ENAC
School of Architecture,
Civil and Environmental
Engineering

LEURE
Laboratory of
Environmental and Urban
Economics

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

LINKING ELECTRICITY PRICES AND COSTS IN BOTTOM-UP TOP-DOWN COUPLING UNDER CHANGING MARKET ENVIRONMENTS

SOPHIE MAIRE, FRANK VÖHRINGER, PHILIPPE THALMANN

WORKING PAPER

2015- 1

LEURE-ENAC/EPFL, Lausanne, Switzerland

Please cite as:
Maire, Sophie, Vöhringer, Frank, and Thalmann, Philippe (2015), “Linking electricity prices and costs in bottom-up top-down coupling under changing market environments”, EPFL Working Paper Series in Environmental and Urban Economics No.1, April.

Research funding:
SWISS FEDERAL OFFICE OF ENERGY (SFOE)
Energy - Economy - Society (EES) Research Programme

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

LEURE-ENAC/EPFL
Bâtiment Polyvalent
CH-1015 Lausanne
Tel: +41.(0)21.693.93.93
http://leure.epfl.ch

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Editor:

EPFL	ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
ENAC	School Of Architecture, Civil And Environmental Engineering
LEURE	Laboratory of Environmental and Urban Economics

Cover photo: Bernina Pass (Sophie Maire)

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

Sophie Maire*[1], Frank Vöhringer[1,2], and Philippe Thalmann[1]

[1]Laboratory of Environmental and Urban Economics (LEURE), Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
[2]Econability, Bern, Switzerland

April 7, 2015

Abstract

Electricity market liberalization is altering the pricing mechanisms for wholesale electricity and thus the links between generation costs and user prices. This will affect the effectiveness of climate and energy policies. In this paper, we simulate a tightening of these policies under the alternative regulatory assumptions of (1) continued cost-plus price regulation and (2) gradual market liberalization. For these simulations, we developed a modeling framework composed of a technology-rich model of electricity generation and an applied computable general equilibrium (CGE) model. The first is used to minimize generation costs, the second to compute equilibrium prices and quantities. The two models are soft-linked by relating these costs and prices, whereby the relationship between costs and prices depends precisely on the regulatory assumption. Using this framework, we find, for Switzerland, that a tax on electricity is more effective in reducing electricity demand in a liberalized market than under cost-plus regulation.

---

*Corresponding author: sophie.maire@epfl.ch

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, 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, each with its strengths and weaknesses (for a review of the methods, see e.g. Böhringer and Rutherford, 2009). 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 fact, the link between costs and prices depends on the regulation. This paper investigates whether assuming different market evolutions, and therefore different price formation mechanisms, has an important implication on the results when modeling electricity markets and their interaction with the rest of the economy under climate and energy policies.

---

[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 (UVEK/BFE, 2013) 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.

We build a coupled framework designed to analyze electricity markets and trade in Switzerland. This 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 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 market evolution expectations, have 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.

The outline of the paper is as follows: Section 2 describes the two models and the coupling approaches. Section 3 defines the scenarios. Section 4 identifies the mechanisms at work to understand the results presented in section 5. Section 6 concludes.

2 Framework

We build a coupled bottom-up top-down framework that consists of two models: the technology-rich bottom-up model Cross Border TIMES Electricity Model (CROSSTEM-CH), and the dynamic multi-sectoral Computable General Equilibrium (CGE) model (GENESwIS) of the Swiss economy. These two models are coupled through an iterative soft link, where

- the electricity generation production function in the CGE model is determined by the cost structure optimized by the bottom-up model;
- the sectoral electricity demand variations that occur in the CGE as a result of changes in prices, as well as factor and intermediate input price variations are sent back to the bottom-up model.

Before describing the coupling method, we shortly introduce the two models.

2.1 Models

2.1.1 Bottom-up model: CROSSTEM-CH

The Cross Border TIMES Electricity Model (CROSSTEM)[3] is a technology rich bottom-up optimization model of the electricity system in Switzerland and its four neighboring countries

---

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

developed on the basis of the TIMES framework. TIMES 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 and taking into account a set of constraints (Loulou et al., 2005). 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 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 analysis in this paper, we use the Swiss module of the CROSSTEM model (CROSSTEM-CH), where trade with the neighboring countries is exogenous.

2.1.2 Top-down model: GENESwIS

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

In GENESwIS, agents act rationally and are forward-looking over the time horizon 2010-2050. Households maximize utility under given preferences and a budget constraint. Firms maximize profit under given production technologies and perfect competition. The Government collects taxes to provide public goods. Domestic and foreign goods are assumed to be imperfect substitutes (Armington, 1969). Non-satiation in consumption implies that demand must equal supply in all markets under flexible positive prices.

The energy sector is disaggregated to allow for energy and environmental policy analysis. 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 (ETS, CO_2 tax). The electricity sector has been split into 'Electricity Generation' and 'Electricity Transport and Distribution' to permit the differentiation between wholesale electricity and retail electricity prices.

Capital is modeled as putty-clay. Thus, capital invested into one sector (industry, services or electricity) cannot be transformed into capital for another sector.

2.2 Coupling

The "soft link" coupling method (Wene, 1996), 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 of allowing the use of detailed and complex models, which we deem important for an analysis of the impact of climate and energy policies on the electricity sector and the entire economy. It permits for the representation of the electricity sector's interaction with the other sectors of the economy (Schäfer and Jacoby, 2005), and allows for different types of policies to be adequately modeled: market instruments in the CGE model and technology standards in the bottom-up model.

Coupling through a soft link prioritizes the strengths of each model: The electricity generation mix and costs from the bottom-up model are given priority over the electricity production function of the CGE model. The latter effectively becomes a Leontief function which is parametrized with information from the latest bottom-up run. On the other hand, the endogenous electricity demand reaction of the top-down model is given precedence over the initial demand assumption for the electricity supply model. Additionally, the variations of factor and intermediate input price variations due to general equilibrium effects modify the investment costs, and operation and maintenance costs of the bottom-up model.

Figure 1 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[4] electricity demand quantities simulated by the GENESwIS model are then sent back to become inputs to the CROSSTEM-CH model. To account for 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 electricity demanded each year converges.

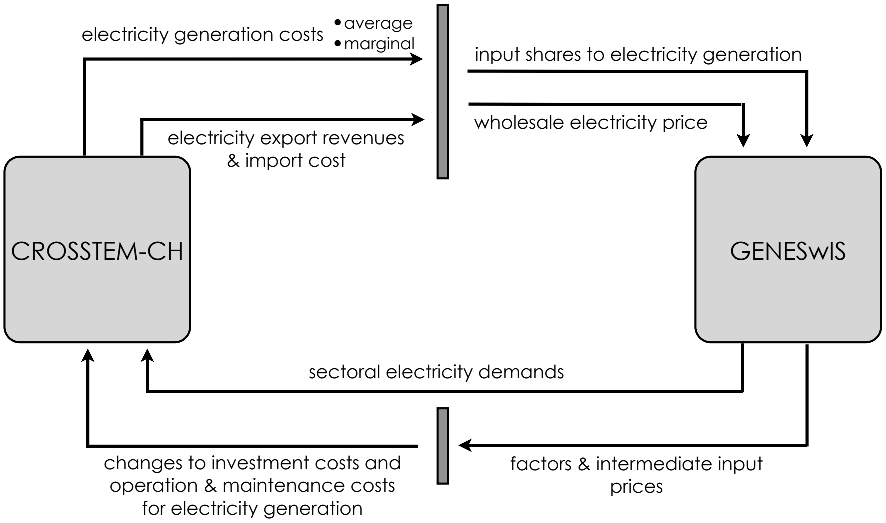


Figure 1: Information exchange between the two component models.

The modeling framework has been set up such that the link between CROSSTEM-CH's generation costs and GENESWIS' wholesale prices for electricity can be modeled in different ways:

---

[4] GENESwIS simulates yearly electricity demands which are distributed to each of the 288 time-slices of the CROSSTEM-CH with the help of sectoral load curves.

- Average cost plus pricing: The wholesale price is set at CROSSTEM-CH's average cost level plus a markup.
- Marginal cost pricing: 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 a long-term marginal cost, or 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.

To help with the convergence of the models, which is hampered by the stepwise behavior of the bottom-up supply curve, we introduce a supply elasticity in the Electricity Transport and Distribution sector of the CGE model. For this purpose, we insert a fixed resource at the top of the Electricity Transport and Distribution's nest. The elasticity of substitution between the fixed resource and the rest of the inputs is calculated[5] such that, given the share of the fixed resource, the supply elasticity of the sector equals a selected value[6] (see Rutherford, 1998). This method was inspired by the work of Lanz and Rausch, 2011 who introduce a demand elasticity to parameterize the bottom-up demand. They 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.

Despite the introduction of a supply elasticity in the Electricity Transport and Distribution sector of the CGE model, it is frequent for the models to lock up into an oscillation between two marginal costs. The electricity demand oscillates between two values and does not converge.To avoid this problem, we introduce a dampening of the demand response in the coupler: Instead of the last electricity demand vector, we send a Gauss-Seidel combination of the CGE electricity demands of the previous iterations (eq. 1) to the bottom-up model:

$$D_{i+1} = \alpha D_i + (1 - \alpha) D_{i-1} \tag{1}$$

where $\alpha \in [0, 1]$ represents the length of the step towards the demand of the last iteration.

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 1).

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 and UVEK/BFE, 2012). They include current policies such as an Emissions Trading Scheme, a CO_2 tax on 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 the electricity demands and CO_2 emissions follow the paths projected by Prognos and UVEK/BFE, 2012.

---

[5] $\sigma = \eta \frac{\theta_R}{1-\theta_R}$ with σ the elasticity of substitution between the fixed resource and the rest of the inputs, η the supply elasticity and θ_R the share of the fixed resource.

[6] The value of supply elasticity can be set such that it helps with convergence (approximating the bottom-up supply elasticity) as it has no impact on the results.

Table 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 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 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.

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).

$$\text{Profit}(t) = \frac{P_m(t) - AC(t)}{P_m(t)} \tag{2}$$

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. It is uncommon in a CGE setting to have two different baselines. Actually, the central targeted baseline parameters, namely electricity demands and CO_2 emissions per fuels, are the same in both of our baselines. However, it was necessary to recalibrate the model framework under the different coupling mechanisms to match the targeted baseline parameters as electricity prices are defined in a different manner.

4 Mechanisms at work

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 2, 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 (figure 2).

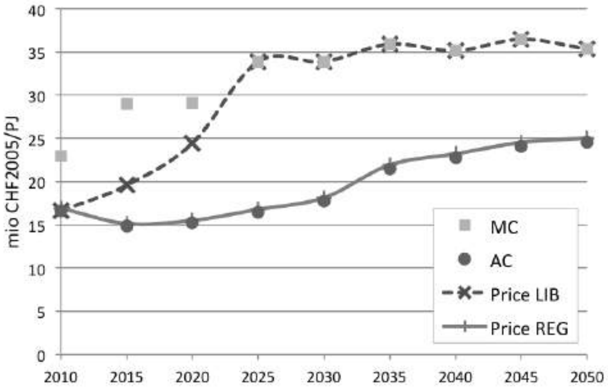


Figure 2: Wholesale electricity pricing under the two baselines (LIB for the liberalized market and REG for the regulated market) in comparison with annual average (AC) and marginal (MC) costs from the CROSSTEM-CH model.

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:

- Electricity demand is flexible: A rise in end-user price will induce 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 1), 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.

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.

5 Results

As we saw in the previous section, the effect of an electricity tax is linked to the demand elasticity and to the reaction of the generation costs to a variation in demand. According to whether we assume a regulated market or a liberalized market, the wholesale electricity prices are linked to respectively the average cost or marginal cost of the bottom-up model. Consequently, the effectiveness of the electricity tax will depend on the reaction of the marginal cost (resp. average cost) in the liberalized (resp. regulated) market. In this section, we analyze the effectiveness of the TAX scenario policies under two different market assumptions: gradual liberalization (LIB) and regulation (REG). To do this, we first investigate the effect of the policies on the generation costs in the Swiss context.

5.1 Generation costs

5.1.1 Marginal cost

As can be seen in figure 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, the marginal technologies, and hence the marginal cost, do not change much in yearly average (although they may change in some particular time-slices).

5.1.2 Average cost

In contrast, average cost is reduced in the TAX scenarios relative to the baselines (figure 3a). Due to a technology mix comprising many depreciated plants and to the optimized cost structure of the CROSSTEM-CH model, variable costs represent a major share of total cost. 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 variable costs in the framework. 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.

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 implies for the wholesale, retail and end-user prices, and for electricity demand under alternative market regulations.

5.2.1 Liberalized market

In the liberalized market scenarios, 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 3a). As a result, wholesale electricity prices (figure 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 3b). End user prices are defined as retail prices gross of tax. The electricity tax included in the TAX scenario increases the end user price of electricity (figure 3c), which reduces electricity demand (figure 3d).

5.2.2 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 3a&b). Consequently, retail electricity prices also decrease relative to the baseline (figure 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 3c. The resulting reduction in demand is therefore smaller in the regulated market than in the liberalized market[7] (figure 3d).

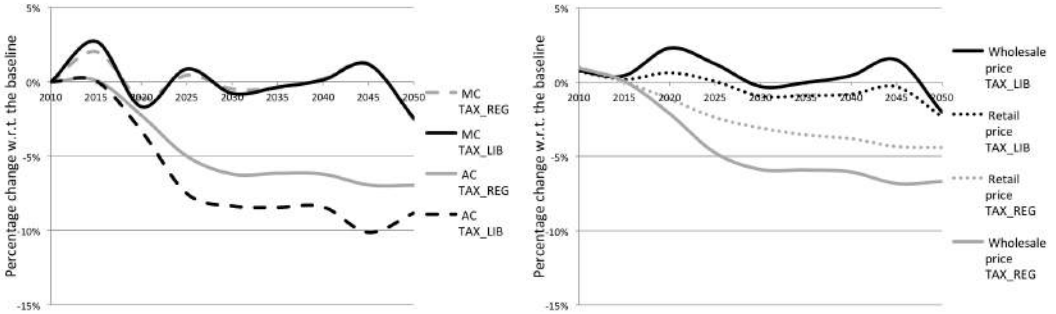
6 Conclusion

In this paper, 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: Assuming a more or less liberalized market implies linking the wholesale electricity price to either the average cost or the marginal cost of electricity generation.

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.

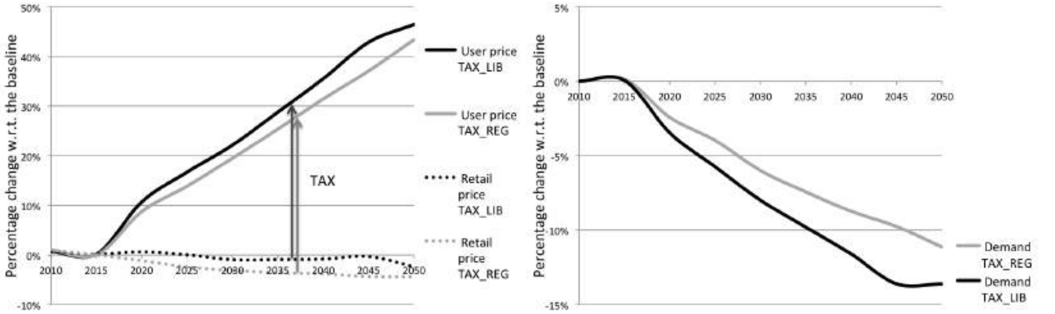
---

[7] These results are qualitatively robust to different calibrations of the CGE model.



(a) Average and marginal costs

(b) Wholesale and retail electricity prices



(c) End user prices (gross of tax) for electricity

(d) Electricity demands

Figure 3: Percentage change of - (a) average cost (AC) and marginal cost (MC), (b) wholesale and retail electricity prices, (c) electricity prices paid by the end users (gross of tax) and retail electricity prices (net of tax), and (d) electricity demands - for the scenarios TAX_LIB and TAX_REG compared to the baselines BAU_LIB and BAU_REG respectively.

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 coupled models' results.

Acknowledgements

This work was funded by the Research Program Energy-Economy-Society of the Swiss Federal Office of Energy (SFOE) through the ELECTRA project: *Electricity markets and trade in Switzerland and its neighboring countries: Building a coupled techno-economic modeling framework*.

We thank Rajesh Pattupara, Kannan Ramachandran and Hal Turton for their modeling work on CROSSTEM-CH model and other project contributions which have helped us to implement the coupling approaches.

We are grateful to Frédéric Babonneau and Marc Vielle for sharing their coupling experience.

References

Armington, P. S. (1969). A Theory of Demand for Products Distinguished by Place of Production. *IMF Staff Papers 16*(1), 159–178.

Böhringer, C. and T. Rutherford (2009). Integrated assessment of energy policies: Decomposing top-down and bottom-up. *Journal of Economic Dynamics and Control 33*(9), 1648–1661.

Fortes, P., A. Pereira, R. Pereira, and J. Seixas (2014). Integrated technological-economic modeling platform for energy and climate policy analysis. *Energy 73*(C), 716–730.

Hoffman, K. C. and D. W. Jorgenson (1977). Economic and technological models for evaluation of energy policy. *The Bell Journal of Economics 8*(2), 444–466.

International Energy Agency (2001). *Competition in electricity markets*. OECD, Paris.

Kannan, R. and H. Turton (2011). Documentation on the Development of the Swiss TIMES Electricity Model (STEM-E).

Lanz, B. and S. Rausch (2011). General Equilibrium, Electricity Generation Technologies and the Cost of Carbon Abatement. *Energy Economics 33*(5), 1035–1047.

Loulou, R., G. Goldstein, U. Remne, A. Kanuida, and A. Lehtila (2005). Documentation for the TIMES Model. *Energy Technology Systems Analysis Programme*.

Martinsen, T. (2011). Introducing technology learning for energy technologies in a national CGE model through soft links to global and national energy models. *Energy Policy 39*(6), 3327–3336.

Prognos and UVEK/BFE (2012). Die Energieperspektiven für die Schweiz bis 2050. Energienachfrage und Elektrizitätsangebot in der Schweiz 2000-2050.

Riekkola, A. K., C. Berg, E. O. Ahlgren, and P. Söderholm (2013). Challenges in Soft-Linking: The Case of EMEC and TIMES-Sweden. *National Institute of Economic Research* (133).

Rutherford, T. (1998). Economic Equilibrium Modeling with GAMS: An Introduction to GAMS/MCP and GAMS/MPSGE.

Schäfer, A. and H. D. Jacoby (2005). Technology detail in a multisector CGE model: transport under climate policy. *Energy Economics 27*(1), 1–24.

UVEK/BFE (2013). Perspektiven für die Grosswasserkraft in der Schweiz. Wirtschaftlichkeit von Projekten für grosse Laufwasser- und Speicherkraftwerke und mögliche Instrumente zur Förderung der Grosswasserkraft.

Vöhringer, F. (2012). Linking the Swiss Emissions Trading System with the EU ETS: Economic Effects of Regulatory Design Alternatives. *Swiss Journal of Economics and Statistics 148*(II), 167–196.

Wene, C.-O. (1996). Energy-economy analysis: linking the macroeconomic and systems engineering approaches. *Energy 21*(9), 809–824.