases where a linear demand function cannot be introduced in the bottom-up model.

1.2 Objectives

The objective of this thesis is to investigate the interplay between the electricity market and the economy in changing policy environments. We use Switzerland as a case study. Switzerland is an interesting case, as many aspects of energy and climate policy are under discussion and undergoing changes. Many of those concern electricity due to the decision - following the Fukushima disaster - to phase-out nuclear power which represents close to 40% of electricity supply.

In Switzerland, both the nature of climate and energy policies, and the liberalization of the electricity market are under discussion. Whether or not - and indeed when - the electricity market will be fully liberalized is an additional unknown in an already complex and undetermined situation. Gaining an understanding on the link between market liberalization and the effectiveness of policies might help design adequate policies despite - and in provision for - the uncertainty related to the state of the market.

Market liberalization changes the way wholesale electricity is priced. Typically, under regulation, prices are set to allow producers to cover their generation costs and achieve an acceptable profit. In a fully liberalized competitive market, wholesale electricity is priced at short-term marginal cost, which does not include fixed costs. This provides no incentive for investment unless there is scarcity of capacity, in which case the wholesale price includes a scarcity rent[3], which, in equilibrium, provides incentive for investment into new capacities (International Energy Agency, 2001).

With the exception of Lanz and Rausch (2016) – who specifically differentiate utilities trading on regulated or free markets – assumptions on market regime are rarely discussed in coupled top-down bottom-up analyses. In energy systems model like MARKAL/TIMES that implement own-price elastic demand, the price of the energy good is the marginal cost of its process, which includes all constraints and costs (incl. fixed costs). They therefore implicitly assume a liberalized market that takes into account scarcity rents. Amongst the studies that explicitly link costs from bottom-up models to prices in computable general equilibrium (CGE) models, different assumptions are made: some link energy prices to average costs (Fortes et al., 2014), while others link it to long-term marginal costs (Martinsen, 2011; Riekkola et al., 2013; Rausch and Mowers, 2014). These different ways of linking generation costs and prices imply different assumptions on the market's institutional framework. However, this is something that is rarely discussed.

To the best of our knowledge, whether climate and energy policy assessment by coupled top-down bottom-up models is robust to electricity markets' regime has not been addressed in the literature.

[2]In contrast with maximizing total surplus with an elastic demand.
[3]On the marginal technology as well.

In this work, we endeavor to investigate whether assumptions on market regime - and hence the link between wholesale electricity prices (top-down) and generation costs (bottom-up) - have an impact on modeling results.

The Energy Perspectives 2050 (Prognos, 2012), commissioned by the Federal Office of Energy, outline three electricity supply options to answer electricity demands taking nuclear phase-out into account: (1) gas-fired power plants, (2) gas-fired power plants and renewables, and (3) renewables with the help of electricity imports.

It is yet unsure whether one of these scenarios would be politically preferred over the other, or if a quasi-selection of technologies might arise from climate policies. Currently, the CO_2 law stipulates that fossil thermal power plants will be approved in Switzerland only if they fully compensate their CO_2 emissions. Additionally, at least 50% of their compensation performance must be rendered domestically. This strong regulation is quite prohibitive and keeps Swiss firms from investing into gas-fired power plants in Switzerland. For gas power plants to be built in Switzerland, the domestic compensation clause would have to be relaxed, or specific compensation projects setups.

While considering the manifold motivations for political influence on technology selection, it is crucial to investigate the costs and impacts of such restrictions. Following the methodological considerations of the previous section, we examine the social cost of a particular type of technology restriction (banning the use of natural gas in electricity generation). Especially, we investigate whether and how a coupled top-down bottom-up framework provides additional value to the analysis, compared to a pure bottom-up view which would mostly be based on the observation of changes in total system cost.

1.3 Thesis outline

In chapter 2, we present the ELECTRA-CH framework, built to analyze electricity markets in Switzerland. It is composed of the dynamic computable general equilibrium (CGE) model of the Swiss economy, GENESwIS and of the dynamic TIMES model of electricity supply CROSSTEM-CH[4]. The two models are coupled through an automated iterative soft link (Wene, 1996; Martinsen, 2011; Rausch and Mowers, 2014), which consists of running the models iteratively with selected input from the other model until convergence is reached on a given criterion. This method permits to keep the models' full complexity, while prioritizing the strengths of each model over the weaknesses of the other.

Chapter 2 shows a few results illustrating the functioning of the ELECTRA-CH modeling framework. Despite the complex structure of the coupled framework, the results can be explained and policy-induced impacts can be tracked down. On a methodological level, we note that a careful harmonization of the models is crucial for framework convergence and for producing dependable results. Also, the variables to be linked between bottom-up and top-down models must be meticulously selected and interpreted in order not to introduce inaccuracies or logic flaws in the framework. This is particularly the case for the link between bottom-up costs and top-down wholesale electricity

[4]Developed by the Energy Economics Group from Laboratory for Energy Systems Analysis (LEA) at Paul Scherrer Institute (PSI).

prices, which we analyze in chapter 3. Finally, the implementation of a demand dampening method - here, Gauss-Seidel - is essential for achieving convergence.

The choice of an adequate way of linking bottom-up generation costs with top-down wholesale electricity price in ELECTRA-CH proved to be challenging. Indeed, market regulations are changing: Swiss electricity markets are partly liberalized and further liberalization is discussed together with the integration in the European market. As we cannot predict market evolution precisely, it is important to understand its impacts on model results.

In chapter 3, we simulate a tightening of climate and energy policies under two different market evolutions: (1) regulated market, and (2) evolution towards a fully liberalized market. In the coupling procedure, the link between wholesale electricity prices (top-down) and generation costs (bottom-up) depends precisely on regulatory market assumptions: In the regulated market, wholesale electricity prices are "cost-plus", while they depend on marginal generation costs in the liberalized market. We show that, in Switzerland, an electricity tax is significantly more effective in reducing electricity demand in the liberalized than in the regulated market. This is due to the fact that marginal cost and average cost do not react in the same way to a reduction in demand. Although the exact variation of these two types of costs may be different under different policy shocks and for different generation systems and technology options, the fact that they do not vary the same way highlights the need to take ongoing and projected market liberalization into account and disclose pricing assumptions when interpreting models' results.

Despite market liberalization, technology restrictions are still widely adopted for various motives (e.g. safety reasons, reducing fuel import dependence, environmental and climate concerns, jobs creation or preservation, political agendas). Instruments inherited from regulation, technology restrictions may have different impacts on the economy in changing market environments. In chapter 4, we focus on how to adequately assess the costs and impact of technology restrictions.

Bottom-up models, with their extensive technological details, are often the first choice to analyze the costs of technology restrictions. However, due to their partial-equilibrium nature, they often only assess direct costs. Top-down models, on the other hand, struggle to model adequately technology restrictions. In chapter 4, we endeavor to investigate the effect of technology restrictions with the added insight of combining top-down and bottom-up information in a single framework.

We use the ELECTRA-CH framework to investigate the prohibition of gas-fired power plants in Switzerland. Although new gas-fired power plants may be deemed the cleaner option in countries with other fossil fuel production, for Switzerland, they represent a large augmentation in CO_2 emissions and increased dependance on fuel imports. We analyze two electricity supply options for Switzerland after nuclear phase-out: (1) a balanced-trade scenario in which Switzerland's annual electricity production must be equal to its consumption and (2) a no-gas scenario that forbids gas-fired power plants, but accepts net electricity imports.

We find that, for Switzerland, the prohibition of gas-fired power plants and relaxation of trade constraints have opposite effects on total system cost and marginal cost: average cost is reduced, while marginal cost increases. In a liberalized market with marginal cost pricing, this means that the electricity price rises, even though savings are obtained on total system cost, which increases profits. Total system cost reductions and the wholesale electricity price increase have opposite effects on welfare. Hence, welfare increases, but not by the full extent of total system cost reduction. A pure bottom-up analysis would therefore overestimate the benefits of the policy.

Technology restrictions alter both cost functions and price levels. Situations where marginal cost and average cost vary in opposite ways are specific to technology mixes composed of largely depreciated plants where marginal (new) technologies are relatively expensive. However, in any circumstances where average cost and marginal cost do not vary exactly in the same way, policy analysis must take both electricity price and total system cost into consideration.

Finally, with electricity markets being further liberalized, policy induced variations of profit margins should not be overlooked.

1.4 Scope of the thesis

This work is part of a collaborative project: *ELECTRA - Electricity markets and trade in Switzerland and its neighboring countries: Building a coupled techno-economic modeling framework* financed by the research program Energy-Economy-Society of the Swiss Federal Office of Energy. Three institutions were involved in the project: the consulting firm Econability, the Laboratory of Environmental and Urban Economics (LEURE) at EPFL, and the Energy Economics Group from Laboratory for Energy Systems Analysis (LEA) at Paul Scherrer Institute (PSI).

This thesis is based on the work that I accomplished within this project. This involved the modification and further development of the GENESwIS model, the conception and implementation of the coupling procedure, as well as the analysis of the coupled results.

The bottom-up model - CROSSTEM-CH - was developed by the Energy Economics Group from Laboratory for Energy Systems Analysis (LEA) at Paul Scherrer Institute (PSI). Through project agreements, I had access to the bottom-up source codes - in the form of text files (I did not have access to front-end and back-end softwares) - only for running the coupling algorithm.

As I do not have any claim on bottom-up intellectual property, this thesis does not include bottom-up model descriptions, detailed discussions on bottom-up modeling assumptions, nor specific bottom-up results. However, some bottom-up results that are required for the analyses performed appear in this thesis. It is indeed difficult - and unreasonably uninformative - not to present any bottom-up results at all in a coupled bottom-up top-down analysis.

For the interested readers who want to know more about the CROSSTEM/CROSSTEM-CH models and their assumptions, please refer to Pattupara (2016), which covers the bottom-up modeling within the ELECTRA project and further work involving the CROSSTEM models.

1.5 Structure of the thesis

The body of this thesis is composed of the compilation of three articles.

Chapter 2 presents *ELECTRA-CH: a coupled energy economic modeling framework for analyzing Swiss electricity markets*, which will be made available as a working paper providing a transparent account of the model and, in particular, the coupling methodology.

Chapter 3 is an amended version of the paper *Linking electricity prices and costs in bottom-up top-down coupling under changing market environments* written by Sophie Maire, Frank Vöhringer and Philippe Thalmann, submitted to The Energy Journal.

Chapter 4 is an amended version of the paper *Welfare effects of technology restrictions for electricity generation*, written by Sophie Maire, Frank Vöhringer and Philippe Thalmann, not yet submitted.

To avoid repetitions, the methodology sections of the otherwise self-containing papers composing chapters 3 and 4 have been cut-out.

Chapter 2

ELECTRA-CH: a coupled energy economic modeling framework for analyzing Swiss electricity markets

Abstract

ELECTRA-CH is a coupled top-down bottom-up framework developed to analyze electricity markets in Switzerland. It is composed of two component models: (1) a dynamic TIMES electricity supply model, CROSSTEM-CH, and (2) a dynamic computable general equilibrium (CGE) model of the Swiss economy, GENESwIS. These two models are coupled through an iterative soft link such that each model keeps its full structure and complexity. The particular strengths of each model are prioritized and used to inform the other model: The bottom-up model provides the technology mix and costs of electricity generation, while the top-down model supplies economic feedback, endogenous prices variations for factors and commodities, and electricity demand variations. The purpose of this chapter is to provide a transparent account of the coupling methodology.

Keywords: *energy modeling; electricity markets; soft-link coupling; top-down general equilibrium model; bottom-up energy supply model*

2.1 Introduction

Switzerland's electricity generation is dominated today by hydro and nuclear technologies. However, following the accident in Fukushima in 2011, the Swiss Government decided not to replace existing nuclear plants at the end of their safe lifetime with new generation plants. Five nuclear power plants - in function since 1969 for the oldest and 1984 for the youngest plant - cover nearly 40% of electricity supply. This, and the fact that Switzerland vouched to reduce its domestic CO_2 emissions by 30% from 1990 to 2030, implies that finding the right set of policies that would meet both these obligations at low cost, low environmental impact and minimum risk to energy security is a challenge (International Energy Agency, 2012). This challenge asks for appropriate tools to analyze electricity markets and their interaction with climate and energy policies.

Climate and energy policy analysis is mostly informed by two modeling approaches: bottom-up and top-down. Bottom-up models are based on extensive technological detail. Because of their large computational requirements, these models cannot conjointly include detailed economic feedback. Top-down models are aggregated, consistent macro-economic frameworks with micro-economic fundations that simulate the interactions between consumers, producers and the public sector. The complexity of all these interactions prevents these models from including detailed technological specifications. Top-down models are designed to assess market-based policies, but struggle to incorporate technology-specific or command-and-control policies adequately.

Combining top-down models with bottom-up models permits to assess both types of policies (market-based instruments and command & control) and their interactions, which brings new insights into policy analysis. These models strive to incorporate the technological explicitness of bottom-up models with the micro-economic representation of agents' behavior in a general equilibrium of flexible markets provided by top-down models into a single framework (Hourcade et al., 2006). A lot of effort has been devoted to developing and assessing coupling methods since the first coupling by Hoffman and Jorgenson (1977). Two main currents emerged: "hard linking", which encompasses the two model types into one single model, and "soft linking", which couples existing full-size models by exchange of variables (Wene, 1996).

The hard linking methodology may be implemented by enhancing one model with a reduced version of the other (Manne and Wene, 1992; Messner and Schrattenholzer, 2000; Kombaroglu and Madlener, 2003; Sue Wing, 2006; Böhringer and Rutherford, 2008), or by writing a hybrid model directly as a mixed complementary problem (MCP) (Böhringer and Rutherford, 2008; Frei et al., 2003). This methodological choice insures consistency within the model but does not permit a high level of detail in both technical specification and economic interactions.

The "soft link" coupling method (Drouet et al., 2005; Schäfer and Jacoby, 2005; Martinsen, 2011; Sceia et al., 2012; Riekkola et al., 2013; Fortes et al., 2014) involves keeping the models' full structure and complexity, exchanging a chosen set of variables and solving the models iteratively until convergence is reached on a given criterion. It has the advantage to permit the use of full-scale models with full dimensionally and complexity. However, Böhringer and Rutherford (2009) warn of the dangers of inter-model inconsistencies and convergence issues when soft-coupling models with fundamentally different logics. They decompose an MCP hybrid model and solve it iteratively, proposing a more consistent way of soft-coupling models. This approach inspired implementations by Tuladhar et al. (2009), Lanz and Rausch (2011), and Rausch and Mowers (2014), the latter with full-scale models.

The ELECTRA-CH framework consists of two component models: a TIMES electricity supply model of Switzerland - CROSSTEM-CH - and a dynamic computable general equilibrium (CGE) model - GENESwIS - of the Swiss economy. These two models are coupled through an iterative soft link. CROSSTEM-CH provides a detailed representation of electricity generation, which is prioritized over the generic function in GENESwIS. Additionally, endogenous electricity demand variations as well as factor and intermediate input price variations simulated by GENESwIS are sent back to CROSSTEM-CH. GENESwIS permits to model market-based policies, while technology restrictions can be introduced in CROSSTEM-CH.

The choice of a soft-link methodology emerged from the following considerations: As electricity is a very specific commodity, a careful and detailed modeling of time-periods, load-curves and technological potentials is crucial, which requires a detailed energy supply model. Furthermore, electricity is a commodity which is used by all sectors and households. It is hence necessary to adequately model the electricity sector's interactions with the other economic actors with the help of a computable general equilibrium model (Schäfer and Jacoby, 2005). In addition, as energy and climate policies in Switzerland involve a wide spectrum of policy types, an appropriate implementation of both market policies and technological restrictions is required. Finally, we want to be able to model existing tax distortions. Hence, the use of full-size models and the prioritization of their respective strengths was preferred over full integration.

This chapter is structured in the following way: Section 2.2 shortly introduces the individual models (GENESwIS and CROSSTEM-CH), while section 2.3 illustrates the way they are coupled. The purpose of this chapter is to provide a transparent account of the coupling methodology. We therefore show only a few results as an illustration in section 2.4. Section 2.5 concludes.

2.2 Models

2.2.1 GENESwIS

GENESwIS is a dynamic computable general equilibrium (CGE) model of the Swiss economy designed to analyze energy and environmental policies (Vöhringer, 2012; Maire et al., 2015).

In GENESwIS, agents act rationally and have perfect foresight over the entire time-horizon (2010-2050). Households maximize their utility under a budget constraint. They earn wages by providing labor and interest by renting out capital. GENESwIS exhibits flexible labor supply as households can choose between labor and leisure. As a further element of income, they receive social benefits from the Government. Households can choose between consuming goods and services, or enjoy leisure time (see nesting structure figure 2.1). They optimize their consumption choice between different periods, which determines saving behavior.

Capital is modeled as putty-clay to incorporate the rigid character of investment decisions and crowding out of investments. Thus, free capital, once invested into one sector (industry, services or electricity), cannot be transformed back into capital for another sector. Investments are treated as solely domestic.

Firms maximize profit under technology constraints and the assumption of perfect competition.

The Government collects taxes (income tax, value added tax, mineral oil tax, CO_2 tax) and uses the revenue for lump-sum transfers (social benefits) and public goods provision. Equal yield is assumed: the income tax rate is modified endogenousely to keep public goods provision constant.

Domestic and foreign goods are assumed to be imperfect substitutes and are aggregated following Armington's description of a small open economy (Armington, 1969).

Non-satiation in consumption implies that demand equals supply in all markets. Relative prices are adjusted until all markets clear.

GENESwIS' sectoral disaggregation is designed for the analysis of energy and environmental policies, with an emphasis on the electricity sector. Accordingly, production technologies specify the use of energy inputs (see nesting structure in figure 2.2). Non-energy industries are separated into aggregates taking into account their possible importance in the formation of capital for the electricity sector and their affiliation to different CO_2 taxation schemes (emissions trading scheme, CO_2 tax). The sectoral disaggregation is displayed in table 2.1 and the commodities demanded in the model in table 2.2.

Table 2.1 – GENESwIS' sectors

Energy	**Transport**	**Non-Energy**
Electricity:	Rail	Agriculture
- generation	Road	Cement and concrete
- transport and distribution	Air & others	Construction
Natural gas		Metals
- transport and distribution		Other sectors with emissions trading
District heating		Rest of industry
Refineries		Rest of services

Table 2.2 – GENESwIS' commodities

Energy	**Transport**	**Non-Energy**
Electricity:	Rail	Agricultural goods
- wholesale	Road	Cement and concrete
- retail	Air & others	Construction
Natural gas		Metals
District heat		Other commodities with emissions trading
Petrol and Diesel		Rest of goods
Light heating oil		Rest of services
Crude oil (imported)		
Nuclear fuel (imported)		

The electricity sector is split into electricity generation and electricity transport and distribution

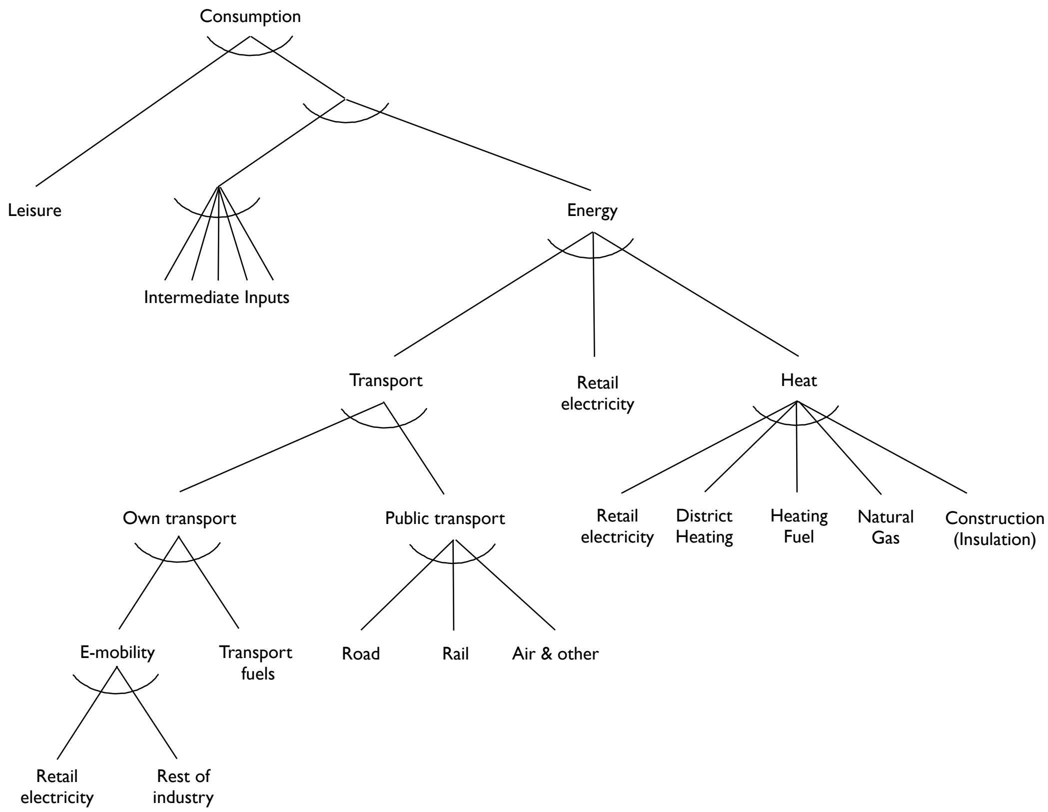


Figure 2.1 – Nesting structure of household consumption in the GENESwIS model. Elasticities of substitutions can be found in Appendix 5.1.

Figure 2.2 – Nesting structure for GENESwIS' production functions. Elasticities of substitutions can be found in Appendix 5.1. Electricity generation, electricity transport and distribution, and rail transport display different structures. They can be found respectively in figure 2.4 p.18, figure 2.6 p.27, and in Appendix 5.5 figure 5.1 p.82.

to permit the differentiation between wholesale electricity and retail electricity prices. Wholesale electricity is either produced by the electricity generation sector or imported. It is demanded by the electricity transport and distribution sector or exported. Retail electricity, after being transported and distributed, is demanded for three different types of uses (appliances, transport, heating), with demand-side substitution opportunities represented separately for each of these uses (see figures 2.1 and 2.2). Thus, electricity used for heating can be substituted only against other heating commodities, electricity used for appliances is considered as a separate form of energy, and electricity used for transport[1] is a substitute to transport fuels.

GENESwIS is based on the 2005 energy-related disaggregation of the Swiss input-output table by Nathani et al. (2011) and own calculations for further disaggregation and allocation of tax revenues (see Appendix 5.2).

2.2.2 CROSSTEM-CH

The Cross Border TIMES Electricity Model - CROSSTEM - is a technology-rich dynamic bottom-up optimization model of the electricity system in Switzerland and its four neighboring countries developed on the basis of the TIMES framework. TIMES (Loulou et al., 2005) is a perfect foresight model that, given a comprehensive set of technologies, allows users to minimize the cost of the technology mix over the time horizon, matching a given demand (inelastic and exogenous) and taking into account a set of constraints. It displays a high level of technological detail including operational and maintenance costs, investment costs, fuel costs, lifetime, construction time, renewable potential and decommissioning. CROSSTEM (Pattupara and Kannan, 2016) was developed from the existing STEM-E model described in Kannan and Turton (2011). CROSSTEM's time slices are disaggregated to take into account the variability of electricity demand across the day (hourly), different types of day (weekday, Saturday, Sunday) and seasons. For the ELECTRA-CH framework, we use the Swiss module of the CROSSTEM model - CROSSTEM-CH -, in which trade with the neighboring countries is exogenous (i.e. electricity import and export prices are set exogenously). Further details on the CROSSTEM-CH model can be found in (Pattupara, 2016).

2.3 Coupling methodology

GENESwIS and CROSSTEM-CH are coupled through an automated iterative soft link. Coupling through soft link involves keeping the models' integrity while prioritizing the strengths of each model to compensate for the shortcomings of the other. Each model is solved iteratively with input information from the other model until convergence is reached on a given criterion. In the case of ELECTRA-CH, the electricity generation production function in the CGE model is determined by the cost structure optimized by the bottom-up model, while the sectoral electricity demand variations that occur in the CGE as a result of changes in prices, as well as factor and intermediate

[1]Electro-mobility is modeled as a sub-nest in transport (see figures 2.1 and 2.2), where it can be substituted with transport fuels through an elasticity of substitution of 10. This very high elasticity of substitution was chosen for calibration purposes due to the very small current share of electro-mobility and high penetration projections by Prognos (2012).

input price variations are sent back as input to the bottom-up model.

Figure 2.3 depicts the exchange of information between the two models. Electricity generation costs and their components as well as export revenues and import costs are extracted from the CROSSTEM-CH model and translated for the CGE model into a) the wholesale electricity price and b) input shares for factors and commodities to the electricity generation cost function. The sectoral electricity demand quantities simulated by the GENESwIS model are then sent back to become inputs to the CROSSTEM-CH model. To account for price and cost relevant changes in the economy, factor and intermediate input prices from GENESwIS are used to modify the investment costs and operation and maintenance costs of the different technologies in the bottom-up model. This sequence is iterated upon until the vector of quantities of total yearly electricity demands converges.

We start the iteration procedure by running the bottom-up model CROSSTEM-CH with baseline electricity demand projections from Prognos (2012) as exogenous input.

2.3.1 CROSSTEM-CH inputs into GENESwIS

In ELECTRA-CH, the purpose of the bottom-up model CROSSTEM-CH is to provide a detailed representation of electricity generation. This detailed representation should, through soft-coupling, be prioritized over the generic representation of electricity generation of the CGE model. Hence, the following outputs of the bottom-up model:

- technology mix in electricity generation,
- costs of electricity generation, and
- electricity trade

should enter the CGE model's electricity generation production function and drive its iterative modification.

CGE models do not encompass the large amount of different technologies inherent to bottom-up models. Hence, the electricity mix cannot be plugged-in as such in GENESwIS. For bottom-up outputs to be prioritized over the usual structure of the GENESwIS model, they must be translated into information that can be used by the latter. Furthermore, the GENESwIS model must be modified such that this information can be treated as direct input without being subject to endogenous modifications within one iteration. Additionally, although generation costs can be inserted into the model, the question of how to link them to wholesale electricity prices is an issue.

In the following sub-sections, we describe the mechanisms involved in translating technology mix and costs optimized by the bottom-up model into electricity generation production function technology and wholesale electricity price for the CGE model.

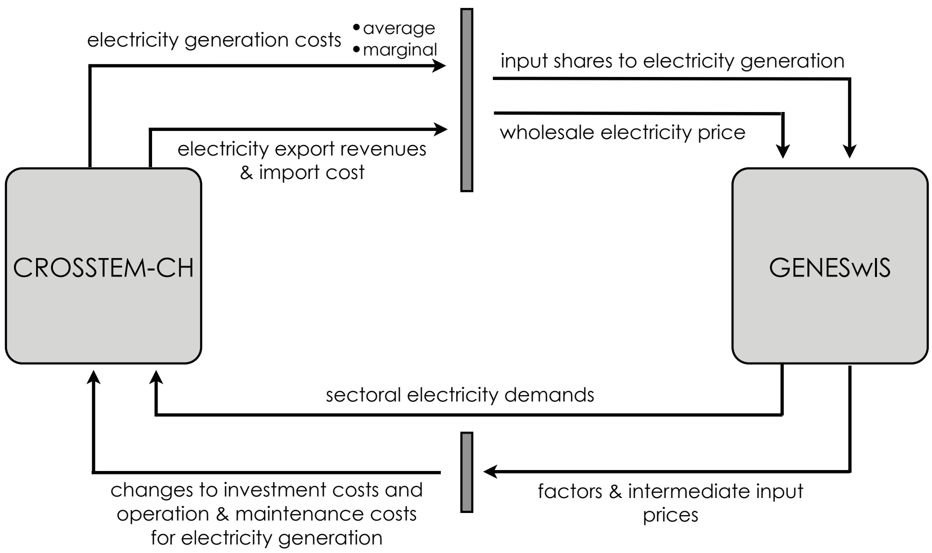


Figure 2.3 – Information exchange between the two component models within one iteration.

Technology mix

In a CGE model, input shares to constant elasticities of substitution (CES) production functions define the technology of production. For electricity generation, this cannot be seen as "technology mix", as no differentiation is made between the different bottom-up technologies (i.e., solar pv, storage hydro, offshore wind, ...). Nevertheless, it gives the ratio of different commodities needed in average to produce a unit of electricity (amount of machinery, operation and maintenance, gas, nuclear fuel,...). A change in technology mix, say the introduction of gas-fired power plants, will be felt in the CGE model mainly through an increase of the share of gas, and maybe a shift in shares of capital and operation and maintenance costs.

The bottom up technology mix must then be translated into CGE technology: the different costs of electricity production calculated by the bottom-up model are aggregated into inputs from commodities defined in the CGE model, specifically natural gas costs, nuclear fuel costs, capital costs, operation and maintenance costs, inter-connector costs, import costs and export revenues. These cost share are then introduced in the electricity generation production function of the CGE to specify the production technology.

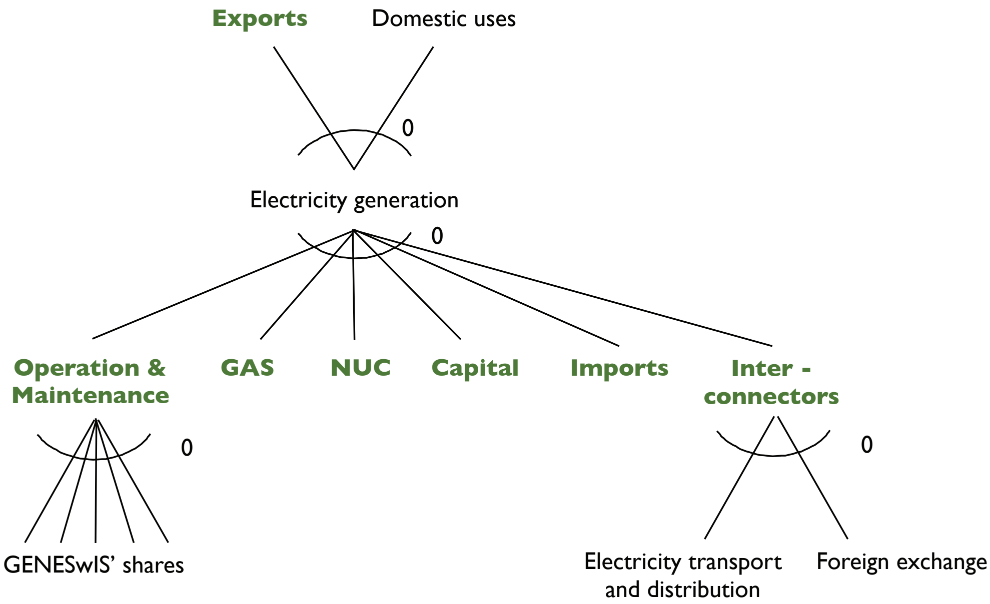


Figure 2.4 – Nesting structure of GENESwIS' electricity generation production function. The labels in bold-green represent inputs from the CROSSTEM-CH model.

For this information to be treated as direct input, the electricity generation production function in GENESwIS is set as a Leontief function (i.e.. with elasticity of substitution zero). Its cost function can then be written as:

$$C_{ELE}(P, Y, t) = Y_{ELE}(t) \cdot \sum_i \tilde{q}_i(t) \cdot P_i(t) \tag{2.1}$$

where $Y_{ELE}(t)$ is the activity index variable of the electricity generation production function at period t, and $P_i(t)$ the price variables and $\tilde{q}_i(t)$ the quantity parameters of the different inputs i entering electricity generation. This way, no substitution is allowed - within one model run - between inputs, which are set as fixed shares. The electricity generation production function's technology in GENESwIS is thus determined by CROSSTEM-CH's cost shares at each iteration. The nesting structure of the production function for electricity generation is represented in figure 2.4.

Operation and maintenance costs are aggregated in the CROSSTEM-CH model. To retain sectoral information in GENESwIS, we preserve the shares specified in the Swiss input-ouptut table (Nathani et al., 2011). Inter-connectors (international transportation lines) are assumed to be owned partly by the Swiss electricity transport and distribution sector and by the trading neighboring country (50% - 50%). Inter-connector costs are hence paid to electricity transport and distribution and to foreign exchange (see figure 2.4).

Electricity transport and distribution is not coupled to the CROSSTEM-CH model, as the latter does not precisely represent transport and distribution costs within the country of production.

Investment

CROSSTEM-CH optimizes investment decisions for electricity generation. Investments costs per technology are disaggregated into finite lifetime annuities[2]. In the coupled framework, the yearly sum of those annuities determines the yearly capital input in GENESwIS' electricity generation production function (see figure 2.4). GENESwIS simulates investment decisions, and hence capital accumulation which satisfy the demand for capital in the electricity sector set by CROSSTEM-CH. In GENESwIS, Capital is modeled as putty-clay. Thus, capital, once it is invested into one sector (industry, services or electricity), cannot be transformed into capital for another sector. Investment in the electricity sector therefore affects investment and capital formation for the other sectors (industry and services) through crowding-out (resp. crowding-in) effects.

Both CROSSTEM-CH and GENESwIS are fully dynamic models (with perfect foresight), which implies an infinite time-horizon. However, applied models can only compute a finite number of time periods. They therefore need to overcome investment issues that rises from a finite horizon.

In TIMES models - like the CROSSTEM-CH model - the objective function is corrected such that investing towards the end of the modeling horizon is not decremental. A salvage value is calculated to take into account the cost of investments and decommissioning for technologies that have a technical lifetime lasting longer than the last modeling period. This salvage value is credited back to the objective function. An identical correction to the objective function is implemented for material and energy that are embedded in processes that do not finish by the end of the horizon (Loulou

[2]In GENESwIS, which is a fully dynamic Ramsey model, annuities are discounted with a fixed rate. To avoid inconsistencies in the definition of annuities within the coupled framework, we endeavored to introduce a finite-lifetime (vintage-based) treatment of annuities in GENESwIS. This new treatment of investments necessited to extract from the bottom-up model annuities generated by investments that occurred prior to the first modeling period (the calibration period in CROSSTEM-CH). However, the CROSSTEM-CH model considers prior investments as sunk costs that don't enter the cost optimization. They are therefore not specifically modeled. Instead of taking assumptions on prior investments, we decided to keep the structure of capital accumulation in GENESwIS unchanged and be aware of the potential consistency issue in the definition of annuities.

et al., 2005).

In applied dynamic CGE models, it crucial to introduce a terminal capital constraint in the last period to approximate an infinite horizon behavior. Without terminal constraint, households would not invest in the last period and all capital would be used. For this purpose, we introduce in GENESwIS the constraint proposed by Lau et al. (2002) which requires investment to grow at the same rate as output in the last period:

$$\frac{I_T}{I_{T-1}} = \frac{Y_T}{Y_{T-1}} \tag{2.2}$$

with I_T investment and Y_T total output in the last period.

Both models are run with time horizon set in 2070, while scenario analyses stop in 2050. Thus, terminal conditions and border effects do not have a strong incidence on the results.

Wholesale electricity price

The electricity generation technology is determined by CROSSTEM-CH's input cost shares. For the wholesale electricity price, things are more complex. As prices cannot be fixed in a CGE model, the wholesale electricity price cannot be plugged directly into the model. However, prices in the CGE can be pushed to a given value by varying the inputs of the production function while keeping output constant. In the following, we describe the way inputs' levels are determined in order to keep the production technology while setting the wholesale electricity price to the right value.

The zero profit condition[3] for electricity generation, assuming the cost function eq.(2.1), can be written as:

$$P_{ELE}(t) \cdot q_{ELE}(t) \cdot Y_{ELE}(t) = Y_{ELE}(t) \cdot \sum_i \tilde{q}_i(t) \cdot P_i(t) \tag{2.3}$$

where $P_{ELE}(t)$ is the price variable of wholesale electricity in period t, $Y_{ELE}(t)$ the activity index variable of the electricity generation production function, $P_i(t)$ the price variables of the different inputs i, and $q_{ELE}(t)$ and $\tilde{q}_i(t)$ the quantity parameters for respectively electricity generation and the different inputs needed for electricity production (see table 2.3). We assume benchmark prices to be set to one, which allows us to treat the quantity parameters as values.

With output quantity parameter of electricity generation $q_{ELE}(t)$ constant (set at benchmark value and not modified through the coupling algorythm), eq.(2.3) implies that a variation of $\tilde{q}_i(t)$ impacts the electricity price $P_{ELE}(t)$. The goal of the exercise is therefore to calculate the $\tilde{q}_i(t)$ parameters, given CROSSTEM-CH's costs $\tilde{c}_i(t)$, such that the $\tilde{q}_i(t)$ push the wholesale electricity price, $P_{ELE}(t)$, to reflect CROSSTEM-CH's total costs divided by the electricity demand. Accordingly, we want:

$$P_{ELE}(t) = \frac{\sum_i \tilde{c}_i(t)}{Y_{ELE}(t) \cdot q_{ELE}(t)} \tag{2.4}$$

[3]We omit tax distortions and inequalities in this explanation for ease of notation.

Table 2.3 – Definition of variables and parameters

Variables	
$Y_{ELE}(t)$	Activity index for electricity generation at period t
$P_{ELE}(t)$	Price of wholesale electricity at period t
$P_i(t)$	Price of commodity i at period t
Parameters	
$q_{ELE}(t)$	quantity of electricity generation (benchmark value)
$\tilde{q}_i(t)$	quantity of input i needed for electricity generation (determined from CROSSTEM-CH's outputs)
$\tilde{c}_i(t)$	cost of commodity i to electricity generation (CROSSTEM-CH's outputs)
$p_{i,k-1}(t)$	equilibrium price of commodity i at the previous iteration
$y_{ELE,k-1}(t)$	equilibrium activity index of electricity generation at the previous iteration

Therefore, from (2.3), we obtain that input quantities $\tilde{q}_i(t)$ must be calculated such that:

$$\tilde{q}_i(t) = \frac{\tilde{c}_i(t)}{P_i(t) \cdot Y_{ELE}(t)}. \tag{2.5}$$

However, all price and quantity indices constantly vary in the GENESwIS model within one model run. It is therefore not possible to determine the $\tilde{q}_i(t)$ within GENESwIS using current prices and indices. To circumvent this issue, input quantity parameters $\tilde{q}_i(t)$ can be calculated using input prices $P_i(t)$ and electricity activity index $Y_{ELE}(t)$ from the GENESwIS run of the previous iteration. Eq.(2.5) becomes:

$$\tilde{q}_i(t) = \frac{\tilde{c}_i(t)}{p_{i,k-1}(t) \cdot y_{ELE,k-1}(t)} \tag{2.6}$$

for iteration k. Although previous iteration prices might differ from present prices, once the framework converges, input prices converge as well. Likewise, as the convergence criterion is set on electricity demand, the electricity production index $Y_{ELE}(t)$ is bound to have converged as demand always equals supply in a CGE model.

By calculating input quantities this way, the wholesale electricity price $P_{ELE}(t)$ reflects the average cost of the CROSSTEM-CH model. This is fine when assuming a regulated wholesale electricity market. However, the Swiss wholesale electricity market is already partly liberalized and is expected to be liberalized further in the coming years. In a liberalized market, prices are set at marginal cost level and not at average cost level.

As investigated in chapter 3, assumptions on electricity market liberalization affect the effectiveness[4] energy policies.

Currently, Swiss electricity markets are partly liberalized. An independent regulatory authority - the Federal Electricity Commission (ElCom) - is responsible for monitoring and supervising the liberalization of the market. The transmission grid has been separated and is under the control of the publicly owned firm Swissgrid. More than six hundred players take part in the Swiss wholesale electricity market, including about 80 power producers of varying importance. The majority of those

[4]An electricity tax is more effective in reducing demand in a liberalized market than under regulation.

players are publicly owned by municipalities and cantons. They trade on energy only (Day-ahead and Intraday) and reserve markets. In Switzerland, no future market is setup and such transactions take the form of bilateral contracts (Swiss Federal Office of Energy, 2013b). Large consumers (annual consumption > 100 MWh), representing approximately half of the Swiss electricity demand, can choose their supplier and decide to pay market prices instead of regulated tariffs. Full market liberalization has been postponed and will depend on the advancement of the legislative work on the Energy Strategy 2050, the situation of the electricity market, and the negotiations with the European Union regarding the full integration of the Swiss electricity market into the European electricity market, which are still ongoing.

Although we do not know exactly how wholesale electricity markets will develop, assuming a fully regulated market would be misguided. For this study, we assume a progressive evolution to a liberalized electricity market, where prices increasingly reflect long-term marginal cost. By "long-term marginal cost", we mean marginal cost including a portion of fixed cost. Indeed, CROSSTEM-CH minimizes the total cost of electricity generation and trade over the full period 2010 to 2050. The marginal cost calculated by the CROSSTEM-CH model is the shadow price of the commodity balance at a given time, and represents the increase in total system cost due to an increase of a unit of demand (Loulou et al., 2005). It includes all constraints and costs (incl. fixed costs) and can therefore be seen as a long-term marginal cost, or marginal cost including scarcity rents. As the CGE model's simulates a year and not each of the 288 time-slices displayed in the bottom-up model, CROSSTEM-CH's marginal cost is converted to an annual demand-weighted marginal cost (MC):

$$MC = \frac{\sum_{\tau} D_{\tau} \cdot MC_{\tau}}{\sum_{\tau} D_{\tau}} \tag{2.7}$$

where D_{τ} and MC_{τ} are the demand and marginal cost at time-slice τ.

The use of long-term marginal cost as wholesale price implies that scarcity rents are taken into account (i.e. utilities recover their fixed costs). We assume that the market is fully liberalized and the market price equals the long-term marginal cost of the CROSSTEM-CH model from 2025 onwards; in 2010, the price is given by input-output table data, while in the years in between, the market is gradually liberalized and prices reflect a combination of regulated prices and marginal cost pricing (see figure 2.5).

For the price in GENESwIS to reflect the wholesale electricity market price, a markup[5] is set on average cost. The markup is calculated in such a way that the price of wholesale electricity is pushed from the average cost AC given by the CROSSTEM-CH model to the assumed market price[6] P_m as per equation (2.8). The profit is redistributed lump-sum to the representative household.

$$\text{Profit markup}(t) = \frac{P_m(t) - AC(t)}{AC(t)} \tag{2.8}$$

In GENESwIS, all sectors display constant returns to scale. This is the common assumption in

[5] This markup is a markup over average cost, allowing the model to reach marginal cost levels in a perfect competition setting. It is not to be mistaken with a markup over marginal cost as is usually defined in cases of imperfect competition.

[6] The assumptions on market liberalization illustrated in figure 2.5 translate into: $P_m(2010)$ = IOT price, $P_m(2015) = \frac{2}{3}AC(2015) + \frac{1}{3}MC(2015)$, $P_m(2020) = \frac{1}{3}AC(2020) + \frac{2}{3}MC(2020)$, and $P_m(t \geq 2025) = MC(t)$.

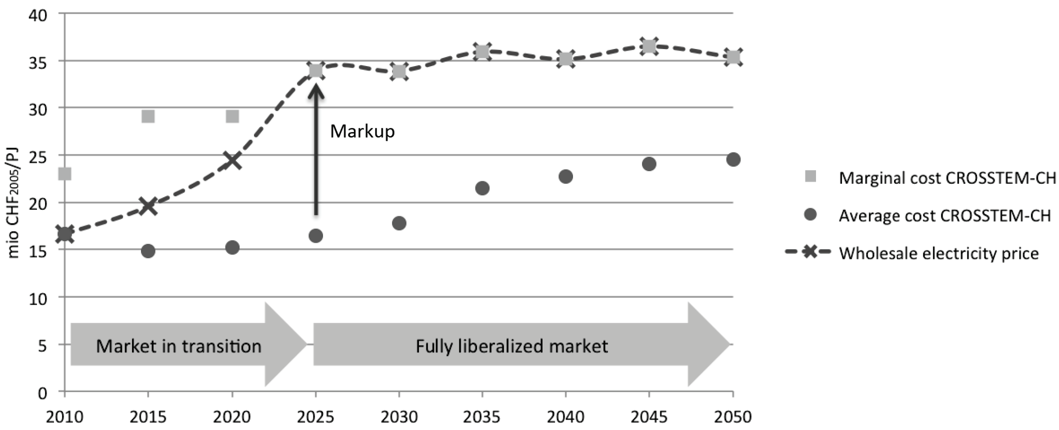


Figure 2.5 – Market liberalization assumptions: wholesale electricity market price in comparison with baseline annual average and marginal costs from the CROSSTEM-CH model.

computational equilibrium models that do not explicitly model imperfect competition. Diminishing returns to scale is effectively introduced in GENESwIS' electricity generation production function through the coupling of the models: the profit introduced in the CGE model is equal to the producer surplus from the bottom-up model. This way, the model takes into account sub-marginal rents and income effects from binding constraints in the bottom-up. We do not, however, model imperfect competition, but marginal cost pricing in liberalized markets.

The Swiss electricity market may be imperfectly competitive. However, with the increased exchange with the European market, the expansion of renewable production and the vertical disintegration of generation, transport and distribution, strong market power is unlikely. Moreover, market inefficiencies such as imperfect competition cannot be modeled in optimization frameworks, as these models impose efficient allocation (Böhringer and Rutherford, 2009). In the presence of imperfect competition, the player exercising market power decides to modify its production in order to influence the market price. This is not a behavior that can be modeled - or even approximated - in the CROSSTEM-CH model. Introducing imperfect competition in the CGE model would thus bring consistency issues between the two models. We therefore decided not to introduce an endogenous formulation of imperfect competition in the coupled framework.

Although we determine, at each iteration, the value of the input quantity parameters and the profit markup rate to push the wholesale electricity price to market price level, the wholesale electricity price is endogenous in GENESwIS. It is determined by supply and demand through an appropriate market clearing condition: The GENESwIS model simulates a coherent equilibrium. The wholesale electricity price determined by GENESwIS in the earliest iterations might differ from the market price calculated from CROSSTEM-CH's costs. However, when the framework approaches convergence, the wholesale electricity price aligns to the market price (see figure 2.9 p.31).

2.3.2 GENESwIS inputs into CROSSTEM-CH

The CGE model, GENESwIS, simulates the reactions of the economy to the policies implemented and to the changes in electricity generation technology and wholesale electricity price provided by the bottom-up model. We include these reactions, namely endogenous electricity demand variations and factor and commodity prices variations, into the bottom-up model.

Electricity demands

In CROSSTEM-CH, electricity demands are set exogenously. At each iteration, yearly sectoral electricity demands are extracted from GENESwIS and given as inputs to the CROSSTEM-CH model. GENESwIS' yearly electricity demands[7] are converted into demands for each of the 288 time-slices of the CROSSTEM-CH model through load curves.

To help with convergence, the electricity demand response of the GENESwIS model is not sent directly, but dampened (see section 2.3.3).

Factor and input prices variation

Fuel costs are set exogenously for both models as Switzerland does not have an impact on world prices. However, general equilibrium variations of domestic prices should be taken into account for the other bottom-up aggregated input costs, namely investments, and operation and maintenance (O&M) costs.

To do so, we create price-variation coefficients for each technology[8]. These coefficients are composed of the weighted average of the price variation of each factor and commodities; the weighting being equal to the share of expenditure.

The decomposition of investment costs is based mostly on Ragwitz et al. (2009). The price variation coefficients are calculated as the weighted average (weights given in table 2.4) of the price variation of each input compared to the benchmark prices. In GENESwIS, transport sectors are disaggregated between road, rail, and air and other transport. The transport price coefficient is therefore composed of a combination of the different transport sectors prices using Swiss input-output table shares of intermediate consumption of transportation by the electricity generation sector.

Operation and maintenance costs include labor, material and other service costs. Labor shares were estimated by Hal Turton for an analysis in the EU-NEEDS project. The other sectors' shares are computed from the Swiss input-output table (Nathani et al., 2011). As transport is considered here only for thermal plants, it is considered to be composed solely of pipeline transport (included in air

[7]Electricity demands for 2010 are not exchanged. Due to the calibration of the baseline to Prognos (2012) projections and to the inter-temporal nature of the CGE model, some undesirable border effects appear in 2010. It is hence not instructive to couple 2010 values, which are anyways historical values.

[8]We class the different production technologies into four main groups: hydro generation, thermal generation, solar photovoltaics, and other renewable technologies.

and other transport). The price-variation coefficients' weights for operation and maintenance are given in table 2.5.

Table 2.4 – Composition of the price variation coefficients modifying CROSSTEM-CH's investments costs per technology.

	ETS goods	**Metals**	**Constru -ction**	**Other goods**	**Trans -port**	**Other services**
Thermal plants	1%	9%	10%	61%	13%	7%
Hydro plants	0%	5%	27%	45%	4%	19%
Solar PV	16%	30%	1%	42%	9%	2%
Other renewables	0%	24%	12%	56%	3%	4%

Table 2.5 – Composition of the price variation coefficients modifying CROSSTEM-CH's operation and maintenance costs per technology.

	Labor	**Metals**	**Constru -ction**	**ETS goods**	**Other goods**	**Trans -port**	**Other services**
Thermal plants	10%	0%	3%	0%	47%	2%	38%
Hydro	80%	1%	3%	0%	2%	0%	13%
Solar PV	50%	2%	11%	1%	7%	0%	28%
Other renewables	50%	2%	11%	1%	7%	0%	28%

2.3.3 Harmonization and convergence

The first main challenge when soft-coupling two models of different natures such as GENESwIS and CROSSTEM-CH is for the models to react in a reasonable and stable way to the coupling. Indeed, input values that vary too much from the values the models are used to receive can lead to solution problems. For example, a too high electricity demand might push the CROSSTEM-CH model to reach boundaries of production potentials. It then must use stop-gap production technologies with very high costs that prevent the model from crashing due to an infeasible solution. These very high costs, when sent to the GENESwIS model, will bring the electricity demand down drastically. When sent back to CROSSTEM-CH, a very low demand might, for example, result in CROSSTEM-CH generating negative costs due to trade revenues. Negative costs are not allowed in the GENESwIS model, and solving the framework becomes impossible.

Hence, a careful harmonization of the models is necessary before attempting the coupling (see below).

The second main challenge is to reach convergence. First of all, a solution must exist for the framework to converge to. CGE models are built on CES functions to ensure convexity and solvability. It is not possible to determine the solution space of the combination of two big models with different structures and logic. We can, however, convince ourselves that, as marginal cost and electricity demand react in opposed ways, a solution should exist.

When solutions do exist for the scenario simulated, the framework must converge to the existing solution. Convergence is not easy to achieve due to the stepwise behavior of the bottom-up model. Special solving techniques had to be applied in the coupling procedure to avoid the framework getting locked in oscillations (see below).

Harmonization of the models

Variables that exist in both models should have the same values. For this, the models must be harmonized.

For exogenous data, harmonization is trivial. Both models use a discount rate of 4.5% and identical world energy prices (import prices) and CO_2 permit prices for the Emissions Trading Scheme (see table 2.6).

Table 2.6 – World energy prices [CHF_{2010}/GJ] (International Energy Agency, 2010), and CO_2 permit prices [CHF_{2010}/ton] for sectors that belong to the emissions trading scheme (Prognos, 2012).

	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Crude oil	12.26	15.60	17.08	18.12	18.98	19.50	19.90	20.30	20.65
Gas	8.54	10.61	11.61	12.31	12.91	13.31	13.48	13.74	13.96
CO_2	15.58	27.53	39.48	43.63	47.79	51.95	55.06	56.62	58.18

Endogenous variables are much more difficult to harmonize while keeping the structure and data consistency of both models. For the models to behave smoothly, both electricity generation costs and demands must be compatible.

GENESwIS is based on the Swiss input-output table (Nathani et al., 2011), which also includes information on energy prices. It is important to ensure that average and marginal costs of electricity from the CROSSTEM-CH model (in terms of annual averages) are reconciled with input-output table prices. Also, to ensure economic consistency, average annual marginal cost generated by CROSSTEM-CH should not be smaller than annual average cost in any given year. For this purpose, some input data in the CROSSTEM-CH model were modified. Especially, capital costs for existing plants were included in generation costs[9].

The baseline scenario for this study is based on the "weiter wie bisher" (business as usual) scenario of the Swiss Energy Perspectives (Prognos, 2012). CROSSTEM-CH initial demands are exogenously set on demand projections by Prognos (2012). For the full framework to reproduce this given baseline scenario, GENESwIS is re-calibrated[10] along the baseline demand path, taking into account inputs from CROSSTEM-CH.

[9] The fact that bottom-up prices for the first modeling years do not include all costs is also pointed out by Glynn et al. (2015).

[10] By modifying autonomous energy efficiency indices.

Supply elasticity in GENESwIS

The seminal soft-linking method by Böhringer and Rutherford (2009) introduces flexibility[11] in the coupling algorithm by locally calibrating a linear price-responsive demand function in the bottom-up model that is re-benchmarked at each iteration on a Marshallian demand approximation of the CGE model demand curve. This was not possible in our situation, because demand is a fixed exogenous input to the CROSSTEM-CH model. The TIMES framework allows for the introduction of elastic demand functions, calibrated from a reference run and given constant own-price elasticities (Loulou et al., 2005). However, this is a delicate task and our partners[12] did not have the resources to implement it.

Alternatively, to help with the convergence of the models, we introduce a supply elasticity in the electricity transport and distribution sector of GENESwIS. To set a given supply elasticity for the electricity transport and distribution sector, we insert a fixed resource at the top of its nest (see figure 2.6). The elasticity of substitution σ between the fixed resource and the rest of the inputs is calculated as per eq.(2.9), given a supply elasticity η and the share of fixed resource θ_R (see Rutherford, 1998).

$$\sigma = \eta \frac{\theta_R}{1-\theta_R} \tag{2.9}$$

The value of the supply elasticity, η, can be set such that it helps with convergence (approximating the bottom-up supply elasticity). Lanz and Rausch (2011) - implementing the Böhringer and Rutherford (2009) decomposition technique - show that the choice of demand elasticity does not affect the results but that a good approximation of the top-down demand response reduces the number of iterations needed for convergence. For these simulations, we use a supply elasticity of $\eta = 2$. With $\theta_R = 0.024$, eq.(2.9) yields an elasticity of substitution of $\sigma = 0.05$.

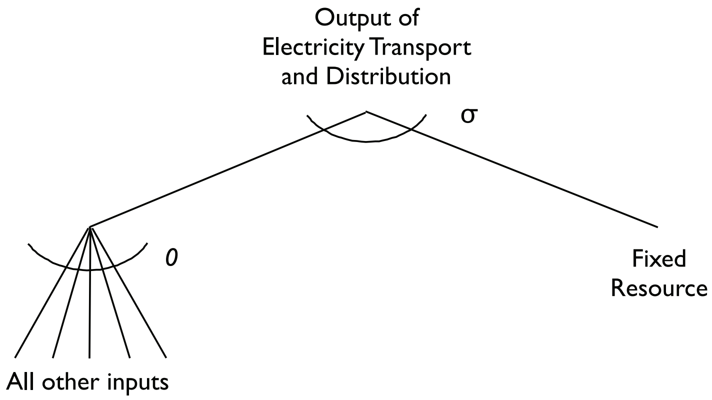


Figure 2.6 – Nesting structure of the electricity transport and distribution production function in GENESwIS.

[11] And the natural interpretation that the bottom-up model solves - in each iteration - a partial equilibrium problem for the energy sector, maximizing total surplus (the sum of producer and consumer surplus).

[12] This thesis work is part of a collaborative project. I did not have access and the right to modify the bottom-up model code.

Dampening of the demand response

Due to the stepwise nature of the bottom-up supply curve, and despite the introduction of a supply elasticity for the electricity transport and distribution of the CGE model, it is frequent that the models locks up into an oscillation between two different marginal costs. The resulting electricity demand hence oscillates between two values and does not converge. To reduce this problem, we introduce a dampening of the demand response between sub-sequent iterations into the coupler. Instead of sending the sectoral demands from the CGE directly to the bottom-up model, we send a Gauss-Seidel (Labriet et al., 2010; Hageman and Young, 1981) combination of the previous demands.

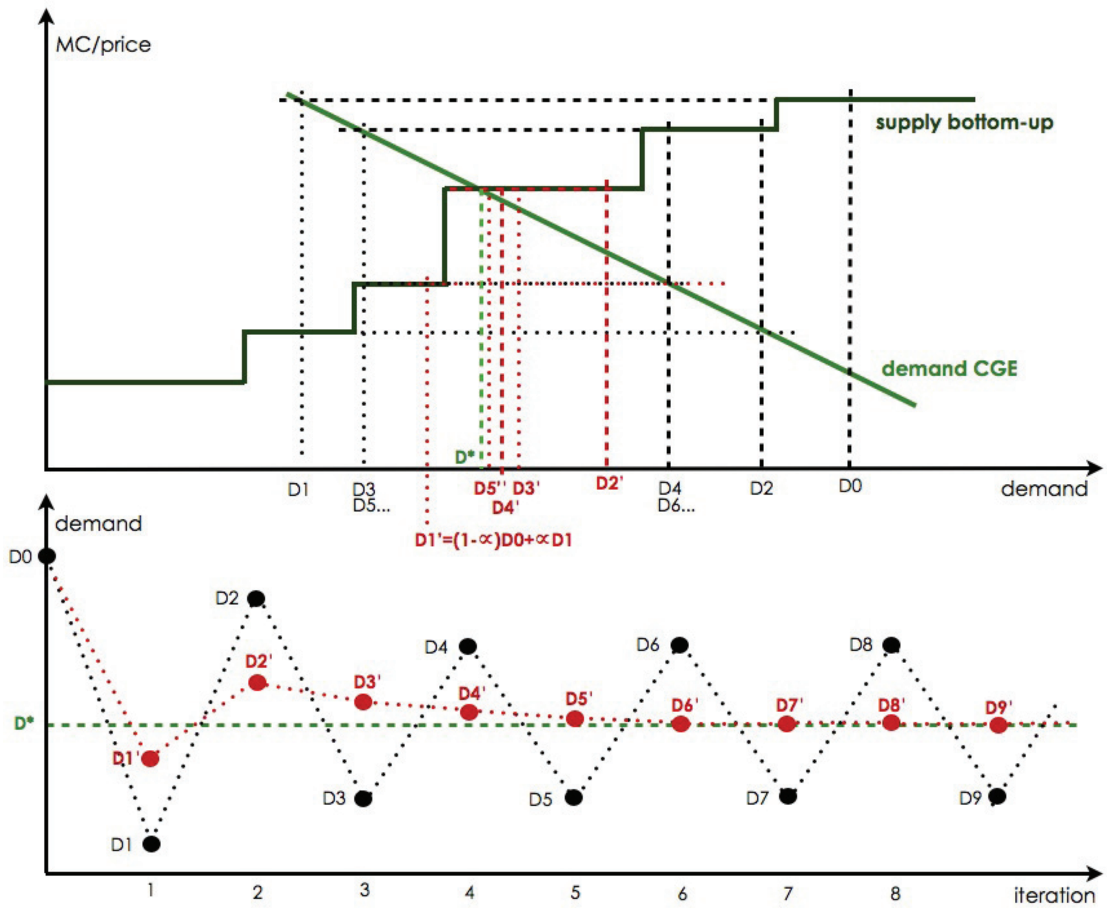


Figure 2.7 – Illustration of demand-dampening (Gauss-Seidel) for a bottom-up-top-down coupled framework.

Let D_k be the demand estimated by the CGE model at iteration k. The demand $D_k^{'}$, introduced in CROSSTEM-CH is determined such that:

$$D_k^{'} = \alpha D_k + (1 - \alpha) D_{k-1}^{'} \tag{2.10}$$

The calibration of the α parameter is critical. Taking too small steps increases the run time, when too large steps will not solve the oscillations' issue. We found that α=0.3 is a good choice for our framework.

Figure 2.7 gives an illustration of the demand-dampening (Gauss-Seidel method) for our framework. The representation is merely an illustration, because the depicted supply and demand curves are much too simplistic.

Let us assume a bottom-up step-wise supply function and a demand curve for the CGE model. The equilibrium solution lies at demand D^*. The coupling framework's goal is to converge to this solution. Let us start with an initial demand D_0. The bottom-up model optimizes the electricity supply system and provides the CGE model with a given marginal cost (wholesale electricity price). With this information, the CGE model reaches equilibrium at demand D_1. D_1 is then sent to the bottom-up model. With D_1 for input, a much lower marginal cost is reached, which, sent to the CGE, will bring a solution at D_2. This routine is performed until convergence is reached. However, with this configuration, the framework never converges. It stays stuck, oscillating between 2 solutions (D_3 and D_4) indefinitely. This is when the Gauss-Seidel method becomes useful. Let us start with the same initial demand D_0. The demand sent to the bottom-up model ($D_1^{'}$, in red ink in figure 2.7) is a combination of the previous demands as per eq.(2.10). The same dampening is applied to the next demands. This way, the steps are reduced, and the framework does not get stuck oscillating between two states. It is hence able to converge towards the solution D^*.

The demand-dampening approach does not create artificial equilibria, but merely helps to approach the solution in a smoother way.

Convergence criterion

The coupling procedure iterates until the electricity demand converges. To test this convergence, the following criterion ζ is introduced:

$$\zeta = \frac{\sqrt{\sum_t (D_{t,k} - D_{t,k-1})^2}}{\sqrt{\sum_t D_{t,k}^2}} \leq z \tag{2.11}$$

where $D_{t,k}$ is total electricity demand at period t for iteration k.

The framework stops iterating when the stopping criterion ζ goes below a given precision parameter z. We verify post-simulation that convergence has also been reached for other variables (marginal cost, average cost, sectoral output etc.).

2.4 Some illustrative simulations

We present some simulations that aim at testing the functioning of the ELECTRA-CH framework and illustrating its capacities. For this purpose, we model a fictional but plausible scenario of strengthened energy and climate policies in Switzerland and compare it to a baseline. It will allow us to test for convergence. It will also show how changes in prices, quantities, technologies or welfare, can not only be estimated, but explained, providing insights into the transmission of policy shocks.

2.4.1 Scenarios

The baseline scenario is based on the 'weiter wie bisher' scenario of the Energy Perspectives (Prognos, 2012). It includes the following policies:

- Nuclear power plants are phased-out at the end of their assumed lifetime (50 years) and not replaced by new generation plants. Effectively, no electricity is produced with nuclear technology after 2035.
- Electricity trade is constrained such that Switzerland may not import more than it exports on a yearly average (in quantity terms [PJ]; the model is left to optimize trade revenue).
- An Emissions Trading Scheme (ETS) is implemented such that CO_2-intensive sectors can compensate their emissions. The Emissions Trading Scheme is linked to the European ETS. We assume that Switzerland does not have an effect on CO_2 prices. CO_2 permit prices are hence exogenously set on projections by Prognos (2012) - see table 2.6, p. 26.
- A tax on CO_2 emissions is set on the consumption of natural gas and heating fuels by households and sectors that do not participate in the ETS. Tax rates are set at 36 CHF/t in 2010, 60 CHF/t in 2015 and at 72 CHF/t from 2020 to 2050.
- 280 mio CHF/year from CO_2-tax revenues are recycled through a subsidy program for energy-efficient refurbishment of buildings (Building program).

The TAX scenario represents a strengthening of market-based climate and energy policy instruments on top of the baseline policies:

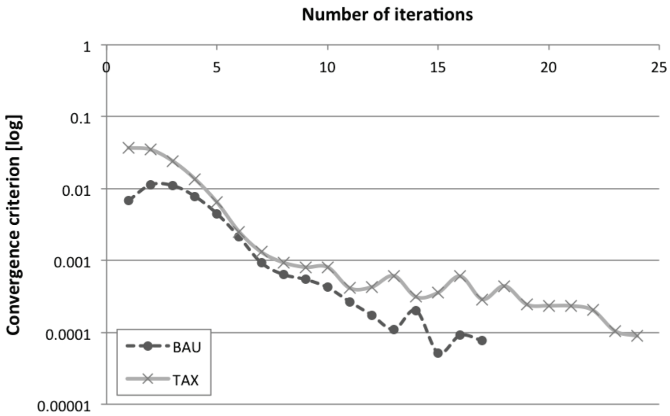
- A tax is levied on electricity consumption at a rate of 10% on retail electricity price in 2020, increasing linearly up to 50% in 2050.
- The Emissions Trading Scheme stays identical as in the baseline scenario (same assumptions on permit prices as we assume no modifications of international policies).
- The CO_2 tax on natural gas and heating fuels is increased linearly from 2020 level (72 CHF/t) to 200 CHF/t in 2050.
- A CO_2 tax on transport fuels is introduced at 50 CHF/t in 2035, reaching 200 CHF/t in 2050.

Market based policies are modeled in GENESwIS, while command and control policies (nuclear phase-out, electricity trade constraints) are modeled in CROSSTEM-CH.

2.4.2 Convergence

For the two scenarios, the framework converges well and reasonably fast. The convergence criterion on total electricity demand (see eq.(2.11) p.29) reaches a precision of $< 1 \cdot 10^{-4}$ in respectively 15 and 24 iterations (figure 2.8).

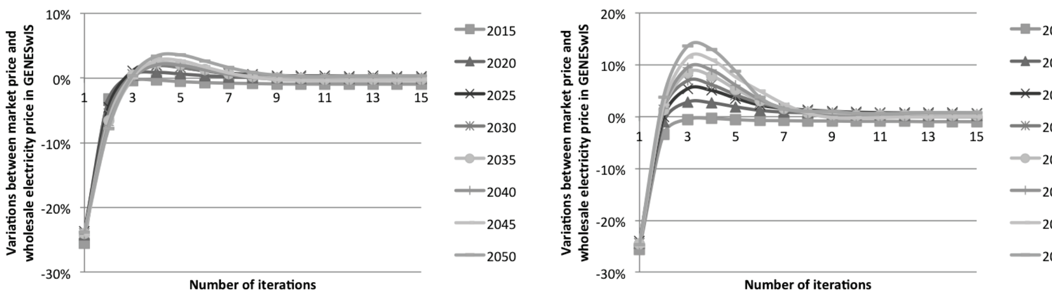
After convergence, we check the convergence of other important variables. For these runs, the maximum deviation of marginal and average costs in any given year is in the order of 10^{-4}.



Convergence criterion	Number of iterations BAU	TAX
$< 1 \cdot 10^{-2}$	4	5
$< 1 \cdot 10^{-3}$	7	8
$< 1 \cdot 10^{-4}$	15	24

Figure 2.8 – Convergence performance for the Baseline (BAU) and TAX scenario: Number of iterations needed for the demand convergence criterion ζ - eq.(2.11) - to reach different precision values.

As discussed in section 2.3.1 p.20, our coupling algorithm determines input quantities and the profit markup rate such that wholesale electricity price is pushed to market price level (assumed to follow the long-term marginal cost calculated by the CROSSTEM-CH model from 2025 onwards). However, the wholesale electricity price is endogenous in GENESwIS and determined by supply and demand through an appropriate market clearing condition. Nonetheless, we can see on figure 2.9 that wholesale electricity price matches the market price $P_m(t)$ determined from CROSSTEM-CH's costs rapidly.



(a) Baseline

(b) TAX scenario

Figure 2.9 – Percentage difference between the market price determined by CROSSTEM-CH's costs and the wholesale electricity price at each iteration for the different modeling periods for (a) the baseline and (b) TAX scenario.

For scenarios with very demanding technological constraints, especially when expensive marginal technologies with limited capacities and potentials are involved, the framework can still lock-up in oscillations between two marginal costs without obtaining convergence, despite the Gauss-Seidel dampening of demand responses. This is probably due to the fact that this method does not allow for convergence on a vertical step of the supply curve.

2.4.3 Technology mix and total system cost

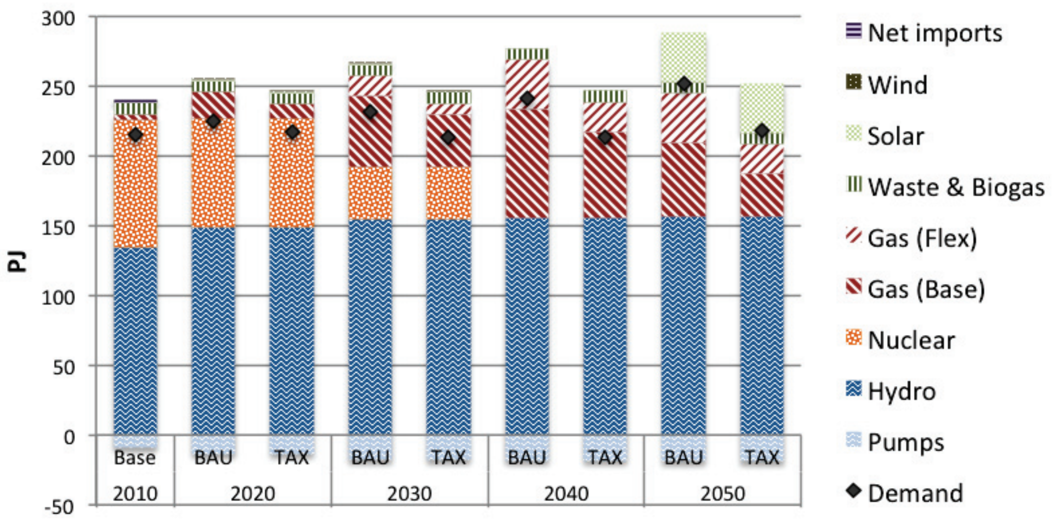
Due to the nuclear phase-out, by 2035 almost no electricity is produced with nuclear technology. In both the baseline and TAX scenarios, this capacity is replaced by base and flexible natural gas power plants (figure 2.10a). The flexible gas plants are installed to optimize electricity import/export patterns and create maximum trade revenue. By 2050, solar PV becomes competitive due to technology learning and increasing natural gas and CO_2 prices, and replaces some of the base gas power plants. Hydro production reaches its full potential in each period. The reduction in electricity demand fostered by the market-based policies of the TAX scenario is met mostly by a smaller share of gas power plants (both base and flexible).

Total system cost increases over the time horizon for both scenarios (figure 2.10b). A large share of total cost increase is due to natural gas. Electricity trade revenue increases overtime, counter-balancing partly the increase in natural gas cost, as some production from flexible gas plants is used to maximize electricity trade revenue. Although trade volumes are constrained in CROSSTEM-CH such that no net electricity imports are allowed on a yearly average, the model maximizes trade revenue by exporting in time-slices where exogenous foreign prices are high. Electricity trade prices are assumed to increase over time. This increase has two effects: (1) as the model can still optimize in order to export at times where prices are highest, an increase in trading prices motivates the model to increase total trade volumes and (2) the revenue increases as import and export prices increase proportionally. Taxes reported on figure 2.10b include expenses for CO_2 permits in the emissions trading scheme (EU ETS), and for the Federal levy on nuclear fuel for decommissioning and disposal funds. The cost of the latter vanishes gradually with the nuclear phase-out, while expenses into CO_2 permits increase due to the larger share of natural gas and the increase in permit prices.

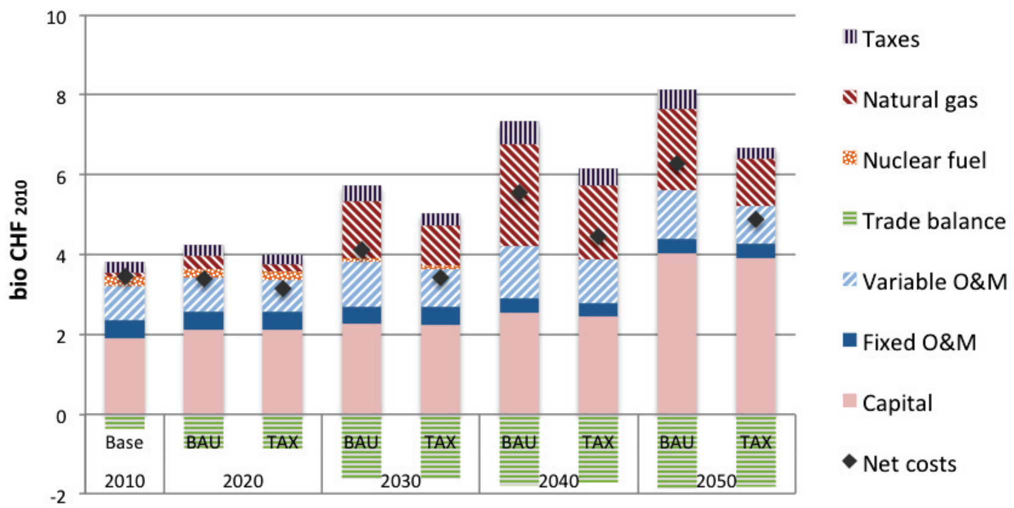
The lower demand in the TAX compared to the baseline scenario (figure 2.11b) reduces cost levels. Costs savings come mostly from smaller expenses for natural gas. The reduction in total discounted system cost over the whole modeling horizon amounts to1.9 bio CHF_{2010} in the TAX scenario compared with the baseline.

2.4.4 Electricity prices and demand

In the TAX scenario, the wholesale electricity price does not vary much compared to the baseline scenario (figure 2.11a). This is due to the only minor variations in marginal cost. Indeed, the same technologies compose the technology mix in both scenarios (figure 2.10a) and marginal technologies are the same (at least in yearly average). The price paid by users for retail electricity includes transport, distribution and taxes. Due to the TAX scenarios' policies, namely the electricity tax,



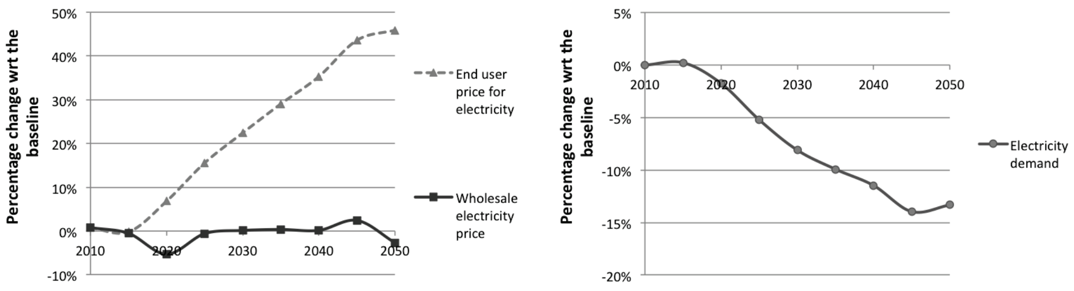
(a) Technology mix for electricity generation



(b) Total system cost

Figure 2.10 – Technology mix for electricity generation [PJ] and total system cost [bioCHF$_{2010}$] for the Baseline (BAU) and TAX scenario.

the user price of electricity increases (figure 2.11a). This user price increase induces a reduction of the electricity demand (figure 2.11b) with regard to the baseline.



(a) Electricity prices variation (b) Electricity demand variation

Figure 2.11 – Variation of (a) wholesale electricity price and electricity price for users (including distribution costs and tax) and (b) total electricity demand - for the TAX scenario with regard to the baseline.

2.4.5 Sectoral effects

The environmental and energy policies of the TAX scenario affect the energy sectors the most (figure 2.12), as can be expected. We observe a noticeable reduction of production for the natural gas transport and distribution, refineries and electricity generation sectors with regard to the baseline. The refineries' reduction in output might be unrealistic. In real life, the refineries might cut down on refined fuels imports instead of slowing production.

The increase in production of the district heating sector and, to a smaller extent, of the construction and cement and concrete sectors, are due to a substitution from natural gas and heating fuels to district heating and insulation (provided by the construction sector). We are aware that these effects might be somewhat overestimated. In GENESwIS, cement and concrete are demanded solely by the construction sector and exports, which implies that output changes for the construction sector usually induce similar output changes for cement and concrete. While in reality some insulation is indeed achieved with thicker and/or improved concrete walls, we may have overstated the positive effect on the cement and concrete sector due to the usual homogeneous commodity assumption for CGE models, which also applies to construction. District heating production is not linked to combined heat and power plants capacities. Also, bounds on the quantity of available waste are not taken into account. This may result in an overestimation of the opportunity for increase in district heat production.

Public transports see their activities increase slightly, while the energy-intensive industries such as metal production and rest of industry experience a small decrease in output (< 1%).

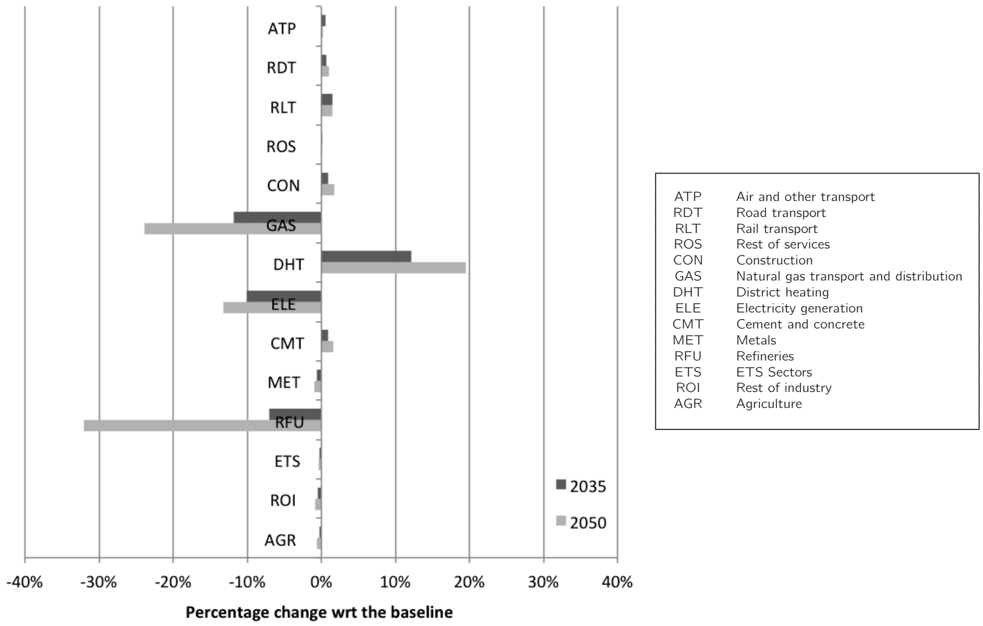


Figure 2.12 – Variation of sectoral production in the TAX scenario compared to the baseline for the years 2035 and 2050.

2.4.6 CO_2 emissions

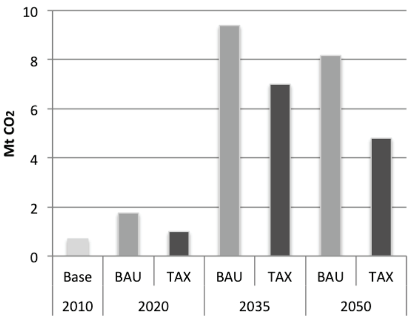
CO_2 emissions from electricity generation are small in 2010. They increase in both scenarios with the introduction of gas-fired power plants (figure 2.13a). The penetration of solar PV technology in 2050 due to increasing natural gas and CO_2 permit prices curbs emissions.

CO_2 emissions are lower in the TAX scenario than in the baseline as the reduction in demand caused by TAX policies results in a lower share of natural gas in electricity generation.

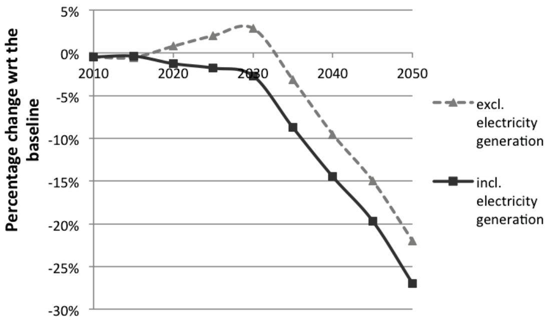
For the economy as a whole, we also observe a decrease of CO_2 emissions in the TAX scenario relative to the baseline (figure 2.13b). This is the expected outcome for scenarios that include market-based CO_2 policies. It is however interesting to note the presence of a substitution effect: although total CO_2 emissions decrease, CO_2 emissions from the other sectors (excl. electricity generation) increase in the TAX scenario relative to the baseline.

Analyzing the CO_2 emissions paths by fuel, we observe a regrettable consequence of policies timing: In the TAX scenario, the CO_2 tax on heating fuels is increased from 2020 to 2050. An electricity tax is introduced in 2020, increasing until 2050. Transport fuels, in contrast, are taxed through the CO_2-tax scheme only from 2035 onwards. The different timings of these policies affect the respective fuel demands and related emissions, triggering the increase in emissions from non-electricity sectors until 2030.

CO_2 emissions from light heating oil are reduced from 2025 onward, due to the CO_2 tax (figure

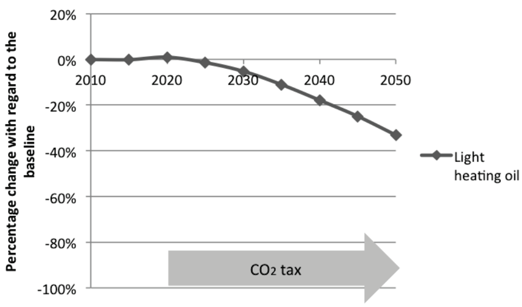


(a) CO_2 emissions from electricity generation

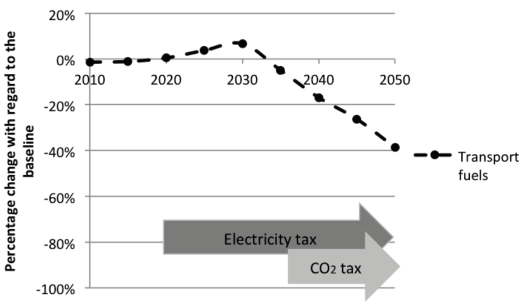


(b) Total CO_2 emissions

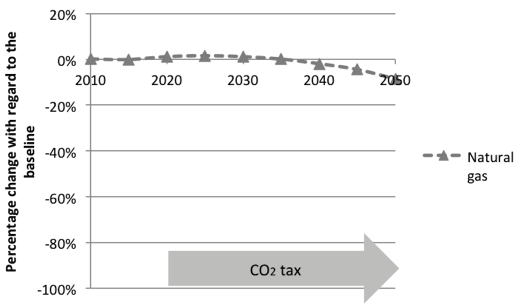
Figure 2.13 – CO_2 emissions - (a) due to electricity generation for the baseline (BAU) and TAX scenarios [$MtCO_2$] and (b) from fuel consumption by all sectors - including and excluding electricity generation - for the TAX scenario [percentage variation with regard to the baseline].



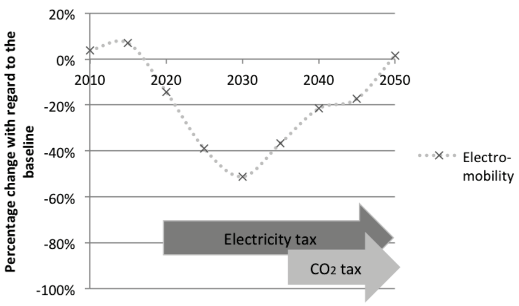
(a) CO_2 emissions from light heating oil



(b) CO_2 emissions from transport fuels



(c) CO_2 emissions from natural gas



(d) Electricity demand from electro-mobility

Figure 2.14 – Variation of CO_2 emissions due to (a) light heating oil (b) transport fuels and (c) natural gas (excluding emissions from electricity generation) in comparison with (d) electricity demand from electro-mobility - for the TAX scenario with regard to the baseline.

2.14a). We notice a slight increase of CO_2 emissions until 2020 due to inter-temporal effects.

For natural gas, the emission reduction is somewhat delayed (figure 2.14c). Although natural gas is a fossil fuel, its emission intensity is lower than light heating oil's. This implies that under a CO_2 tax, there is not only substitution away from natural gas, but also some substitution from oil to natural gas heating, especially as long as there is still a sizeable share of existing oil heaters.

CO_2 emissions from transport fuels increase until 2030 compared to the baseline (figure 2.14b). As electricity is taxed earlier, i.e. from 2020 onward, the switch to e-mobility is somewhat discouraged, and more transport fuels continue to be used. Once transport fuels are also taxed, this effect is reversed, and e-mobility becomes more attractive (figure 2.14d). This effect is quite strong in our model, because of the high elasticity of substitution we had to assume between e-mobility and transport fuels. In reality, the effect might be smaller. However, it demonstrates, at least qualitatively, that the timing of policies is crucial for the market penetration of new and cleaner technologies.

2.4.7 Welfare

The introduction of climate and energy policies in the TAX scenarios induces a small reduction of welfare with regard to the baseline (0.1% $\simeq$ 2 bioCHF). The welfare reduction is mainly due to the increase of the CO_2 tax, the revenues of which are recycled through the Buildings program (subsidy of 280 mio CHF) and lump-sum transfers. It is indeed unlikely that it originates from the simulated electricity tax, as its revenues are recycled through the income tax (equal yield constraint) which does not greatly alter the total excess burden of the tax system.

This welfare loss is likely offset by the benefits of reduced climate change as well as side benefits of abatement, such as health improvements due to reduced air pollution.

2.4.8 Overall framework assessment

The results presented in this section illustrate the functioning of the ELECTRA-CH modeling framework and the possible analyses that can be conducted with it. This simulation exercise has demonstrated that ELECTRA-CH is capable of providing meaningful results. Despite the complex structure of the coupled framework, the results can be explained and policy-induced impacts can be tracked down. Furthermore, the framework converges relatively rapidly to robust solutions.

ELECTRA-CH permits to simulate different types of energy policies: market-based instruments are modeled in GENESwIS, while technology restrictions related to electricity generation are included in CROSSTEM-CH. The results presented in this section demonstrate how impacts of policy shocks can be observed through variations of sectoral production, CO_2 emissions, electricity prices and demand or overall welfare, as well as on the technology mix[13] and total system cost of electricity generation.

[13]The scenario modeled in this section did not drastically modify the technology mix. Stronger impacts can be observed in chapter 4.

A specific added value of the coupled framework concerns electricity demand and pricing. In ELECTRA-CH, electricity demand varies endogenously due to policy-induced changes in prices in the general equilibrium model. Wholesale electricity prices depend directly on electricity generation costs and not on generic constant elasticity of substitution production functions as it would be the case in a pure computable general equilibrium model. In a pure computable general equilibrium setting, the reduction in electricity demand due to the electricity tax would affect wholesale electricity price: At equilibrium, the end-user price increase would be smaller than the tax, and wholesale electricity price would be lower than before the tax. With the link to the bottom-up model, wholesale electricity price is linked to the marginal cost - and hence directly to the technology. In our scenarios, the decrease in demand does not affect marginal costs. Therefore, the wholesale electricity pice hence does not vary (see results sub-section 2.4.4). The demand reduction is therefore stronger than what it would be in a pure general equilibrium setting.

2.5 Conclusion

The ELECTRA-CH framework couples a dynamic computable general equilibrium model of the Swiss economy (GENESwIS) with a TIMES electricity supply model for Switzerland (CROSSTEM-CH). It permits to adequately model both market-based policies and technology restrictions, and analyze the interactions between these different types of policies and initial tax distortions. ELECTRA-CH simulates the implications for the different economic actors (firms, consumer, government) and their reactions to climate and energy policies, taking into account the policy induced modifications in electricity generation. Moreover, ELECTRA-CH allows to investigate the type of electricity generation mix that is cost optimal in a given policy environment. Electricity prices are linked to the technologies used, accounting for both system costs and profit. The degree of liberalization of the electricity market can be represented appropriately.

The coupling methodology described in this chapter is an alternative to the seminal soft-coupling algorithm proposed by Böhringer and Rutherford (2009) in situations where a calibrated linear demand function cannot be introduced in the bottom-up model. In ELECTRA-CH, the bottom-up model receives the electricity demand simulated by the CGE as an exogenous input and minimizes total system cost. The flexibility in the algorithm comes from the top-down model. The electricity generation production function is set as Leontief to ensure that inputs from the bottom-up are set as fixed shares within one iteration. Additionally, the value of the input quantity parameters and the profit markup rate are determined - at each iteration - to push the wholesale electricity price to market price level. However, the wholesale electricity price is endogenous in GENESwIS: It is determined by supply and demand through an appropriate market clearing condition. Nonetheless, when the framework approaches convergence, the wholesale electricity price aligns to the market price. To help with the convergence of the models, we introduce an elasticity of supply in the electricity transport and distribution sector of the CGE model GENESwIS and dampen the demand reaction with the help of a Gauss-Seidel method. Our computational experience showed that the framework behaved nicely, and converged to meaningful results.

The development of the ELECTRA-CH framework has highlighted that a careful harmonization of the component models is crucial for framework convergence and for producing dependable results.

Also, the variables to be linked must be meticulously selected and interpreted not to introduce inaccuracies or logic flaws in the framework. This is particularly the case for the link between bottom-up costs and top-down wholesale electricity prices. This link and its relationship with market liberalization is investigated in chapter 3. Finally, the implementation of a demand dampening method (here Gauss-Seidel) is essential for achieving convergence.

A sizeable, but non-exhaustive wish-list of improvements and enhancements of the model framework would include:

- Opening the ELECTRA-CH framework to a more precise representation of international electricity trade: While we were developing the coupled framework ELECTRA-CH, the CROSSTEM model (Pattupara and Kannan, 2016) has been developed to represent both Switzerland and its neighboring countries, with endogenous trade. An alternative to coupling GENESwIS with CROSSTEM could be to inform the CROSSTEM-CH model with trade prices estimated in CROSSTEM.
- Calibration: The ELECTRA-CH framework was developed as part of a project work for the Swiss Federal Office of Energy. To stay harmonized with the Swiss Energy Perspectives, we calibrated the framework on projections of electricity demands and CO_2 emissions by Prognos (2012). This calibration required the use of autonomous energy efficiency indices that are not based on projections of technology improvement, but chosen to fit Prognos' pathways. For future work, a different approach to calibration could be chosen.
- Disaggregate electricity commodities in the CGE model: CROSSTEM-CH models 288 time-slices for each modeling period. It could be instructive to take advantage of this disaggregation and introduce different electricity commodities (e.g. peak/off-peak) in GENESwIS. These commodities would display different cost structures.
- A better representation of renewables: Self-production and consumption from domestic renewable systems are not modeled in CROSSTEM-CH, which neglects costs savings related to grid use. Furthermore, feed-in tariff (RPC) and investment subsidies for renewables are also not taken into account in CROSSTEM-CH.
- Include differentiated households in the CGE model to enable analyses on distributional effects.
- E-mobility is crudely modeled in our framework as a sub-nest of transport in GENESwIS. The penetration projections by Prognos (2012) are high, while the existing share of e-mobility is very small. To calibrate e-mobility demand to the Prognos path, we had to introduce an elasticity of substitution of 10 between e-mobility and transport fuels. Due to this very high elasticity, small changes in relative prices between retail electricity and transport fuels have large impacts on e-mobility demand. Despite this over-sensitivity, the scenarios illustrate that the timing of policies is crucial for market penetration of new and cleaner technologies. However, a more bottom-up type of modeling would improve the representation of e-mobility. For example, displaying discrete technological responses, as in Böhringer (1998) and Böhringer and Rutherford (2008), could be an option.
- District heating production in ELECTRA-CH is not linked to combined heat and power plants capacities. Also, bounds on the quantity of available waste are not taken into account. This results in an overestimation of the opportunity for substitution into district heat. Modeling combined heat and power generation by taking heat credits into account in the bottom-up model CROSSTEM-CH would solve this issue.

Chapter 3

Linking electricity prices and costs in bottom-up top-down coupling under changing market environments

Abstract

Electricity market liberalization is altering pricing mechanisms in wholesale electricity markets, which will affect the effectiveness of climate and energy policies. Models used to simulate such policies must be responsive to pricing rules. We show how this can be done and simulate a tightening of climate and energy policies. We use a soft-coupled framework composed of a top-down dynamic computable general equilibrium model and a bottom-up dynamic electricity supply model. The first simulates equilibrium prices and quantities, while the second minimizes electricity generation costs. In the coupling procedure, the link between wholesale electricity prices (top-down) and generation costs (bottom-up) depends precisely on regulatory market assumptions. In the regulated market, wholesale electricity prices are "cost-plus", while they depend on marginal generation costs in the liberalized market. We show that, in Switzerland, an electricity tax is significantly more effective in reducing electricity demand in the liberalized than in the regulated market.

Keywords: *electricity markets; market regulation; policy effectiveness; computable general equilibrium model; bottom-up energy model; soft-link coupling.*

3.1 Introduction

Price formation depends on market structure and regulation. Traditionally, wholesale electricity prices were regulated to allow producers to cover their generation costs and achieve an acceptable profit. Such price regulation provides incentives for new capacity additions as firms are guaranteed an acceptable return on investment. Moreover, investment into new capacity may additionally be fostered with the help of different types of subsidies, whether open or covert. In a fully liberalized competitive market, wholesale electricity is priced at marginal cost. This provides no incentive for investment unless there is scarcity of capacity, in which case the wholesale price includes a scarcity rent[1], which, in equilibrium, provides incentive for investment into new capacities (International Energy Agency, 2001).

The current European wholesale electricity market can be described as a largely liberalized market with overcapacity. Wholesale electricity is increasingly priced at short-term marginal cost. However, this price is currently too low to provide incentive for investment into new capacity[2]. In a liberalized market, such incentive will emerge only as expected prices reflect new capacity needs through scarcity rents at the margin. Today, it is yet unclear whether markets will be fully liberalized or whether elements of central planning will reappear out of the fear of undesired consequences of scarce capacity such as outages and price spikes.

The impacts of changing regulatory environments on price formation are potentially relevant for the effectiveness of energy and climate policies. They must, therefore, be modeled carefully. An adequate way of modeling electricity markets is to couple bottom-up and top-down models to take advantage of the qualities of both model types: The bottom-up model provides a detailed set of electricity generation technologies and minimizes generation costs, while the top-down model simulates the interactions between economic agents and computes equilibrium prices and quantities.

For their coupling, many approaches have been developed since Hoffman and Jorgenson (1977). Two main currents emerge: "hard linking", which encompasses the two model types into one single model, and "soft linking", which couples existing full-size models by exchange of variables (Wene, 1996). The hard linking methodology may be implemented by enhancing one model with a reduced version of the other (Manne and Wene, 1992; Messner and Schrattenholzer, 2000; Kombaroglu and Madlener, 2003; Sue Wing, 2006; Böhringer and Rutherford, 2008), or by writing a hybrid model directly in MCP format (Böhringer and Rutherford, 2008; Frei et al., 2003). This methodological choice ensures consistency within the model, but does not permit a high level of detail in both technical specification and economic interactions. The "soft link" coupling method (Drouet et al., 2005; Schäfer and Jacoby, 2005; Martinsen, 2011; Sceia et al., 2012; Riekkola et al., 2013; Fortes et al., 2014) involves keeping the models' full structure and complexity, exchanging a chosen set of variables and solving the models iteratively until convergence is reached on a given criterion. Böhringer and Rutherford (2009), decompose an MCP hybrid model and solve it iteratively, proposing a more consistent way of soft-coupling models. This approach inspired

[1] For simplification purposes and in line with the scope of our models, we do not consider here transmission constraints, load ranges nor network externalities. Nonetheless, the general argument remains valid.

[2] For example, a study from the Swiss Federal Office of Energy (2013a) deems 24 out of 25 potential future hydro projects not viable due to low wholesale electricity prices. The average discounted cost of new hydro plants is estimated at 141 CHF/MWh, which is considerably higher than the production costs of older plants or current average wholesale prices.

implementations by Tuladhar et al. (2009), Lanz and Rausch (2011), and Rausch and Mowers (2014), the later with full-scale models.

Few studies explicitly link costs from bottom-up models to prices in CGE models. Amongst the studies that do, different assumptions are made:

- Fortes et al. (2014) link total energy costs (average cost) variation from TIMES-Portugal to energy prices in GEM-E3 Portugal.
- Martinsen (2011) couples MARKAL Norway and the MSG6 CGE model, linking electricity marginal cost (weighted annual average) to wholesale electricity price.
- Riekkola et al. (2013) link the shadow price (marginal cost) of electricity from TIMES-Sweden to the electricity price in their CGE model. They note that the price issue is not fully resolved.
- In Rausch and Mowers (2014), electricity is traded at market price, which is set at marginal cost level as calculated by the ReEDS model. Profits are distributed in the CGE model USREP to the relevant households.
- Lanz and Rausch (2016) differentiate between regulated operators, whose wholesale price is linked to average generation costs, and operators trading on semi-competitive wholesale electricity markets. They find that, in the presence of price-regulated operators, freely allocating CO_2 permits has a negative impact on the efficiency of the emissions trading system.

In fact, the link between costs and prices depends on the regulation. This chapter investigates whether assuming different market evolutions, and therefore different pricing mechanisms, has an important implication on the results when modeling electricity markets and their interactions with the rest of the economy under climate and energy policies.

We build a coupled framework designed to analyze electricity markets and trade in Switzerland. This framework consists of two component models: a TIMES dynamic electricity supply model of Switzerland - CROSSTEM-CH - and a dynamic computable general equilibrium (CGE) model - GENESwIS - of the Swiss economy. These two models are coupled through a soft link methodology such that each model keeps its full structure and coherence and the particular strengths of each model are used to inform the other model.

The translation of variables between two fundamentally different models represents a challenge: The main difficulty comes from the fact that the TIMES electricity supply model yields costs of electricity generation, whereas the CGE model uses wholesale electricity prices. Moreover, prices are the main drivers of the CGE model and have a direct impact on the electricity demand that is reinserted as input to the TIMES model.

We analyze a climate policy scenario for Switzerland under two different market assumptions requiring two different coupling approaches: (1) a fully regulated market, where wholesale electricity is priced such that it equals the average cost of electricity production plus a markup, and (2) a progressive evolution to a fully liberalized market, in which the marginal cost of electricity production including scarcity rents defines the price of wholesale electricity.

We show that the way in which costs are linked to prices, and therefore the expectation on market evolution, has a sizable impact on the results. Notably, we observe a variation of the reduction in electricity demand induced by the same climate and energy policies.

3.2 Framework

The modeling framework used for this analysis is described in chapter 2.

It permits to model the link between CROSSTEM-CH's generation costs and GENESWIS' wholesale prices for electricity in different ways:

- Cost plus pricing: The wholesale price is set at CROSSTEM-CH's average cost level plus a markup to reflect agreements under regulation, where firms are guaranteed to recover their costs and earn an acceptable return on investments.
- Marginal cost pricing: Electricity is priced at CROSSTEM-CH's marginal cost[3] level and profit is introduced in GENESwIS to represent producer surplus.

3.3 Scenarios

We simulate a baseline and a policy scenario for two different types of electricity markets in Switzerland: a regulated market, and progressive liberalization to a fully liberalized market (see table 3.1).

Table 3.1 – Scenarios matrix

		Policy scenarios	
		Baseline (BAU)	Tax (TAX)
Market regulation scenarios	Regulated market	BAU_REG	TAX_REG
	Liberalized market	BAU_LIB	TAX_LIB

The baseline (BAU) scenarios are based on the "weiter wie bisher" (i.e. "more of the same") scenario of the Swiss Federal Office of Energy (Prognos, 2012). They include current policies such as an Emissions Trading Scheme, a CO_2 tax on natural gas and heating fuels for the non-ETS sectors and households, and a subsidy program for the energy refurbishment of buildings. For each pricing scenario, the GENESwIS model is calibrated such that electricity demands and CO_2 emissions follow the paths projected by Prognos (2012).

The TAX scenarios represent more stringent climate and energy policies. A tax is levied on electricity at a rate of 10% in 2020, increasing linearly to 50% in 2050. The Emissions Trading Scheme stays identical as in the BAU scenario, but the CO_2 tax on natural gas and heating fuels is increased linearly from current level (60 CHF/t) to 200 CHF/t in 2050. A CO_2 tax on transport fuels is introduced at 50 CHF/t in 2035, reaching 200 CHF/t in 2050.

Under regulation (scenario REG), firms are usually allowed to cover their costs and make an appropriate profit. We assume accordingly that electricity is priced at average cost plus a small markup.

[3] CROSSTEM-CH's marginal cost is the shadow price of the commodity balance and represents the increase in total system cost due to an additional unit of demand (Loulou et al., 2005). It reflects all constraints and costs (incl. investment cost) and can therefore be seen as marginal cost including scarcity rents for capacity. As the CGE model does not disaggregate the year into 288 time slices, the marginal cost is aggregated to an annual demand-weighted marginal cost.

We assume in the liberalized market scenario (LIB) that the electricity market will be entirely liberalized from 2025 onwards and that the price will then follow the long-term marginal cost of the bottom-up model. From 2010 to 2025, the market is in transition and prices reflect an increasing importance of marginal cost pricing. Profit is calculated such that the price of wholesale electricity is pushed from the average cost given by the CROSSTEM-CH model (AC) to the assumed market price (P_m)[4].

$$\text{Profit}(t) = \frac{P_m(t) - AC(t)}{AC(t)} \tag{3.1}$$

We analyze the policy scenarios for the two market regulation assumptions TAX_LIB and TAX_REG as deviations from the respective baseline scenarios BAU_LIB and BAU_REG[5].

3.4 Mechanisms at work

3.4.1 Prices in the baseline scenarios

As mentioned above, the wholesale electricity market prices simulated in the baselines for the two different market regulation scenarios diverge. As can be seen in figure 3.1, annual average and marginal costs for the targeted baseline demands are distinct not only in level, but also in evolution. According to whether we assume a regulated market (REG) or a liberalized market (LIB), the wholesale electricity prices are linked to respectively the average cost or marginal cost of the bottom-up model. This largely specifies the level and evolution of the prices in each market scenario.

3.4.2 The effects of an electricity tax

A tax on electricity consumption increases end-user prices for electricity. In equilibrium, however, this end-user prices increase does not amount exactly to the level of the tax. The reasons are twofold:

[4] With $P_m(2010)$ = historical price, $P_m(2015) = \frac{2}{3}AC(2015) + \frac{1}{3}MC(2015)$, $P_m(2020) = \frac{1}{3}AC(2020) + \frac{2}{3}MC(2020)$, and $P_m(t \geq 2025) = MC(t)$.

[5] It is uncommon in a CGE setting to have two different baselines. Actually, policies and central targeted baseline parameters, namely electricity demands and CO_2 emissions per fuels, are identical in both the regulated and the liberalized baseline. However, for the targeted parameters to follow these baseline trends, it is necessary to recalibrate the model framework. Indeed, under the different coupling mechanisms, electricity prices are linked either to average or marginal costs, which have different levels (figure 3.1). Autonomous energy efficiency indices are hence modified in the CGE model such that electricity demand follows the baseline trend in both situations.This allows us to analyze how the variation of marginal (respectively average) costs influences the efficiency of energy and climate policies. In this experiment, we do not focus on the issue of how absolute cost levels affect the economy. For this reason, comparing a regulated baseline to a liberalized scenario would not serve our purpose. Instead, we need one baseline definition for both market settings, in terms of electricity demand. Otherwise, differing demand paths would push the bottom-up model to opt for different technology mixes already in the baseline. This would severely complicate the analysis of regulatory assumptions.

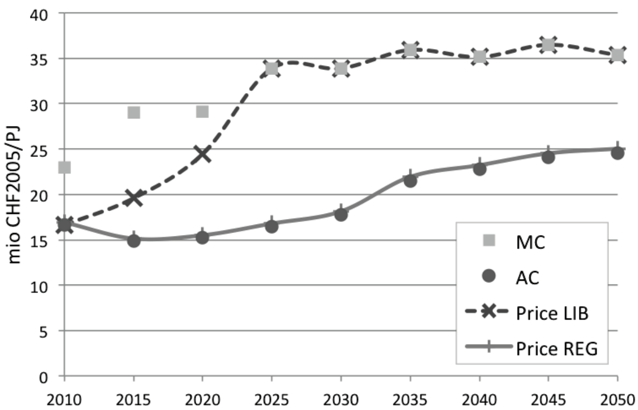


Figure 3.1 – Wholesale electricity prices under the two baselines (LIB for the liberalized market and REG for the regulated market) in comparison with annual average (AC) and marginal (MC) costs from the CROSSTEM-CH model.

- Electricity demand is flexible: A rise in end-user price induces a reduction in demand. The new equilibrium price will hence be lower than the initial price plus the tax.
- This new (and reduced) electricity demand is then passed on to the CROSSTEM-CH model (see figure 2.3), which lowers electricity generation and hence alters generation costs. As generation costs are linked to the wholesale electricity price, their alteration will, in turn, have an effect on end-user prices.

To analyze the effects of an electricity tax on the electricity demand reaction and end-user prices, we thus also need to analyze the influence of changes in demand on generation costs.

3.4.3 The effect of demand changes on marginal and average generation costs

Both average and marginal costs generated by the CROSSTEM-CH model include all relevant costs, i.e. fuel costs, operation and maintenance costs, investment costs, taxes, and the electricity trade deficit (which is usually negative for Switzerland, i.e. a trade surplus). They both depend on the composition of the technology mix, albeit in different ways: The marginal cost is linked to marginal technologies, whereas the average cost depends largely on the degree of utilization of technologies with high variable costs, such as gas-fired power plants.

Thereby, technology restrictions, or an increase in demand large enough to require the introduction of a more expensive technology, will increase the marginal cost. Likewise, a reduction in demand important enough to make the most expensive technology obsolete, will decrease the marginal cost.

For the average cost, things are more complicated, because the direction of change depends not only on the marginal technology, but on the technology and cost structure as a whole. For example, if the technology mix is composed mostly of technologies with high fixed costs, a decrease in demand increases average cost. In contrast, if the technology mix includes a large share of technologies with high variable costs, a decrease in demand also decreases average cost.

3.5 Results

In this section, we analyze the effects of the TAX scenario policies under two different market assumptions: gradual liberalization (LIB) and regulation (REG) in the Swiss context.

3.5.1 Generation costs

Electricity generation mix and total system cost

In 2010, Switzerland's electricity generation mix was largely CO_2-free, composed mostly of hydro- and nuclear-generated electricity. The nuclear phase-out implies, for our model, that the oldest nuclear power plant reaches the end of its lifetime in 2020, and that, by 2035, almost no electricity is produced with nuclear technology. In answer to this phase-out, CROSSTEM-CH chooses a mix of base and flexible gas plants[6]. The purpose of flexible gas plants is to optimize import/export patterns and create maximum trade revenue. By 2050, solar PV becomes competitive[7] (figure 3.2a) due to technology learning and increasing natural gas and CO_2 permit prices. Although the TAX scenarios reduce electricity demand, the types of technologies installed stay identical to the baseline. Solely the amount of electricity produced with gas-fired power plants varies.

As can be seen on figure 3.2b, the total system cost is composed mostly of capital, operation and maintenance (O&M), natural gas and nuclear fuel costs, taxes, and trade revenue[8]. Capital costs increase in 2050 with the investment into solar technology. Although electricity production by gas-fired power plants decreases in the later years, expenses into natural gas stay important due to increasing prices assumptions. Although all costs decrease in the TAX scenarios with regard to the baseline, most of the cost-saving is due to a reduction of natural gas and associated CO_2 permit costs.

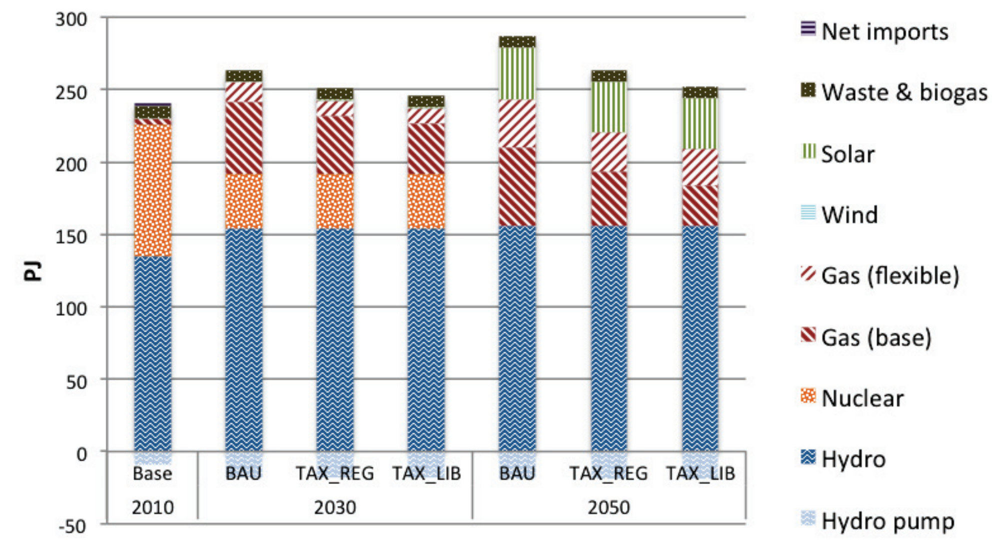
Marginal cost

As can be seen in figure 3.3a, the marginal cost does not vary greatly for the TAX scenarios relative to the baselines for either of the market regulation scenarios. Demand reductions under the TAX scenarios are not large enough to shock the technology mix deeply, and there are no technology restrictions in addition to the baselines. Therefore, marginal technologies (figure 3.2a), and hence

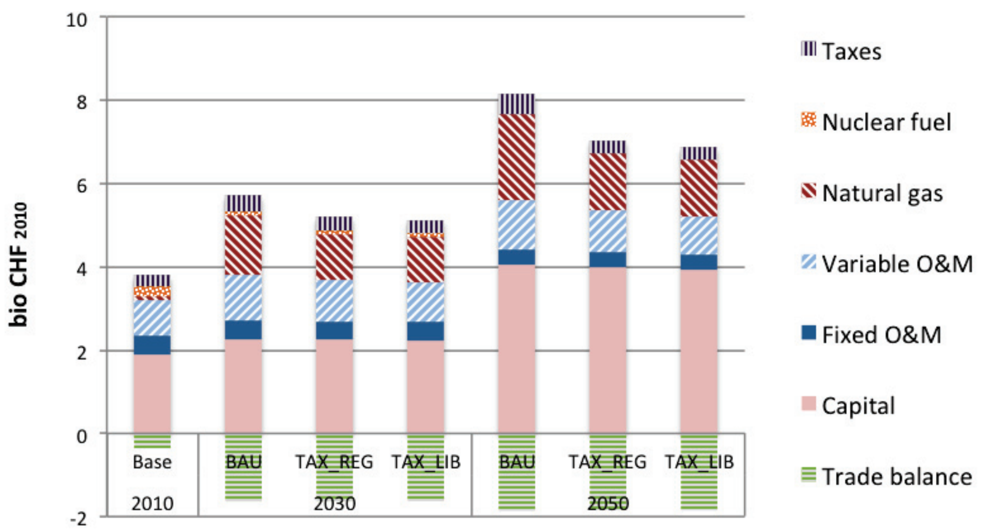
[6] Coal and oil technologies are prohibited.

[7] No subsidies for renewable technologies are modeled in the CROSSTEM-CH model.

[8] Although trade is constrained such that no net imports are allowed, resulting in a net trade of zero in energy terms, the model optimizes hydro pumps and flexible gas production to export when prices are high and thus create a net-trade revenue.



(a) Electricity generation mix



(b) Undiscounted system costs of electricity generation

Figure 3.2 – Electricity generation mix [PJ] and undiscounted system costs of electricity generation [bio CHF_{2010}] for the baseline BAU (results for BAU_REG and BAU_LIB are identical) and for the TAX scenarios TAX_REG (regulated market) and TAX_LIB (gradually liberalized market).

the marginal cost, do not change much in annual average (although they may change in some particular time-slices).

Average cost

In contrast, average cost is reduced in the TAX scenarios relative to the baselines (figure 3.3a). Variable costs represent a major share of total cost (figure 3.2b - variable costs are pictured in patterned, and fixed costs in solid color bars). This is due to a technology mix comprising many depreciated plants and to the optimized cost structure of the CROSSTEM-CH model. Furthermore, at each iteration, the investment decisions as well as running-schedules are re-optimized over the entire time horizon of the model, which further increases the total proportion of costs that are effectively variable in the simulations. A dominant share of variable costs implies that average cost is lower when less electricity is produced.

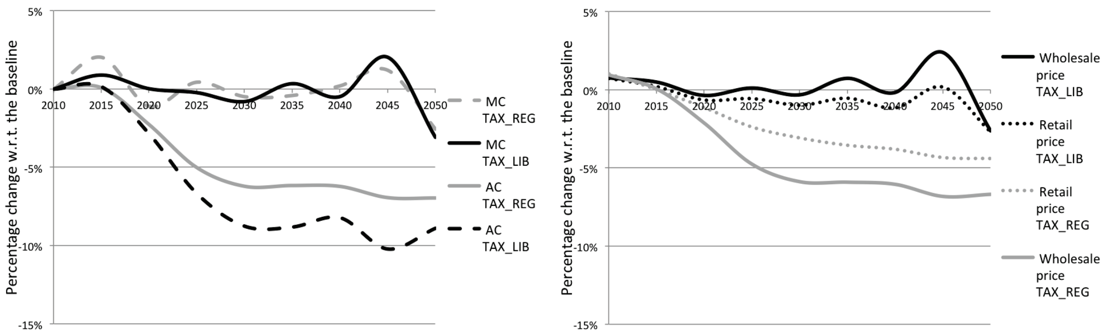
The variation of average cost for the liberalized market (TAX_LIB) is greater than under regulation (TAX_REG). This is due to the fact that total electricity demand is reduced further in the liberalized market scenario than in the regulated market scenario.

3.5.2 From costs to end user prices under alternative market regulation

We will now investigate what the different responses of the marginal and average costs imply for the wholesale, retail and end-user prices, and for electricity demand under alternative market regulations in Switzerland.

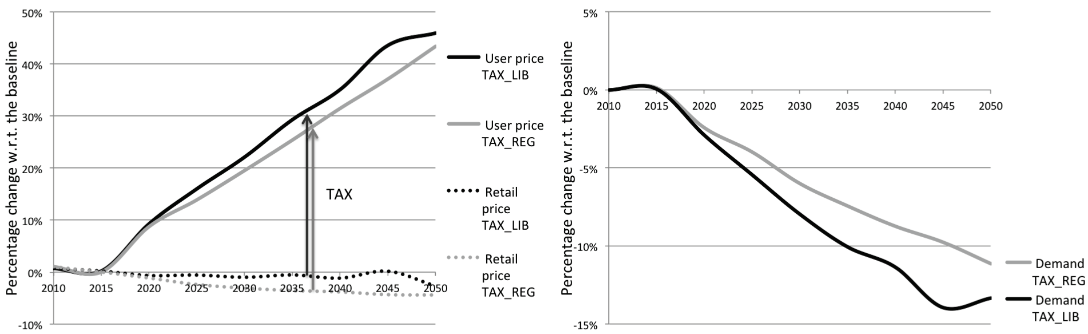
Liberalized market

In the scenarios with gradual market liberalization, wholesale electricity prices are increasingly linked to the marginal cost. We observe that the marginal cost is not greatly affected by the demand reduction induced by the TAX_LIB scenario (figure 3.3a). As a result, wholesale electricity prices (figure 3.3b) are impacted only slightly. Retail electricity corresponds to electricity transported and distributed to the users. An important share of its production cost is due to the purchase of wholesale electricity. The prices of commodities and services constituting the remaining share are not affected greatly by the policies of the TAX_LIB scenario. Hence, retail electricity prices vary in the same direction as wholesale electricity prices, although this variation is dampened (figure 3.3b). End user prices are defined as retail prices plus tax. The electricity tax included in the TAX scenario raises the end user price of electricity (figure 3.4a), which reduces electricity demand (figure 3.4b).



(a) Average and marginal costs (b) Wholesale and retail electricity prices

Figure 3.3 – From costs to retail prices: Percentage change of - (a) average cost (AC) and marginal cost (MC), and (b) wholesale and retail electricity prices - for the scenarios TAX_LIB and TAX_REG compared to the baselines BAU_LIB and BAU_REG respectively.



(a) End user prices (gross of tax) for electricity (b) Electricity demands

Figure 3.4 – From retail prices to demands: Percentage change of - (a) electricity prices paid by the end users (gross of tax) and retail electricity prices (net of tax), and (b) electricity demands - for the scenarios TAX_LIB and TAX_REG compared to the baselines BAU_LIB and BAU_REG respectively.

Regulated market

For the regulated market scenarios, wholesale electricity prices are closely linked to average cost. They are therefore reduced as a result of the electricity demand reduction induced by the energy policies, namely the electricity tax, included in the TAX_REG scenario (figures 3.3a&b). Consequently, retail electricity prices also decrease relative to the baseline (figure 3.3b). Hence, the end user price increase (gross of tax) is smaller in the regulated market (TAX_REG) than in the liberalized market (TAX_LIB), as can be seen in figure 3.4a. The resulting reduction in demand is therefore smaller in the regulated market than in the liberalized market (figure 3.4b).

3.6 Conclusion

In this chapter, we show that assumptions on the future evolution of electricity market regulation have an impact on the effectiveness of electricity taxes to curb demand. In a coupled bottom-up top-down modeling framework, the way we translate costs into prices needs to reflect the nature of market regulation.

The regulated market, which links wholesale electricity market prices to average costs, is easier to model, because it avoids the numerical convergence issues stemming from the stepwise behavior of marginal costs. However, if the market is not tightly regulated, this linking assumption is inappropriate and leads to its misrepresentation. As a consequence, the estimation of the effectiveness of energy or climate policies is erroneous. As we have shown, the electricity demand reduction fostered by market-based policies is stronger in a liberalized setting than in a regulated market.

Before generalizing this result, some caveats are in order. First of all, the marginal cost assumed in our modeling framework is a demand-weighted annual average of the marginal costs for all time slices, which is a strong simplification. In addition, we assume that electricity generation is optimized over the full modeling horizon with perfect foresight. Finally, we make specific, albeit representative for Switzerland, assumptions about policy changes and available technologies. Further research is needed to explore the consequences of modified pricing mechanisms in (partially) liberalized markets under different national circumstances, policies and technological options.

Notwithstanding, it is important to take ongoing and projected market liberalization into account and to disclose pricing assumptions when interpreting models' results.

Chapter 4

Welfare effects of technology restrictions for electricity generation

Abstract

Technology restrictions are still widely used in energy policy. Concerns about security, climate, or jobs preservation induce political quasi-selections of electricity generation technologies. Instruments inherited from regulation, technology restrictions may have different impacts on the economy when markets are largely liberalized. We use ELECTRA-CH, a coupled top-down bottom-up model framework to analyze two electricity supply options for Switzerland after nuclear phase-out: (1) a balanced-trade scenario in which Switzerland's annual electricity production must be equal to its consumption and (2) a no-gas scenario that forbids gas-fired power plants, but accepts net electricity imports. We find that technology restrictions alter both electricity generation cost functions and price levels. For Switzerland, the prohibition of gas-fired power plants and relaxation of trade constraints lower average cost while increasing marginal cost. With marginal cost pricing in liberalized markets, this increases profits. Reduction in total system cost and increase in electricity price affect welfare in opposite ways. A pure bottom-up analysis would overestimate the benefits of technology restrictions.

Keywords: *electricity markets; technology restrictions; soft-link coupling; top-down model; bottom-up model; policy analysis*

4.1 Introduction

Despite market liberalization, technology restrictions and political quasi-selection of electricity generation technologies have increased rather than decreased in many countries. Motivations to do so are multiple: safety concerns, reducing import dependence, environment and climate protection, the will to create or keep jobs in a region, competitiveness issues, or political agendas. Although there may be good reasons to opt for technology restrictions, this chapter focusses on how to adequately assess the costs of such choices.

Switzerland, with its energy policy in full transition, is an interesting case study. The Energy Strategy 2050, elaborated by the Swiss Federal Council, has for objective to warrant an energy supply for Switzerland that is cost-effective, respectful of the environment and secure. The policy focus is on the improvement of energy efficiency and the promotion of renewables. This focus is planned to be achieved, from 2020, through market-based policies. The Swiss electricity market is partly liberalized and to be further integrated within the larger European market.

Switzerland's current electricity generation park is composed mostly of nuclear (37.9%) and hydro power plants (56.4%) (Swiss Federal Office of Energy, 2015). Following the Fukushima nuclear disaster in 2011, the Swiss Federal Council decided to decommission nuclear power plants at the end of their safe operational lifetime (the nature and time scale of which is yet to be agreed upon) without replacing them by newer generation nuclear plants. Switzerland has been now accustomed to a largely CO_2-free electricity generation, and has vouched to domestically reduce its emissions by 30%[1] in 2030 compared with 1990.

The Energy Perspectives 2050 (Prognos, 2012), commissioned by the Federal Office of Energy, imagine three energy policy scenarios, resulting in different demand paths, as well as three electricity supply options to answer electricity demands taking nuclear phase-out into account. These supply options are the following: (1) gas-fired power plants, (2) gas-fired power plants and renewables, and (3) renewables with the help of electricity imports. Prognos (2012) simulate this set of scenarios with a bottom-up model performing an "If-then" type of analysis: Exogenous border conditions on energy prices, population and GDP growth drive the model, while the different policy measures and objectives modify the possible options and pathways. This modeling study captures only the direct costs on the energy system.

To complement the analysis, Ecoplan (2012) investigate the economic effects of the energy policy scenarios put forward in the Energy Perspectives 2050 with the help of a computable general equilibrium model. They simulate policies[2] (CO_2 tax on heating and transport fuels, emissions trading system for big emitters, and electricity tax) such that CO_2 emissions and energy demands follow projections by Prognos (2012). All simulations are done with the electricity supply option that includes gas-fired power plants.

Gas-fired power plants are, in many countries with existing coal-fired power plants, considered to be the cleaner option. However, in Switzerland, a future generation park including gas-fired power plants would drastically increase CO_2 emissions from electricity generation. These additional emis-

[1]Switzerland vouched to reduce it's emissions by 50% in 2030, the majority of which (minimum 30%) domestically. The remaining 20% can come from quality overseas projects.

[2]The policies implemented are not exactly the policies planned in the Energy Perspectives.

sions would have to be compensated by stronger efforts in other sectors of the Swiss economy. Currently, the CO_2 law[3] stipulates that fossil thermal power plants will be approved in Switzerland only if they fully compensate for their CO_2 emissions. Additionally, at least 50% of their compensation performance must be rendered domestically. This strong regulation is quite prohibitive and keeps Swiss firms from investing into gas-fired power plants in Switzerland. Alternatively, they invest abroad in gas-fired power plants[4]. For the gas-fired power plants supply options of the Energy Strategy to materialize, the domestic compensation condition of the CO_2 law might have to be relaxed or alleviated through carbon capture and sequestration.

To keep a CO_2-free electricity generation sector, Switzerland could promote renewables. However, investments into renewable energy might not be important enough[5] in the mid-term to answer electricity demand. Without drastic energy efficiency measures to reduce electricity consumption, Switzerland would have to rely on electricity imports from its neighbors. This supply scenario raises concerns about energy security (although Switzerland would be less reliant on gas imports) and public control[6].

The nuclear phase-out is perhaps, of late, the most widely studied technology restriction for electricity generation in Switzerland. Some studies involve bottom-up models (Weidmann et al., 2012; Prognos, 2012), which are, by construction, very detailed technically but model only partial equilibrium. They report variations on total system cost (only direct costs). Others analyze the nuclear phase-out with computable general equilibrium models, whose electricity generation production function has been modified to display discrete technological response (Böhringer et al., 2001; Bretschger et al., 2012). These studies are able to analyze the effects on welfare (Hicks equivalent variation) and the economy as a whole, as well as changes in the overall excess burden of the tax system. However, their hybrid representation of electricity generation options has limited technological detail compared to full-size bottom-up models.

In this chapter, we endeavor to investigate the effect of technology restrictions concerning gas-fired power plants, with the added insight of combining top-down and bottom-up information in a single framework (Hourcade et al., 2006).

We analyze two scenarios, inspired by the supply options of the Energy Perspectives: (1) a balanced-trade scenario in which Switzerland's annual electricity production must be equal to its consumption; and (2) a no-gas scenario which forbids gas-fired power plants, but accepts net electricity imports. The policy landscape is the same in both scenarios, including strengthened market-based energy and climate policies, liberalization of electricity markets, and the decommissioning of nuclear power-plants after a 50-year operational lifetime. We conduct this analysis with the help of the top-down bottom-up coupled framework ELECTRA-CH, developed in this thesis.

The chapter is organized as follows: Section 4.2 refers to the methodology description in chapter 2 and is followed by a description of the scenarios in section 4.3. Section 4.4 discusses the results

[3] Loi fédérale du 23 décembre 2011 sur la réduction des émissions de CO_2 (Loi sur le CO_2), RS: 641.71 et Ordonnance du 30 novembre 2012 sur la réduction des émissions de CO_2 (Ordonnance sur le CO_2), RS: 641.711.

[4] For example, BKW invested in gas-fired power plants in Italy, and Alpiq in Czech Republic, Hungary and Italy.

[5] Despite the technical potential being available, economic, administrative and social issues reduce the real potential of renewables. Specifically, projects implementations are slowed down by the long waiting list for feed-in tariff, authorization procedures and lack of social acceptance (Swiss Federal Office of Energy, 2012).

[6] In Switzerland, municipalities and cantons are the shareholders holding the majority of electricity generation firms.

and section 4.5 concludes.

4.2 Model

The coupling procedure and models used for this analysis are described in chapter 2. For this study, we assume a gradual liberalization of electricity markets (see figure 2.5, 23).

4.3 Scenarios

We compare simulation results for two scenarios inspired by the Swiss Energy Strategy: GAS and NoGAS, which differ from each other mainly by the prohibition of gas-fired power plants and restriction on net trade for the electricity sector.

The GAS scenario is inspired by the supply option C of the Swiss Energy Strategy, where part of the nuclear power plants capacity is replaced with gas-fired power plants. In the following analysis, we consider the GAS scenario to be the reference scenario. We do not, however, refer it as such, as we are not in a liberal world with completely free-markets. The GAS scenario indeed already includes many restrictions (e.g. nuclear phase-out, import restrictions, no coal production). We assume that, for gas-fired power plants to be built in Switzerland, the domestic compensation condition of the CO_2 law would have to be relaxed. We therefore consider CO_2 emissions from gas-fired power plants in the GAS scenario to be compensated through the emissions trading scheme (ETS), which is linked to the European ETS.

The NoGAS scenario forbids gas-fired power plants: all domestic electricity must be produced with renewables. As in supply option E of the Swiss Energy Strategy, we let Switzerland be a net importer of electricity annually.

Both scenarios include the following energy and climate policies:

- Nuclear power plants are phased-out at the end of an assumed lifetime of 50 years and not replaced by new-generation plants. Effectively, no electricity is produced with nuclear technology after 2035.
- A tax on electricity consumption amounting to 10% of the electricity retail price in 2020, increasing linearly to 50% in 2050.
- An emissions trading scheme (ETS), linked to the European ETS. Switzerland is not expected to have a large impact on CO_2 prices, which are thus exogenous, following projections by Prognos (2012).
- A CO_2 tax on natural gas and heating fuels consumption for the non-ETS sectors and households. The level of this tax is set at 36 CHF/t in 2010, increasing linearly to 200 CHF/t in 2050. A share of 250 mioCHF from the CO_2 tax revenue is recycled through a building (insulation) subsidy.

- A CO_2 tax on transport fuels consumption starting at 50 CHF/t in 2035, increasing linearly to 200 CHF/t in 2050.

In the GAS scenario, net electricity trade is constrained such that Switzerland cannot be a net importer on annual average. However, the CROSSTEM-CH model optimizes trade revenue within the year: importing when it needs to or when exogenous foreign prices are low, and exporting when prices are high. This usually results in trade volumes being equal, and the creation of a positive trade revenue.

In the NoGAS scenario, gas-fired power plants are prohibited. However, the trade constraint is relaxed: a given amount of net electricity can be imported annually. This amount[7] was chosen to be equivalent to the quantity (in energy units) of natural gas imported for electricity generation in the GAS scenario. This assumption is a very crude way of designing scenarios that might be equivalent with regard to energy security, without knowing the relative supply risk of each energy carrier.

A recapitulation of the energy and climate policies for the GAS and NoGAS scenarios can be found in table 4.1.

Table 4.1 – Comparison of the energy and climate policies (market instruments - modeled in GENESwIS - and technology & import restrictions applied to the electricity sector - modeled in CROSSTEM-CH) for the GAS and NoGAS scenarios.

	GAS	**NoGAS**
Market instruments	ETS scheme	same as GAS
	CO_2 tax (gas and heating fuels)	same as GAS
	CO_2 tax (transport fuels)	same as GAS
	Electricity tax	same as GAS
Technology & import restrictions	Nuclear phase-out	same as GAS
	No coal-fired power plants	same as GAS
	No net imports of electricity (annually)	Net imports allowed (annually)
	-	No gas-fired power plants

4.4 Results

4.4.1 Generation costs and technology mix

The nuclear phase-out implies that, by 2035, almost no electricity is produced with nuclear technology. In the GAS scenario, this capacity is replaced by base and flexible natural gas power plants. The flexible gas plants are installed to optimize import/export patterns and create maximum trade revenue. By 2050, solar photovoltaics becomes competitive due to technology learning and increasing

[7]The model does not reach this upper-bound.

natural gas and CO_2 prices[8] (figure 4.1a).

In the NoGAS scenario, gas-fired power plants are prohibited, and some net imports allowed. In the near and medium term, the CROSSTEM-CH model deems more cost-effective to import electricity rather than invest in expensive renewable technologies[9]. By 2045, however, electricity import prices assumptions[10] have risen, and renewable technologies such as solar PV and wood/biomass plants become competitive.

The total system cost (figure 4.1b) is noticeably lower for the NoGAS scenario than for the GAS scenario. The system saves mostly on variable costs: fuel cost (natural gas), taxes (CO_2 permits), and variable operation and maintenance costs. Despite Switzerland being a net importer in the NoGAS scenario, the optimization of trade within the time slices permits the system to make a net surplus for most of the model horizon (except in 2035). As no gas-fired power plants are built in the earlier years, capital costs are lower. However, in the later years, more renewable capacities are installed and capital cost is slightly higher than for the GAS scenario.

As an aggregate over the whole modeling horizon, the present value[11] of total system cost is reduced by 4.2 bio CHF_{2010} in the NoGAS scenario with regard to the GAS scenario.

4.4.2 Electricity costs, prices and demand

The marginal cost of electricity in the NoGAS scenario is generally higher than in the GAS scenario (figure 4.2a) due to trade price assumptions, which increase at a much higher rate than natural gas prices. In the immediate (2015), however, the price of imported electricity is lower (22.86 CHF_{2010}/GJ) than the marginal cost of gas-fired power plants (38.4 CHF_{2010}/GJ for an existing plant, and 28.5 CHF_{2010}/GJ for a new plant); it is therefore cheaper to import electricity rather than relying on generation by gas-fired power plants. By 2020, import prices are comparable to the marginal cost of gas-fired power plants, and from 2025 onwards, electricity generated by gas plants is cheaper than imported electricity. Hence, the long-term marginal cost increases from 2020 on in the NoGAS scenario compared with the GAS scenario.

As a consequence, the wholesale electricity price increases accordingly (figure 4.2b). The electricity price paid by users includes the purchase of wholesale electricity, transport and distribution costs, and taxes. The prices of commodities and services needed for transport and distribution are not affected by the prohibition of gas-fired power plants, and market-based policies are identical for both scenarios. Hence, end-user prices vary in the same way as wholesale electricity prices, although this variation is dampened (figure 4.2b).

As an expected consequence of the end-user price increase, total electricity demand decreases (figure

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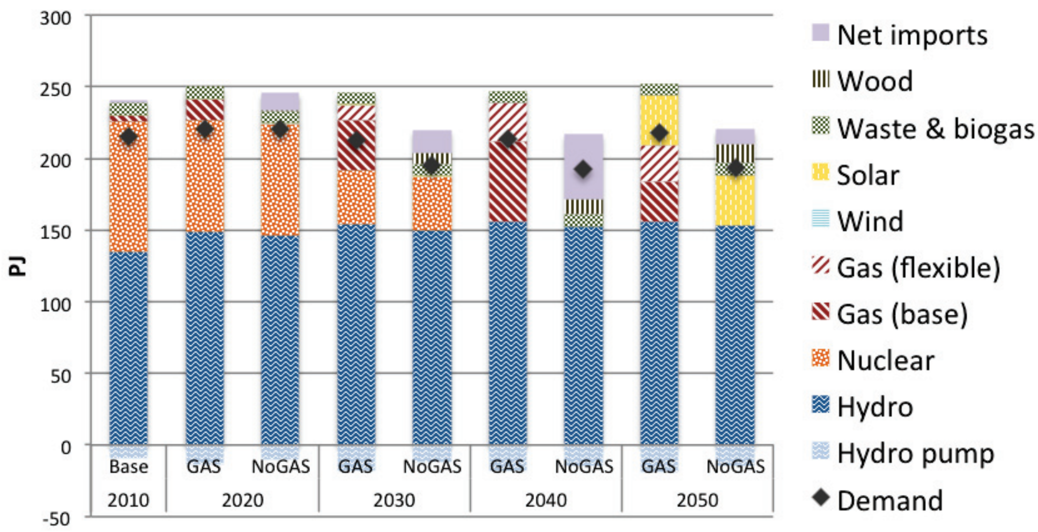
[8] Sources: gas price from World Energy Outlook (International Energy Agency, 2010) and CO_2 prices following EU ETS permit prices projections by Prognos (2012).

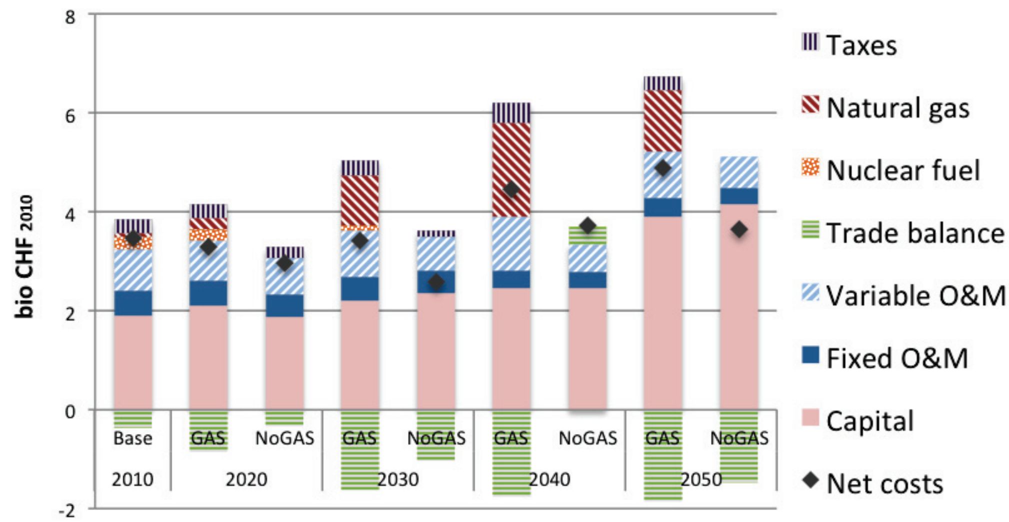
[9] No subsidies or feed-in tarrif for renewable technologies are modeled in the CROSSTEM-CH model.

[10] Trade prices assumptions are specified for the four neighboring countries: France, Italy, Austria and Germany. Yearly import prices are taken from the ADAM project (www.adamproject.eu). Export prices are pegged to import prices. A description of the determination of time-slice variations of import prices can be found in Kannan and Turton (2011)

[11] Discount rate of 4.5%

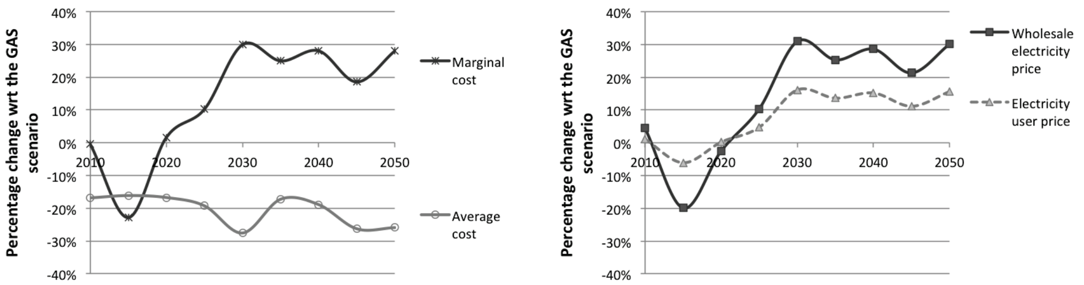


(a) Electricity generation mix



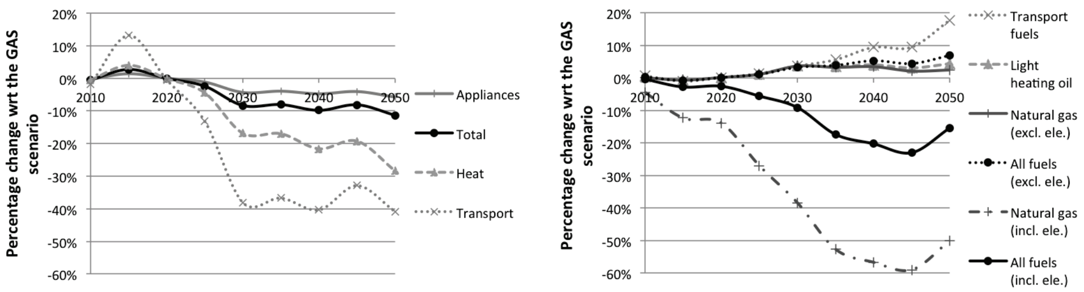
(b) Total electricity system cost

Figure 4.1 – Swiss electricity generation mix [PJ] and total undiscounted system cost of electricity generation [bio CHF_{2010}] for the GAS and NoGAS scenarios.



(a) Marginal and average costs of electricity generation

(b) Electricity prices



(c) Electricity demand

(d) CO_2 emissions from fuels

Figure 4.2 – Variation - for the NoGAS scenario with regard to the GAS scenario - of (a) marginal and average costs of electricity generation, (b) wholesale electricity price (net of tax) and electricity price for users (gross of distribution costs and tax), (c) electricity demand per type of use (appliances, heat and transport), and (d) CO_2 emissions from fuels (transport fuels, light heating oil, and natural gas (including and excluding emissions from electricity generation)).

4.2c) in the NoGAS scenario with regards to the GAS scenario. Electricity used for appliances does not react strongly to the end-user price increase as it is not easily substituted. For heating, however, natural gas, light heating oil, district heating and better insulation can be chosen over electricity use (see nestings on figure 2.1 p.13 and figure 2.2 p.14). We can see on figure 4.2d that CO_2 emissions from light heating oil and natural gas (excluding emissions from electricity generation) increase as a result of the substitution away from electricity for heating purposes. The decrease in electricity demanded for transportation is overstimated. This strong reaction to the electricity price increase is due to the high elasticity of substitution assumption on e-mobility, chosen to calibrate the model to high penetration projections by Prognos (2012). The related increase in CO_2 emissions from transport fuels is accordingly strong.

Due to the prohibition of gas-fired power plants, CO_2 emissions from natural gas, including the intermediate demand for electricity generation, decrease through time in the NoGAS scenario compared with the GAS scenario (figure 4.2d - natural gas incl. ele.). This has for effect to reduce overall fuel-related CO_2 emissions. However, total fuel-related emissions excluding electricity generation increase by $\sim 5\%$ in the second half of the modeling period. Indeed, electricity price variations prompted by technology restrictions modify relative prices between electricity and other energy carriers, which induces substitution towards other energy carriers.

Although electricity demand is lower in the NoGAS scenario compared with the GAS scenario, the total system cost decreases more than proportionally: Average cost is approximately 20% lower in the NoGAS scenario than in the GAS scenario (figure 4.2a).

4.4.3 Investment

In the coupled framework, the CROSSTEM-CH model optimizes investment decisions for electricity generation, which determine yearly capital inputs in GENESwIS' electricity generation production function. GENESwIS simulates[12] investment decisions, and hence capital accumulation which satisfy the demand for capital in the electricity sector. This affects investment and capital formation for the other sectors (industry and services) through crowding-out effects.

The NoGAS scenario requires less capital for electricity generation than the GAS scenario (figures 4.1b and 4.3), simply because no gas plants are built and imports increase. This has a crowding-in effect on the other sectors. Variations of capital for industry sectors are more responsive than for services (relative to their size).

In the NoGAS scenario, the CROSSTEM-CH model invests in solar photovoltaics capacity ($\simeq 10$ PJ), which becomes competitive in 2045, instead of 2050 in the GAS scenario. This explains the abrupt[13] increase in investment in 2040 (figure 4.3) in the NoGAS scenario in comparison with the GAS scenario.

[12] In GENESwIS, Capital is modeled as putty-clay. Thus, capital, once it is invested into one sector (industry, services or electricity), cannot be transformed into capital for another sector. Households optimize total welfare over the whole modeling horizon by choosing between consumption in a given year or saving to increase their utility at another time. Utilities of different years can be substituted to each other through an inter temporal elasticity of substitution of 0.2.

[13] These types of sharp transitions are intrinsic to bottom-up modeling and transpire through the coupling of the models.

Despite the crowding-in effect, total investment is reduced in the NoGAS scenario compared with the GAS scenario (figure 4.3). Actually, relative factor prices change by 3% in favor of labor in the NoGAS scenario with regards to the GAS scenario.

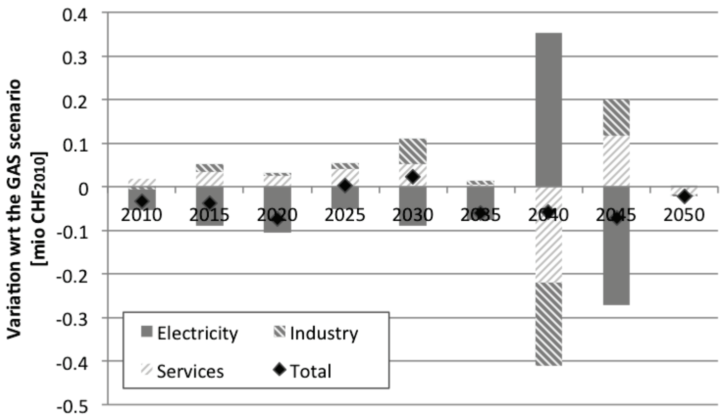


Figure 4.3 – Variation of investments for the electricity, industry and services sectors in the NoGAS scenario with regard to the GAS scenario [mio CHF_{2010}].

4.4.4 Welfare and consumption

We observe an increase in welfare[14] of 0.05%, amounting to a present value of 0.98 bio CHF_{2010} in the NoGAS scenario compared to the GAS scenario, indicating that prohibition of gas-fired power plants and relaxation of the trade constraints have a positive effect on the economy. Yet, the electricity supply model, CROSSTEM-CH, shows a reduction in the present value of total system cost of 4.2 bio CHF_{2010}. General equilibrium effects usually tend to smoothen policy shocks and maximize utility. In this sub-section, we investigate the effect responsible for welfare increasing less than the decrease in total system cost.

To understand this difference, we have to go back to the way wholesale electricity is priced. In our simulations, the wholesale electricity price is linked to the marginal cost of electricity generation (market fully liberalized from 2025 onwards). It is composed of the average cost of electricity generation plus a markup (see eq. (2.8) p.22), which pushes wholesale electricity price to marginal cost level. Profit is redistributed lump-sum to the representative household.

The prohibition of gas-fired power plants and relaxation of the trade constraints have an opposite effect on marginal and average costs: marginal cost increases, while average cost decreases (figure

[14]Benefits from the reduction of external effects are not taken into account in our welfare assessment. Also, we do not keep the CO_2 emissions target constant for Switzerland across scenarios: With an emissions trading scheme (ETS) linked to the European ETS, the additional domestic emissions in Switzerland will be offset elsewhere in Europe. The electricity sector is part of the ETS and we assumed Switzerland to be a price taker on the permits market. The small open economy assumption also implies that the Swiss equilibrium remains unaffected by any terms of trade effects which could in fact be prompted by the additional abatement abroad. Hence, we believe that a welfare assessment with these scenarios is still valid under the set of assumptions of the modeling framework.

4.2a). This means that electricity is more expensive in the NoGAS scenario, although total system cost is lower. As a consequence, the markup increases (figure 4.4), generating larger profits.

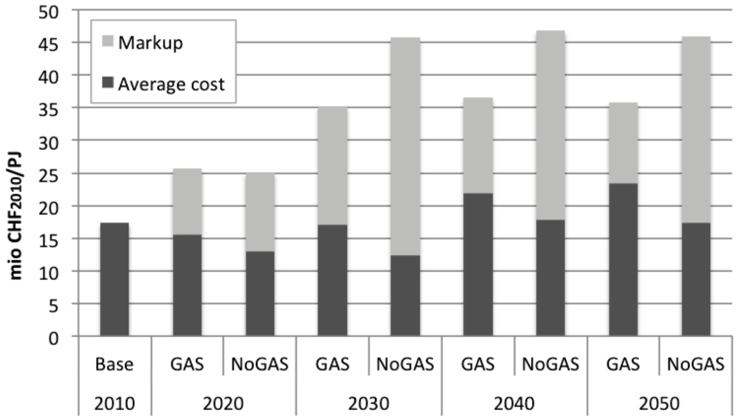


Figure 4.4 – Wholesale electricity price and its components: average cost and profit markup for the GAS and NoGAS scenarios [mio CHF_{2010}/PJ].

The variations of total system cost and wholesale electricity price have different effects on welfare:

1. The cost saving effect associated with the reduction in total system cost is translated into an increase in welfare.
2. The increase in marginal cost, and hence in wholesale electricity price, has a negative effect on welfare.

The resulting combination is an increase in welfare that is smaller than what would be expected from looking only at the total system cost reduction.

Let us illustrate item 2 with a simplified partial-equilibrium representation (figure 4.5). Let us assume a demand curve D, and a supply curve S_1 for the GAS scenario. The equilibrium is reached at quantity q_1, with marginal cost MC_1. In this situation, total system cost is TSC_1. As the price is equal to the marginal cost, producers make a profit π_1. Let us now assume that gas plants are prohibited. The new supply curve is now illustrated by S_2, and equilibrium is reached at (q_2, MC_2). Although total system cost is smaller (TSC_2<TSC_1) the electricity price is higher (MC_2>MC_1). The profit generated is hence much larger (π_2>π_1). However, this change of supply curve creates a loss in total net surplus (grey shaded area).

This is a specific case, although it illustrates the Swiss situation with its large hydro capacities and renewable technologies. Furthermore, this kind of situation may be found in any system comprising largely depreciated plants with low variable costs where new marginal technologies are relatively expensive. The fact that, in these circumstances, marginal cost and average cost vary in opposite directions has the advantage to make a strong example: As electricity price increase and total system cost decrease have opposite impacts on welfare, the need to take both into account for policy analysis is clear. Nonetheless, this holds in any case where marginal and average cost react differently to policy shocks.

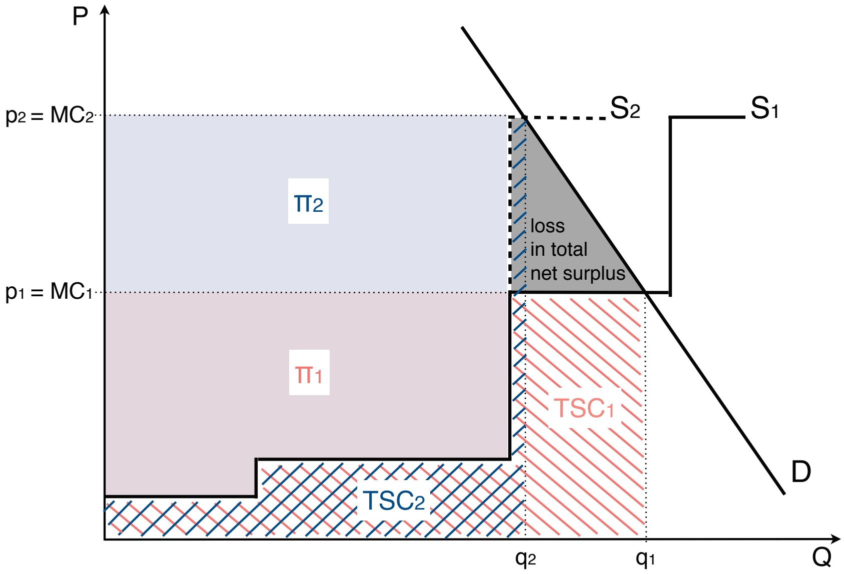


Figure 4.5 – Partial equilibrium illustration of the loss in total net surplus due to variations in the cost structure of electricity generation.

In the coupled framework, with general equilibrium effects and the fact that supply curves are re-optimized and change for each time-slice, things are more complex. The CGE sees changes in the supply curve as a modification of the electricity generation cost function: Intermediate input levels are reduced, while profit is increased. In GENESwIS, profit is represented by a markup over average costs with lump-sum recycling to the representative agent. In modeling terms, this is similar to an output tax on electricity generation. However, the efficiency loss is not due to a tax-induced distortion, but related to a natural feature of competitive pricing under diminishing returns to scale.

In our framework, profit is redistributed lump-sum to the representative household. Despite municipalities and cantons composing the majority of shareholders in big electricity utilities in Switzerland, this is a strong simplification. Profit may be re-invested elsewhere, possibly abroad, instead of being re-distributed to Swiss citizens.

4.5 Conclusion

The results presented in this chapter indicate that is is not sufficient to look at variations of total system cost to assess the benefits of policies including technology restrictions. In the Swiss case, a pure bottom-up analysis would overestimate the benefit of the NoGAS policies. Although bottom-up models are required to model adequately technology restrictions, the analysis should go further. Indeed, effect on price levels and associated profits of such a restriction have an important impact on welfare.

We find that technology restrictions alter both electricity generation cost functions and price levels. In Switzerland, the prohibition of gas-fired power plants and relaxation of trade constraints have opposite effects on total system cost and marginal cost: average cost is reduced, while marginal cost increases. In a liberalized electricity market, with marginal cost pricing, this means that, although savings are made on average, the price of wholesale electricity rises, creating additional profits.

Total system cost reductions and wholesale electricity price increase have opposite effects on welfare. It is therefore crucial for policy assessment to take both into account. This involves a framework that permits to adequately model electricity generation costs, wholesale electricity prices, general equilibrium effects, and welfare impacts.

The analysis of these specific scenarios shows that technology restrictions can have large effects on profits, which is particularly relevant with marginal cost pricing in liberalized markets. With electricity markets being further liberalized, policy induced variations in profit margins should not be overlooked.

Average cost and wholesale electricity price varying in opposite ways is specific to our case study. It is indeed linked to the Swiss technology mix, and heavily reliant on electricity and natural gas import prices assumptions. If electricity foreign trade prices assumptions were to be lower than natural gas world prices projections, the wholesale electricity price would decrease. However, these conclusions are relevant for all situations where marginal and average cost behave differently, but especially when the technology mix is composed of largely depreciated plants and marginal (new) technologies are relatively expensive.

In our scenarios, the impacts of the technology restriction on electricity prices modify relative prices of other energy carriers. The prohibition of gas-fired power plants reduces greatly CO_2 emissions in the electricity generation sector. However, as other fuels become cheaper relative to electricity, substitutions in intermediate and final consumption increase fuel-related CO_2 emissions in other sectors and in consumption. If the purpose of technology restrictions is to reduce the environmental impact of electricity generation, which is the case in prohibiting gas-fired power plants (alongside reducing fuel import dependence), special care should be taken for reducing sectoral leakage effects.

We are careful not to rate the two scenarios simulated, or to judge on the merits and disadvantages of technology restrictions in general. Indeed, bottom-up model results are heavily reliant on assumptions regarding the evolution of import prices (both for electricity and natural gas). Also, in GENESwIS, the marginal cost (and hence price markup) is averaged over the whole year, which is a strong simplification.

Chapter 5

Conclusion

The objective of this work was to investigate the interplay between the electricity market and the economy in changing policy environments. We developed a coupled top-down bottom-up model framework to analyze Swiss electricity markets. In particular, we focussed on the role of market liberalization on the effectiveness of energy policies (in terms of demand reduction) and on the impacts of technology restrictions.

Our framework's strength lies in the capacity of exploring interactions in a complex economic system. Using this framework as a predictive model would be misguided. We therefore focus on gaining an understanding of the mechanisms at work, and do not advance policy recommendations specific to Switzerland, nor pass judgement on scenarios performances.

With the exception of Lanz and Rausch (2016) – who specifically differentiate utilities trading on regulated or free markets – market liberalization assumptions are rarely discussed in coupled top-down bottom-up analyses. However, we show that assumptions on market liberalization matter for modeling results.

For Switzerland, an electricity tax is more effective in reducing demand in a liberalized than in a regulated market. This is due to average and marginal costs reacting differently to policy-induced changes in demand. The exact relation between the variations of marginal and average cost depends on the technology mix and the policy applied, and is therefore specific to each country/region. However, the fact that they do not vary the same way can be generalized and indicates that assumptions on market liberalization, i.e. the way bottom-up costs are linked to electricity prices, matter. It is therefore crucial to take ongoing and projected market liberalization into account and disclose pricing assumptions when interpreting models' results. It also indicates that market structure should be considered when assessing or designing policy instruments.

Bottom-up models are widely used to assess technology-related scenarios in energy modeling. However, due to their partial-equilibrium nature, they mostly report on direct costs. We show that it is not sufficient to look at variations of total system cost to assess the benefits of technology restrictions. Although bottom-up models are required to model adequately technology restrictions, the analysis should go further. This involves a framework, such as the one developed for this dissertation, which permits to adequately model electricity generation costs, wholesale electricity prices, general equilibrium effects, and welfare impacts.

We show that technology restrictions can have large impacts on profits, which is particularly relevant with marginal cost pricing in liberalized markets. With electricity markets being further liberalized, policy induced variations in profit margins should not be overlooked. Our simulations also illustrate that the timing of policies is crucial for penetration of new (clean) technologies. In our scenario, an electricity tax is introduced in 2020, while transport fuels are taxed only from 2035 onwards. As end-user electricity prices increase earlier, the switch to e-mobility is somewhat discouraged, and more transport fuels continue to be used. Once transport fuels are also taxed, e-mobility becomes more attractive.

At the end of this research, it has been shown that energy modelers must communicate and temper their results carefully. While much has been said about the impact of assumptions on substitution elasticities and exogenous costs projections on modeling results, this research adds to the awareness on the effects of market liberalization assumptions and choice of modeling framework on policy assessment.

Further research

We focussed on the interplay between the electricity market and the economy in changing policy environments in a domestic setting. Further work would benefit from widening the analysis to the impacts of non-domestic policies.

Switzerland is a small economy that is closely interlinked with Europe and the rest of the world, with the latter influencing to a great extent the Swiss economy through trade.

This inter-linkage is even more pronounced for the electricity sector. With the liberalization of the electricity market, electricity is traded extensively all across Europe. With the appearance of renewable technologies, the inter-connection of the whole European network became increasingly important. Switzerland may be affected by European policies not only through political agreements, but also through the electricity market, the emissions trading market, or fuel prices.

In principle, international integration can be modeled through exogenous assumptions (import and export prices, world energy prices, CO_2 price etc.), which is the case in the ELECTRA-CH framework. This is fine when analyzing Swiss policies. However, to adequately simulate impacts of international climate and energy policy scenarios, exogenous assumptions are often not sufficient. For example, variations in the electricity mix of European countries may greatly influence CO_2 permit prices.

This would require the development of a larger framework with an explicit representation of Switzerland and its neighboring countries in both the bottom-up electricity supply component and in the top-down multi-sectoral computable general equilibrium part. The goal of such a coupling would be to reflect the high level of Switzerland's integration into international commodity markets and European electricity markets. Notably, it would permit one to simulate the impact of foreign climate and energy policies on the Swiss economy in general and on the Swiss electricity sector in particular.

The individual models for such a larger framework exist, with the CROSSTEM (Pattupara and Kannan, 2016) model, the GENESwIS model and the multi-regional computable general equilibrium model GEMINI-E3[1] (Bernard et al., 2008). In such a coupling, CROSSTEM would provide the technological details of electricity supply and trade for Switzerland and its neighboring countries. GENESwIS would model the Swiss economy, and GEMINI-E3 add the global trade dimension to the framework and the possibility to explicitly model market instruments of international policies.

In building such a framework, one can foresee several challenges. Notably, issues related to the prioritization of trade between CROSSTEM and GEMINI-E3: a choice has to be made between prioritizing trade volume or trade revenue and as such the consistency of the model framework is compromised. Furthermore, the CROSSTEM model minimizes the aggregate total system cost of all modeled countries, while, in the CGE models, the agents of each country maximize their utility/profit. Also, CROSSTEM and GENESwIS are fully dynamic models, while GEMINI-E3 is dynamic recursive.

Although this large coupling framework offers thrilling prospects in terms of integrated analysis, it might be too complex to ensure full consistency. However, further development and testing work is needed before concluding whether or not this framework could deliver a sound analysis of integrated electricity markets.

[1] http://gemini-e3.epfl.ch

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Appendix - GENESwIS data

5.1 Elasticities of substitution

The elasticities of substitution used in GENESwIS are listed in table 5.1.

The elasticities of substitution between capital and labor (figure 2.2 p.14), are derived from Mohler and Müller (2012). Mohler and Müller (2012) compute elasticities for a similar structure as GENESwIS' for the Swiss manufacturing industry on a timeframe of 14 years and give elasticities for the metal industry, sectors participating in the emissions trading scheme, and the rest of industry. To account for long-time elasticities as much as short-time elasticities in GENESwIS, the elasticities of substitution are set to be linearly dependent of time. As the elasticities in Mohler and Müller (2012) are calculated on a 14 year database, these values are used for 2025 and are doubled for 2050. A linear approximation is fitted through these two points. It is assumed that the remaining sectors will display the same elasticity as the rest of industry.

The elasticities between energy and the capital and labor nest (figure 2.2 p.14) - are taken from Mohler and Müller (2012) for the metal industry, sectors participating in the emissions trading scheme and the rest of industry, and from Ban and Okagawa (2008) for the other sectors. A similar linear fit as for the elasticities between capital and labor is set up. As Ban and Okagawa (2008) compute their elasticities on a timeframe of 19 years, the base-points of the elasticities are set in 2030, doubling in 25 years.

Elasticities of substitution for the heating nest are chosen to increase linearly from 0.5 in 2010 to 2.5 in 2050 to account for the fact that substitution is more likely in the long-term than in the short-term due to the lifetime of existing heating installations.

Elasticities of substitution for transport were taken from Vöhringer et al. (2013) and European Commission (1999). As gas and unrefined oil products, transported by pipelines, will not change readily transport modes, the elasticities of substitution between the different transport modes are set to zero for the gas transport and distribution and refineries sectors.

The inter temporal elasticity of substitution, which governs how households are willing to substitute this year's consumption for that of another year, is set to 0.2.

The Armington representation of trade treats domestic and foreign goods and services as imperfect substitutes. Armington elasticities (table 5.2) are taken from GTAP and GTAP-E data (Hertel,

Table 5.1 – GENESwIS' elasticities of substitution. Refer to figure 2.2 p.14 for sectorial production and figure 2.1 p.13 for household consumption.

Nest	Sector	2010	2025	2050
Top nest	all sectors	0		
Between leisure and rest of consumption	household cons.	1		
Between capital and labor	ETS[1]	0.202	0.505	1.01
	MET[2]	0.200	0.500	1.000
	ROI[3]and all others	0.237	0.594	1.189
Between capital-labor and energy	ROI[3]	0.187	0.466	0.931
	ETS[1]/MET[2]	0.208	0.519	1.039
	AGR[4]	0.103	0.412	0.927
	CMT[5]	0.082	0.328	0.738
	GAS[6]/DHT[7]/RFU[8]	0.051	0.204	0.459
	CON[9]	0.106	0.424	0.954
	RLT[10]/RDT[11]/ATP[12]	0.056	0.224	0.504
	ROS[13]	0.091	0.364	0.819
Between intermediate inputs and energy	household cons.	0.091	0.364	0.819
Between intermediate inputs	all sectors	0		
	household cons.	1		
Energy nest	all	0.2		
Heat nest	GAS[6]/DHT[7]/RFU[8]	0		
	others	0.5	1.25	2.5
Transport nest	RFU[8]/GAS[6]	0		
	household cons.	1.3		
	others	2		
Transport services nest	RFU[8]/GAS[6]	0		
	household cons.	0.2		
	others	0.1		
Land transport nest	all sectors	0.5		
Own transport nest	RLT[10]	0.2		
	ATP[12]	none		
	others	10		
E-mobility nest	all	0		
between exports and domestic production	all sectors	1		

1 ETS - Other sectors with emissions trading;
2 MET - Metals;
3 ROI - Rest of industry;
4 AGR - Agriculture;
5 CMT: Cement and concrete;
6 GAS - Natural gas transport and distribution;
7 DHT - District heating;
8 RFU - Refineries;
9 CON - Construction;
10 RLT - Rail transport;
11 RDT - Road transport;
12 ATP - Air and other transport
13 ROS - Rest of services.

1997; Burniaux and Truong, 2002), except for the following goods:

- No raw natural gas is mined in Switzerland, all the raw product is imported. However, the energy disaggregated Swiss input-output table (Nathani et al., 2011) displays some domestic production in the gas transport and distribution sector that accounts for transport and distribution services. In order to keep the right technology (raw fuel in proportion with transport and distribution costs), the Armington elasticity of natural gas is set to zero.
- Crude oil and nuclear fuels are solely imported goods, while district heat is produced only domestically.
- When coupling GENESwIS to CROSSTEM-CH, electricity trade is governed by the CROSSTEM-CH model.

Table 5.2 – GENESwIS' Armington elasticities. Source: Hertel (1997) and Burniaux and Truong (2002).

Commodity	Armington elasticity
Petrol and diesel	1.9
Light heating oil	1.9
Wholesale electricity	0
Natural gas	0
Crude oil	only imports
Nuclear fuel	only imports
District heat	only domestic
Metals	2.2
Cement and concrete	2.8
Other ETS commodities	2.05
Agricultural goods	2.47
Rest of goods	2.95
Construction	1.9
Rail transport	1.9
Road transport	1.9
Air and other transports	1.9
Rest of services	1.9

5.2 Disaggregation of input-output data

GENESwIS is based on the 2005 energy disaggregation of the Swiss input-output table (Nathani et al., 2011). To better suit the needs of an analysis of the electricity sector and climate and energy policies, the following disaggregation was performed:

- Value added - It is crucial for the model to separate labor, capital and income taxes. Labor was calculated from: "full time equivalent 2005" data (T2.8a BFS) and "gross monthly wage according to economic sector, 2006" (BFS). Income taxes were taken from OECD data. Capital was then set as the remainder of total value added from the input-output table.

- Cement and concrete - The non metallic mineral products sector and commodities are divided into cement and concrete, and rest of non metallic mineral products. Data source: (Cemsuisse, 2005, 2011). It is assumed that the whole production of the cement and concrete commodity is consumed by the construction sector.

- Refined fuels - The commodity coke and refined mineral products is separated into heating fuels, transport fuels, and other refined mineral products (the latter is allocated to rest of industry). The refinery sector is kept aggregated, because of the integrated nature of its processes. Sources: Energy NAMEA (Nathani et al., 2011), and Swiss Federal Office of Energy (2005).

- Crude oil is separated from products of mining and quarrying. It is solely composed of imports and demanded by the refineries.

- Mineral oil - the mineral oil tax and climate cent are disaggregated per fuel type and per sector (because of existing sectoral subsidies). Source: Energy NAMEA.

- To model insulation, an input from the construction sector is included in the heating nest. This way, energy used for heat can be substituted against better insulation. The share of insulation represents 5% of total construction demand, excl. own demand and road infrastructure, which amounts for 1/3 of total construction (Körber and Kaufmann, 2007). The input of insulation into each sector is distributed according to the respective sector's share in total demand for heat. This way, each sector has the same benchmark value share of insulation in its heating nest. Insulation is not modeled for the energy sectors[2] because their inputs of heating fuels are used mostly for industrial processes rather than for heating buildings. Moreover, insulation is not modeled for the construction and transport sectors.

5.3 Steady state calibration

GENESwIS is a Ramsey-Cass-Koopmans model based on a steady state growth path. In the steady state, all quantities in the model such as capital, output, consumption, etc. grow at the same constant rate

$$Q(t) = (1+g)^t \cdot Q(t_0) \tag{5.1}$$

with quantity Q, growth rate g and time-period t.

At a given period, the present value of utility is given by $((\frac{1}{1+r})^t \cdot Utility)$, where the factor $(\frac{1}{1+r})^t$ relates to the time preference of the consumer, reflected in the interest rate r.

To ensure that capital grows on the steady state path, initial investments I_0 are defined proportion-

[2]Electricity generation, electricity transport and distribution, gas transport and distribution, district heating and refineries.

ally to the initial capital stock VK_0 (see for example Paltsev, 2004) such that:

$$I_0 = \frac{(\delta + g)VK_0}{\delta + r} \tag{5.2}$$

with growth rate g, interest rate r and discount rate δ.

We assume a growth rate of g=1%, an interest rate of r=4.5% and depreciation rate δ=4.58%. The same interest rate is adopted in the CROSSTEM-CH model.

5.4 Baseline calibration

The chosen baseline (or reference) scenario for this study is based on the *weiter wie bisher* scenario of the Swiss Energy Perspectives (Prognos, 2012). As this scenario realistically deviates from a steady state growth path, we calibrate the model such that labor, GDP, electricity demand and CO_2 emissions follow the respective paths projected by Prognos (2012).

Labor growth is composed of two factors: (1) active population growth and (2) productivity growth. The full-time equivalent forecast is taken from the scenario (A-00-2010) of the FSO. The SECO, in their GDP projection, assume a productivity growth of 0.9% per year. GDP growth follows SECO projections used in Prognos (2012).

Electricity demand per sector (industry, services, transport and households) and per use (transport, heating and appliances), as well as CO_2 emissions per fuel (natural gas, transport fuels and heating fuels) are calibrated to follow the forecast by Prognos (2012) with the help of autonomous energy efficiency indices.

5.5 Nesting structure for rail transport

Rail transport does not display the same substitution possibilities as the other sectors (see nesting figure 5.1). Electricity enters the own-transport nest directly (no e-mobility modeled) as rail is already largely electrified.

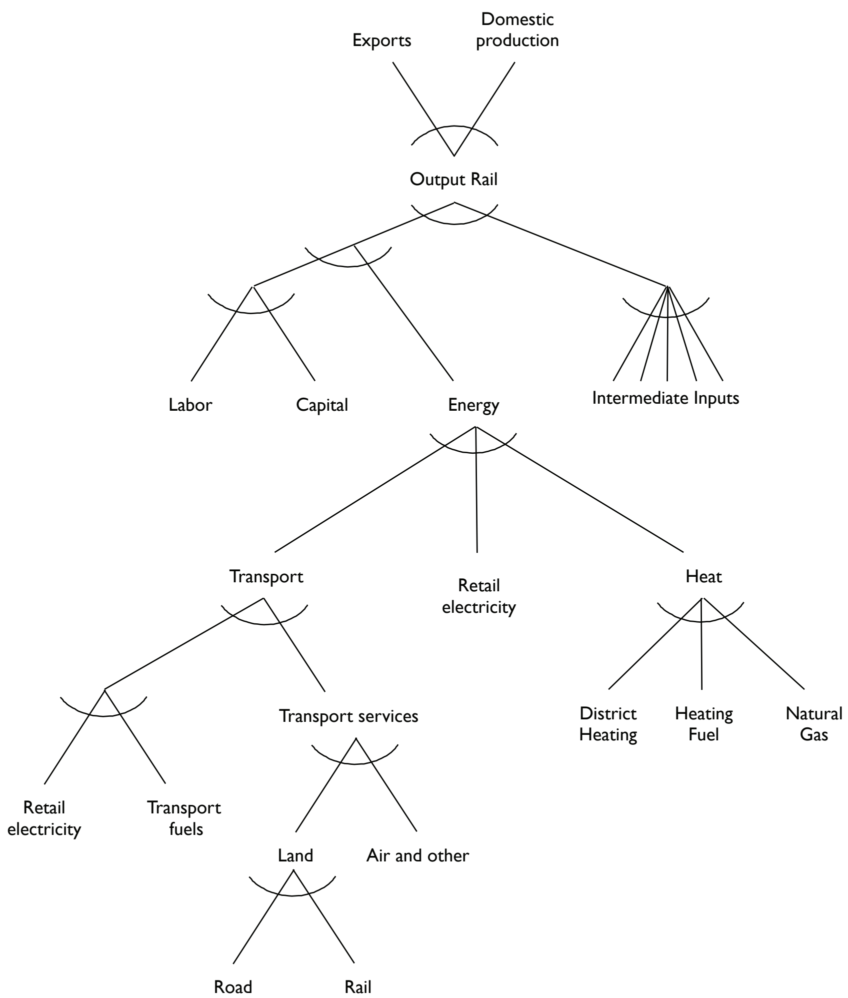

Figure 5.1 – Nesting structure for GENESwIS' rail transport production function. Elasticities of substitutions can be found in Annex 5.1.

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