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Department of the Environment,
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Swiss Federal Office of Energy SFOE
Energy Research

Final report

ElMaR - Electricity Market Design and Renewables

Model Framework for the Analysis of Electricity Market Design and the Integration of Renewable Electricity Production in Switzerland

ECOPLAN Forschung und Beratung in Wirtschaft und Politik

Loch Alpine Economics, Inc.

Date: 30 09 2018

Place: Bern

Publisher:
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SFOE contract number: SI/501316-01

Content

Summary

ElMaR (**El**ectricity **Ma**rket Design **a**nd **R**enewables) lays the modelling foundations to be able to address key questions concerning the shift in energy generation towards more renewable energy sources. ElMaR offers an innovative energy-economy model framework, which combines and links state of the art large-scale bottom-up partial equilibrium electricity market model with top-down general equilibrium model in a multi-regional setting. The bottom-up partial equilibrium electricity market model features a detailed engineering representation of power generation and dispatch over a representative year. It accounts for physical restrictions of the Swiss power network. For each individual hour, electricity demand, supply, dispatch and transmission can be displayed in high regional resolution. The top-down general equilibrium captures economic transactions amongst firms (industries) and households. The regional disaggregation (18 regions / cantons) allows the analysis of regional distribution effects of policy measures. In order to use ElMaR for the evaluation of the impact of policy measures, the parametrization of the model would have to be further refined and complemented.

Zusammenfassung

Mit ElMaR (**El**ectricity **Ma**rket Design **a**nd **R**enewables) werden die modellmässigen Grundlagen bereitgestellt, um Schlüsselfragen zum Ausbau der erneuerbaren Stromproduktion zu beantworten. ElMaR ist ein innovatives energiewirtschaftliches und multiregionales Modelltool, das ein bottom-up-Modell (partielles Gleichgewichtsmodell) mit einem top-down-Modell (allgemeines Gleichgewichtsmodell) kombiniert und verbindet. Das partielle Gleichgewichtsmodell für den Strommarkt zeichnet sich durch eine detaillierte Erfassung der Stromerzeugung und Stromverteilung über ein repräsentatives Jahr aus. Die physikalischen Restriktionen des schweizerischen Hochspannungsnetzes werden berücksichtigt. Für jede einzelne Stunde kann der Stromverbrauch, die Produktion, der Dispatch und die Übertragung in hoher regionaler Auflösung angezeigt werden. Das allgemeine Gleichgewichtsmodell erfasst die wirtschaftlichen Transaktionen zwischen Unternehmen und Haushalten. Die regionale Disaggregation (18 Regionen / Kantone) ermöglicht die Analyse der regionalen Verteilungseffekte von Politikmassnahmen. Um ElMaR für die Analyse der Auswirkungen politischer Massnahmen nutzen zu können, müsste die Parametrisierung des Modells überarbeitet und ergänzt werden.

Résumé

ElMaR (**El**ectricity **Ma**rket Design **a**nd **R**enewables) fournit les éléments fondamentaux basés sur un modèle pour répondre aux questions sur l'expansion de la production d'électricité renouvelable. ElMaR offre un cadre de modèle d'économie d'énergie innovant, qui combine un modèle d'équilibre partiel et un modèle d'équilibre général. Le modèle d'équilibre partiel du marché de l'électricité se caractérise par une représentation détaillée de la production et de la distribution d'électricité sur une année représentative. Il tient compte des restrictions physiques du réseau électrique suisse. Pour chaque heure individuelle, la demande électrique, la production, le dispatch et la transmission peuvent être affichées en haute résolution régionale. Le modèle d'équilibre général couvre les transactions économiques entre entreprises et ménages. La désagrégation régionale (18 régions / cantons) permet d'analyser les effets des mesures politiques sur la répartition régionale. Afin d’utiliser ElMaR pour analyser les effets des mesures politiques, la paramétrisation du modèle devrait être affinée et complétée.

Executive Summary

Renewables and the electricity market

To date, hydro power already accounts for more than 50% of Swiss electricity production. The remaining bulk share comes from nuclear power. Switzerland's energy strategy entails the phase out of nuclear power and an increase of production from renewables. Due to limitations on additional sites for hydro power, an expansion of renewable power in electricity production implies the development of new renewables like wind and solar. Both wind and solar technologies are characterized by intermittency, i.e. variability in the supply that depends on weather conditions. Intermittency is not only a challenge for the reliability of a power system based on (intermittent) renewable energy; it also provides a challenge for maintaining investment incentives. The reason is that intermittency reduces the market value of renewables as their share in the international market system rises. These key characteristics of photovoltaics and wind power are well-known, but the economic implications of these traits are less well understood.

Aim of the project

The overall objective of the project is to **develop a model framework** for the economic impact assessment of renewable power promotion in Switzerland. More specifically, the ElMaR (**El**ectricity **Ma**rket Design **a**nd **R**enewables) model should lay the modelling foundations to be able to address key questions concerning the shift in energy generation towards more renewable energy sources.

Modelling challenges

Photovoltaics and wind exhibit decreasing returns to scale, i.e. the value of solar or wind capacity declines as more is added. The three factors potentially driving this are:

- intermittency (time profile is "inconvenient", storage is costly)
- spatially dispersed plants (transmission is costly or constrained)
- physical constraints on resource base

Many electricity market models focus on overall constraints of resource availability without more specific time resolution. Yet, the stochastic variations of renewable power supply and energy demand over time are central to the economic potential of renewable technologies. Since, supply and demand pattern may not only differ substantially over time but also across space, power transmission and electricity network constraints are potentially of high importance. Within the more narrow boundaries of the electricity market, the further penetration of renewables poses key challenges for regulation along various dimensions including:

- Investment incentives for capacity (energy markets only versus capacity markets)
- Storage options (e.g. Swiss hydro power – in particular pump storage – as an option for balancing supply and demand and exploiting intertemporal arbitrage with neighboring countries)
- Grid stability and network expansion needs (energy security)

Electricity and energy – although only constituting a very small share in overall Swiss value-added – is key to economy-wide activities in production and consumption. Hence, electricity market reforms may have substantial spillover effects to and feedback effects from the rest of economy. Such spillover and feedback effects should not only be taken into account with respect to the cost-effective design of electricity market regulations. Often there are non-negligible trade-offs between cost-effectiveness and regional (cantonal) cost-incidence which vary across alternative policy options.

Against this background, ElMaR is developed as an integrated multi-cantonal bottom-up top-down model for Switzerland which allows for the comprehensive economic impact assessment of electricity market reforms while taking into account fundamental physical restrictions of the power system.

ElMaR – an integrated bottom-up top-down model for Switzerland

ElMaR (see figure A) combines a **bottom-up partial equilibrium model** of the Swiss electricity system **(PE model)** with a **top-down multi-regional general equilibrium model** of the Swiss economy **(GE model)**.

The **PE model** of ElMaR features a detailed engineering representation of power generation and dispatch over a representative year. It accounts for physical restrictions of the Swiss power network and imposes energy balance constraints at each network node and time segment. Given the paramount importance of hydro power for the Swiss electricity system, ElMaR explicitly incorporates endogenous dynamic hydro scheduling where the marginal cost of generation and prices of electricity in future months determine how much water should be used and how much should be stored. ElMaR furthermore covers a dynamic extension to resolve both dispatch and capacity expansion decisions in new power plants (investment).

The **GE model** of ElMaR is a computable general equilibrium model building on the standard Arrow-Debreu general equilibrium framework to capture economic transactions amongst firms (industries) and households in the various Swiss cantons. With the cantonal disaggregation, ElMaR can not only address economy-wide efficiency implications of alternative regulatory designs but also their incidence across cantons – in this vein, ElMaR accommodates policy-relevant analysis on how aggregate cost and benefits trade off with the distributional consequences across cantons.

The **PE and GE models** are integrated towards a combined techno-economic model framework which allows for the comprehensive economic impact assessment of electricity market reforms thereby accounting for fundamental technological constraints on the one hand but also figuring in spillover and feedback effects with the broader Swiss economy.

ElMaR – an innovative energy-economy model framework

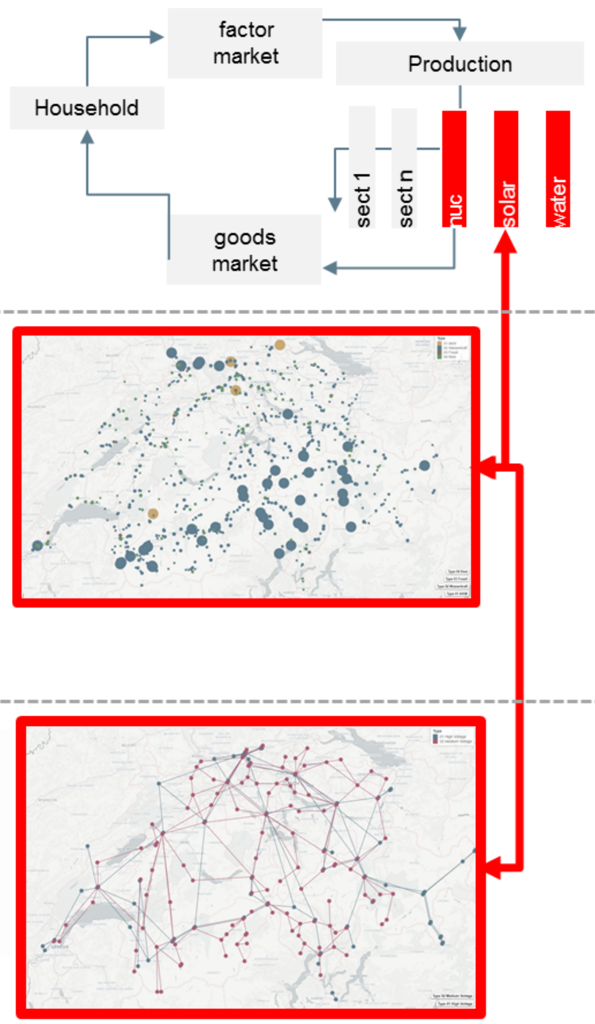
ElMaR offers an innovative energy-economy model framework, which combines and links state of the art large-scale bottom-up partial equilibrium electricity market model with top-down general equilibrium model in a multi-regional setting. The **modular framework** of ElMaR allows to

run the PE and GE model stand alone. This allows more thorough testing, an efficient project work and insights into the relative importance of top-down versus bottom-up perspectives on specific policy questions. The **regional disaggregation** (18 regions / cantons) allows the analysis of regional distribution effects of policy measures. Reduced-form **technology foundation of power generation** allows activity analysis by power technology. Further, ElMaR offers an outstanding **visualization tool**: For each individual hour, electricity demand, supply, dispatch and transmission can be displayed in high regional resolution. To our knowledge it is the first model that incorporate all these features and solves amazingly fast within several minutes on a common personal computer.

ElMaR – some issues still open

In order to use ElMaR for the evaluation of the impact of policy measures, the parametrization of the model would have to be further refined and complemented. In the current ElMaR model framework foreign border crossing restrictions are recorded in a simplified way by means of import supply and export demand elasticities. In order to impose physical transmission restrictions at border crossings, it is necessary to implement a targeted congestion management system with Germany, France, Italy and Austria. Further, the foreign electricity price is to be determined endogenously for Germany/Austria, France and Italy by implementing the electricity production in neighbouring countries Austria, Germany, France and Italy. In order to address the transition path to exogenous policy shocks the model dynamics could be further extended towards an intertemporal setting with multiple time periods.

Figure A: ElMaR – model framework to analyse the integration of renewable power production



Integrated PE GE model		temporal resolution	resolution	model characteristics	data
GE model	**top-down general equilibrium model**	**year**	18 regions (cantons)	**GE model** of the whole economy: 1 household per region 21 sectors 3 energy sectors 7 power technologies Trade via national pool *(no direct inter-regional trade due to lack of data)*	**Swiss IOT** *(FSO)* **cantonal GDP** *(FSO)* **sectoral desaggregation** *(Ecoplan, ARE)*
PE model	**bottom-up partial equilibrium model of power generation…** (without network constraints, copper plate approach)	**hour** month year	- 630 hydro and 230 other plants in 18 regions (cantons) - exports and imports to 4 neighbouring countries	**PE model** of the electricity market:: - hydro scheduling framework - 9 power technologies *(running hydro, storage hydro, pump storage, circular pump nuclear, fossil, waste, wood, wind, solar)*	**regional production and consumption** *(Swissgrid)* **hydro power plants** *(SFOE)* **other power plants** *(WEPP)*
	...and dispatch (with network constraints, PTDF approach)	**hour** month	150 nodes 250 lines	**PTDF approach** *which accounts for loop-flow constraints on transmission and network effects (**P**ower **T**ransfer **D**istribution **F**actor, allows approximation of real power flows and their market consequences)*	**network data** *(ENTSOE)* **nodal production**: *based on proximity-based power plant production shares* **nodal consumption**: *based on proximity-based population shares*

1 Introduction

Renewable energy sources and the Swiss electricity market

Electricity production from renewable energy sources (RES-E) is at the core of the transition towards a low-carbon economy. In Switzerland hydropower is the most important domestic energy source covering more than half of the Swiss electricity generation. The second pillar in Swiss electricity production is nuclear which contributes to more than a third to Swiss electricity generation but remains quite contentious as a permanent asset in the Swiss power production portfolio.

The planned expansion of renewable power production in Switzerland along with a decline in nuclear power and the fact that hydropower capacities are largely exhausted calls for a significant expansion of new renewable power production like photovoltaics or wind with currently very low shares in Swiss power generation. Both technologies are characterized by intermittency, i.e. variability in the supply that depends on weather conditions. Intermittency is not only a challenge for the reliability of a power system when the share of intermittent energy exceeds are certain threshold. It also provides a challenge for maintaining investment incentives. In principle, power storage is a remedy against the intermittency of energy supply but might become quite costly. In addition, the spatial dispersion of renewable energies for electricity production may require investments in additional power transmission capacities.

Policy instruments to promote renewable electricity production

In order to promote the penetration of RES into electricity production, there is a broad range of policy instruments such as feed-in tariffs, market premiums, subsidies for wind and photovoltaics, investments incentives to energy storage, quotas on domestic production, differentiated electricity taxes, import taxes, demand side management via flexible consumer pricing, the introduction of capacity markets or grid expansions to make the power system more reactive to the variability of solar and wind power.

Capture the direct effects of electricity market regulations

Electricity market regulation in first place will affect the outcome of the electricity market itself, i.e., electricity prices, supply and demand quantities, remuneration to power producers and grid operators, etc. A systematic cost-benefit analysis of alternative electricity market reforms thus calls for a quantitative partial equilibrium bottom-up model of the power market which takes into account the fundamental (physical) constraints of power generation and power transmission via the electricity network.

Capture the indirect spillover und feedback effects of electricity market regulations

Beyond, the direct impacts of regulation on the electricity market, there are indirect spillover and feedback effects to the rest of the economy – for example, an increase in electricity prices due to more costly supply options may decrease labor and capital productivity, thereby reducing real income of the representative Swiss household. In order to capture such indirect effects the electricity market focus must be widened to an economy-wide perspective which in turn requires a macroeconomic simulation model linked to the bottom-up electricity market model in a coherent manner. Regarding the macroeconomic perspective, computable general equilibrium (GE) models constitute the state-of-the-art method to perform economic impact assessment of policy interference based on sound microeconomic theory and empirical data.

Aim of the project

The overall objective of the project is to develop a model framework for the economic impact assessment of renewable power promotion in Switzerland. More specifically, the ElMaR (Electricity Market Design and Renewables) model should lay the modelling foundations to be able to address key questions concerning the shift in energy generation towards more renewable energy sources

Structure of this report

The remainder of this report is organized as follows. Section 2 provides a brief literature review. Section 3 offers a summary of the top-down multi-region multi-sector general equilibrium (GE) model which captures the economic structure of Switzerland in production and consumption as well as trade linkages with the rest of the world. Section 4 features a description of the bottom-up multi-region partial equilibrium (PE) model of the Swiss electricity market. Section 5 briefly sketches how the PE and GE model components are coupled and solved in an iterative manner. Section 6 reports on an illustrative model application. Section 7 concludes with lines for future research. Appendices A-C include technical documentations on the data buildstream for the GE model (Appendix A) and the PE model (Appendix B) as well as the integration of both model components (Appendix C); The core elements of the GAMS code are set out in in Appendix D. Appendix E shows the model results reported in EXCEL. Appendix F shows the storage capacities for the storage power plants.

2 Literature Review

Mathys et al. (2012) and more recently del Granado et al. (2018) give an overview of energy-economy models designed for the impact assessment of major energy policy reforms such as the decarbonisation of the energy system. Del Granado et al. (2018) discuss energy system models that are internationally widely adopted such as E3ME, MARKAL, TIMES, or REGEN. Mathys et al. (2012) focus on nine modelling approaches that have been used in the past for energy policy analysis in Switzerland.[1] Both – Mathys et al. (2012) as well as del Granado et al. (2018) – classify energy-economy models in three broader categories: (i) top-down approach, (ii) bottom-up approach and (iii) hybrid approach.

2.1 Top-down approach

Top-down models concentrate on economy-wide interactions in production (at the level of sectors/industries) and consumption (at the level of households) of the domestic economy taking into account international trade relationships. They do not though usually feature details for energy market regulations nor technological details of energy supply, energy conversion, energy trade, or energy consumption. A wide-spread class of top-down models for energy policy analysis are computable general equilibrium (CGE) models. CGE models are based on microeconomic theory. Households and firms interact with price-responsive supply and demand decisions on markets for goods and factors thereby maximizing households' welfare and firms'profits. Standard CGE models feature multiple production sectors (commodities) to capture complex relationships of intermediate input flows. Pending on the policy topic and data availability, the regional resolution may boil down either to a single region with an open-economy closure (via export supply to and import demand functions from the rest of the world) or a multi-region structure with explicit bilateral trade flows.[2] As to time treatment, models are either of static or dynamic nature where the latter is further distinguished into recursive-dynamics or intertemporal settings. With recursive dynamics, the static model version is essentially solved step by step in time based on myopic expectations. With an intertemporal setting, complete foresight of agents is typically assumed and the model optimizes simultaneously all decision variables over the entire time horizon subject to rational expectations.

According to the summary by Granado et al. (2018) the strength of standard CGE models "is that they incorporate the interactions between the different agents as well as the feedbacks through the whole economy". This strength trades off with weaknesses as perceived by Granado et al. (2018) such as "the high level of aggregation and therefore an unrealistic view

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[1] CEPEl (ETHZ CEPE), CITE (ETHZ CER), ETEM (ORDECSYS), GEMINI-E3 (EPFL REME), GENESsIS (Econability), MERGE-ETL (PSI), Swiss MARKAL (PSI), Swissgem Switzerland (Ecoplan), and Swissgem Worldwide (Ecoplan).

[2] Trade representations can be mixed such as in ElMaR where the GE component provides a cantonal (multi-region) resolution whereas trade of the cantons with the rest of the world follow a (small) open economy closure with infinitely elastic foreign export supply and import demand functions – in other words: Switzerland is treated as a price-taker on international markets.

of the energy sector as well as the high level of time aggregation". The limitations in technological, temporal and spatial resolution seem to be of particular relevance with respect to the economic impact assessment of renewable energy promotion policies. Renewable solar and wind power generation has a major influence on the daily and seasonal profile of electricity supply. The accentuated peaks in electricity production due to renewable energies can lead to bottlenecks in the electricity grid. Both – details concerning the intermittency of renewable electricity production and incorporation of the electricity grid – can hardly be integrated directly into a CGE model.

The virtual platform SimLab gives an overview of some CGE models used in Switzerland for applied policy analysis:[3]

- *CEPE* is a multi-sector multi-region general equilibrium model of the world economy with a regional focus on Western Europe (including Switzerland as an explicit region). There is a static and a recursive-dynamic model version. One distinct feature of CEPE is the possibility to differentiate policy incidence across heterogeneous households.
- *CITE* is an intertemporal multi-sector multi-region general equilibrium model of the world economy (including Switzerland) with a focus on the role of policy-induced technological change in the energy system.
- *GEMINI-E3* is a multi-country, multi-sector, recursive-dynamic computable general equilibrium model with a rather detailed representation of technological energy system options.
- *Swissgem* is a static or recursive-dynamic general equilibrium model for Switzerland with special focus on the energy market and CO_2-emission control policies (Böhringer, Müller (2014)) - used more recently for shaping the energy perspectives of the Office Federal Office of Energy and for the analysis of environmental tax reforms in Switzerland. Based on *Swissgem*, Rausch et al. (2017) included some more details concerning policy instruments like open competitive bidding, buildings programs, standards for new passenger vehicles and electrical appliances.

All of the Swiss CGE models share the fundamental strengths and weaknesses of CGE models mentioned by del Granado et al. (2018), although some CGE models take into account a more stylized bottom-up representation of electricity production technologies which would already qualify them as sort of hybrid (direct linked) top-down bottom-up models. Yet, with such CGE approaches – even cast as hybrid integrated models – potentially important details of electricity market regulation which are inherently linked to high time resolution and spatial electricity network characteristics cannot be satisfactorily captured.

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[3] http://www.simlab.ethz.ch/models.php.

2.2 Bottom-up approach

Bottom-up approaches to energy system analysis record power technologies in detail and often rely on optimization (mathematical programming) to find least-cost solutions on satisfying energy demands (wee e.g. MARKAL or TIMES). Some of the bottom-up models (like TIMES, REGEN) may still rely on a stylized grid representation of the power flows. According to del Granado et al. (2018) such reduced-form representations over the electricity network miss fundamental physical constraints for optimal power flow or dispatch (OPF) – in contrast, OPF models analyse the power balance in the electricity grid at each node considering voltage and line limits.

The general weakness of bottom-up approaches is the rather rudimentary treatment of energy demands – in fact, energy demands are often taken as exogenous without accounting for empirical evidence on price- and income-effects as estimated via demand and income elasticities.

Furthermore, bottom-up models miss out on spillover effects to and feedbacks from the rest of the economy.

SimLab lists the bottom-up approaches used for impact assessments of regulatory measures in the Swiss electricity market sector:

- *CROSSTEM* is a multi-region electricity model of five countries, viz. Austria, Switzerland, Germany, France, and Italy. The model optimises electricity supply for an exogenously given electricity demand over time horizons (to account for long-term policy goals and investment decisions) while simultaneously representing intra-annual detail (i.e., seasonal, weekly and hourly). The *CROSSTEM* model builds on the MARKAL/EFOM System framework (TIMES).
- *STEM* - Swiss TIMES energy system model (*STEM*) - is a comprehensive and flexible model of the Swiss energy system. It is a bottom-up, technology-rich model built in the Integrated MARKAL EFOM System (TIMES) framework.
- *Enerpol* is an integrated electricity and gas networks model. For central Europe, the model features a transmission grid with 1900 individual transmission lines (220, 380 and 400 kV) and 3000 individual geo-referenced conventional and renewable power plants. For the electricity and gas markets, hourly *chronological* simulations are undertaken.
- *ETEM-SG* is a “robust optimization” based capacity expansion model for an ensemble of energy related infrastructures that seeks for an optimal use of resources subject to energy demand and greenhouse gas (GHG) emission constraints in urban communities.
- *ETEM* is a linear programming model, which represents the optimal capacity expansion in production technology. The model features multiple energy carriers, with a particular attention devoted to electricity.
- *EXPANSE* has the structure of a standard bottom-up (technology-rich) mathematical programming model to meet exogenous energy demands in an intertemporal (perfect foresight) setting.
- *SCS* is a year-around (annual) simulation model of the Swiss electric energy supply used for the cross-comparison of dispatch decisions under alternative policy (scenario) settings.

- *Swissmod* is a numerical model of the of the Swiss electricity market. It covers the Swiss high voltage transmission network (220 and 380kV) as well as a detailed representation of the Swiss hydropower structure. The latter includes specific characteristics of run-of-river, yearly storage and pumped storage power plants and their hydraulic coupling via the Swiss river and water stream system. Although the regional focus of *Swissmod* is Switzerland, surrounding countries are included to capture the impact of European market developments on the Swiss electricity system. In total *Swissmod* covers about 200 nodes within Central Europe, about 150 of which are within Switzerland, and about 400 transmission lines.

Swissmod (Schlecht and Weigt 2014) is – to our current knowledge – the only Swiss model, which captures the production flexibility of storage and pump storage hydro plants endogenously which makes it quite suitable to study the promotion and expansion of intermittent renewable energies for Switzerland.

2.3 Hybrid approach

To overcome the weaknesses of top-down and bottom-up models used in isolation, energy modelling deals since long with hybrid frameworks combining top-down with bottom-up models (Herbst et al. 2012).

The main challenge of such hybrid models is to keep theoretical consistency while preserving computational tractability. In this vein, Böhringer and Rutherford (2009) present a powerful algorithm for coupling top-down computable general equilibrium models and large-scale partial equilibrium energy system models – with the key idea that demand functions and cost structures in the bottom-up model are iteratively updated by top-down results where the latter in turn account for bottom-up information on energy supplies.

The linking routine by Böhringer and Rutherford has proven to provide robust convergence in various model implementations (e.g. REGEN). A less stringent, more heuristic approach in coupling is still wide-spread owing to the fact that disciplinary cultures in bottom-up and top-down models may differ (Herbst et al. 2012). Del Granado et al. (2018) e.g. envisage in their Nexus project the linkage of multiple pre-existing bottom-up and top-down models via an interface, which allows “automatic” exchange of information and results between the models. It, however, remains unclear how such soft links will live up with fundamental consistency requirements and show robust convergence characteristics.

The linking between bottom-up and top-down is also addressed in the ongoing work within NRP 70.[4] Within the joint project “AFEM - Assessing future electricity markets" the project AFEM-

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[4] http://www.nfp70.ch/de/projekte.

MODEL[5] has the following main objectives: Develop a methodology to link economic and engineering network models, develop a methodology to match the different spatial and temporal resolutions of top-down/aggregated and bottom-up/detailed electricity market models, combine those linkages to derive a consistent model framework.

Further the ongoing project AFEM-FUTURE[6] addresses similar issues to those of the present project. AFEM-FUTURE explores the question of how possible future market environments should be designed to ensure adequate investment incentives for generation and transmission capacity and to guarantee sufficient temporal and spatial flexibility of power generation in light of fluctuations brought about by intermittent renewable energy sources.

2.4 Lessons learnt for ElMaR design

The above literature presents us with the following challenges for this project, in which a model package for the analysis of electricity market design and integration of renewable electricity production is to be built. Firstly, we need a bottom-up partial equilibrium model of the electricity market with a high resolution in time and sufficient regional and technological disaggregation. Secondly, for Switzerland, the dispatch for storage and pumped storage hydroelectric power stations must be captured endogenously (similar to Swissmod). Thirdly, the electricity grid must be captured with its physical properties. And fourth, the large-scale bottom-up partial equilibrium model of the electricity market is to be linked in a consistent manner with a top-down multi-regional general equilibrium model. According to our knowledge, there is currently no model that unites all these aspects.

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[5] http://p3.snf.ch/project-153733.

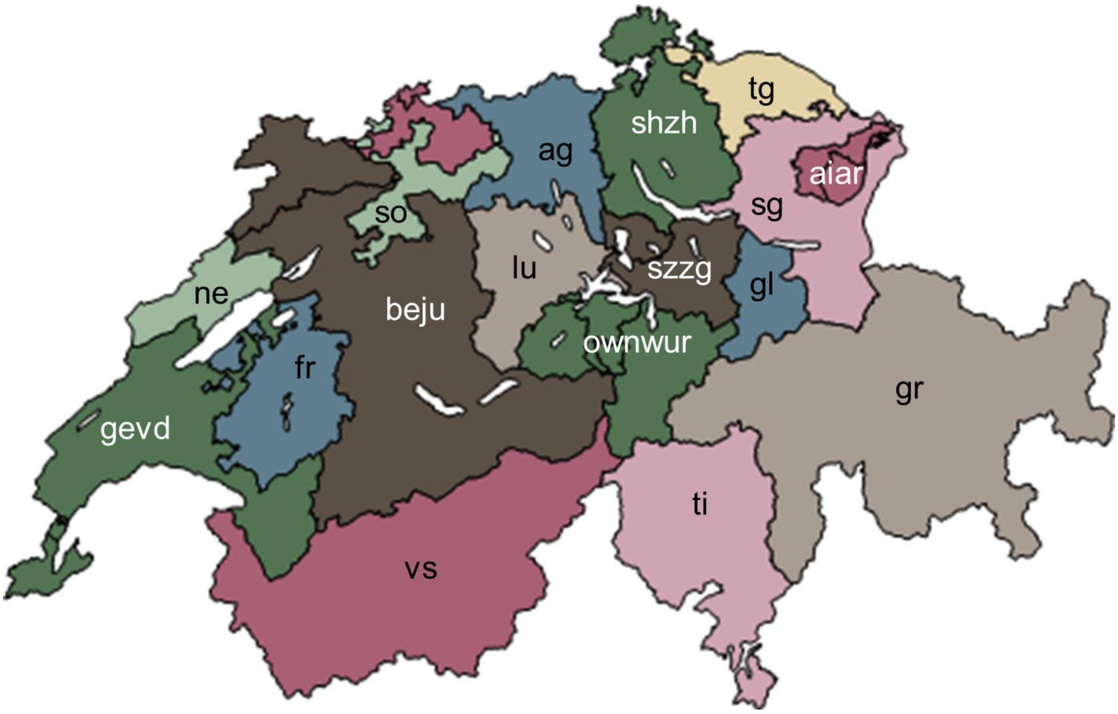
[6] http://p3.snf.ch/project-153967.

3 Top-down multi-region GE model for Switzerland

The top-down component of ElMaR stands out for two specific features as compared to standard GE models for Switzerland. Firstly, it disaggregates national economic accounts across cantons building on regional gross-valued-added accounts.[7] Secondly, it includes a bottom-up description of discrete power technologies such that generation by power technology and cantons reflects physical data based on Swissgrid information.

Figure 1 shows a map of the regions incorporated in the top-down model. The choice of regions is determined by the availability of detailed electricity market data provided by Swissgrid (see chapter 4.2.3).

Figure 1: Swiss regions in ElMaR



Section 2.1 below provides a non-technical summary of the top-down GE component. Section 2.2 briefly refers to data sources for model parametrization. Section 3.3 characterizes technical aspects of model implementation.

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[7] To our knowledge, this is the first time that a cantonal, multi-regional computable equilibrium model has been developed and used for Switzerland.

3.1 Non-technical model summary

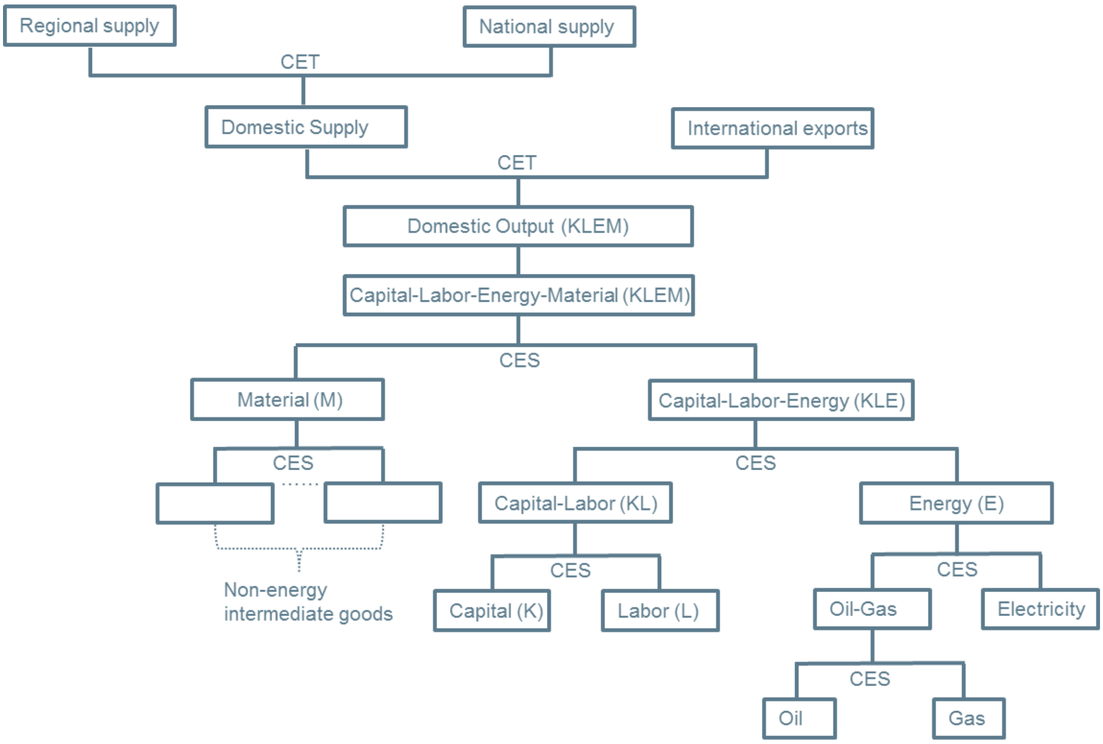
GE models accommodate counterfactual ex-ante comparisons of policy reforms, assessing the outcomes of changes in policy regulation against a business-as-usual reference without regulatory changes. GE models are rooted in rigorous microeconomic general equilibrium theory combining assumptions on the optimizing behavior of economic agents with the analysis of equilibrium conditions: producers employ primary factors and intermediate inputs at least cost subject to technological constraints; consumers with given preferences maximize their well-being subject to budget constraints. A fundamental strength of the GE approach is its comprehensive representation of price-responsive market interactions and economy-wide income-expenditure constraints. GE analysis quantifies the changes in key macroeconomic indicators (e.g. gross domestic product) as well as sector-specific economic activities (e.g. output, export, import) together with its implications for real income and welfare of heterogeneous agents. Thus, GE analysis also allows for normative rankings of alternative policy options to achieve some given policy target such as the promotion of renewable energy.

The ElMaR GE model for Switzerland captures characteristics of cantonal production and consumption patterns. Cantons are linked via trade flows through national commodity markets with endogenous price formation whereas Swiss cantons take international prices as given for exports to and imports from abroad.

Production technologies and firm behavior

Firms operate in perfectly competitive markets and maximize their profits by selling their products at a price equal to marginal cost. Industries produce gross output using primary inputs labor (L) and capital (K) as well as intermediate inputs of energy (E) and materials (M). Intermediate inputs are composed of a domestically produced variety and an imported variety. We employ separable nested constant-elasticity-of-substitution (CES) cost functions to characterize price-responsive trade-offs across inputs in production. Figure 2 provides a diagrammatic representation of the nesting structure in production for each region and sector.

Figure 2: Sectoral production in each region

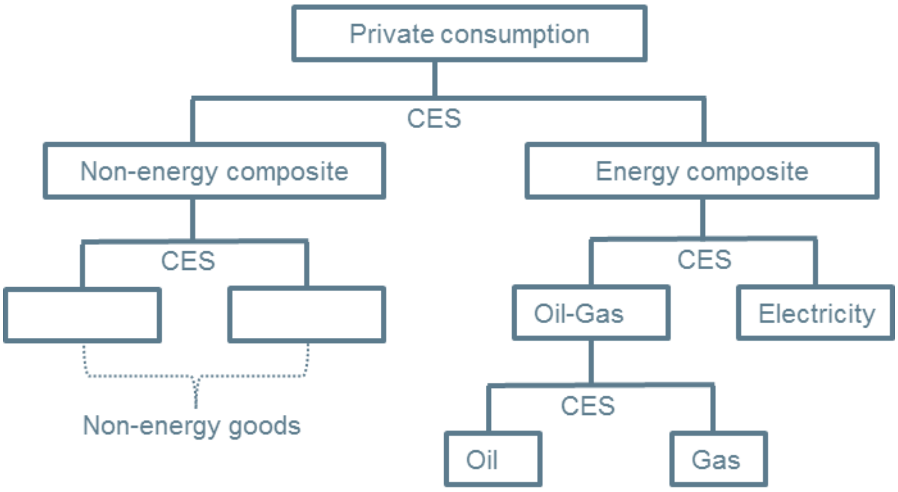


In the bottom-level nest, oil and gas trade off at a constant elasticity of substitution. The oil-gas composite enters at the next level with electricity to form a CES energy aggregate. The latter then combines with a value-added composite of labor and capital. At the top input level, the composite of energy and value-added trades off with a CES aggregate of material inputs. On the output side, domestic production splits into domestic supply and international exports subject to a constant elasticity of transformation (CET). Domestic supply in turn splits into supply to the regional itself and to the national market.

Preferences and household behavior

In each region, final consumption demand is determined by a representative agent who maximizes welfare subject to a budget constraint with fixed savings which determines investment demand. The representative household receives income from net factor earnings and government transfers. The disposable income is then spent across consumption categories (according to the Classification of Individual Consumption by Purpose - COICOP) at given prices subject to CES preferences where the different consumption categories are traded off at a constant elasticity of substitution. Each consumption category consists of goods produced by industrial sectors. Figure 3 depicts the nesting structure in final consumption.

Figure 3: Final consumption in each region



At the bottom level oil and gas form a CES aggregate which combines at the next level with electricity to form an energy composite. At the top level, the energy composite trades off with a CES non-energy goods subject to a constant elasticity of substitution.

Government

The regional government collects taxes to finance transfers and the provision of a public good. The public good is produced with commodities purchased at market prices. In policy counterfactuals, we typically keep the level of public good provision constant at the benchmark level in order to assure a meaningful cross-comparison analysis without the need to trade off private consumption and government (public) consumption. By default, the equal-yield public good provision is warranted through lump-sum transfers between the government and households.

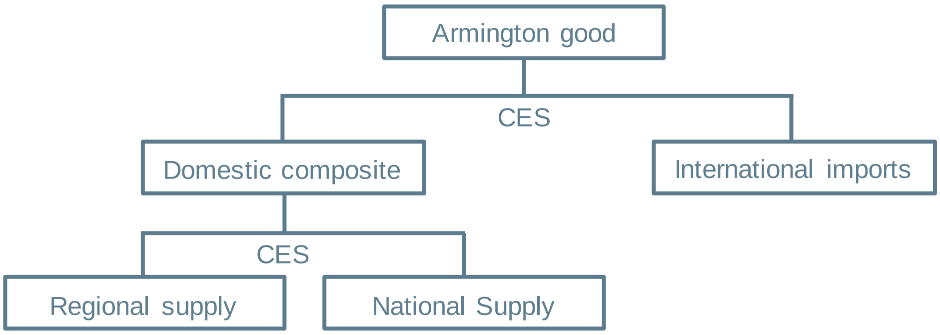
Factor markets

Labor is treated as perfectly mobile between sectors within a region whereas capital is considered to be sector-specific within each region.

Trade

On the export side, goods destined for the region itself, for the national market and for the international markets are treated as imperfect substitutes, produced subject to a constant elasticity of transformation. Regional demand for traded goods in intermediate and final consumption is based on the Armington approach of product heterogeneity, so domestic and foreign goods of the same variety are distinguished by origin. The Armington composite for a traded good is a CES function of international imports and a domestic composite. The domestic composite is a CES function of regional supply and national supply. Figure 4 depicts the nesting structure of the Armington composite for each good in each region.

Figure 4: Production structure of Armington composite



All Swiss regions are assumed to be price takers in the world market, i.e., changes in Swiss trade volumes have no effect on its terms of trade – import supply and export demand from abroad are perfectly elastic. There is an imposed balance of payment constraint to ensure trade balance between Switzerland and the rest of the world. The value of imports from the rest of the world to Switzerland must equal the value of exports from Switzerland EU to the rest of the world adjusted for the benchmark trade surplus of deficit. The balance of payment constraint is warranted through an endogenous real exchange rate.

Electricity sector representation

Given the paramount importance of the electricity sector with respect to the promotion of renewable energy we distinguish discrete generation technologies that produce electricity by combining technology-specific capital with inputs of labor, fuel, and materials. Electricity output from different technologies is treated as a homogeneous good. For each technology, power generation takes place with decreasing returns to scale and responds to changes in electricity prices according to technology-specific supply elasticities. In addition, lower and upper bounds on production capacities can provide explicit limits to the decline and the expansion of technologies.

3.2 Data and model parametrization

The data sources used for model parameterization include (i) the symmetric national input-output table at basic prices for 2008 with power generation differentiated by discrete technologies, (ii) the gross value added share per canton and 21 sectors for the year 2011[8] (Ecoplan 2016), and (iii) power generation statistics by technology and canton provided by Swissgrid (see chapter 4.2.3). We disaggregate the national input-output table using gross-value added shares per canton and sector and bottom-up electricity market data from Swissgrid. We assume export intensity uniform across all cantons resp. regions. No interregional trade flows are

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[8] Data for 2008 are not available.

mapped. All regional and cantonal exports and imports take place between the canton and the higher national level. In addition, canton-specific aspects such as the tax system were not differentiated in this project.

For the parameterization of the multi-region multi-sector GE model we follow the standard calibration procedure in applied general equilibrium analysis. Base year input–output data determines the free parameters of functional forms (i.e., cost and expenditure functions) such that the economic flows represented in the data are consistent with the optimizing behavior of the economic agents. The responses of agents to price changes are determined by a set of exogenous elasticities (see Table 5). The choice of regions and production sectors (commodities) in the model has been driven by the mutual consistency between national IO statistics, cantonal NOGA accounts, and Swissgrid data. Tables 1-4 provide a summary of the regions, sectors (production goods), power technologies, and consumption goods included in the top-down GE model.

Table 1: Regions (cantons) in the GE model

Mnemonic	Region / Cantons
ag	Aargau
fr	Fribourg
gl	Glarus
gr	Graubünden
lu	Luzern
ne	Neuchâtel
sg	St. Gallen
so	Solothurn
tg	Thurgau
ti	Ticino
vs	Valais
aiar	Appenzell Innerrhoden + Ausserrhoden
beju	Bern + Jura
blbs	Basel
gevd	Geneva + Vaud
ownwur	Nidwalden + Obwalden + Uri
shsz	Schaffhausen + Zürich
szzg	Schwyz + Zug

Table 2: Sectors (production goods) except power generation technologies and energy sectors included in the GE model

Mnemonic	Sector (production good)
Primary sector	
agr	Agriculture, forestry, fishing
Secondary sector (industrial sector without energy sectors)	
foo	Food industry
roi	Rest industry
pap	Paper
chm	Chemistry
nmm	Non-metals
mtl	Metals
enr	energy
bau	Construction
Tertiary sector (service sector without transport sectors)	
trd	Trade
rst	Restaurants
trn	Transport
com	Communication
bnk	Banks
Ins	Insurances
csl	Consulting
adm	Administration
edu	Education
hea	Health
ser	Other services
wst	Waste

Table 3: Power technologies and energy sectors included in the GE model

Mnemonic	Sector
Power technologies	
run	Electricity from run-of-river hydro power plants
sto	Electricity from storage hydro power plants
nuc	Electricity and heat from nuclear power plants
fos	Electricity from public fossil power plants
woo	Electricity from public wood power plants (incl. CHP)
wnd	Electricity from public wind and PV power plants
ewi	Electricity from waste incineration
Energy sectors	
oil	Manufacture of coke and refined petroleum products
gas	Gas supply
ele	Electricity distribution and trade, public heat supply

Table 4: Consumption goods included in the GE model

Mnemonic	Sector
food	Food and non-alcoholic beverages
alco	Alcoholic beverages, tobacco and narcotics
clot	Clothing and footwear
hous	Housing, water, electricity, gas and other fuels
furn	Furnishings, household equipment and routine household maintenance
heal	Health
tran	Transport
comm	Communication
recr	Recreation and culture
educ	Education
rest	Restaurants and hotels
misc	Miscellaneous goods and services

Table 5: Elasticities in the GE model

Elasticity	Value *)
KLEM-Elasticities in production (see Figure 2)	
M versus KLE	0.5
K versus L	0.5
KL versus E	0.5
Electricity versus Oil / Gas	0.5
Oil versus Gas	0.5
KLEM-Elasticities in consumption (see Figure 3)	
Energy composite versus non-energy composite	0.5
Electricity versus Oil / Gas	0.5
Oil versus Gas	0.5
Armington import elasticity of substitution (see Figure 4)	
Armington import elasticity of substitution	4

*) The same elasticities were chosen for all sectors. A differentiation by sector can, of course, easily be made.

3.3 Model implementation

The top-down GE model is solved as a mixed complementarity problem capturing an economic equilibrium through three classes of fundamental conditions: zero profit, market clearance, and income balance. The programming language for model implementation is GAMS (General Algebraic Modelling System), a higher-level model language for the development of large-scale mathematical programs and the processing of extensive datasets. Numerically, we solve the model using the PATH solver. When operated without linkage to the bottom-up electricity network model, the GE solution represents a macro-economic perspective on the outcome of policy interference abstracting from more detailed technical/physical restrictions on power generation/availability and transmission constraints. The top-down GE model stand-alone allows for a comparative static assessment of exogenous policy shocks.[9]

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[9] This can be complemented by investment dynamics in power technologies via a linkage with the bottom-up partial equilibrium model of electricity system.

4 Bottom-up partial equilibrium PE model of the Swiss electricity market

Swiss-PEM is a dynamic partial equilibrium model of the Swiss electricity market with a spatial resolution of the Swiss electricity network and transmission lines to neighbouring countries. The model determines the economic dispatch of power plants to meet price-elastic electricity demands together with cross-border exports and imports at the lowest possible cost, recognizing transmission and operational constraints. The dispatch of power plants is optimized by hour and month over a one-year horizon. Electricity balances apply at each network node with accounting for power generation, electricity demand, as well as nodal transmission inflows and outflows subject to transmission capacity constraints on adjacent network arcs. Beyond the identification of optimal dispatch choices, the model can track endogenous investment decisions in new power generation capacities.[10]

At the technological level, the model distinguishes different types of power plants, i.e. hydro, nuclear, thermal (fossil fuel based), waste incineration, biomass (wood), solar as well as wind. Given the importance of hydroelectricity in Switzerland, Swiss-PEM has an explicit treatment of run-of-river, storage, and pumped-storage power plants – with hydro-storage providing some intertemporal flexibility to shift energy across hours and months.

With price-responsive linear demand functions[11], Swiss-PEM is specified as a quadratic programming model in which the sum of consumer and producer surpluses are maximized subject to nodal balances, capacity and transmission constraints.

The model accommodates both efficiency and incidence analysis of exogenous (policy shocks): It keeps track of overall economic surplus as an efficiency metric as well as of physical quantities and prices translating into costs and rents across the different Swiss cantons.[12] Data for model parametrization is reconciled from different public and commercial sources (see chapters 4.2 and 4.3) for the model base-year 2015. Technically the model is formulated using the programming language GAMS[13] (Brooke, Kendrick, and Meeraus 1998) and solved using CPLEX (IBM 2015).

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[10] In a similar vein as with generation capacity, the model could be operated to determine optimal expansion decisions for network transmission capacities.

[11] For the integrated Swiss-PEM-GEM, cost parameters and demand functions in the bottom-up PEM are iteratively recalibrated based on top-down GEM information.

[12] The regional disaggregation corresponds to the areas reported explicitly in the Swissgrid dataset (see chapter 4.2.3).

[13] The programming language GAMS (General Algebraic Modelling System) is a higher-level model language for the development of large-scale mathematical programs and the processing of extensive datasets.

4.1 Algebraic model summary

For the algebraic representation of Swiss-PEM we use the denotations listed in Table 6.

Table 6: Denotations used in the formulation of Swiss-PEM

Sets (Indices)	
m	Set for months
h	Set for hours
n	Set for network nodes (aliased with *i* and *j*)
p	Set for power generation plants
t	Set for power technologies
r	Set for regions (cantons)
c	Set for neighboring countries
crc_p	Subset of hydro power plants with circular pumping
pmp_p	Subset of hydro power plants with pump storage
arc_{ij}	Set of network arcs (links)
$cnmap_{cn}$	Mapping of neighboring countries to network nodes
$nrmap_{nr}$	Mapping of network nodes to regions
$pnmap_{pn}$	Mapping of power plants to network nodes
$ptmap_{pt}$	Mapping of power plants to technologies
Parameters	
$\bar{F}_{mp}$	Water inflow by month and hydro power plant (GWh)
μ_p	Pumping efficiency of hydro power plant (%)
$\theta_p^{\bar{F}}$	Secondary water inflow fraction for hydro power plant (%)
$\bar{y}_{mhp}$	Upper capacity (generation) bound by month and hour on extant power plant (GWh)
$\bar{k}_{tn}$	Upper annual capacity (generation) bound on new power production by technology *t* at node *n* (GWh)
γ_{tnmh}	Availability index of natural resource for renewable technology *t* at node *n*
$\overline{gc}_p$	Variable generation cost for extant power plant (CHF/MWh)
$\overline{dc}_{tn}$	Variable generation cost for new technology *t* at node *k* (CHF/MWh)
$\overline{kc}_{tn}$	Capital (investment) cost for new capacity of technology *t* at node *k* (CHF/MW)
$\bar{p}^M_{mhc}$	Reference price for imports from neighboring country *c* (CHF/MWh)
$\bar{p}^E_{mhc}$	Reference price for exports to neighboring country c (CHF/ MWh)
$\bar{p}^D_{mhr}$	Reference price for domestic demand in region *r* (CHF/ MWh)
$\bar{M}_{mhc}$	Reference import supply by neighboring country *c* (GWh)
$\bar{E}_{mhc}$	Reference export demand neighboring country *c* (GWh)
$\bar{D}_{mhr}$	Reference consumption demand by region *r* (GWh)
ϵ^M	Import supply elasticity
ϵ^E	Export demand elasticity
ϵ^D	Elasticity of (domestic) demand
	Elasticity of aggregate demand by demand category *j*
θ^D_{rn}	Demand share of region *r* in node n (%)

α	Cost coefficient in quadratic capacity expansion cost
ω_m	Number of days in month *m*
Variables	
Y_{mhp}	Dispatch by month and hour of extant power plant *p* (GWh)
YN_{tnmh}	Dispatch by month, hour and node of new technology *t* (GWh)
Z_{mhp}	Dispatch by month and hour from circular pump storage hydro power plant *p* (GWh)
RL_{mp}	Primary reservoir level by month and storage hydro power plant (GWh)
RP_{mhp}	Reservoir level by month and hour of circular pump storage hydro power plant (GWh)
RS_{mp}	Secondary reservoir level by month and pump storage hydro power plant (GWh)
HS_{mhp}	Hydro pumping for pump storage plant (GWh)
H_{mhp}	Hydro pumping for circular pump storage hydro power plant (GWh)
X_{mhij}	Power transmission by month and hour on arc$_{ij}$ (GWh)
NE_{mhcn}	Net exports by month and hour to country *c* at node *n* (GWh)
D_{mhr}	Electricity demand by month and hour in region *r* (GWh)
M_{mhc}	Import supply from neighboring country *c* (GWh
E_{mhc}	Export demand by neighboring country *c* (GWh)
KN_{tn}	New capacity for technology *t* at node *n* (GWh)

Swiss-PEM determines the economic dispatch by maximizing economic surplus subject to capacity and network transmission constraints. The time resolution of dispatch is by hour *h* and month *m*.

The electricity dispatch Y_{mhp} thus indicates how many GWh of electricity is generated by plant *p* in month *m* and hour *h* (summarized over all days of the month).[14] In order to obtain the monthly generation by power plant one must sum dispatch over hours ($\sum_h Y_{mhp}$) and to obtain the annual generation one must sum over hours and months ($\sum_{mh} Y_{mhp}$).[15] Dispatch is limited by upper bounds on generation capacities for power plants which is provided in terms of electrical power (wattage) by hour and month

$$Y_{mhp} \leq \bar{y}_{mhp}$$

The operation of storage hydro power plants allows for flexibility of power generation shifting across time segments. Beyond conventional storage hydro power plants without pumping Swiss-PEM explicitly accounts for pump storage facilities (pmp_p) and circular pump storage

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[14] For the implementation of the algebraic model structure formulated below, refer to Appendix D, GAMS Model Code 1.

[15] Note: The time resolution of the model can be increased as exogenous data on production and consumption profiles by Swiss regions is provided in 15 min intervals (by Swissgrid) but for the current application we limit the time resolution to hours and months (i.e. 24*12 = 288 time slices) for the sake of dimensionality restriction and speed of computation.

facilities (crc_p) at hydro power plants.[16] Conventional storage plants are operated on a single (primary) reservoir, which just gets filled by exogenous natural water inflows so there is only limited scope for shifting hydro generation. With pump storage facilities (pmp_p) there is for some storage plants the possibility to add capacity to the primary reservoir by pumping water with feed pumps subject to some efficiency losses from a secondary reservoir. In Swiss-PEM such pumping increases – depending on the size of the secondary reservoir - flexibility of power dispatch. With circular pumping (crc_p) there is the possibility to shift dispatch across hours – again such shifting comes at an efficiency loss. Note that endogenous hydro scheduling provides flexibility to respond to variable resource availability of wind and solar or fluctuations in international electricity prices; marginal cost of generation and prices of electricity in future periods determine how much water should be used and how much should be stored (or pumped) on a monthly or hourly base.

The stock-flow energy balance for storage plants operating with a primary reservoir is given as:

$$RL_{mp} + \left(1-\theta_p^{\bar{F}}\right)\bar{F}_{mp} + \sum_{h,pmp_p} \mu_p HS_{mhp} \geq RL_{(m+1)p} + \sum_h Y_{mhp}$$

That is: The primary reservoir level in the current month plus water from natural inflows plus efficiency-adjusted additional water from pumping (pending on a secondary reservoir) determines the primary reservoir level in the following month plus the dispatch of hydro power in the current month.

For storage power plants disposing of a secondary reservoir the stock-flow condition reads as:

$$RS_{mp} + \theta_p^{\bar{F}}\bar{F}_{mp} \geq RS_{(m+1)p} + \sum_h HS_{mhp}$$

That is: The secondary reservoir level in the current month plus water inflows equals the reservoir level in the next month plus the use of hydro power for pumping of water from the lower-level secondary reservoir to the upper level-primary reservoir.

For circular pump storage the reservoir level in the current hour plus the efficiency loss adjusted pumping in the current hour rules the current dispatch plus the reservoir level available in the next hour:[17]

$$RP_{mhp} + \mu_p H_{mhp} \geq Z_{mhp} + RP_{m(h+1)p} \quad \forall\, crc(p)$$

Swiss-PEM does not only include dispatch decisions for extant power plants but allows for the expansion KN_{tn} in new capacities by technologies at network nodes. The new capacity provides an upper bound for dispatch YN_{tnmh} after taking into account the exogenous resource availability γ_{tnmh} (in our case for wind or solar capacity expansions):

$$YN_{tnmh} \leq \gamma_{tnmh}\, KN_{tn}\omega_m$$

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[16] Note that a plant g may have capacities for both pumping (pmp(g)) and circular pumping (crc(g)).

[17] Note that without loss of generality we can represent circular pumping without an explicit secondary reservoir.

For setting up the energy balances at each node of the network one must include net exports NE_{mhcn} at boundary network nodes to neighbouring countries:

$$\sum_{cnmap_{cn}} NE_{mhcn} = E_{mhc} - M_{mhc}$$

One can then write down the nodal energy balance for each node *n* in month *m* and hour *h* as follows:

$$\sum_{arc_{in}} X_{mhin} + \sum_{pnmap_{pn}} \left(Y_{mhp} + Z_{mhp}\right) + \sum_{tmh} YN_{tnmh}$$

$$=$$

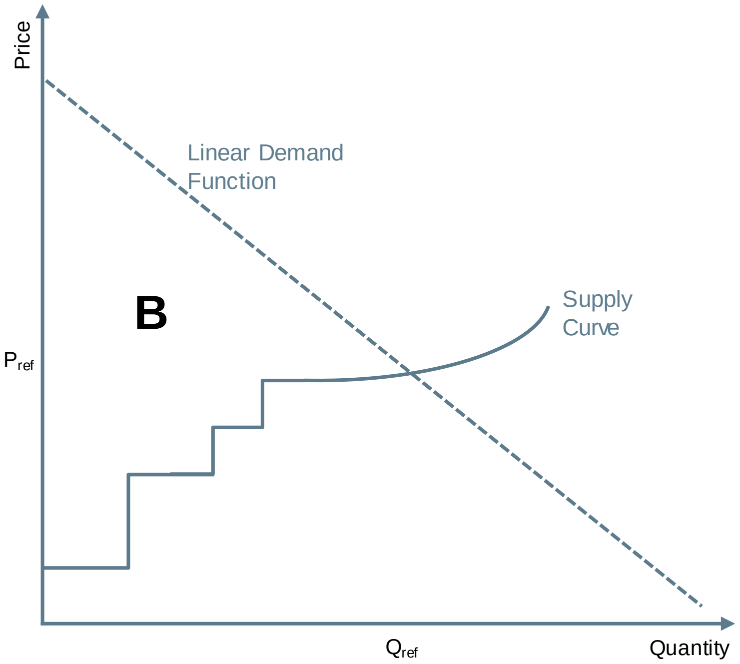
$$\sum_{arc_{jn}} X_{mhnj} + \sum_{r} \theta_{rn}^{D} \bar{D}_{mhr} + \sum_{pnmap_{pn}} \left(H_{mhp} + HS_{mhp}\right) + \sum_{cnmap_{cn}} NE_{mhcn}$$

The nodal market clearance conditions feature all fundamental decision variables of the electricity system (i) dispatch by extant power plants, (ii) dispatch by new power plants (i.e. generation from newly installed capacity), (iii) transmission of power between network nodes, (iv) cross-border electricity trade, (v) electricity demands as well as (vi) endogenous pump storage operation. These decision variables must be taken in mutual consistency to secure physical energy flow balances in each node of the spatial network by temporal resolution (here: by month and hour). For the system integration of power dispatch, power demand, cross-border power trade and power transmission, effective supply and demand in each node of the grid must balance at each time segment. This means that all transmission inflows into a specific node plus the net dispatch by all power plants to this node plus potential cross-border nodal imports must equal all transmission outflows from that node plus the allocated electricity demands to that node plus potential cross-border nodal exports. In short: Total nodal inflows must equal total nodal outflows.

The electricity network is described through network nodes that are connected by transmission lines (arcs) subject to transmission capacities. The network representation requires a detailed specification of transmission line characteristics including topology, circuits, nominal voltage and nominal capacity.

The physical relationships of the electricity system as laid out above enter as side constraints to a mathematical (quadratic) program of economic surplus maximization (producer surplus plus consumer surplus over all regions and time intervals). Producers' surplus is defined as total revenue less producers' cost. Consumers' surplus is defined as total consumer value (equal to the integration over quantity of the demand function, which is a measure of marginal willingness to pay, or equivalently value) less total expenditure. Since producers' revenue is equal to consumers' expenditure, total surplus is equal to the area under the demand curve less producers' cost (see Figure 5). Note that maximizing total surplus is analogous to minimizing total costs with the option of "backing down" demand at a marginal cost identical to the demand function.

Figure 5: Economic surplus maximization (area B)



More specifically, the maximand in the objective function of the mathematical program is given as the revenues from export demand plus the consumer surplus from domestic demand minus the variable cost of dispatch from extant power plants[18] minus the variable cost of dispatch from production of new power plants minus the capital cost for capacity of new power plants expansion minus the cost for import supply:

$$\sum_{mhc}\left(\bar{p}^{E}_{mhc}\,E_{mhc}(1-\left(\frac{E_{mhc}}{2\,\bar{E}_{mhc}}-1\right)/\epsilon^{E}\right)$$

$$+\sum_{mhc}\left(\bar{p}^{D}_{mhc}\,D_{mhc}\,(1-\left(\frac{D_{mhc}}{2\,\bar{D}_{mhc}}-1\right)/\epsilon^{D}\right)$$

$$-\sum_{mhc}\left(\bar{p}^{M}_{mhc}\,M_{mhc}\,(1-\left(\frac{M_{mhc}}{2\,\bar{M}_{mhc}}-1\right)/\epsilon^{M}\right)$$

$$-\sum_{mhp}\overline{gc}_{p}Y_{mhp}-\sum_{tnmh}\overline{dc}_{tn}YN_{tnmh}-\sum_{tn}\left(\overline{kc}_{tn}\left(KN_{tn}+\alpha\,{KN_{tn}}^{2}\right)\right)$$

Note that the linear functions to describe price-responsive elastic import supply, export demand, and domestic demand are stated in calibrated share form with observed reference prices and reference quantities which then also show up in the respective integrals of the economic surplus components.

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[18] As the variable costs for hydro power plants are very small (we assume 0.2 CHF/MWh production-related maintenance costs) there is no need to differentiate the variable costs according to the different hydro power plants.

Box: Hydro power plants in the model

Hydro power plants are distinguished in two main categories in Swiss-PEM:

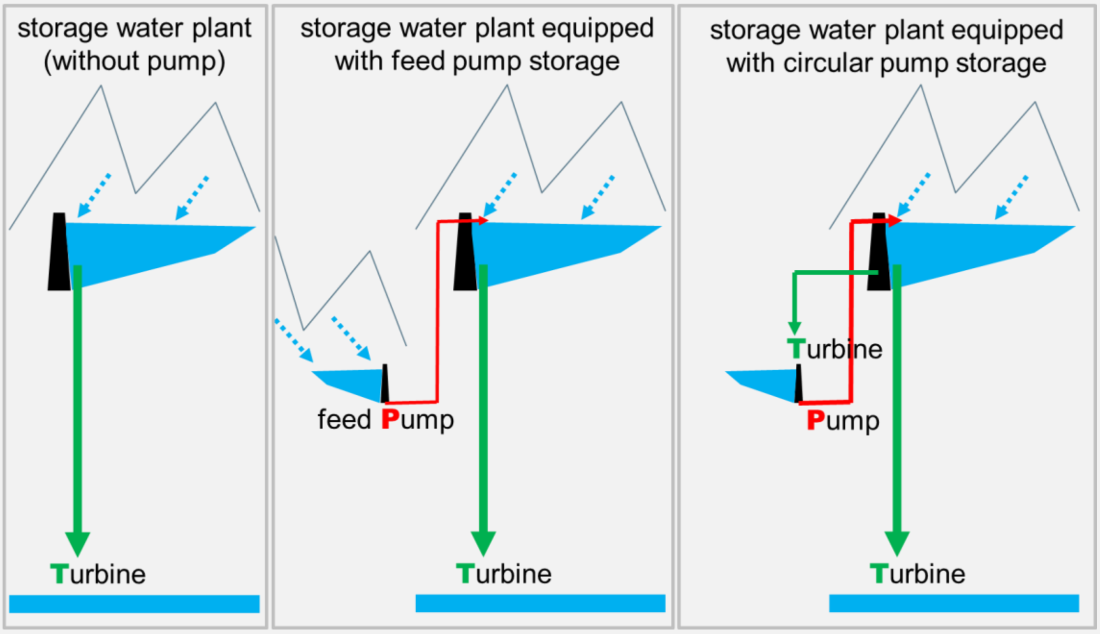
- run-of-river
- storage water, among storage water plants a subset of plants may be equipped with
  - pump storage
  - circular pump storage

  Note that a storage water plant may have capacities for both pump storage and circular pumping.

The characterisation of storage power plants into plants without pumping, plants with pumping and plants with circular pumping is important since this will define the degree of when-flexibility in power generation from storage water (see Figure 6):

- For ordinary storage there is a primary reservoir which is filled by exogenous natural inflows so shifting hydro generation across months is limited by the storage capacity and the exogenous natural inflow.
- For some pump storage plants there is the possibility to add capacity to the primary reservoir by pumping water with feed pumps (with a level adjusted 20% loss) from a secondary reservoir to the primary reservoir. This increases – depending on the size of the secondary reservoir - the flexibility of power dispatch. However, the gain in flexibility is very small. More important is that the electricity consumption of the pumps is recorded to match the nodal balance.
- With circular pumping we obtain the flexibility to shift dispatch across hours with an efficiency loss of 20%. The net dispatch from circular pumping at hour h in month m is the gross power generation Z_{mhp} minus the pumping demand H_{mhp} at that point in time.

Figure 6: Characteristics of storage water plants



4.2 Data

Swiss-PEM is parametrized to empirical data for the base-year 2015. The data sources can be segmented in three parts: (i) network data, (ii) power plant data, and (iii) electricity market statistics in spatial and temporal resolution on power production, power consumption as well as cross-border power trade.

4.2.1 Network data

Network data for Switzerland is provided by ENTSOE (the European Network of Transmission System Operators for Electricity).[19] The topology of the transmission network is specified using information on the latitude and longitude of nodes and their circuit connections. To define distances between nodes we calculate the straight-line distances between the nodes. We can then account for the curvature of the earth and define the so-called great circle distances which are used to approximate the length of transmission lines. The next step is to calculate reactances together with transmission capacities for all lines. Reactance describes how much the line resists changes in current or voltage.

Based on the network data one can approximate power flow characteristics by means of Power Transfer Distribution Factors (PTDFs). PTDFs indicate the fraction of power flow along any given line in the network to any given injection-withdrawal transaction.

The network is static and does not adapt to endogenous conditions, but the influence of an additional or omitted transmission line can easily be included in the analysis.

For reasons of data availability, the network of neighbouring countries was not included. Foreign border crossing restrictions are recorded in a simplified way by means of import supply and export demand elasticities.

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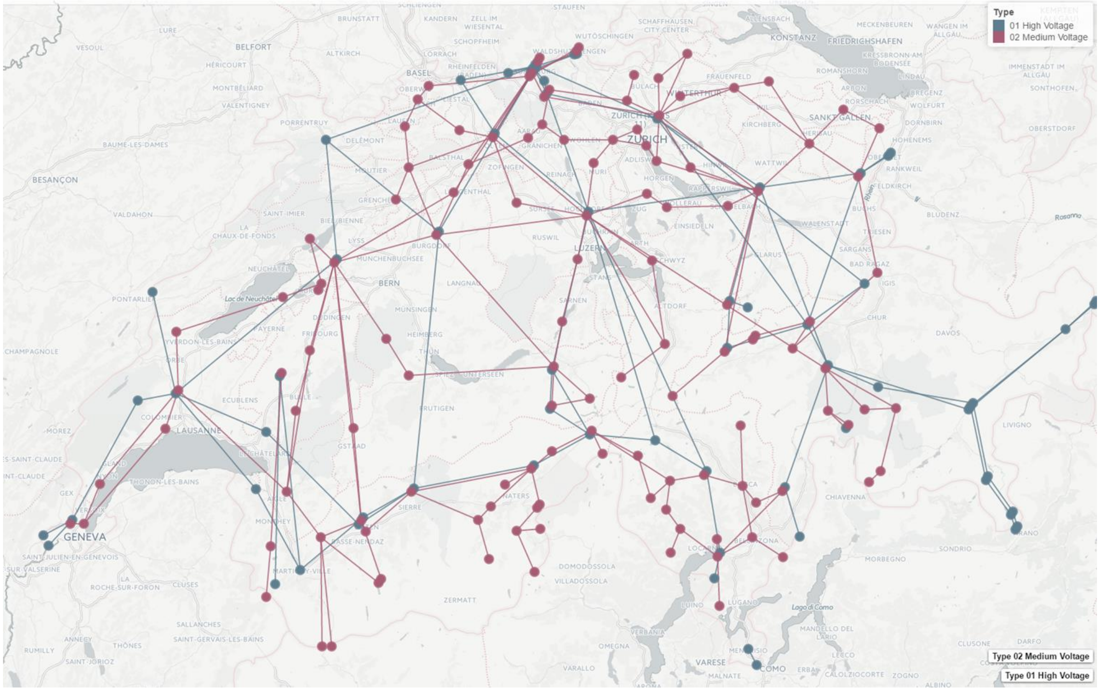
[19] We used the ENTSOE (2016) Input grid datasets for the preparation of the TYNDP 2016. https://www.entsoe.eu/publications/statistics-and-data/#entso-e-on-line-application-portal-for-network-datasets

Figure 7: Swiss electricity network



Future data and model work:

- Implementation of a targeted congestion management system with Germany, France, Italy and Austria.

4.2.2 Power plant data

The data sources on power plants are twofold. For hydro power plants – run power, storage power, and pump storage – we use public data from the Swiss Federal Office of Energy (BFE 1974, 1982, 2016a). For non-hydro power plants – nuclear, fossil, wood, waste incineration, as well as wind and PV – we draw on the commercial World Electric Power Plants Data-base (WEPP) from Platts (2016). The two data sets feature plant-specific information on plant type, geographic location, generation (kWh), capacity (MW), etc.

Furthermore, we include monthly data from the annual SFOE report on power generation by technology class, electricity exports and imports, as well as reservoir storage and reservoir capacity (BFE 2016b). The latter information together with monthly water storage inflow data is used in the calibration of the hydropower management cycle for Swiss storage water. Regarding the availability of natural resources (sun and wind) for renewable power generation, we use data from Pfenninger and Staffel (2016) provided by hour, day, and month.

Future data and model work:

- Implementation of the electricity production in neighbouring countries Austria, Germany, France and Italy.

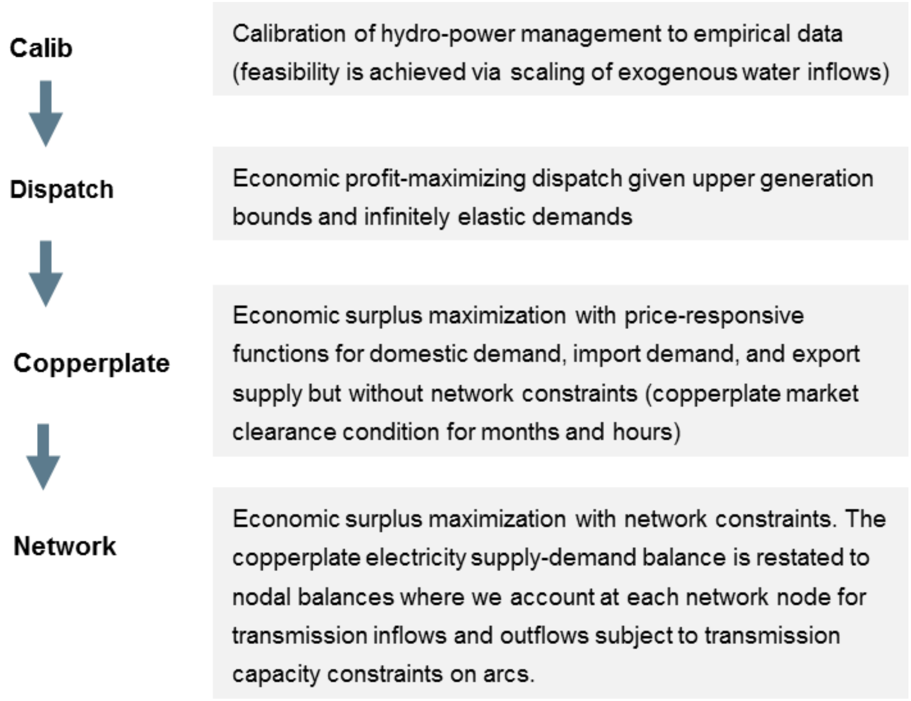
4.2.3 Electricity market statistics

Swissgrid, the Swiss transmission grid operator, provides a detailed dataset on power generation and consumption in 15 minutes intervals across Swiss regions and information on cross-border power trade with neighbouring countries (Swissgrid 2016). We aggregate this data to obtain production, consumption and trade data by hour and region which then enters the calibration of the network model. Demand data by region is shared across network nodes using population accounts for Swiss cities and their geographical proximity to network nodes.

4.3 Model calibration

The calibration of the electricity market model to empirical data involves four steps which are sketched in Figure X:

Figure 8: Four steps to calibrate the electricity market model



Calib

Calibration of hydro-power management to empirical data (feasibility is achieved via scaling of exogenous water inflows)

Dispatch

Economic profit-maximizing dispatch given upper generation bounds and infinitely elastic demands

Copperplate

Economic surplus maximization with price-responsive functions for domestic demand, import demand, and export supply but without network constraints (copperplate market clearance condition for months and hours)

Network

Economic surplus maximization with network constraints. The copperplate electricity supply-demand balance is restated to nodal balances where we account at each network node for transmission inflows and outflows subject to transmission capacity constraints on arcs.

4.3.1 Water inflow calibration (*Calib*)

We **scale exogenous water inflows by month and power plant** such that we can match the hydro power operation with given technological resp. physical constraints to empirical data at the plant level (see GAMS Model Code 2, Appendix D):[20]

- exogenous seasonal generation by storage power plants
- exogenous pumping demand by season
- exogenous generation from circular pumping by season

The initial reference level of water inflows and their monthly shares are depicted in Figure 9 for the model base-year 2015.[21]

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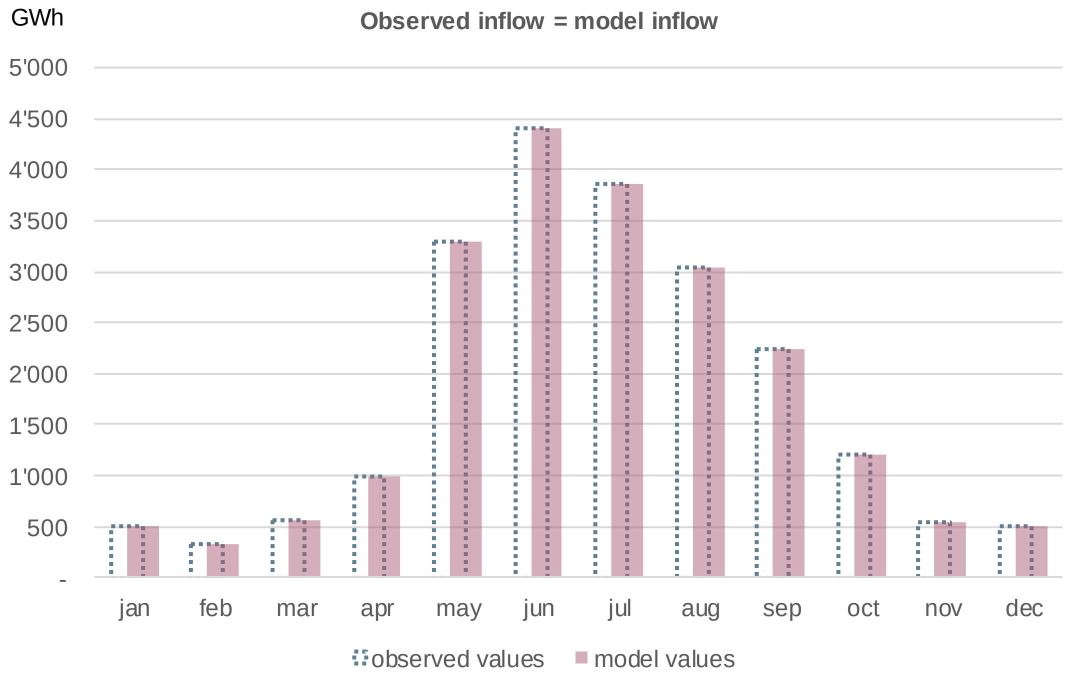
[20] BFE (2016a), Statistik der Wasserkraftanlagen der Schweiz 1.1.2016.

[21] BFE (2016b), Gesamte Erzeugung und Abgabe elektrischer Anergie in der Schweiz, Jahr 2015.

Figure 9: Total water inflow



The recalibrated water inflow schedule per hydro power plant is then fixed for all subsequent steps of the model parametrization and model simulations.

4.3.2 Economic dispatch with fixed demands (*Dispatch*)

We solve for the **profit-maximizing dispatch pattern** with fixed run-of-river[22], renewable (wind and solar) and nuclear generation at the base-year level 2015 and upper bounds on storage water as well as thermal power generation (see GAMS Model Code 3, Appendix D). In this step, we assume that demand is infinitely elastic at the hourly day-ahead price for Switzerland.

Generation by run-of-river and nuclear power plants are provided on a monthly basis and spread uniformly over time.[23] For wind and solar we apply an average capacity factor (see Figure 10 and Figure 11).[24]

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[22] The dispatch of run-of-river was derived from the calibration process. This derived dispatch was fixed at this level.

[23] BFE (2016b), Gesamte Erzeugung und Abgabe elektrischer Anergie in der Schweiz, Jahr 2015.

[24] Pfenninger and Staffel (2016).

Figure 10: Capacity factors for wind power plants

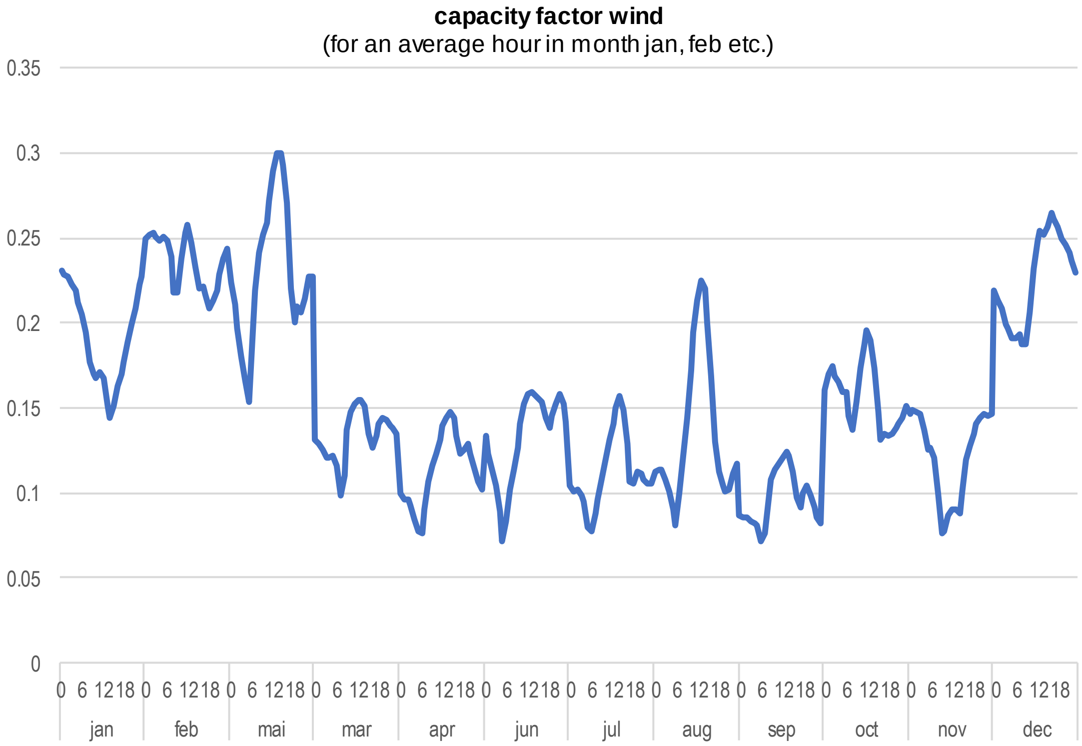
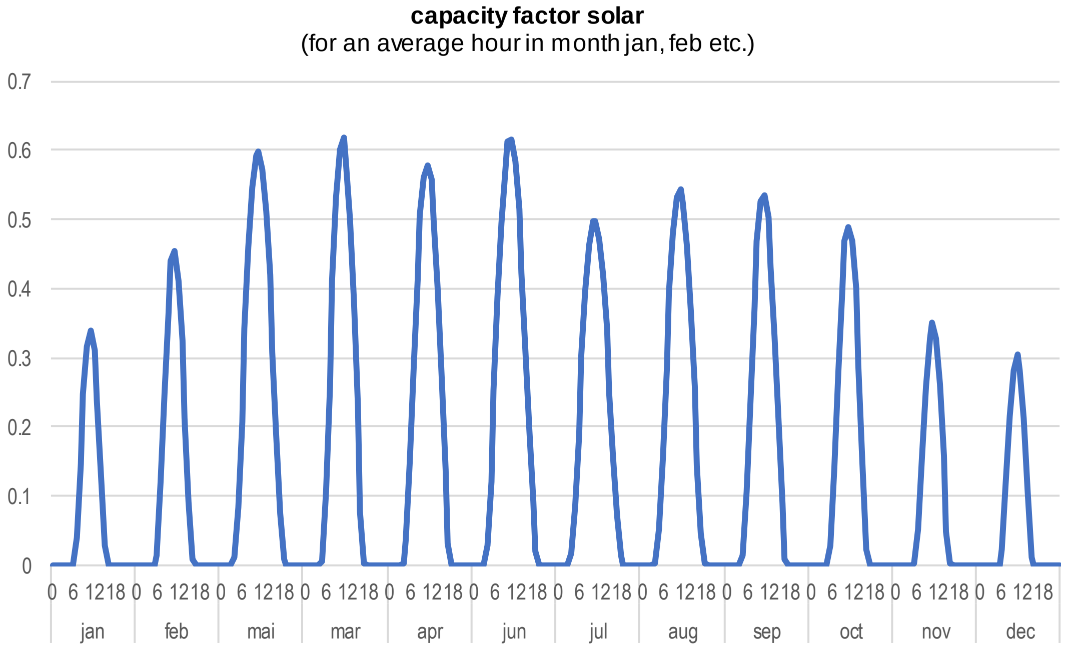


Figure 11: Capacity factors for solar power plants



4.3.3 Economic surplus maximization without network constraints (*Copperplate*)

With flexible (linear) functions for domestic demand, import demand, and export supply, we can solve an economic dispatch problem **maximizing economic surplus** (see GAMS Model Code 4, Appendix D)**.** In this step, we do not assume any network restrictions in the Swiss network and thus just apply a copperplate market clearance condition for months and hours.

Connecting with foreign electricity market: In the current ElMaR model framework we have exogenous import prices and foreign border crossing restrictions are recorded in a simplified way by means of import supply and export demand elasticities. In order to impose physical transmission restrictions at border crossings, it is necessary to implement a targeted congestion management system. Further, the foreign electricity price is to be determined endogenously by implementing the electricity production in neighbouring countries.

4.3.4 Economic surplus maximization subject to network constraints (*Network*)

In this last step we add the **network constraints** (see GAMS Model Code 5, Appendix D) and **maximize the economic surplus**. We restate electricity balances at the network nodes accounting for transmission inflows and outflows subject to transmission capacity constraints on arcs (see GAMS Model Code 6, Appendix D).

4.3.5 Benchmark check

In order to assess the quality of our model calibration, we can compare the values in key primal and dual variables (here: quantities and prices) of the calibrated model with observed market data.

Note that in our calibration we fix the monthly water inflow pattern to the storages and that we assume a fixed run-of-river and nuclear production pattern on a monthly basis and a fixed production pattern for solar and wind on an hourly and monthly basis.[25]

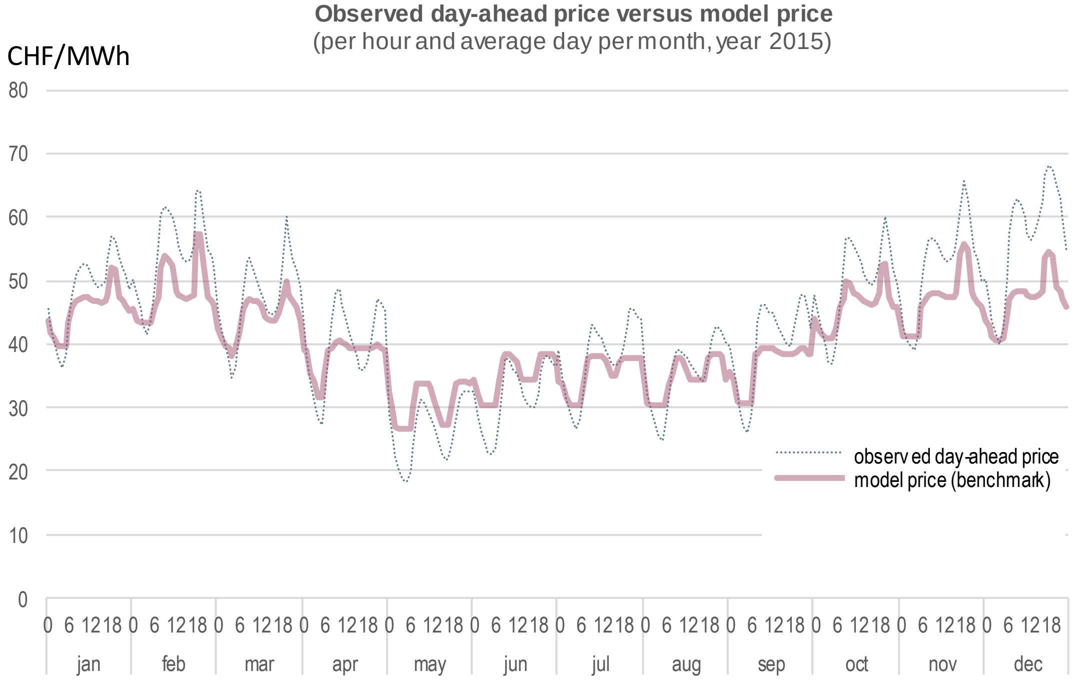
Electricity price

The model captures the empirically monthly resp. seasonal price pattern quite accurately -- see Figure 12. The price peaks are less pronounced in the model than in reality. The main reasons for this gap are twofold. Firstly, we didn’t implement a proper congestion management system with Germany, France, Italy and Austria (we applied a yearly uniform export demand elasticity and import supply elasticity). Secondly, the model assumes perfect foresights over the annual time horizon; in the real world, we would expect bigger peaks due to uncertainty.

---

[25] Note that in our calibration we fix the monthly water inflow pattern to the storages and that we assume a fixed run-of-river and nuclear production pattern on a monthly basis and a fixed production pattern for solar and wind on an hourly and monthly basis.

Figure 12: Observed day-ahead price versus model price



Electricity trade volume and consumption

Figure 13 and Figure 14 show how the model meets the observed electricity trade volumes resp. the observed domestic consumption.

Figure 13: Observed electricity trade volumes versus model trade volumes

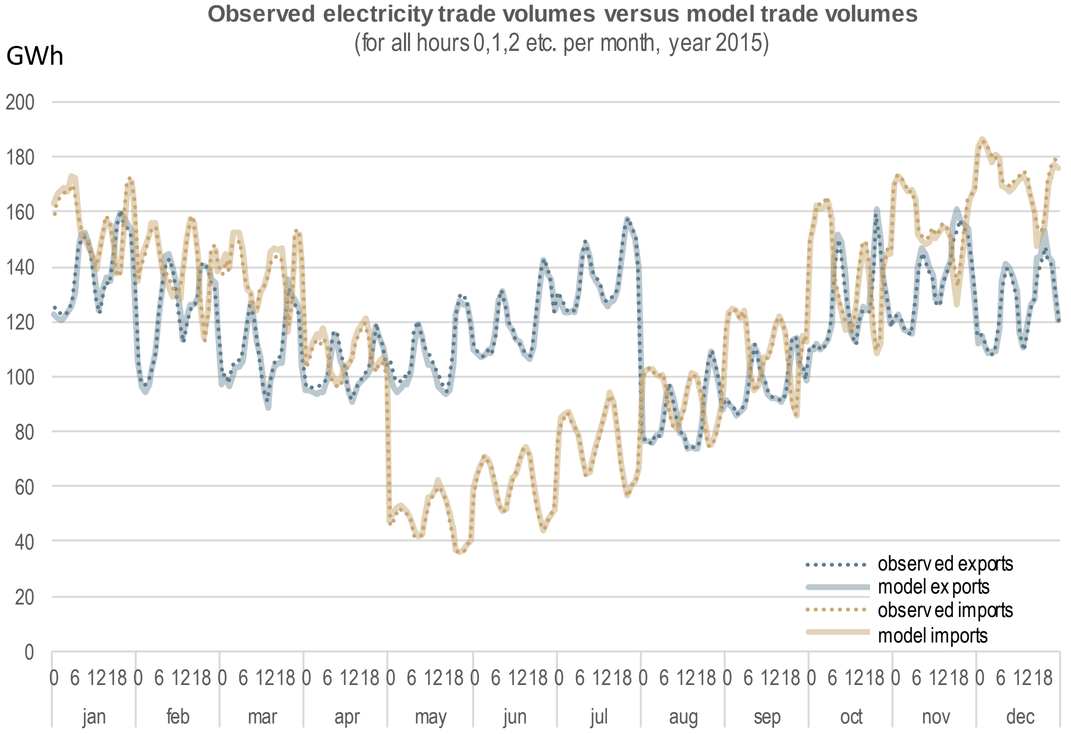
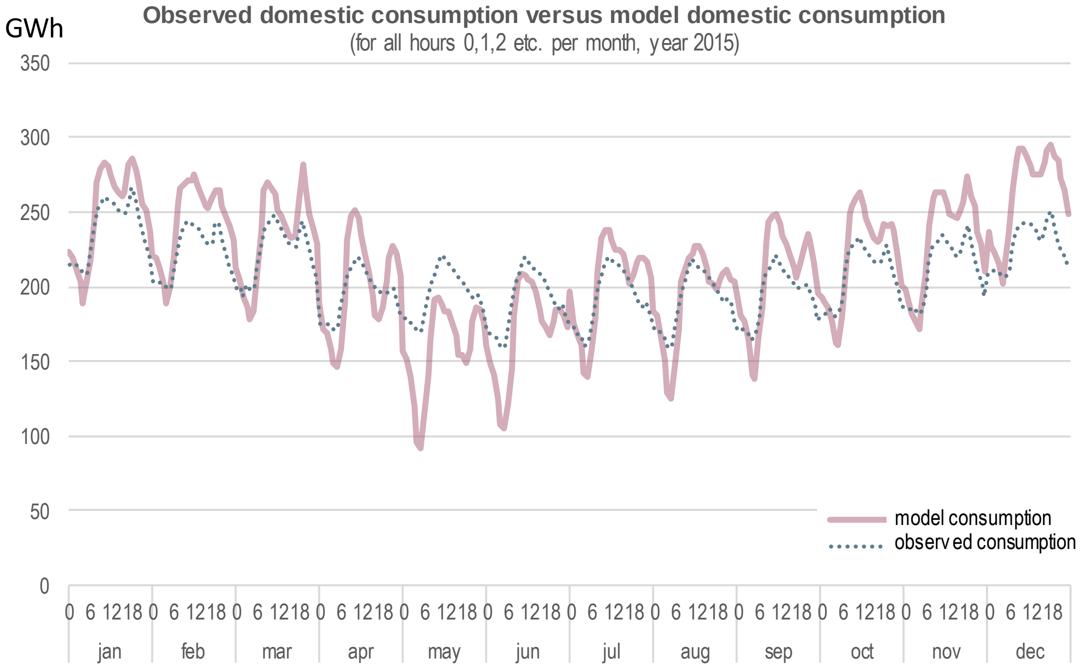


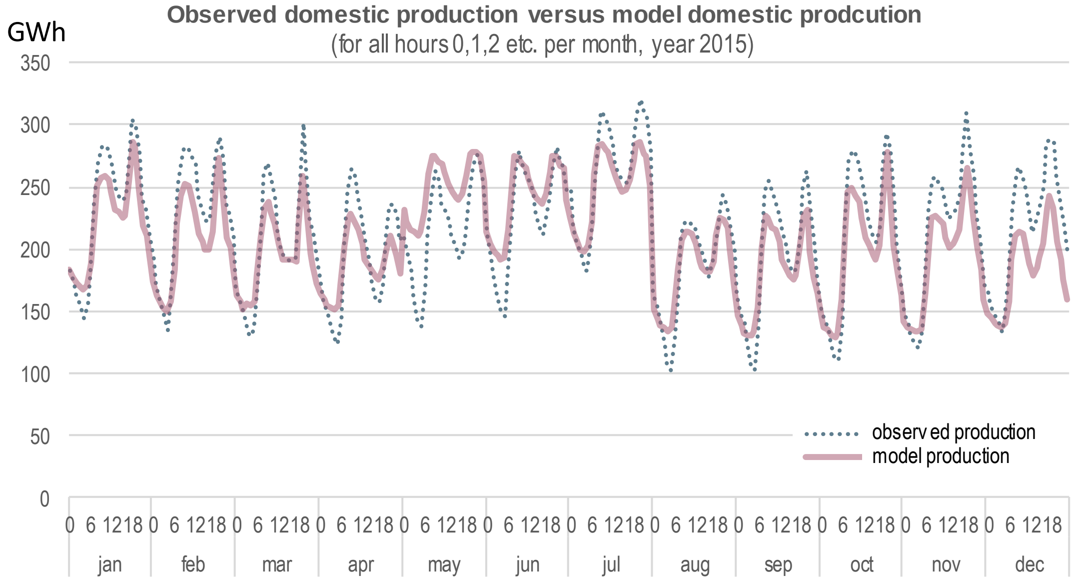
Figure 14: Observed domestic consumption versus model domestic consumption



Electricity production

The model captures the monthly resp. seasonal production pattern as shown in Figure 15. In correspondence with the deviations in observed price peaks, production peaks are also less pronounced in the model than in reality.

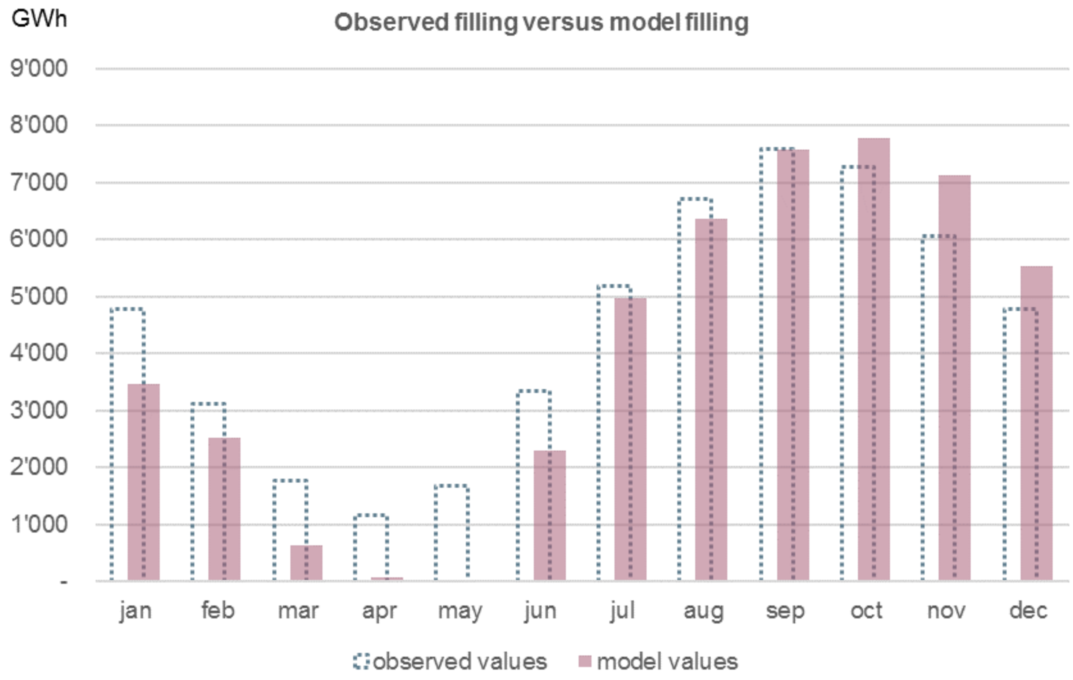
Figure 15: Observed domestic production versus model domestic production



Storage level

A central innovative feature of Swiss-PEM is the ability to endogenously determine the use of storage water. We only fix a monthly water inflow pattern for each plant (see first calibration step). Figure 16 indicates how the model follows the shape of the observed storage level in hydro.

Figure 16: Observed storage level versus model storage level



5 Combining top-down and bottom-up: GE-PE model

Both models – the top-down multi-sector multi region GE model as well as the bottom-up electricity network PE model – can be operated separately to investigate the implications of energy policy reforms for Switzerland.

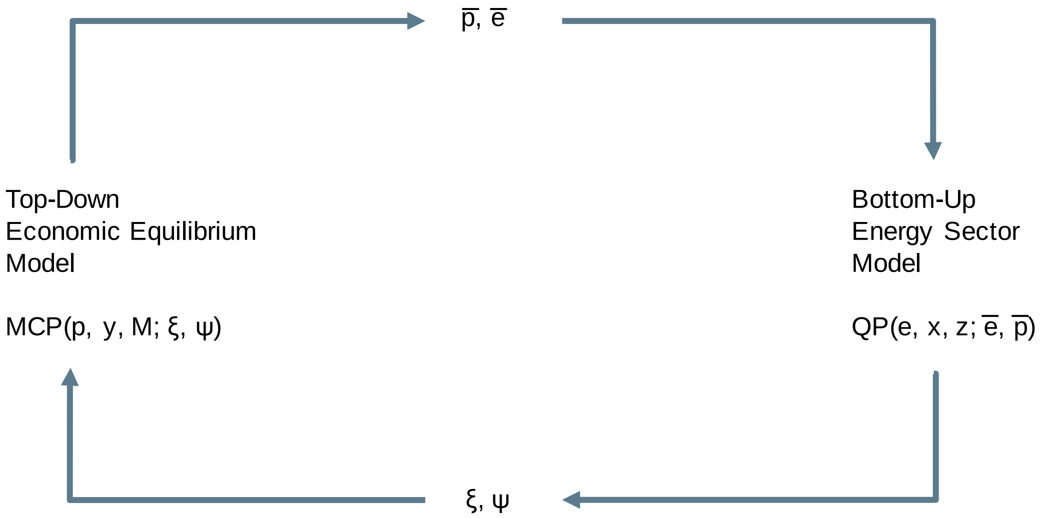
In the base-year (2008) national economic accounts, the retail value of power production accounts for less than 1% of Swiss GDP whereas the value at the retail level (including transmission and distribution margins) amounts to slightly above 2%. This applies also for our neighbouring countries. Given the small fraction of aggregate economic output, it seems reasonable to assume that electricity sector can be analyzed in isolation from the remainder of the economy. If, however, electricity market reforms are faced with very limited adjustment options in the power system and electricity demand substitution in the overall economy are very low, there is a likely need for two-way interaction between the power sector and the rest of the economy. For example, a nuclear phase out without cheap backup via imports or renewable energies may cause a substantial increase in electricity prices with non-negligible macroeconomic repercussions. Bottom-up partial equilibrium models stand-alone furthermore do not account for potentially important tax interaction or tax revenue recycling effects associated with changes in electricity taxes of technology-specific subsidies.

Top-down models on the other hand may oversimplify technological details of energy production and conversion. Our top-down GE model of the Swiss economy already adopts a hybrid modeling approach with bottom-up components since discrete power technologies are separated out with lower and upper bounds on expansion and decline paths as well as an endogenous monthly management submodule for storage water. Yet, the top-down model even with its technological foundation of power generation falls short of accounting for more sophisticated power system economics. For instance, our approach cannot reflect that a renewable technology such as solar may be a substitute for gas at low solar production levels, while the two become complements at higher levels of solar power generation. Likewise, network transmission restrictions are not incorporated.

While the mathematical format of our GE model implementation, the so-called mixed complementarity format in principle permits the full integration of more complicated bottom-up energy (electricity) system models, dimensionality imposes practical limitations to such an extension. Bottom-up programming models of the energy system often involve a large number of bounds on decision variables. These bounds are treated implicitly in mathematical programs but introduce unavoidable complexity in the integrated complementarity formulation since they must be associated with explicit price variables in order to account for income effects.

Against this background, we focus on energy-economy models in which the underlying integrated model can be portrayed as a mixed complementarity problem but adopt a decomposition approach that permits consistent combination of large-scale top-down GE models and large-scale bottom-up energy (electricity) system models. With our approach (following Böhringer and Rutherford 2009), complementarity methods are used to solve the top-down economic equilibrium model and quadratic programming is applied to solve the underlying bottom-up electricity model. Rapid convergence of our iterative (Jacobi) solution algorithm relies on the fable of the elephant and the rabbit, i.e., the electricity sector gross-value added should be a small fraction of GDP. Figure 17 illustrates the basic steps involved in the iterative model solution.

Figure 17: Iterative Decomposition Algorithm



The top-down model is solved as a mixed complementarity problem (MCP) (Böhringer and Rutherford 2008). The fundamental unknowns of the MCP are prices p, activity levels y, and income levels M: p is a non-negative vector of prices for all goods and factors associated with market clearance conditions; y captures a non-negative vector of activity levels for constant-returns-to-scale (CRTS) production sectors associated with zero profit conditions; and M denotes a vector of consumer income levels associated with income-expenditure balance conditions. In the top-down model, electricity system netputs ξ, i.e. electricity system outputs minus inputs, and electricity sector rents ψ to households are taken as given (i.e. price responsiveness of electricity supply is thus ignored in this step). The general equilibrium solution determines reference prices $\bar{p}$ and a set of linear demand curves D(p,ε) where ε denotes a vector of exogenous demand elasticities. These demand curves and relative prices parameterize the bottom-up electricity market model which is solved as a quadratic program (QP). In the QP, *z* is a vector of decision variables of the electricity system, *e* denotes electricity sector supplies and *x* stands for electricity sector demands which together yield the netput vector ξ.

More specifically, the (diagonal) system of electricity demand functions in the QP based on initial observations of prices $\bar{p}_i$ and quantities $\bar{e}_i$ and exogenous demand elasticities ε_i can be expressed in calibrated share form as:

$$e_i(p) = \bar{e}_i \left[1 - \varepsilon_i \left({}^{p_i}/_{\bar{p}_i} - 1\right)\right]$$

which has an inverse demand function

$$p_i(e) = \bar{p}_i \left[1 + \left(1 - {}^{e_i}/_{\bar{e}_i}\right)/\varepsilon_i\right]$$

and an integrated marked demand function

$$\int p_i(e)\, de_i = \bar{p}_i\, e_i \left[1 - \frac{e_i - 2\bar{e}_i}{2\,\varepsilon_i \bar{e}_i}\right]$$

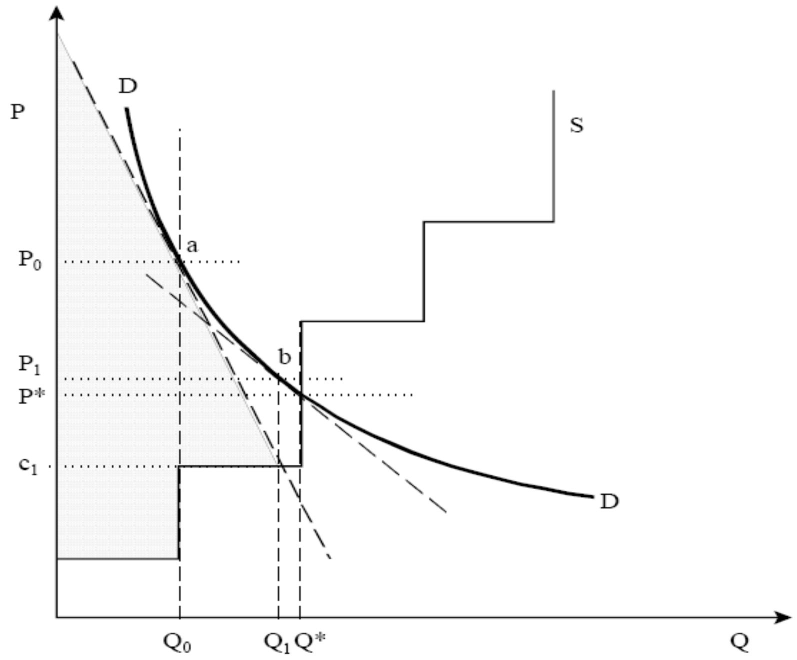
The associated economic surplus maximization problem then translates into the following QP:

$$max\ \ p^T(e - x) - \frac{1}{2}\sum_i \frac{\bar{p}_i e_i}{\varepsilon_i \bar{e}_i}(e_i - 2\bar{e}_i)$$

The linear demand function system implies a changing elasticity as quantity changes. We take it as a local approximation to the more realistic constant-elasticity implementation of electricity demands in the macroeconomic model. The iterative solution algorithm then provides an effective scheme for the approximation of a general equilibrium demand system in a partial equilibrium subproblem.

Figure 18 sketches the iterative solution process for a simplified partial equilibrium model where we neglect general equilibrium and cross-market price effects. Here, we essentially use the decomposition procedure to compute a single sector Marshallian market equilibrium with a nonlinear demand curve (DD) and a piecewise linear supply schedule (S). The starting point of the algorithm is an initial estimate Q_0 of the quantity of energy supply. This quantity has an associated market price (marginal willingness to pay) of P_0 and market equilibrium point ***a***. Having computed this equilibrium (ignoring the supply schedule), the algorithm next evaluates the energy market based on a linear demand curve calibrated to the market equilibrium at point ***a***. The solution to the supply problem maximizes the sum of consumer and producer surplus (the shaded area), resulting in an equilibrium supply of $\boldsymbol{Q_1}$ at a marginal cost of $\boldsymbol{c_1}$. Given $\boldsymbol{Q_1}$, the algorithmic steps are repeated to converge at the equilibrium solution ($\boldsymbol{P^*}$, $\boldsymbol{Q^*}$).

Figure 18: Iterative Adjustments for a Single Market Partial Equilibrium



With the decomposition method as laid out above (see also Böhringer and Rutherford 2009), the linkage of our top-down multi-sector multi-region GE model of the Swiss economy and the bottom-up network model of the Swiss electricity markets is straightforward: The GE model is solved taking the electricity market supplies less demands as given. The GE solution for the Swiss economy then determines electricity demand curves and prices. These are used to parameterize the bottom-up electricity market model. This linkage solves amazingly fast within few minutes on a personal computer.

6 Illustrative Scenarios

Introduction

In this section, we sketch an illustrative policy simulation on RES-E promotion to demonstrate the use of ElMaR for applied energy policy analysis in Switzerland. A powerful feature of ElMaR is its ability to provide detailed implications of electricity market regulations within an economy-wide framework. The combined BU-TD framework does not only secure that electricity market impacts account for economy-wide feedback and spillovers but likewise we can quantify the implications of regulatory policies for the Swiss economy as a whole as well as the incidence on regions (cantons). At a more practical level, the generic data buildstreams for both the PE and GE modules accommodate a flexible aggregation over time and space which helps to cut down solution time at the outset of policy analysis with compact datasets which then can be further disaggregated upon specific requirements in later steps of policy appraisals.

In the discussion of illustrative scenario results below it should be noted that the objective of the ElMaR research project has been the development of an operational integrated BU-TD modeling framework with a BU network representation of the Swiss electricity grid. As such, data work and parametrization will still require substantial refinements and updates before one should draw viable policy conclusions from model-based simulation analysis.

Important Disclaimer: *The modelling of ElMaR was completed as part of this research project. For the use of Elmar for policy analysis, however, the parameterization of the model needs to be improved and supplemented (see chapter 7). It must therefore be emphasised here that the* ***scenarios have a purely illustrative character****.*

Furthermore – in the current version of ElMaR – we have not implemented a forward calibration for a specific year in the future nor do we use dynamics beyond a representative year to capture the adjustment path to policy shocks over time.

Policy background

Switzerland wants to abandon nuclear energy which currently accounts for well over 30% of total electricity production. If Switzerland phases out nuclear energy, electricity imports will rise sharply to fill the nuclear gap, if no further actions e.g. in favor of RES-E promotion are taken. To date, electricity imports are an inexpensive alternative to domestically produced nuclear power. It is therefore to be expected that without bottlenecks in cross-border transmission capacities and the domestic electricity transport network, the phase-out of nuclear energy will not lead to a substantial increase in domestic electricity prices – the main impact will be negative income effects on owners of nuclear power plants whose assets (rents) will be stranded. Our simulation analysis below focuses on the role of renewable energy as nuclear power is in the future no longer part of the Swiss electricity generation mix.

6.1 Policy scenario: RES-E subsidies

In our illustrative policy simulations, we investigate the impacts of RES-E subsidies on the Swiss electricity market and the Swiss economy. A direct subsidy is just one means of supporting renewable energy. The subsidy shifts the renewable generation supply curve downward, resulting in an equilibrium with more renewables, less generation from fossil fuel, and lower prices." (Fischer 2009). "A part of the incidence of the renewable generation subsidy, will be passed on to consumers as lower electricity prices." This applies at least for larger countries resp. countries or regions with binding border capacity constraints where inexpensive import options are limited.

For our analysis of direct RES-E subsidies, we implement three scenarios:

- Scenario **BAU** (business-as-usual with nuclear energy): This scenario is based on today's electricity production structure (year 2015), in which nuclear energy accounts for about one third of domestic electricity production.

  The BAU features only small amounts of renewable power generation by solar (ca. 1.7% of 2015 base-year total generation) and wind (0.2%) operated at upper capacity levels. We do not need to force this generation into the BAU (via subsidies) assuming that the dispatch costs are very small as compared to import cost and given that other low-cost generation options such as hydro or nuclear are already operated at upper capacity bounds to match base-year power demands. Additional renewable capacities are available in the BAU subject to natural resource constraints but calibrated in their capacity (investment cost) to be non-profitable at the outset.
- Scenario **REF** (reference without nuclear energy): It is assumed that nuclear energy will be phased out. Furthermore, the expansion of hydropower is not possible and no policies supporting renewables are in action.

  In line with empirical evidence we assume that capital installation cost increase in newly installed – technical this is done with a quadratic capital cost function to control convexity thereby smoothening the phase-in of additional renewables should electricity prices increase – e.g. due to a nuclear phase-out. For additional renewable capacity, we assume that solar and wind can be expanded with dispatch to network nodes whenever there are already pre-existing renewable plants mapped to these nodes. The physical availability is provided by generic technology-specific availability factors by hour and month scaled by some uniformly distributed capacity factor (see Figure 10 and Figure 11).
- Scenario **REN** (without nuclear energy and supporting domestic wind and solar power plants via subsidies: In a world without nuclear power plants in Switzerland (scenario REF) we apply a subsidy for wind and solar to achieve the following minimum dispatch for wind and solar:[26]
  - solar: 7030 GWh/year
  - wind: 1760 GWh/year

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[26] Note that these production levels are in line with the targets envisaged in the Swiss Energy Perspectives for the year 2035.

- total wind and solar: 8890 GWh/year

New wind and solar power plants receive a subsidy. The subsidy is determined endogenously and must be high enough to achieve the expansion targets. The subsidy cost to phase-in additional renewable capacities are borne by the respective cantons

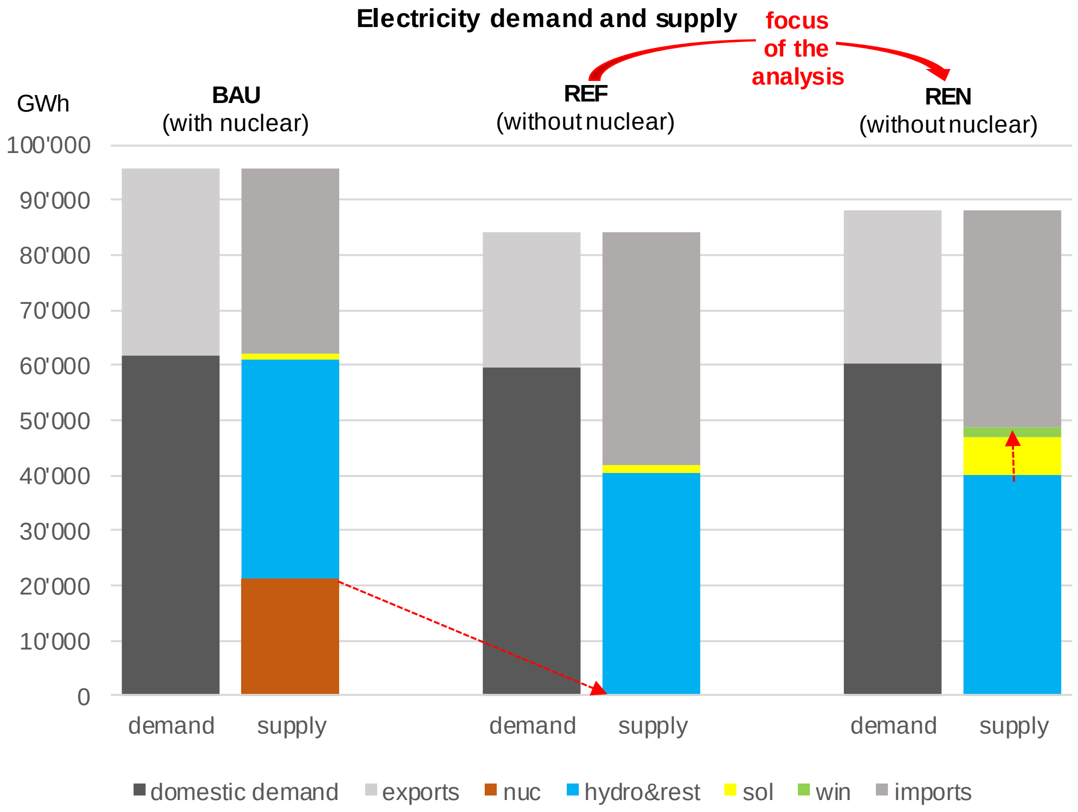
As mentioned above we do not implement a forward calibration for a specific year in the future nor do we use recursive dynamics. We simulate the policy scenarios with supply and demand of the year 2015. Of course, we take into account, that new wind and solar power plants are much cheaper than the already installed power plants (see the section about levelized cost further down). With this kind of scenario analysis we show that ElMaR captures the fundamentals of Swiss electricity market and what results our model can deliver.

6.2 Impact of a RES-E subsidies on the electricity market

Electricity demand and supply

Figure 19 shows the aggregated electricity demand and the electricity supply calculated with ElMaR for these three illustrative scenarios. In the **REF** scenario, nuclear energy is eliminated. Due to the relatively high cost of the renewables, domestic renewable production will only increase to a limited extent (in absolute terms): The production level from wind and solar together increases from 1138 GWh/year to 1517 GWh/year, i.e. this constitutes less than 5% of the nuclear gap when initial nuclear power production of more than 20 GWh per year is abandoned. Other generation options are also quite limited, and work largely at their upper bounds (in particular hydro). Reductions in electricity demand on behalf of consumers are relatively costly. As a consequence, adjustments in electricity trade will to a large extent close the nuclear gap: imports are increasing strongly and exports are declining. Since electricity imports are a cheap substitute of domestic nuclear energy, electricity wholesale prices increase with +0.23 cents/kWh only marginally in the REF scenario. The domestic consumption demand for electricity then remains almost at the level of the BAU scenario.

Figure 19: Electricity demand and supply of illustrative scenarios BAU, REF and REN



In the **REN** scenario, the new renewable electricity production (solar and wind) is being expanded from 1517 GWh/year (scenario REF) to the 8’890 GWh/year. With this 7’300 GWh/year expansion of renewable electricity production, net imports are still the major gap filler but not as pronounced as in scenario REF.

In the following discussion of results, we focus on the impact of RES-E subsidies for Switzerland, i.e. we mainly compare the differential effects between scenario REN and scenario REF.

Electricity prices

For Switzerland we would expect a rather small impact on the electricity price for scenario REF, as there are no strongly binding import resp. cross-border transmission capacity restrictions. With RES-E subsidies in scenario REN, we see an expected slight decrease of -0.13 cents/kWh in the wholesale electricity price: The subsidy shifts the renewable generation supply curve downward, resulting in an equilibrium with more renewables and lower prices.

Levelized cost and market revenue of new power plants

We calculate average levelized costs for new power plants from solar and wind of 9.3 cents/kWh.[27] The market value for new power plants from solar and wind is calculated at 3.4 cents/kWh (average of the sum product of wholesale price and production quantity at hour h and month m). The average wholesale price is 4.3 cents/kWh. This means that the market revenue generated for the new solar and wind power plants is 0.9 cents/kWh or around 20% below the average level.

The difference between market value (3.4 cents/kWh) and the levelized costs (9.3 cents/kWh) corresponds to the RES-E subsidy which is necessary to phase-in additional renewable capacities at the REN target level.

Economic surplus

As expected, we obtain a decline in economic surplus for the domestic stakeholders which is mainly caused by RES-E subsidies for the new solar and wind power plants. Figure 20 shows that the domestic producer loose around 470 Mio. CHF/year due to the cross-subsidization for the new solar and wind power, which amounts to around 430 Mio. CHF/year, and the decline in electricity sales revenues due to slightly lower electricity prices. The domestic consumer profit from the slight decline in electricity prices.

RES-E subsidies in Switzerland implicitly produces an economic surplus for the foreign stakeholders[28] through subsidized electricity exports.[29]

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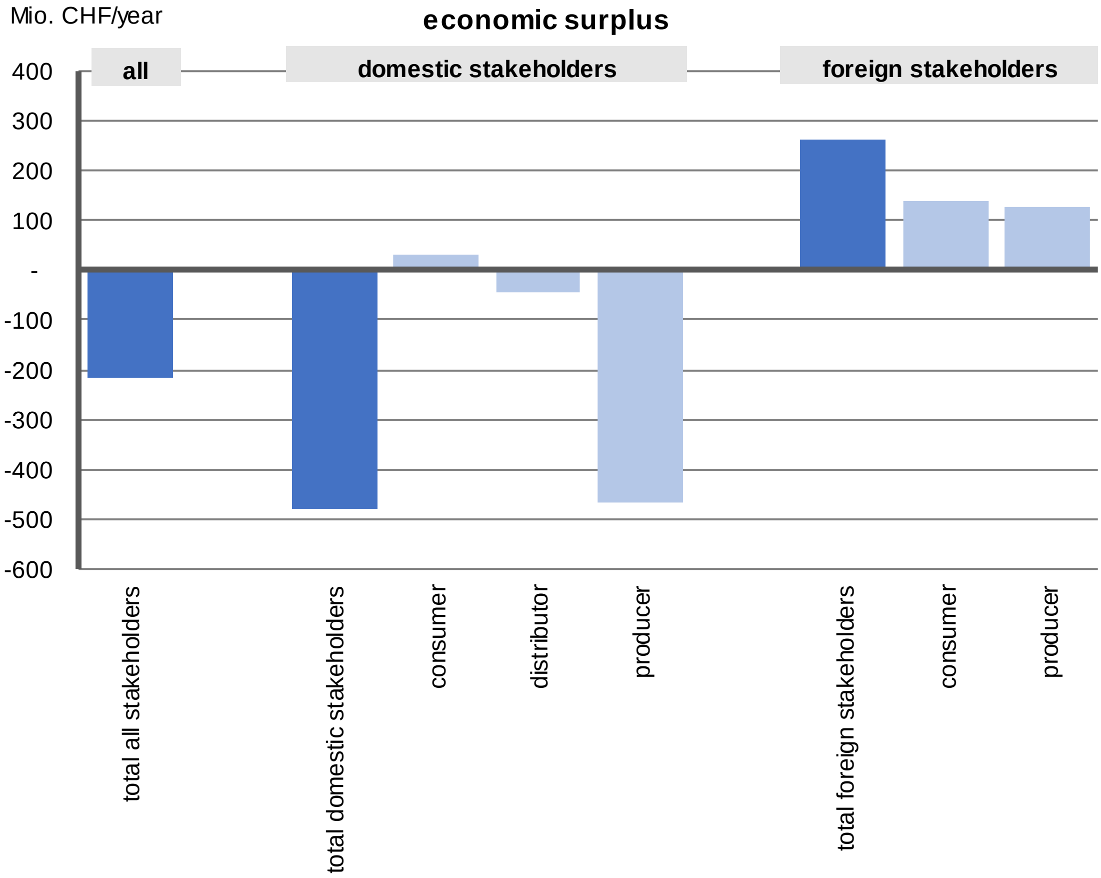
[27] The resulting levelized costs depend strongly on the quadratic cost coefficient for new power plants capacities (parameter α – see Table 6 in chapter 4.1). We have chosen this quadratic cost coefficient so that we get levelized costs between 9 and 10 cents/kWh. This is the case with an α of 4.

[28] The effects on foreign stakeholders are derived from changes in electricity exports and imports and changes in the electricity wholesale prices.

[29] Recall that export demand and import supply are isoelastic functions which are initially calibrated (BaU) to observed prices and quantities.

Figure 20: Rents resp. economic surplus : winners and loosers of RES-E subsidies

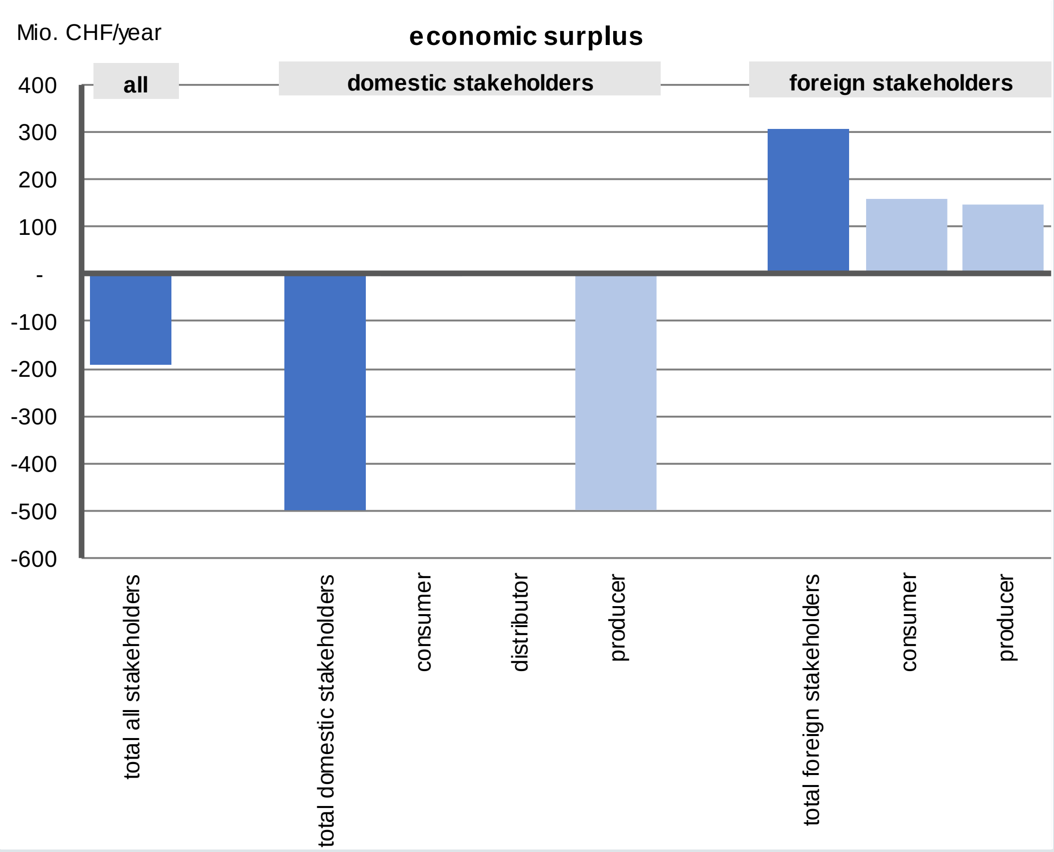


Box: Economic surplus with high and low trade elasticities

The two following figures show the distribution of the economic surplus among the different stakeholders, in a situation with a completely elastic import supply resp. export demand and a situation with inelastic import supply resp. export demand.

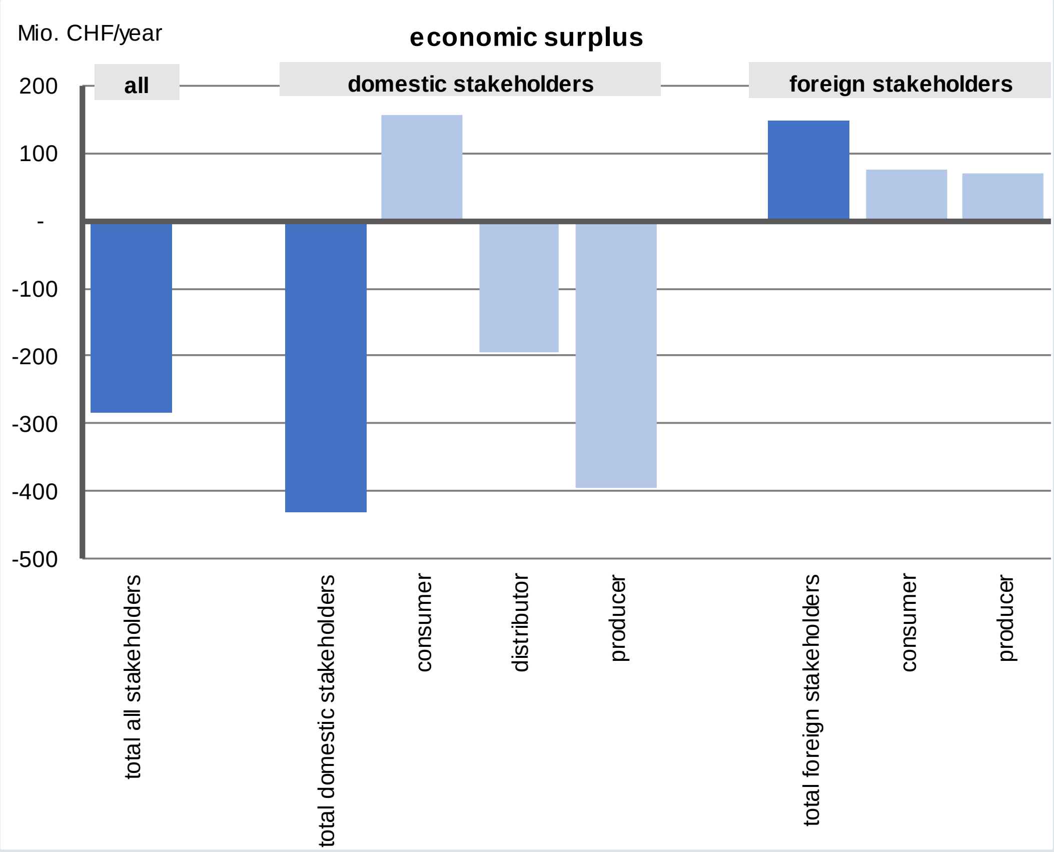
One can see that with high trade elasticities, the domestic producer bears the cost of regulation while the foreign stakeholders could benefit.

Figure 21: Rents resp. economic surplus : High trade elasticities (completely elastic import supply resp. export demand)



In a world with low trade elasticities (see next figure) the domestic producer still has to bear the largest share of the costs for financing renewable electricity production itself and the overall decline in economic surplus for all stakeholders is greater than in a situation with high trade elasticities.

Figure 22: Rents resp. economic surplus: Low trade elasticities (inelastic import supply resp. export demand, elasticity of 0.5)



6.3 Impact of RES-E subsidies on the Swiss economy

Below, we briefly discuss the economic impact of RES-E subsidies on the cantons and for Switzerland as a whole.

Welfare and GDP

Figure 23 resp. Figure 24 show the effects of RES-E subsidies on welfare[30] and gross domestic product (GDP). The effects on Switzerland as a whole are negative, but hardly noticeable: -0.02% for welfare and -0.01% for GDP.[31] Further show the figures that RES-E subsidies leads to regionally differentiated and in some cases small but noticeable welfare resp. GDP losses and gains. There are two main reasons for differences in incidence across cantons: (i) the unequal distribution of the additional investments/subsidies for solar and wind power plants between the cantons and (ii) the change of rents in the electricity system due to the (slightly) changed price profile caused by the additional renewable electricity production.

We see a welfare gains for those cantons which are expected to have a disproportionate share of the additional investments/subsidies in solar and wind power plants.[32] This applies in particular to canton GL, GR, VS and SO.

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[30] Welfare impacts are stated in percentage change of Hicksian equivalent variation (HEV) in income. A 1% HEV loss then means that we would have to give the average Swiss household a 1 % increase in real income such that (s)he can afford the same level of consumption as without policy regulation.

[31] The GDP impacts may differ from the welfare effect since GDP – here expenditure-based GDP -- compromises other components beyond private consumption such as public consumption, investment or the balance of payments. We hold the later three components constant in real terms across our model simulations but the nominal values will typically change due to change in relative prices where the choice of the numeraire might play an important role. GDP is not a precise welfare measure in microeconomic terms but just a widely-used indicator for economic performance -- in fact, GDP could go down for policy scenarios whereas economic welfare goes up (hence to avoid confusion it might be quite appropriate to state welfare changes in money metric utility as percentage changes in GDP so there is no ambiguity for the general reader when interpreting welfare/GDP results).

[32] As mentioned, we have simply assumed that the additional solar and wind power plants will be built where such power plants already exist.

Figure 23: Welfare impact of RES-E subsidies for Switzerland

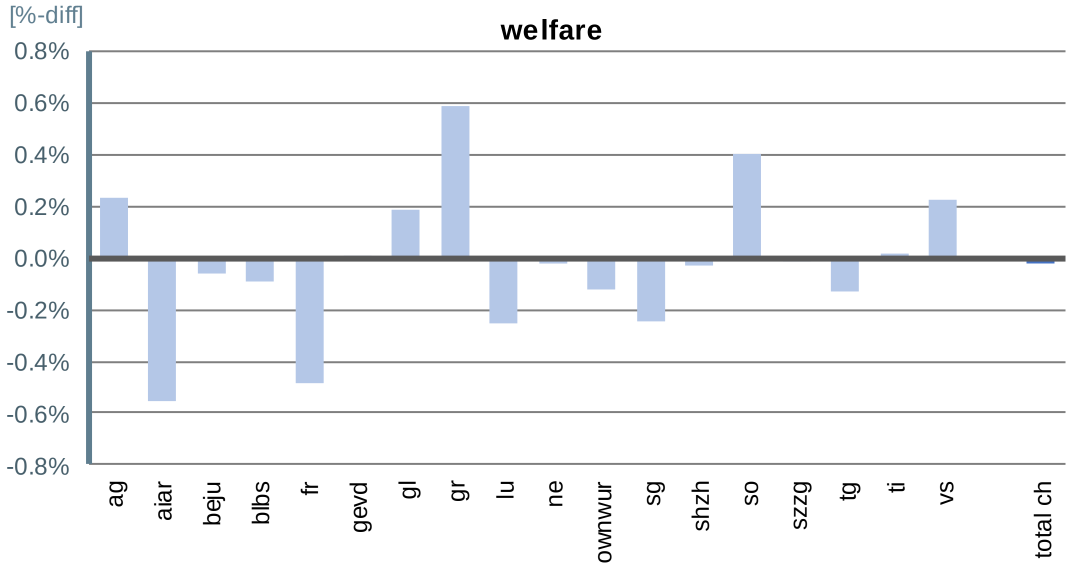
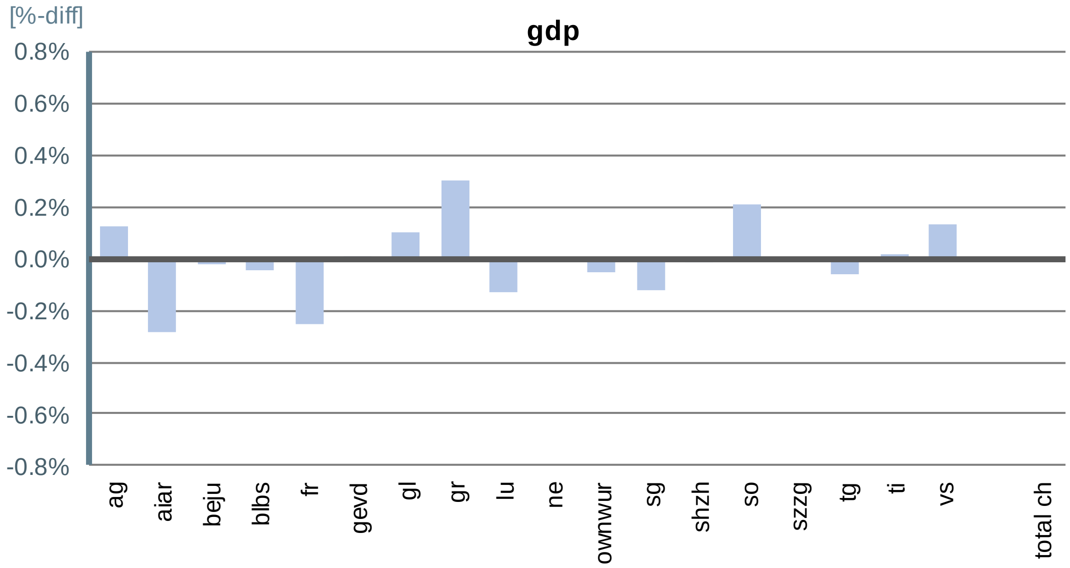


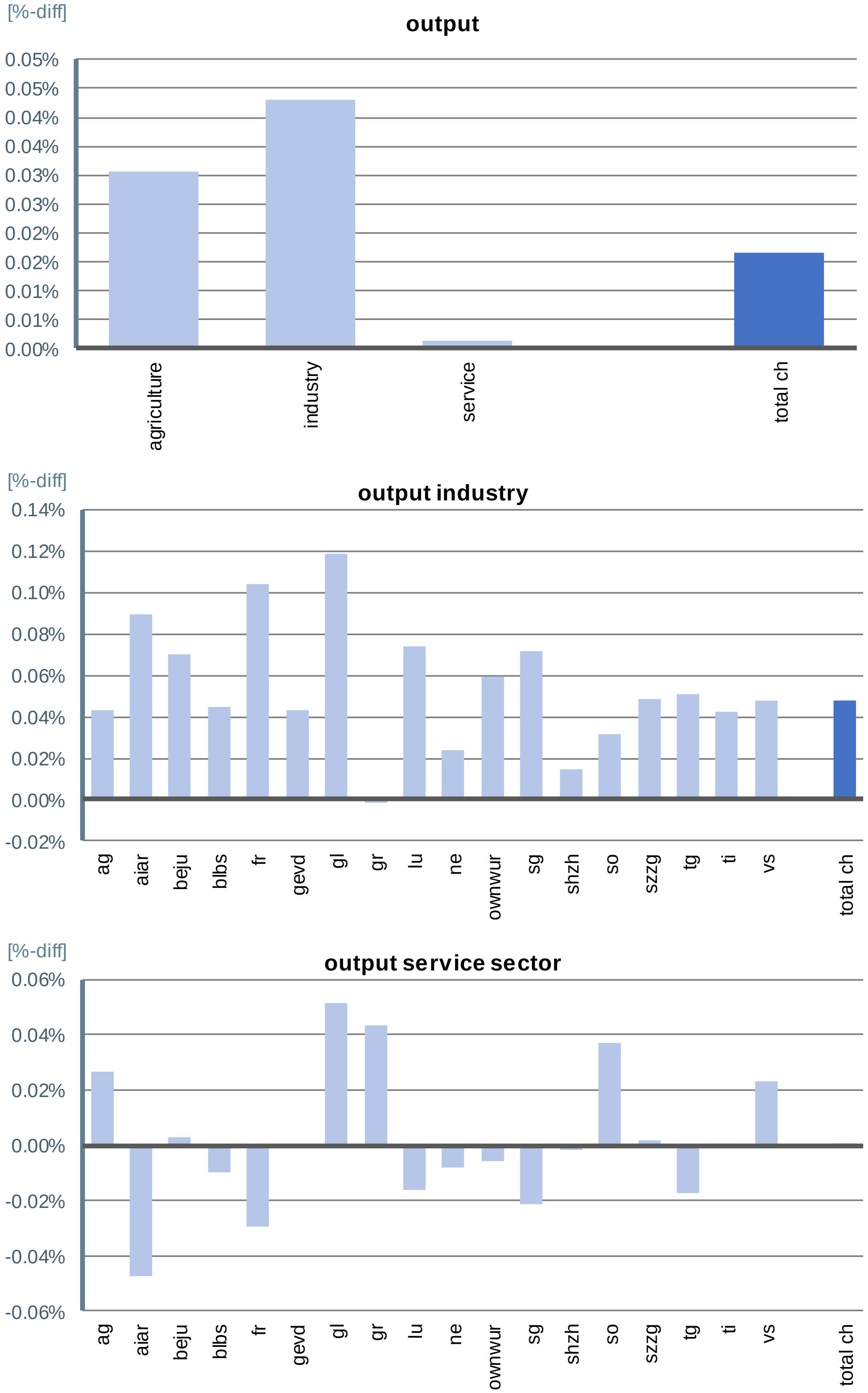
Figure 24: GDP impact of RES-E subsidies for Switzerland



Output

Figure 25 show the effect of RES-E subsidies on gross production value (output). With RES-E subsidies we have more domestic production and less imports, which has a slightly positive effect on output (building new power plants instead of imports). With slightly lower electricity prices we see that in particular electricity-intensive industries gain on the input (cost) side.

Figure 25: Impact on gross production value (output) of RES-E subsidies for Switzerland



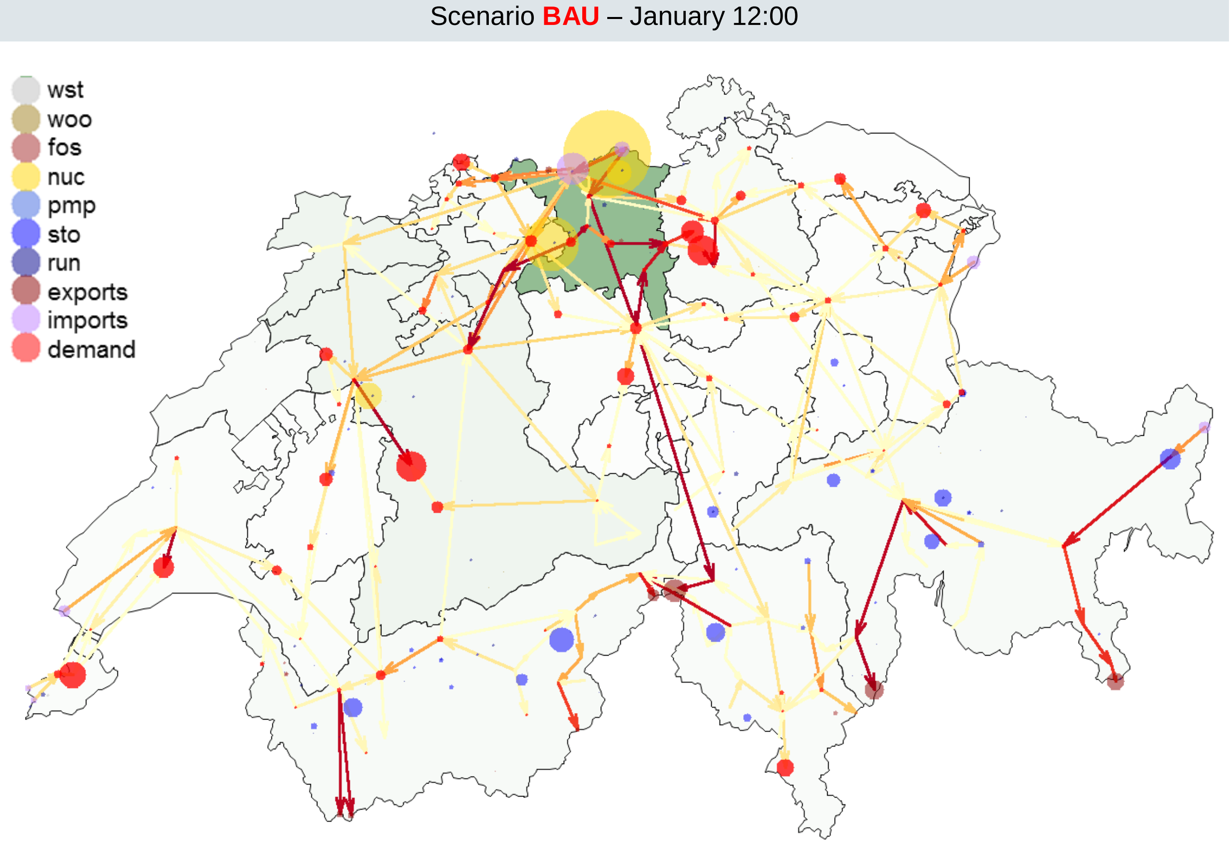
ElMaR visualization tool

ElMaR offers an outstanding visualization tool: For each individual hour, electricity demand, supply, dispatch and transmission can be displayed in high regional resolution. Figure 26 visualizes the electricity flows and production. The following effects are currently displayed in this visualization tool:

- **demand**: for each of the approximately 120 nodes, the size of the hourly electricity demand is shown. The larger the circular area, the greater the demand for electricity.
- **exports / imports**: for each of the approximately 25 border nodes, the size of the hourly electricity import and export is shown.
- **electricity production:** for each of the approximately 850 power plants, the size of the hourly electricity production is shown.
- **Network:** In the electricity network shown, the arrows indicate the direction of electricity flow. The darker the arrow, the greater the load on the grid.

We will not go into the details of this visualization at this point. In the course of the model work it has been shown that this visualization is an excellent aid for (i) the analysis of the electricity market effects and (ii) the debugging of model problems.

Figure 26: Dispatch, demand, supply and transmission status



7 Conclusions

Achievements

In this project we developed the model framework ElMaR (**El**ectricity **Ma**rket Design **a**nd **R**enewables) for the economic impact assessment of renewable power promotion in Switzerland. ElMaR features three models: A bottom-up partial equilibrium model of the Swiss electricity system with a dynamic annual hydro cycle submodule (**PE model**), a top-down multi-regional general equilibrium model of the Swiss economy with an integrated activity analysis on power technologies (**GE model**) and a linked PE GE model, which integrates the bottom-up PE model and the top-down GE model (see the following box for the key features of ElMaR). We have illustrated the functioning of the model using an illustrative scenario.

Each model provides a scientific value-added as compared to what has been done for Switzerland (and maybe elsewhere so far):

- **PE model** features a dynamic dispatch and capacity expansion model with elastic demands and networks constraints solved as economic surplus maximization. PE model is solved as a quadratic programming problem. In this way ElMaR is a next step to the reference by Weigt and Schlecht (2014): Demand in ElMaR is endogenous (not exogenous) and we use the hourly load values on each node for calibration (not the load values for the whole country) in a DC power flow model.
- **GE model** as a hard-linked (all model equations are solved simultaneously) top-down and bottom-up model for power generation with cantonal disaggregation where the bottom-up module features hydro dynamics as a further innovation beyond the fact that we have a multi-regional CGE model for Switzerland. GE model is solved as a mixed complementarity problem
- The "soft-linked" iterated **PE-GE model** where we have a general equilibrium closure to the PE model and can at the same time assess the macroeconomic impacts of electricity market regulation outside the electricity markets. The two models are solved iteratively to convergence, allowing analysis of policy impacts on the electric sector taking into account economy-level price and income effects.

Necessary next steps

Modelling: In the current ElMaR model framework foreign border crossing restrictions are recorded in a simplified way by means of import supply and export demand elasticities. In order to impose physical transmission restrictions at border crossings, it is necessary to implement a targeted congestion management system with Germany, France, Italy and Austria.[33] Further,

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[33] Congestion management at the border: Transmission System Operator (TSO) determines a Net Transfer Capacity (NTC) value for each direction on each border of its control area. The NTC values can be interpreted as the maximum allowable commercial exchange that push a critical network element to its maximum physical flow. To implement a flow-based market coupling we would need to complement the Swiss network with the network of neighbouring countries.

the foreign electricity price is to be determined endogenously for Germany/Austria, France and Italy by implementing the electricity production in neighbouring countries Austria, Germany, France and Italy.

Data: Elmar is currently still based on ad hoc parameterization. A better, updated parameterization would have to be carried out for the use of ElMaR in policy analysis. The main points are:

- Verification and plausibility check of the high and medium voltage electricity network together with experts from Swissgrid: The implemented ENTSOE grid data refers to a future situation with some new lines already added, which we corrected manually. We have also aggregated various nodes. These two points have to be verified with network experts.
- Bottom-up electricity market and top-down economic data must be updated: The bottom-up electricity market model and the top-down general equilibrium model are based on different benchmark years (2015 resp. 2012). This causes some limitations for the current PE GE model linkage.
- Regional distribution of additional renewable power sources: In order to design realistic renewable expansion scenarios we need more detailed information about the regional distribution resp. availability of additional renewable power sources.

With this further steps ElMaR is ready to answer the key questions concerning the shift in energy generation towards more renewable energy sources (see chapter 1) and many more questions like the assessment of capacity markets.

Further expansions of ElMaR

ElMaR could be extended to a multi-country version. This extension makes it possible to assess the impact of foreign energy policy on the swiss market. As a last step we would implement an intertemporal version of the model to capture the adjustment path to policy shocks over time.

Box: ElMaR – key model features

The model framework ElMaR (**El**ectricity **Ma**rket Design **a**nd **R**enewables) for the economic impact assessment of renewable power promotion in Switzerland. ElMaR features three models with the following features:

PE model: Bottom-up partial equilibrium electricity network model for Switzerland featuring

- regional and temporal resolution of power generation and demand, electricity transmission, and cross-border electricity trade with elastic electricity demands: 18 regions/cantons within Switzerland and temporal resolution of maximal 15 minutes. In our compact default implementation we solve the model by representative hours (24 hours) across months (12 months), this means we limit the time resolution to 288 time slices for the sake of dimensionality restriction and speed of computation.
- intertemporal optimization of discrete dispatch decisions over the year (by hour and month). Dispatch is limited by upper generation capacities for power plants which is provided in terms of electrical power (wattage) by hour and month
- detailed representation of optimal storage hydro-power management: storage plants without pump, storage plants with pump, pump storage plants with circulation mode
- endogenous capacity expansion decisions[34] applicable to new power plant capacities (e.g. solar, wind) and exogenous transmission line extensions
- PE model in stand-alone modus operates as a quadratic programming problem with the maximization of economic surplus subject to nodal balances: We restate electricity balances at the network nodes accounting for transmission inflows and outflows subject to transmission capacity constraints on arcs. The PE model can be used without network constraints (copper plate) and with network constraints on the medium- (220 kV) and high-voltage (380 kV) network. The low-voltage distribution network is concerned as a copper plate power grid – issues concerning the distribution network cannot be addressed with ElMaR model framework. The model is calibrated for 2015 and is able to reproduce the Swiss price, supply and demand pattern
- visualization tool: For each individual hour, electricity demand, supply, dispatch and transmission can be displayed in high regional resolution.
- PE model provides responses to exogenous policy shocks (electricity market regulations) with respect to power dispatch by power plants, network transmission, power trade, electricity demands and the built-up of additional power capacities (transmission capacities) leading into a new steady-state power market over the year (by 24 hours over the representative day and across 12 months)

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[34] Investments in new power plants are made until the economic surplus, the sum of producer and consumer surplus, is maximized (dynamic maximization over a representative year). In this economic surplus maximizing state, the last new power plant to be built can just cover its variable costs and capital costs (depreciation and interest payment) through the electricity revenue.

GE model: Top-down multi-regional general equilibrium model of the Swiss economy

- Comparative static multi-regional general equilibrium model with 18 regions/cantons within Switzerland with standard CES[35] description
- one representative household per region, 21 sectors and 3 energy sectors
- decomposition of power generation into 7 technologies with an integrated bottom-up-top-down decomposition as described by Böhringer and Rutherford (2008) without large-scale bottom-up representation. A variant of the GE model includes hydro-power operation with higher time resolution.
- trade via national pool (no direct inter-regional trade due to lack of trade data between cantons)
- -GE model can also be run stand-alone and is calibrated for 2008.

PE GE model resp. Interface

- PE GE model combines the advantages of both model approaches – the bottom-up and top-down approach
- Generic coupling routine as laid out in Böhringer and Rutherford (2009)

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[35] CES constant elasticity of substitution.

Appendix A: Data buildstream for multi-regional GE model

The programming language used to formulate the ElMaR model framework is **GAMS** (General Algebraic Modelling System). GAMS is a higher-level model language for the development of large-scale mathematical programs and the processing of extensive datasets (Brooke, Kendrick, and Meeraus, 1998). Furthermore, the GAMS modelling environment provides access to a range of powerful solution algorithms such as PATH (Dirkse and Ferris, 1995) which is used here to solve the MCP problem.

N.B.:To run the full GE data buildstream stand-alone the gedata.gms routine and the data file bottomup.gdx must reside in the GEBUILD directory (within the full GE-PE data/model package bottomup.gdx gets generated in the PEBUILD buildstream and copied over in the GEBUIL buildstream directory while the routine gedata.gms which is used in various model files resides in the upper model PEGE directory.

Directory and file structure

- **Directory GEDATA**: Main directory for the bat-master-file and all gms-routines

– **gebuild.bat**	Batch file to invoke the top-down (GE) data buildstream
– **readiot.gms**	Read and partition the (2008) national IO table
– **national.gms**	Calibrate and replicate the benchmark for a generic national GE model
– **readgva.gms**	Read table of gross value-added by canton and sector
– **disagg.gms**	Disaggregate the national table
– **geaggr.gms**	Aggregate disaggregate dataset to target aggregation
– **static**.**gms**	Check GE consistency of target GE dataset

- Upper level directory:

– **gedata**.**gms**	Routine for reading in cantonal (GE calibrated) IO data
– **bottomup**.gdx	Data file with regional eletricity generation shares produced by PE buildstream

- **Directory GEDATA\xlsdata**: Directory with external input data files (xls, xlsx)

– **Energie_IOT_CH_2008_publ.xls**	Swiss national input-output table for 2008 with power generation sectors (copied to **iodata.xls**)
– **GVA2011.xlsx**	Gross value added data for 2011by canton and industries

- **Directory GEDATA\gdxdata**: Directory with generated GAMS dataset (gdx)

– **gdxdata\siot.gdx**	GDX file with national Swiss IOT data
– **gdxdata\gva2011.gdx**	GDX file with gross value added by sectors and cantons
– **gdxdata\disagg.gdx**	GDX file with disaggregate cantonal IO data

  - **gdxdata\%target%.gdx** GDX file which is aggregated from disagg.gdx towards a target mapping, provided by the mapping file %target% (by default %target%==macro)
- **Directory GEDATA\mappings**: Directory with mapping files for regions and sectors in the model dataset
  - **macro.map** Mapping of the disaggregate dataset to a composite dataset with all Swissgrid regions and four composite economic sectors (agr - agriculture, mfr - manufacturing, ser -services, trn - transport), electricity distributions and trade (ele) and seven distinct power generation technologies (run - running hydro, sto - storage hydro, nuc - nuclear, fos - fossil power, woo -- wood power, wnd - wind and PV, ewi - waste)

  N.B.: Other mapping files with alternative sector/region aggregations include full.map, g20.map, g21.map.

  N.B.: The gms-routines geaggr.gms and static.gms invoke a generic data-read routine gedata.gms for reading in cantonal (GE calibrated) IO data from the higher-level PE-GE model directory -- $include ..\gedata.gms.

Batch file

- Batch file: **gebuild.bat**: The batch file gebuild.bat invokes the series of GAMS programs to process the data buildstream for the top-down cantonal general equilibrium model and calls the following GAMS routines: --> **readiot.gms** --> **national.gms** --> **readgva**.gms --> **disagg.gms** --> **geaggr.gms** --> **static.gms**

GAMS routines

- **readiot.gms**: Read and partition the (2008) national IO table
  - Input data: xlsdata**iodata.xls** (a copy of the original data file **Energie_IOT_CH_2008_publ.xls**)
  - Output data: gdxdata**siot.gdx**:

  The routine **readiot.gms** reads in the national IO table (here for 2008), partitions and labels the IO table in data arrays - e.g. y0 (production) or ld0 (labor demand) - which subsequently enter as parameters into the fundamental IO/GE balance conditions (zero-profit, market clearance, income balance). The original units of the national IO table are in million CHF which we scale down by 1000 to be stated in billion CHF for subsequent economic analysis.

  At the end, the routine **readiot.gms** produces the dataset **siot.gdx** (set definitions and benchmark data arrays):

execute_unload 'gdxdata\siot.gdx'

with the following details:

– set s (alias g)	Production sectors (#68 -- enumerated from 1 to 68)
– set cg	COICOP consumption goods/categories (#12 - COICOP: Classification of Individual Consumption by Purpose)
– set et(s)	Subset of discrete power generation technologies
– set gas(s), oil(s), fos(s), wnd(s), nuc(s), ele(s)	Singelton sets to denote discrete power generation technologies
– parameter y0(s)	Production
– parameter d0(s)	Domestic supply
– parameter e0(s)	Export
– parameter id0(g,s)	Intermediate demand
– parameter ld0(s)	Labor demand
– parameter kd0(s)	Capital demand
– parameter a0(g)	Armington supply
– parameter m0(g)	Imports
– parameter tr0(s)	Indirect tax revenue
– parameter zc0(s,cg)	Inputs to final consumption
– parameter i0(s)	Investment
– parameter g0(s)	Public demand
– parameter le0	Labor endowment
– parameter vb0	Trade deficit or surplus (balance of payment)

- **national.gms**: Calibrate and replicate the benchmark for a generic national GE model
  - Input data: xlsdata\%ds%.gdx (where %ds%==siot by default)

  The routine **national.gms** reads in the national input output data (here: **siot.gdx**) and verifies that the dataset is calibrated to replicate the economic benchmark for (i) a generic national small open economy GE model (generic) and (ii) a slightly refined energy-economy model (static) -- both models coded in MPSGE.

- **readgva.gms: **Read table of gross value-added by cantons and industries
  - Input data: xlsdata**gva2011.xlsx**
  - Output data: gdxdata**gva2011.gdx**

  The routine **readgva.gms** reads in gross value added (GVA) data across Swiss cantons (#26) and industries (#21) based on the NOGA classification of industries (NOGA = Nomenclature Générale des Activités économiques - Allgemeine Systematik der Wirtschaftszweige). The NOGA GVA data is based on 2011 so again -- as with the electricity market data (for 2015) -- there is a mismatch of the base-year of the satellite data (here: GVA) and the base-year of the central input-output data (2008). In follow-up work, we should make sure to have a common base-year across all data sources.

The routine **readgva.gms** aggregates GVA data from 26 cantons to the 18 Swissgrid regions and relabels industry classifications from numerical numbers (1..21) to 3-digit-alphabetical acronyms. The GVA data by Swissgrid region and sector will be used further down in the buildstream (**disagg.gms**) to decompose the national IO table for Switzerland into regional accounts.

At the end, the routine **readgva.gms** produces a dataset

execute_unload 'gdxdata\gva2011.gdx',gva_=gva;

with the following details:

– parameter gva(r,s)	Gross valued added in billion CHF across Swissgrid regions r and industries s for 2011

- **disagg.gms**: Reads in the calibrated national IO dataset together with the regional information on gross-value added across industries

– Input data:	gdxdata**siot.gdx** gdxdata**gva2011.gdx**
– Output data:	gdxdata\

The routine **disagg.gms** reads in the calibrated national IO dataset **siot.gdx** together with the regional information on gross-value added across industries from gva2011.gdx. The latter information is used to split down the national IO accounts into cantonal sub IO accounts which are then used to calibrate a regional (cantonal) GE model for Switzerland. Since we have no information on bilateral trade flows between cantons intra-swiss trade is modeled as a national hub-market (with more detailed information and a potential focus on intra-Swiss trade issues we can insert bilateral trade flows at some later stage). For the construction of the regional dataset the lowest level of disaggregation is in our case of electricity market analysis provided by the regional classification of Swissgrid, i.e. we map the 26 cantons to the 18 Swissgrid regions (rmap). At the sectoral level, we maintain the lowest level of disaggregation as provided by the 68 national IO sectors. We simply attribute the 68 IO sectors to the 21 NOGA sectors to infer how the respective IO sector is allocated across regions using the associated NOGA GVA shares. Note that at the end of the sector disaggregation we introduce the regional power generation shares by technologies as provided by the PE buildstream (bottomup.gdx) such that the disaggregate dataset features discrete electricity generation sectors where the national output is split down according to the PE bottom-up numbers.

The routine **disagg.gms** employs two MPSGE GE models to check for the fundamental GE conditions -- the model "national" to check consistency of the incoming national IO data and the "model" regional to check consistency of the regional IO data.

At the end, **disagg.gms** produces a regional/cantonal input-output dataset for 18 Swissgrid regions and 68 sectors.

execute_unload 'gdxdata\disagg.gdx'

where the sets and parameters correspond to those generated in **readiot.gms** for the national dataset (see above) but expanded for a regional index r (N.B.: we add one more parameter rx0(r,s) to denote re-exports).

*N.B.: **Disagg.gms** features a flag ($set eledemand yes) for including some electricity demand reporting (parameter eledemand) at the end of the routine.*

- **geaggr.gms** Reads in the disaggregate cantonal dataset disagg.gdx and aggregates the economic accounts

– Input data:	gdxdata**disagg.gdx**
– Output data:	gdxdata\%target%.gdx (where %target% is the target aggregation file specified by %targe% and the associated mapping file %target%.map -- default: %target%=macro)

The routine **geaggr.gms** reads in the disaggregate cantonal dataset **disagg.gdx** and aggregates the economic accounts subject to some target mapping. The cantonal dataset is read in using the generic routine **gedata.gms** residing in the upper level model directory ($include ..**gedata.gms**). The target mapping for the aggregate dataset is provided in subdirectory \mapping and seleted via $include mappings\%target%.map where %target% denotes the name of target mapping (by default %target% = macro).

At the end, **geaggr.gms** produces a composite regional IO dataset for Switzerland

execute_unload 'gdxdata\%target%.gdx'

where the sets and parameters correspond to those generated in **readiot.gms** and **disagg.gms** respetively.

Recall that the set definitions then include

– set r	Regions (cantons) in the dataset
– set s	Sectors in the datasets (including discrete power sectors (technologies) and the composite electricity transmission-distribution sector (ele)
– set i(s)	Sectors except for power technologies (et) and composite electricity sector (ele)
– set et(s)	Subset of power technology sectors
– set ele(s)	Composite electr. transmission and distribution sector (ele)
– set cg	Consumer goods (COICOP categories)

In addition, we include two parameters that charaterize cantonal exports/supplies to and imports/demands from the national Swiss market:

– parameter ns0(r,g)	Supply to national market
– parameter nd0(r,g)	Demand from the national market

- **static.gms** Reads in the prespecified dataset and calibrates the multi-regional GE
  - Input data: gdxdata\macro (by default we include the **macro.gdx** dataset)

  The routine **static.gms** reads in the prespecified dataset (by default: $if not set ds $set ds gdxdata\macro or via the batch routine: gams static --ds=<target> where <target> is the name fo the dataset of choice). The dataset is then used to calibrate a generic cantonal GE model (MPSGE name: $model:static) and a more refined cantonal electricity-economy GE model for Switzerland. In case there is a data inconsistency with the benchmark dataset the routine will abort and the deviations of marginals to the central equilibrium variables (activity levels, prices, incomes) will reveal where the replication check fails (zero profit, market clearance, income balance) -- as a starting point for subsequent debugging.

Appendix B: Data buildstream for electricity network model

Directory and file structure

- **Directory PEDATA**: Main directory for the bat-master-file and all gms-routines

– **pebuild.bat**	Batch file to invoke the bottom-up data buildstream
– **network.gms**	Read the network dataset, filter and delete redundant nodes
– **ptdf.gms**	Compute the PTDF (Power Transfer Distribution Factors)
– **foedata.gms**	Extract the data for hydro power plants (based on SFOE data)
– **weppdata.gms**	Extract the data for non-hydro power plants (based on WEPP data)
– **plants.gms**	Merge the data on hydro- and non-hydro power plants
– **swissgrid.gms**	Read the national Swissgrid data on generation and demand (with 15 min intervals mapped by hour)
– **aggregate.gms**	Aggregate the Swissgrid data
– **cities.gms**	Compute proximity of network nodes to cities
– **avail.gms**	Translate data on availability of solar and wind

- **Directory PEDATA\xlsdata**: Directory with external input data files (xls, xlsx)

– **network.xlsx**	Network data (network nodes, transmission lines, etc.)
– **plantdata.xlsx**	Plant-specific data on power generation units (provided by WEPP and SFOE)
– **EnergieUebersichtCH_2015.xls**	Swissgrid data on power production, consumption, and trade across Swiss cantons
– **generation.xlsx**	Monthly generation data on power technology categories (provided by SFOE)
– **geonames.xlsx**	Information on geograhical location and population of Swiss cities

- **Directory PEDATA\gdxdata**: Directory with generated GAMS data files (gdx)

Batch file

The batch file **pebuild.bat** invokes the series of GAMS programs to process the data buildstream for the bottom-up partial equilibrium electricity network model and calls the following GAMS routines: --> **network.gms** --> **ptdf.gms** --> **foedata.gms** --> **weppdata.gms** --> **plants.gms** --> **swissgrid.gms** --> **aggregate.gms** --> **cities.gms** --> avail.**gms**

GAMS routines

- **network.gms**: Read the network dataset, filter, and delete redundant nodes gams network
  - Input data: xlsdata**network.xlsx**
  - Output data: gdxdata**network.gdx**

  The routine **network.gms** reads in data on the Swiss high voltage electricity grid (380KV and 220KV transmission lines).

  The data is filtered to skip own-circuit lines (direct flows from a node to the same node) and identify two-directional arcs that would create infeasibilities in the network representation. Furthermore, the routine identifies nodes (subset of nodes) that are not interconnected with the grid and drops these nodes from the network data.

  At the end, **network.gms** produces a clean dataset on the electricity network

```
execute_unload 'gdxdata\network.gdx', nd=n, bn, bnmap, cty, cd=c, r, L, rmap, cmap,
                                       entsoname, loc, dis, linedata, loaddata;
```

  with the following details:

  - set n: All network nodes (here: #144)
  - set bn(n): boundary nodes bn as a subset of n (here: #23)
  - set cty: Neighboring countries (AUT, FRA, ITA, DEU)
  - set bnmap(cty,n): Mapping of boundary nodes to neighboring countries
  - set c: Circuits in the dataset (c1,...,c241) -- here #241
  - set r: Cantons and composite cantons as of Swissgrid dataset (model regions) - here #18
  - set rmap(n,r) Mapping of nodes to regions
  - set cmap(c,n,n) Mapping from circuits to arcs
  - set L(n,nn) Links (arcs) in the networks -- here #203
  - set entsoname(n) ENTSOE names for nodes
  - parameter loc(n,*) Latitude ("lat") and longitude ("lon") location for each node
  - parameter dis(n,n) Great circle distances between nodes (km)
  - parameter linedata(c,linedatacols)
    Line circuit data -- physical data (on voltage, Line R, Line X, charging B, in service, thermal line rating)
  - parameter loaddata(n,loaddatacol)
    Load data in nodes (pload (MW) - real power; Qload(Mvar) reactive power)

- **ptdf.gms**: Compute the PTDF (Power Transfer Distribution Factors)

  Background: The complex highly non-linear interaction between node injections and withdrawal of electricity requires simplifying modelling assumptions leaning on principles of power flow analysis. One common approach for the simplified physical network representation is based on the so-called Power Transfer Distribution Factors (PTDFs) that use DC[36] Linear approximations to power flow equations. PTDFs indicate the fraction of power flow along any given line in the network to any given injection-withdrawal transaction. Including PTDFs may increase the empirical/natural science foundations of electricity market analysis. The PTDF network representation requires a detailed specification of transmission line characteristics including topology, circuits, nominal voltage and nominal capacity.

In our PE electricity model (see **pe**.**gms**) we can replace the node balance equation which defines a standard flowgate (energy balance) setting with the PTDF constraints. We may have to filter the PTDF matrix ptdf(n,nn,nn), which indicates how injecton/withdrawal in a node (n) affects power flows along a network line (nn-nn) for small values to reduce the overall size of the PTDF model and make it numerically tractable.

At the end, **ptdf**.**gms** produces PTDFs

```
execute_unload 'gdxdata\ptdf.gdx',ptdf,tcap;
```

with the following details:

– parameter ptdf(n,nn,nn)	PTDF matrix
– parameter tcap(n,n)	Total capacity (megavolt amps (reactive) -- MVAR)

which enters the algebraic PTDF constraints in the PTDFnetwork model (see **pe**.**gms**):

```
ptdf_pos(m,hr,L). .tcap(L)*days(m) =g=  sum(gmap(g,n), ptdf(L,n)*(Y(m,hr,g)+MS(m,hr,n)));

ptdf_neg(m,hr,L).. tcap(L)*days(m) =g= -sum(gmap(g,n), ptdf(L,n)*(Y(m,hr,g)+MS(m,hr,n)));
```

where:

– set gmap(g,n)	Mapping of generator g to node n
– variable Y(m,hr,g)	Generation by plant g in month m and hour hr (GWh),
– variable MS(m,hr,n)	Imports by node n in momth m and hour hr (GWh)
– parameter days(m)	Number of days in month m

- **foedata**.**gms**: Extract the data for hydro power plants (based on SFOE data)

– Input data:	xlsdata**plantdata.xlsx**
– Output data:	gdxdata**foedata.gdx**

The routine **foedata**.**gms** reads in SFOE (Federal Office of Energy) locatonal and capacity/power production data on hydro power plants (run-of-river, storage without pumping facilities, storage with pumping (2nd reservoir, and circular pump storage) -- see sheet "che_plants_water_FOE" in XLSX input file plantdata.xlsx. If plants miss a regional (cantonal) association, the plants are attributed to cantons based on their locational data.

At the end, **foedata**.**gms** produces a dataset on hydro power plants

---

[36] DC direct current.

execute_unload 'gdxdata\foedata.gdx',id,foeinfo_=foeinfo,foedata;

with the following details:

– set id(*)	Identification number of plant facility (as of SFOE)
– set foeinfo(id,r,et))	Plant information by plant identification number (id), Swissgrid region (r) and hydro power technology type (et -- hydro power types are a subset of power generation types and include
– run	Run of the river generation
– sto	Storage power plant generation
– pmp(sto)	Storage with pumping (subset of sto)
– crc(sto)	Storage with circular pumping (subset of sto)
– parameter foedata(id,foecol)	Characterisation of plant facility (id) by capacity and production as well as location

- **weppdata.gms**: Extract the data for non-hydro power plants (based on WEPP data)
  - Input data: xlsdata**plantdata.xlsx**
  - Output data: gdxdata**weppdata.gdx**

The routine **weppdata** extracts data for non-hydro power plants based on the WEPP database (The World Electric Power Plants Database (WEPP) is a commercial global inventory of electric power generating units). The routine uses the same XSLX input file as the routine foedata.gms but reads out non-hydro power plant data from sheet "che_plants_no_water_WEPP".

Note again that we take hydro specific power plant data directly from the Swiss Federal Office of Energy (see above **foedata.gms**) rather than WEBB.

At the end, **weppdata.gms** produces a dataset on non-hydro power plants

execute_unload 'gdxdata\weppdata.gdx',id,weppinfo_=weppinfo,weppdata_=weppdata;

with the following details:

– set id	Identification number of plant
– parameter weppinfo_(id,r,et,yr)	Indicates the installation year for power plant id of generation technology et located in Swissgrid region r
– parameter weppdata_(id,weppcol)	Plant data on capacity (MW) and location (lat,lon);

- **plants.gms**: Merge the data on hydro- and non-hydro power plants (BFE and WEPP data)
  - Input data: gdxdata**foedata.gdx**
    gdxdata**weppdata.gdx**
    xlsdata**generation.xlsx**
  - Output data: gdxdata**plants.gdx**

The routine **plants.gms** merges the plant data (location, capacities) on hydro installations (SFOE data) and on non-hydro installations (WEPP data) and adds data from the Federal Office of Energy (SFOE = BfE(Bundesamt fuer Energie)) on national power generation by technology category and months over the year. For the benchmark of the network model we use generation data for the year 2015-2016. Note that Swissgrid data (generation.xlsx) features regional production and consumption data only from 2015 onwards (before the data is aggreated at the national level). In addition, the routine generates mappings from generating units (plants) to nodes in the network based on a minimum distance calculation. Finally, using the information on the location of generators and the type of generators embedded in foedata.gdx (foeinfo) and weppdata(weppinfo), we set out explicit mappings from plants to regions (grmap(g,r)) and mapping of of plants toe technologies (etmap(g,et)).

At the end, **plants.gms** produces a comprehensive dataset for power plant characterisation

execute_unload 'gdxdata\plants.gdx',g,gn,gh,grmap,etmap,foeinfo,foedata,wepinfo, weppdata, gdis, gmap, generation;

with the following details:

– set g	All generators (plants)
– set gn(g)	Subset of non-hydro generators
– set gh	Subset of hdyro generators
– set grmap(g,r)	Mapping of generators to regions
– set etmap(g,et)	Mapping of generators to power technology typews
– set gmap(g,n)	Mapping of generators to nodes
– parameter foeinfo	see above **foedata.gms**
– parameter foedata	see above **foedata.gms**
– parameter weppinfo	see above **weppdata.gms**
– parameter weppdata	see above **weppdata.gms**
– parameter gdis(g,n)	Great circle distance from plants to nodes
– parameter generation(m,et,yr)	SFOE power generation data by months and technologies across years

swissgrid.gms: Read the national Swissgrid data on generation and demand

– Input data: xlsdata**EnergieUebersichtCH_%yr%.xls** (where %byr% denotes the base-year; by default: 2015).

– Output data: gdxdata**\%byr%.gdx**

The routine **swissgrid.gms** reads in detailed power production and consumption data together with electricity trade at 15 min intervals over the year (from 2015 onwards). The routine furthermore generates mappings to different time scales (hours, months) which we use later on to operate the electricity network model at an hourly level. Note that the regions provided in the Swissgrid dataset provide the minimum disaggregation of regions (cantons/composite cantons) in the electricity network model

At the end, **swissgrid.gms** dumps out regional data on power production,consumption, exports, imports, and prices across cantons by 15 min intervals

```
execute_unload 'gdxdata\%yr%.gdx',items, tpn, hr, data, datecodes, hmap, daymap, hourmap, monthmap;
```

with the following details:

– set tpn(*)	Numeric time periods in the dataset (here: quarterly hours over the year = 4*8760 (leapyear: 8784))
– set hr	Number of hours in the year (8760 (leapyear: 8784))
– set items	Items in the Swissgrid dataset (e.g. production (kWh), consumption (kWh), cross-border exhange (kWh)
– set hmap(tpn,hr)	Mapping of quarterly time segments (1 to 35040) to numeric hours (1 to 8760) in the year
– set daymap(weekday,hr)	Mapping of weekdays (1 to 7) to numeric hours (1 to 8760)
– set hourmap(hour,hr)	Mapping of day hours (0 to 23) to numeric hours (1 to 8760) over the years
– set monthmap(month,hr)	Mapping of months (1 to 12) to numeric hours (1 to 8760)
– set datecodes(tpn,weekday,hour,month)	Mapping of numeric (quarterly) time periods to weekday, hour , and months
– parameter data(tpn,items)	Swissgrid electricity data by numeric time period and data item

NB.: From 2015 data items are provided by Swissgrid regions -- e.g. prd_ag:= electricity production in Aargau

- Routine **aggregate.gms**: Aggregate the Swissgrid data

– Input data:	gdxdata**\%byr%.gdx** ==> gdxdata**2015.gdx**
– Output data:	gdxdata**sgdata.gdx**

The routine **aggregate.gms** uses the disaggregate Swissgrid data provided at quarterly time segments over the year and aggregates the data to a coarser time schedule at an hourly basis. The key output data then are generation, consumption, exports and imports by trading partners. The data is scaled from KWh to GWh which is the unit used in the annual data on power production by electricity technology provided by SFOE (generation.xlsx) and is the unit adopted in the electricity network model.

At the end, **aggregate.gms** dumps up electricity data by hour (0 to 23) and month (1 to 12) over the year across Swissgrid cantons

```
execute_unload 'gdxdata\sgdata.gdx',sgdata,sgd,month,hour,cty,r,days;
```

with the following details:

– set month	Months of the year (1 to 12)
– set hour	Hours over the day (0 to 23)
– set days	Number of days in a specific month
– set cty	All neigboring trading partners (aut, deu, fra, ita)
– set r	Swissgrid regions (cantons and composite cantons)
– set sgd	Items in the aggregated Swissgrid data set (M Imports, E Exports, C Consumption by canton, Y Generation by canton)
– parameter sgddata (sgd,month,hour,*)	Composite Swissgrid electricity dataset by region (in MWh)

*N.B.:sgddata then reports how much electricity is produced (consumed, exported, imported traded) in a specific month and hour, i.e., we sum the more disaggregate data which is provided for quarterly time segments over the year (35040 time segments) over the days in that month such that we end up with 12*24 = 288 observations rather than 8760 observations at an hourly scale and 35040 observations at a quarterly-hour scale*

- **cities**.**gms**: Compute proximity to cities for node assignment

– Input data:	gdxdata**network.gdx** xlsdata**geonames.xlsx**
– Output data:	gdxdata**cities.gdx**

The routine **cities**.**gms** uses node and city location data to attribute power demands by cantons to nodes in the network based on the proximity of cities to network nodes. Together with network node locations wee read in geographical (longitude-latitude) information and population numbers by city as well as the association of cities with cantons (note that we focus here on the top-50 cities (k50)in each region in terms of population). We determine which node n in the network is closest to each of the city k in each region r (set citynode(k,r,n)). With the assumption that demand is proportional to the city population share, we then can attribute the demand of region r which must be satisfied by node n in the network (see parameter thetad(r,n) in **model**.**gms**).

At the end, **cities**.**gms** provides data on city population, location and proximity to network nodes which is used later on to share out regional electricity consumption to network nodes

```
execute_unload 'gdxdata\cities.gdx', citydat, citynode,  citylist;
```

with the following details:

– citydat(k,r,"ctyshr")	Share of city k (k largest) in overall population across all top50 cities in region r
– citynode(k,r,n)	Nearest node n to the kth largest city in region r
– citylist(k,r,cityid,city)	List of cities by region, city id and city name

- **avail.gms**: Approximate physical availability of natural resources (sun and wind) for renewable power generation

  At the end, **avail.gms** provides physical data on wind and sunshine by hour and month (for representative days)

  ```
  execute_unload 'gdxdata\avail.gdx',avail_=avail;
  ```

  with the following details:

  – parameter avail (et, m,h) Physical availability of sun and wind (GWh)

Appendix C: Description of the integrated PE-GE electricity-economy model

Introduction

The integrated electricity-economy model framework for Switzerland consists of a bottom-up partial equilibrium (PE) model of the Swiss electricity system and a top-down general equilibrium (GE) model of the Swiss economy.

The PE model is formulated as a network model with transmission lines between network nodes where generators (plants) dispatch electricity to satisfy domestic electricity demands taking into account cross-border electricity import supply and export demand. The PE model is solved as a quadratic programming problem which maximizes economic surplus as the area between price-responsive demand and price-responsive supply curves.

The GE model features a cantonal representation of production and consumption activities with intra-Swiss trade and international exports and imports. It combines data from Swiss input-output tables with assumptions about market structure and elasticities that govern how responsive supply and demand are to price changes. The electricity system within the GE component is represented in reduced form as a netput vector of electricity system output (here: electricity supply to satisfy electricity demands in industries, services and final demand) and electricity system demands (here: inputs/costs for power generation, transmission, and distribution). The GE model is solved as a mixed complementarity problem where three classes of conditions characterize the economic equilibrium: zero-profit conditions for constant-returns-to-scale producers, market-clearance conditions for all goods and factors, and income-balance conditions for the representative agent in each canton. An equilibrium allocation determines the economic variable that are associated with the economic equilibrium conditions: zero-profit conditions pin down the activity levels of production, market-clearance conditions determine prices for goods and factors, and income-balance conditions identify the income levels of the representative agents.

Following some policy shock to the PE model -- e.g. a nuclear phase-out -- the PE and GE models are interfaced iteratively such that the integrated solution constitutes an outcome which accounts for general equilibrium market interaction and income effects.

Starting from an initial PE solve, the electricity netput vector of the GE model gets updated from the PE model via:

- a canton-specific supply index for electricity by demand segment (industry, service, final demand)
- a canton-specific cost multiplier for electricity distribution cost
- a canton-specific cost multiplier for electricity generation cost
- a canton-specific share of electricity sector rents (e.g. rents on generation capacities, transmission capacities)
- cross-border electricity imports and exports

With the PE input, the GE model then solves for the economy-wide impacts of the electricity sector shock incorporating market interaction effects and income effects via general equilibrium price adjustments. The GE model interfaces to the PE model via:

- a canton-specific price (cost) index for variable inputs to power generation and distribution margins
- an update (recalibration with recentered reference prices and demands) of the electricity demand functions by canton and demand segment which enter the economic surplus maximization of the PE model

The iterative coupling stops after some prescribed deviation tolerance for variables in subsequent solves is met. The formal coupling procedure is described in more detailed by Böhringer and Rutherford (2009).

Note that we can run the PE model in isolation to obtain a partial equilibrium result for electricity market variables (e.g. dispatch by generators, transmission flows, rents on generator capacities, etc.). To run the GE model in isolation, we need to re-introduce some basic endogeneity into the description of electricity supply such as price-elastic power generation by discrete aggregate technologies (e.g. runriver, nuclear, storage) and a power transmission/distribution sector. The subdirectory GE-Stand-Alone features such an extended GE logic which allows for a stand-alone GE analysis of electricity market shocks with discrete power technologies but absent any representation of power network constraints.

Directory and file structure

The main model directory features the following subdirectories:

• \GEdata	GE data subdirectory for building the general equilibrium dataset -- see GEdata.txt
• \PEdata	PE data subdirectory for building the partial equilibrium dataset -- see PEdata.txt
• \scenarios	Subdirectory with policy scenarios
• (\output)	(Invoked) subdirectory which keeps iterative PE and GE solutions for each scenario

The following files reside in the main directory:

– **run.bat**	Batch-file which invokes a series of GAMS programs for calibration of the integrated PE-GE submodels and the iterative solution process of policy scenarios
– **pe.gms**	Electricity network model calibrated to PE data
– **pege.gms**	Electricity network model reconciliating PE and GE data
– **accounting.gms**	Subroutine for PE analysis which cross-checks physical flow balances as well as implicit economic value balances
– **pereport.gms**	Reporting routine of variables for the PE network model

– **ge.gms**	Top-down GE model with exogenous treatment of the electricity sector
– **gedata.gms**	Routine for reading in cantonal (GE calibrated) dataset
– **gereport.gms**	Reporting routine of variables for the GE cantonal model
– **iterate.gms**	Outer iteration program for interfacing the PE-GE models
– **geiter.gms**	Subroutine invoked by iterate.gms to load the PE solution and solve the GE model
– **peiter.gms**	Subroutine invoked by iterate.gms to load the GE solution and solve the PE model
– **peresults.xlsx**	Pivot-charts-tables with PE results
– **geresults.xlsx**	Pivot-charts-tables with GE results

Batch file

The batch file **run.bat** invokes the series of GAMS programs to process the integrated PE-GE analysis and calls the following GAMS routines: --> **pe.gms** --> \gebuild**disagg.gms** --> **geaggr.gms** --> **pege.gms** --> **ge.gm**s --> **iterate.gms**

GAMS routines

- **pe.gms**: Calibrates the PE network model to bottom-up data and solves the PE network model

  gams pe s=pe

– Input data:	PEdata\gdxdata**network.gdx**: Data file on electricity network characteristcs (nodes, arcs, etc.) PEdata\gdxdata**cities.gdx**: Data file with city population, location and proximity to network nodes PEdata\gdxdata**plants.gdx**: Data file with plant/generator data (type, location, capacity) PEdata\gdxdata**sgdata.gdx**: Data file Swissgrid information on cantonal electricity supply and demand by hour and month PEdata\gdxdata**ptdf.gdx**: Data file with power transfer distribution factors and transmission capacities PEdata\gdxdata**rainfall.gdx**: Data file with water inflows and reservoir capacities
– Output data:	GEdata\gdxdata**bottomup.gdx**: Data file with regional eletricity generation shares produced by PE buildstream

The routine **pe.gms** solves a sequence of partial equilibrium electricity market models where we modify/add constraints towards the final model setting "eqtrade" which serves as the reference for our PE network model of the Swiss electricity market. The model determines power dispatch by plants, transmission flows, nodal demands and expots as well as imports (currently we keep with a time resolution for disptach across hours (0..23) and months (1..12).

The sequence of models is as follows:

– copperplate:	Cost minimization of power generation to meet exogenous demands with upper limits for nuclear power generation and fixed trade flows
– thermalgen:	Same as initial copperplate but with targeted generation of thermal production as of SFOE 2015
– copperplate:	We adjust the cost coefficient for thermal plants to account for the marginal of the production target and then drop the explicit production constraint.
– network:	Here we include flexible demand functions and recast the objective function in terms of economic surplus maximization. We also restate electricity node balances (equation nodebal) accounting for transmission inflows and outflows subject to transmission capacity constraints on arcs.
– (-ptdfnetwork):	A slight variation of network where we include PTDFs and replace the nodebal-equation (flowgate) by PTDF relationships (ptdf_pos and ptdf_neg)
– eqtrade:	Our final reference for the PE electricity market model with elastic import supply and export demand functions. The solution of eqtrade serves for centering the demand functions (dref,pref).

As an input for the disaggregation of national input-output accounts into cantonal IO tables the PE model unloads technology generation shares by canton:

```
execute_unload 'GEdata\gdxdata\bottomup.gdx',etshares;
```

We keep track of the PE model as a save-file from which we can do subsequent restarts.

- **disagg.gms / geaggr.gms** : **Disagg.gms** use PE data to disaggregate GE data, **geaggr.gms** aggregate the GE data to the target mapping

```
gams disagg

gams geaggr --target=macro  o=macro.lst
```

The PE regional power technology shares generated by pe.gms are used to disaggregate the national GE electricity generation by technologies into cantonal accounts. We first change the work directory to \gedata (cd gedata) and then invoke

– gams **disagg.gms**	Reads the national IO dataset **siot.gdx** together with the regional information on gross-value added across industries from gva2011.gdx plus the technology shares in **bottomup.gdx** to generate a cantonal input-output dataset for Switzerland (**disagg.gdx**).
– gams **geaggr.gms**	Reads in the disaggregate cantonal dataset **disagg.gdx** and aggregates the economic accounts subject to some target mapping (by default: mapping macro.map with a compact sector aggregation.

At the end, **geaggr.gms** produces a composite regional IO dataset for the target mapping %target% (by default: %target% == macro)

```
execute_unload 'gdxdata\%target%.gdx'
```

which is used subsequently as the input data for the top-down GE model.

N.B.: We can build the GE dataset from scratch -- via: call gebuild.bat -- if the buildstream has not been invoked before separately in \gedata (see GEbuild.tdoc).

- **pege.gms / ge.gms**: pege.gms solves the PE model calibrated to GE data, ge.gms checks if the initial PE-GE handshake holds

```
gams pege s=pege r=pe gdx=pege

gams ge --pechk=yes s=ge o=pechk.lst
```

The routines **pege.gms** and **ge.gms** constitute the PE and GE model components of the integrated PE-GE modeling framework.

The model **pege.gms** follows up with a restart from the partial equilibrium network logic/data provided as /eqtrade/ in **pe.gms**. First, we invoke the GE model from within **pege.gms** $call 'gams ge gdx=ge s=ge' in order to retrieve some top-down electricity market data on generation cost, distribution cost and capital earnings for comparison with the bottom-up PE model solution. For the GE alignment of the PE mode, we move differences between BU and TD data into margin demands and specify initial electricity market rents (capital earnings) in line with the TD data.

Furthermore, we extent the PE network model /eqtrade/ towards the model /pe/ with electricity demands by canton and demand segments which in aggregate (across demand segments) must be equal to the specific electricity demands by month and hour (see **pege.gms**):

– positive variable AD(r,ds)	Annual demand index;
– equation	aggdemand(m,hr,r)$dref(m,hr,r).. D(m,hr,r) =e= sum(ds, refd(m,hr,r,ds)*AD(r,ds));

The routine **ge.gms** invokes the GE model with the reduced from representation of the electricity model as a netput vector (outputs and inputs) of the electricity system (see the composite sector) $prod:ELEUP in **ge.gms** which gets updated from the PE solution.

The initial electricity (sub-)sectors of the GE stand alone model

- electricity distribution and transmission ($prod:ye(ele))
  ==> ele: "Electricity distribution and trade (40e)
- electricity generation by technologies ($prod:X(r,et))
  ==> et: run (run-off hydro), sto (storage hydro), nuc (nuclear), fos (fossil), woo (wood), wnd (wind and PV), ewi (waste incineration)

no longer appear in the integrated GE-PE model version.

As we invoke **ge.gms** with the environment variable --pechk=yes we can test if the GE model can be correctly recalibrated to the PEGE model solution with international exports and imports after loading the PE interface values that enter into the GE model (see above).

- **iterate.gms** / **geiter.gms** / **peiter.gms**: Iterative scenario solves

Iterative PE-GE solves for policy shocks as specified in scenario files residing within subdirectory \scenarios (here: bau, ref, bal) ==> set scn=scen

gams iterate --scn=%scn% o=%scn%.lst gdx=%scn%

Prior to to the iteration routine -- **iterate.gms** -- we must have solved the PE-GE calibrated model (see above: gams **pege** s=pege r=pe gdx=pege).

The **pege.gms**-routine first retrieves top-down data from the GE model with an internal solve ($call 'gams ge gdx=ge s=ge') which is used subsequently to recalibrate the PE network model (note that we start from the initial network model **solve** r=pe).

Within **iterate.gms** we solve for a counterfactual policy shock by iteratively interfacing the GE top-down model (gams **geiter** r=ge) with the PE bottom-up model (gams **peiter** r=pege). The GE interface variables to the PE model get written out from **ge.gms** to the file **gesol.gdx** which subsequently is read in by **pe.gms**. The PE interface variables to the GE model get written out from **pe.gms** to the file **pesol.gdx** which subsequently is read in by **ge.gms**

Within run.bat we solve three scenarios

– \scenarios**bau.gms**	BaU replication check
– \scenarios**ref.gms**	Nuclear phase out

– \scenarios**bal.gms**	Nuclear phase out with energy security constraint (no change in nettrade vis-à-vis BaU)

- **Merge.gms**: Merge the scenario results and produce XLSX GE and PE reports

  gams merge

– Input data:	results\ge*.gdx: Scenario gdx-files with results for GE sub-model results\pe*.gdx: Scenario gdx-files with results for PE sub-model
– Output data:	**ge_results.xlsx**: Pivot-tables/charts with GE results **pe_results.xlsx**: Pivot-tables/charts with PE results

The merge routine merges the GDX results file for invoked scenarios (\scenarios) both for the GE as well as the PE model solutions. The merged GDX files are then extracted to yield Excel report files with Pivot-tables/charts. For the specific items and formats of the report see the descriptions in **gereport.gms** and **pereport.gms**.

Appendix D: GAMS code

GAMS Model Code 1: Dispatch of hydro generation by storage plants

```
nonnegative
variables         Y(m,hr,g)          Production profile,
                  Z(m,hr,g)          Production profile -- circular mode,
                  F(g)               Water inflow by plant (index)

                  RL(m,g)            Reservoir level (primary reservoir),
                  RS(m,g)            Reservoir level (secondary reservoir)
                  RP(m,hr,g)         Reservoir level (circular pumped storage),

                  HS(m,hr,g)         Hydro pumping (secondary storage plant)
                  H(m,hr,g)          Hydro pumping (circular generation)

                  AS(m,hr)           Aggregate supply;

variable          PI                 Aggregate value of production,
                  WU                 Water use;


equations         profit             Accounting of revenues from hydro power supplies (AS) ,
                  water              Aggregate demand for water inflows (used for calibration) ,
                  supply             Aggregate supply of hydro electricity (just an accounting device for AS))
                  primary            Energy balance at primary reservoir,
                  secondary          Energy balance at secondary reservoir,
                  pumpstorage        Energy balance for circular pump storage,
                  pmp_dem            Pumping demand,
                  sto_gen            Hydro generation by storage plants,
                  crc_gen            Hydro generation by circula pumping plants;

...

*       Electricity generation including net generation from circular pumping  (Y+Z-H)  minus pump storage demand (HS)
*       equals aggregate electricity supply (demand)
supply(m,hr)..                       sum(g, Y(m,hr,g) + (Z(m,hr,g) - H(m,hr,g))$crc(g) - HS(m,hr,g)$pmp(g)) =e= AS(m,hr);

*       Aggregate water use equals the sum across all inflows
water..                              WU =e= sum(g, F(g)*sum(m,inflow(m,g)));

*       Inter-period energy balance for storage plants operating with a primary reservoir
*       The reservoir level in month m + water inflows in month m + additional water from pumping (from potential
*       secondary reservoirs adjusted for losses) equals the reservoir level in the next month + the dispatched
*       hydro power
```

```
primary(p_primary(m++1,sto(g)))..
                RL(m,g)  + F(g)*(1-sflow(g))*inflow(m,g)   + sum((hr,pmp(g)),  (1-0.2*head(g))*HS(m,hr,g))
                        =g=
                RL(m++1,g)  + sum(hr,Y(m,hr,g));

*       Inter-period energy balance for storage plants operating with a secondary reservoir
*       The reservoir level in month m + water inflows in month m equals the the reservoir level in the next month
*       + hydro power used for pumping of water from the lower level secondary to the upper level primary reservoir

secondary(p_secondary(m++1,pmp(g)))..
                RS(m,g)  + F(g)*sflow(g)*inflow(m,g)  =g= RS(m++1,g)  + sum(hr, HS(m,hr,g));

*       For circular pump storage the reservoir level in period m /hour plus the efficiency loss adjusted pumping
*       in period m/hour equals the reservoir level in the next period + dispatch

pumpstorage(p_pumpstorage(m,hr++1,crc(g)))..
                RP(m,hr,g)  + (1-0.20)*H(m,hr,g) =g= Z(m,hr,g)  + RP(m,hr++1,g);

*       Target dispatch for storage power plants by season

sto_gen(sto(g),season)$stogen(g,season)..       sum((sm(m,season),hr),Y(m,hr,g))  =e= stogen(g,season);

*       Target pumping demands for circular mode hydro power plants

pmp_dem(pmp(g),season)$pmpdem(g,season)..       sum((sm(m,season),hr),HS(m,hr,g)) =e= pmpdem(g,season);

*       Target dispatch for circular mode hydro power plants

crc_gen(crc(g),season)$crcgen(g,season)..       sum((sm(m,season),hr),Z(m,hr,g))  =e= crcgen(g,season);
```

GAMS Model Code 2: Calib – first calibration step

```
*       Define the basic (first-pass) calibration model for hydro-power operation (feasibility)
* ----------------------------------------------------------------------------------------------
model calib /water, profit, supply, primary, secondary, pumpstorage, sto_gen, crc_gen, pmp_dem/;
* -----------------------------------------------------------------------------------------------
*       All relationships in the calibration routine are linear so we can solve an LP
*       As laid out above, we try to match exogenous data as close as possible by minimizing
*       the total water use (inflow) --  F(g) which scale the exogenous water inflow is used as
*       flexibility variable here
solve calib using lp minimizing WU;

parameter       profile         Monthly profile on power operation;
profile(m,"price")      = sum((hr,rgeo(r)),pscp(m,hr)*sgdata("c",m,hr,rgeo)) /
                          sum((hr,rgeo(r)),sgdata("c",m,hr,rgeo));
profile(m,"inflow")     = sum(g, inflow(m,g)*F.L(g));
profile(m,"spill")      = sum(sto(g), RL.L(m,g) + inflow(m,g)*F.L(g) - sum(hr,Y.L(m,hr,g)) - RL.L(m++1,g));
profile(m,"storage")    = sum(sto(g), foedata(g,"storage"));
profile(m,"RL.L")       = sum(sto(g), RL.L(m,g));
profile(m,"run")        = sum((hr,typ("run",g)),Y.L(m,hr,g));
profile(m,"sto_")       = sum((hr,g)$(sto(g) and not (pmp(g) or crc(g))), Y.L(m,hr,g));
profile(m,"pmp")        = sum((hr,g)$(pmp(g) and not crc(g)), Y.L(m,hr,g) -HS.L(m,hr,g));
profile(m,"crc")        = sum((hr,g)$crc(g), Y.L(m,hr,g) + Z.L(m,hr,g)-H.L(m,hr,g));
profile(m,rnw)          = sum((hr,etmap(g,rnw)),Y.L(m,hr,g));
profile(m,oth)          = sum((hr,etmap(g,oth)),Y.L(m,hr,g));
profile(m,"nuc")        = sum((hr,etmap(g,"nuc")),Y.L(m,hr,g));
profile(m,"supply")     = sum((hr,g), Y.l(m,hr,g) + (Z.l(m,hr,g) - H.l(m,hr,g)) -HS.l(m,hr,g));

parameter gen_sto       Generation of storage power plants;
gen_sto("all")          = sum((hr,m,g)$sto(g), Y.l(m,hr,g) + (Z.l(m,hr,g) - H.l(m,hr,g)) -HS.l(m,hr,g));
gen_sto("sto_")         = sum(m, profile(m,"sto_"));
gen_sto("pmp")          = sum(m, profile(m,"pmp"));
gen_sto("crc")          = sum(m, profile(m,"crc"));
gen_sto("chk")          = gen_sto("all") - gen_sto("sto_") - gen_sto("pmp") - gen_sto("crc");

*       We have minimized water inflow to make the calibration feasible.
*       Now we fix the water inflows at the calibrated levels:

F.FX(g) = F.L(g);

*       Other generation: wst (waste incineration), woo (wood-biomass) and fos (fossil = oil, gas):

parameter       thetatherm(g)           Share of thermal generator g in overall thermal generation capacity,
                thermcap                Thermal capacity;

thermcap = sum(etmap(g,oth),weppdata(g,"wepp_mw"));

loop(oth, thetatherm(g)$etmap(g,oth) = weppdata(g,"wepp_mw")/thermcap;);

*       Split FOE monthly thermal generation for base year across thermal plants
*       proportional to capacity share  -- recall that the variable generation in
*       the model is defined by month and hour (cumulated across the days of the month)
*       so we divide monthly generation by the number of hours to assure that thermal
*       generation does not exceed that reported total generation by month.

loop(etmap(g,oth),  Y.UP(m,hr,g) = thetatherm(g)*foegen(m,"therm","2015")/24;);
```

GAMS Model Code 3: Dispatch – second calibration step

```
*       Define model dispatch where we solve for the profit maximizing dispatch
*       pattern with fixed run-of-river generation and upper bounds on storage water
*       as well as thermal power generation (here we assume that demand is infinitely
*       elastic at a given price of pscp)

* -------------------------------------------------------------------------
model dispatch /profit, supply, water, primary, secondary, pumpstorage/;
* -------------------------------------------------------------------------

solve dispatch using qcp maximizing PI;

profile(m,"price")      = sum((hr,rgeo(r)),pscp(m,hr)*sgdata("c",m,hr,rgeo)) /
                          sum((hr,rgeo(r)),sgdata("c",m,hr,rgeo));
profile(m,"inflow")     = sum(g, inflow(m,g)*F.L(g));
profile(m,"spill")      = sum(sto(g), RL.L(m,g) + inflow(m,g)*F.L(g) - sum(hr,Y.L(m,hr,g)) - RL.L(m++1,g));
profile(m,"storage")    = sum(sto(g), foedata(g,"storage"));
profile(m,"RL.L")       = sum(sto(g), RL.L(m,g));
profile(m,"run")        = sum((hr,typ("run",g)),Y.L(m,hr,g));
profile(m,"sto_")       = sum((hr,g)$(sto(g) and not (pmp(g) or crc(g))), Y.L(m,hr,g));
profile(m,"pmp")        = sum((hr,g)$(pmp(g) and not crc(g)), Y.L(m,hr,g) -HS.L(m,hr,g));
profile(m,"crc")        = sum((hr,g)$crc(g),Y.L(m,hr,g) + Z.L(m,hr,g)-H.L(m,hr,g));
profile(m,rnw)          = sum((hr,etmap(g,rnw)),Y.L(m,hr,g));
profile(m,oth)          = sum((hr,etmap(g,oth)),Y.L(m,hr,g));
profile(m,"nuc")        = sum((hr,etmap(g,"nuc")),Y.L(m,hr,g));
profile(m,"supply")     = sum((hr,g), Y.l(m,hr,g) + (Z.l(m,hr,g) - H.l(m,hr,g)) -HS.l(m,hr,g));

*       Next we introduce power generation for renewables and nuclear power
*       We fix these at base-year levels
*       In the base-year (here: 2015) the contribution of renewables to power generation
*       is very small (around 1.7% from solar and 0.2% from wind)

parameter       rnwgen(et,*)    Renewable generation in base year /sol.share 0.017, win.share 0.002/;
.....

*       Fix renewables supplies based on re-scaled estimated availability:

Y.UP(m,hr,win(g)) = round(rnwgen("win","ratio") * avail("win",m,hr) * weppdata(g,"WEPP_MW")/1e3 * days(m),4);
Y.UP(m,hr,sol(g)) = round(rnwgen("sol","ratio") * avail("sol",m,hr) * weppdata(g,"WEPP_MW")/1e3 * days(m),4);

parameter       thetanuc(g)     Share of nuclear capacity by power plant g in overall nuclear capacity;

thetanuc(g) = weppdata(g,"WEPP_MW")/sum(gg$etmap(gg,"nuc"),weppdata(gg,"WEPP_MW"));

*       As with run-of-river plants and renewables plants we fix nuclear power generation at base-year levels
*       based on the assumption of sunk fixed cost and negligible variable cost
loop(etmap(g,"nuc"),
  Y.UP(m,hr,g) = foegen(m,"nuc","2015")/24 * thetanuc(g););

parameter       nucL    Level values of nuclear plants;

nucL(nuc,m,"uniform") =  sum(hr,Y.L(m,hr,nuc));

*       Next we impose observed cantonal nuclear power shares in overall nuclear power generation
parameter       nucshare(r)     Cantonal share of nuclear generation
                nuccap(r)       Cantonal nuclear generation capacity;

nuccap(r) = sum(grmap(nuc(g),r),weppdata(g,"WEPP_MW"));

loop((etmap(g,"nuc"),grmap(g,r)),
  Y.UP(m,hr,g) = foegen(m,"nuc","2015")/24 * nucshare(r) * weppdata(g,"WEPP_MW")/nuccap(r););

nucL(nuc,m,"target") =  sum(hr,Y.L(m,hr,nuc));

*       Resolve dispatch model with nuclear and renewable technologies
solve dispatch using qcp maximizing PI;
```

```
profile(m,"price")      = sum((hr,rgeo(r)),pscp(m,hr)*sgdata("c",m,hr,rgeo))  /
                          sum((hr,rgeo(r)),sgdata("c",m,hr,rgeo));
profile(m,"inflow")     = sum(g, inflow(m,g)*F.L(g));
profile(m,"spill")      = sum(sto(g), RL.L(m,g) + inflow(m,g)*F.L(g) - sum(hr,Y.L(m,hr,g)) - RL.L(m++1,g));
profile(m,"storage")    = sum(sto(g), foedata(g,"storage"));
profile(m,"RL.L")       = sum(sto(g), RL.L(m,g));
profile(m,"run")        = sum((hr,typ("run",g)),Y.L(m,hr,g));
profile(m,"sto_")       = sum((hr,g)$(sto(g) and not (pmp(g) or crc(g))), Y.L(m,hr,g));
profile(m,"pmp")        = sum((hr,g)$(pmp(g) and not crc(g)), Y.L(m,hr,g) -HS.L(m,hr,g));
profile(m,"crc")        = sum((hr,g)$crc(g),Y.L(m,hr,g) + Z.L(m,hr,g)-H.L(m,hr,g));
profile(m,rnw)          = sum((hr,etmap(g,rnw)),Y.L(m,hr,g));
profile(m,oth)          = sum((hr,etmap(g,oth)),Y.L(m,hr,g));
profile(m,"nuc")        = sum((hr,etmap(g,"nuc")),Y.L(m,hr,g));
profile(m,"supply")     = sum((hr,g), Y.l(m,hr,g) + (Z.l(m,hr,g) - H.l(m,hr,g)) -HS.l(m,hr,g));

...

*       Next we incorporate elastic supply/demand functions and make re-cast the simple dispatch model
*       into an economic surplus maximization problem

parameter       etam                    Import supply elasticity,
                etae                    Export demand elasticity,
                epsilon(m,hr)           Elasticity of (domestic) demand,

                msref(m,hr,cty)         Reference import quantity by neighboring country (cty),
                edref(m,hr,cty)         Reference export quantity by neighboring country (cty),
                dref(m,hr,r)            Reference demand;

*       Assign elasticities and reference quantities (the latter based on Swissgrid data):

parameter esub          Generic supply-and-demand elasticity;

esub = 1.0;

etam(m,hr)      = 4;
etae(m,hr)      = 4;
epsilon(m,hr)   = esub;

msref(m,hr,cty)  = sgdata("m",m,hr,cty);
edref(m,hr,cty)  = sgdata("e",m,hr,cty);
dref(m,hr,r)     = sgdata("c",m,hr,r);


*       Impose default marginal cost of generation
parameter       gc(g)   Variable generation cost -- short-run marginal cost (in CHF per MWh);

....

*       Additional logic to include the possible of capacity expansions by
*       power generation technology et at node k

set             ntl(et,k)               Location of new technology to network nodes,
                nta(et,k,m,hr)          New technology available hours;

parameter       dc(et,k)                Dispatch cost (short-run marginal cost),
                kc(et,k)                Capital (investment) cost,
                knlim(et,k)             Upper capacity bound,
                nodal_avail(et,k,m,hr)  Availability for new vintage investment;
```

```
nta(et,k,m,hr)  = no;
ntl(et,k)       = no;
dc(et,k)        = 0;
kc(et,k)            =     0;
knlim(et,k)         =     0;
nodal_avail(et,k,m,hr) = 0;

parameter       alpha   Quadratic cost coefficient for expansion /4/;


parameter mobj          Multiplier of objective function;
*.mobj = 1000;
mobj = 1;


nonnegative variables           D(m,hr,r)       Regional demand (GWh),
                                M_S(m,hr,cty)   Import supply from neighboring country (GWh),
                                E_D(m,hr,cty)   Export demand by neighboring country (GWh),
                                YN(et,k,m,hr)   New vintage generation by technology (GWh),
                                KN(et,k)        New vintage capacity (GWh);

variable                        OBJ     Social surplus objective;

equations       csobjdef, market;

csobjdef..      OBJ =e= 1/mobj * (


*       Variable cost of power generation with extant power plants
                                sum((m,hr,g), gc(g)*Y(m,hr,g))


*       Variable cost of new vintage production
                              + sum(nta(ntl,m,hr), dc(ntl)*YN(nta))

*       Capital cost for capacity expansion
                              + sum(ntl(et,k), kc(et,k) * (KN(et,k)+alpha*SQR(KN(et,k))))

*       Cost for import supply
                              + sum((m,hr,cty)$(M_S.LO(m,hr,cty)<M_S.UP(m,hr,cty)),
                              pmref(m,hr,cty) * M_S(m,hr,cty) *
                              (1 + (M_S(m,hr,cty)/(2*msref(m,hr,cty))-1)/etam(m,hr)))

*       Revenues from export demand
                              - sum((m,hr,cty)$(E_D.LO(m,hr,cty)<E_D.UP(m,hr,cty)),
                              peref(m,hr,cty) * E_D(m,hr,cty) *
                              (1 - (E_D(m,hr,cty)/(2*edref(m,hr,cty))-1)/etae(m,hr)))

*       Total gross consumer surplus associated with  domestic demand (area under the demand curve)
                              - sum((m,hr,r)$dref(m,hr,r),      pref(m,hr,r) * D(m,hr,r) *
                              (1 - (D(m,hr,r)/(2*dref(m,hr,r)) - 1)/epsilon(m,hr)))
                              );

*       Market clearance conditions with flexible demands
market(m,hr)..  sum(g, Y(m,hr,g) + Z(m,hr,g)$crc(g) - H(m,hr,g)$crc(g) - HS(m,hr,g)$pmp(g))
                               + sum(nta(ntl(et,k),m,hr), YN(nta))
                      =e= sum(r, D(m,hr,r)) + sum(cty, E_D(m,hr,cty) - M_S(m,hr,cty));
```

GAMS Model Code 4: Copperplate – third calibration step

```
*       Define copperplate model with elastic demands where we do not account for a transmission network
* ------------------------------------------------------------------------------------
model copperplate / csobjdef, market, primary, secondary, pumpstorage/;
* ------------------------------------------------------------------------------------

D.L(m,hr,r)   = sgdata("c",m,hr,r);
D.UP(m,hr,r)  = +inf;
D.LO(m,hr,r)  = 0;
D.L(m,hr,r)$(not sgdata("c",m,hr,r)) = 0;

*       Fix exports and imports (we then can recalibrate the reference price
*       at a level which differs from the reference price of domestic demand and import supply):

E_D.FX(m,hr,cty)  = sgdata("e",m,hr,cty);
M_S.FX(m,hr,cty)  = sgdata("m",m,hr,cty);
...
solve copperplate using qcp minimizing OBJ;

*       Recalibrate reference prices for export and imports
*       to the market price (market.m) and then resolve copperplate model
*       To obtain prices in CHF per MWh we have to divide the dual
*       of the market clearance condition by objscale

peref(m,hr,cty)  = mobj  * market.m(m,hr);
pmref(m,hr,cty)  = mobj  * market.m(m,hr);
M_S.LO(m,hr,cty)$sgdata("M",m,hr,cty)  = 0;
M_S.UP(m,hr,cty)$sgdata("M",m,hr,cty)  = +INF;
E_D.LO(m,hr,cty)$sgdata("E",m,hr,cty)  = 0;
E_D.UP(m,hr,cty)$sgdata("E",m,hr,cty)  = +INF;
solve copperplate using qcp minimizing OBJ;

$set mdl CopperPlate
```

GAMS Model Code 5: Network calibration

```
*       --------------------------------------------------------------------------------
*       Network calibration:
*       --------------------------------------------------------------------------------

parameter       cref(m,hr,k)            Nodal consumption;

*       We share our regional demands to nodal consumption by means of regional demand shares theta(r,k)
*       which are derived from city population data and cities' proximity to nodes in the network
cref(m,hr,k)  = sum(r,thetad(r,k)*dref(m,hr,r));

nonnegative
variables               X(m,hr,i,j)     Transmission,
                        XR(i,j)         Arcs requiring additional capacity,
                        C(m,hr,k)       Nodal consumption;

variables               NX(m,hr,cty,k)  Net Exports;

equations               networkobj      Economic surplus maximization,
                        nodebal         Energy balance in network nodes,
                        nxdef           Defining equation for net exports,
                        capacity        Capacity restrictions on new vinatage expansion,
                        tgt_et(et)      Targeting of annual generation by technology;

parameter       avail_(et,k,m,hr)       Availability scaled by locational efficiency factor,
                eff(et,k)               Locational efficiency index,
                tgtval(et)              Target annual power generation (zero implies no target);

tgtval(et)  = 0;
eff(et,k)   = 1;
avail_(ntl(et,k),m,hr)  = avail(et,m,hr)*eff(ntl);

nonnegative
variable        DISPOSE(m,hr,k)         Nodes with load shedding;

nodebal(m,hr,k)..       sum(a(i,k), X(m,hr,i,k)) + sum(gmap(g,k), Y(m,hr,g)  + Z(m,hr,g)$crc(g))

                                                  + sum(nta(ntl(et,k),m,hr), YN(nta))

                        =E=

                        DISPOSE(m,hr,k)  +

                        sum(r,thetad(r,k)*D(m,hr,r))  +

                        sum(a(k,j), X(m,hr,k,j))  +

                        sum(gmap(g,k),  H(m,hr,g)$crc(g)  + HS(m,hr,g)$pmp(g))  +

                        sum(bnmap(cty,k), NX(m,hr,cty,k));

nxdef(m,hr,cty)$(edref(m,hr,cty)+msref(m,hr,cty))..

                        sum(bnmap(cty,k),NX(m,hr,cty,k))  =e=  E_D(m,hr,cty)  - M_S(m,hr,cty);

capacity(nta(ntl(et,k),m,hr))..  YN(nta)  =l=  avail_(nta)*KN(ntl)*days(m);

tgt_et(et)$tgtval(et).. sum((r,nta(et,k,m,hr))$rmap(k,r), YN(nta))  +
                        sum((r,etmap(g,et),m,hr,grmap(g,r)),Y(m,hr,g))  =g=  tgtval(et);
networkobj..    OBJ =e= 1/mobj  *  (
```

```
*       Variable cost of power generation with extant power plants
                          sum((m,hr,g), gc(g)*Y(m,hr,g))

*       Variable cost of new vintage production
                        + sum(nta(ntl,m,hr), dc(ntl)*YN(nta))

*       Capital cost for capacity expansion
                        + sum(ntl(et,k), kc(et,k) * (KN(et,k) + alpha*SQR(KN(et,k))))

*       Cost for import supply
                        + sum((m,hr,cty)$msref(m,hr,cty),
                        pmref(m,hr,cty) * M_S(m,hr,cty) *
                        (1 + (M_S(m,hr,cty)/(2*msref(m,hr,cty))-1)/etam(m,hr)))

*       Revenues from export demand
                        - sum((m,hr,cty)$edref(m,hr,cty),
                        peref(m,hr,cty) * E_D(m,hr,cty) *
                        (1 - (E_D(m,hr,cty)/(2*edref(m,hr,cty))-1)/etae(m,hr)))

*       Consumer surplus associated with  domestic demand

                        - sum((m,hr,r), pref(m,hr,r) * D(m,hr,r) *
                        (1 - (D(m,hr,r)/(2*dref(m,hr,r)) - 1)/epsilon(m,hr))) );
```

GAMS Model Code 6: Network – fourth calibration step

```
*       Define electricity model with network constraints
* ----------------------------------------------------------------------------------------------
model network / networkobj, primary, secondary, pumpstorage, nodebal, nxdef, capacity, tgt_et/;
* ----------------------------------------------------------------------------------------------

*       Set upper bound on transmission capacity
X.UP(m,hr,a)  = tcap(a)*days(m);


E_D.LO(m,hr,cty)  = 0;
E_D.UP(m,hr,cty)  = +inf;
M_S.LO(m,hr,cty)  = 0;
M_S.UP(m,hr,cty)  = +inf;

solve network using qcp minimizing OBJ;


*       Center the demand function on the current solution and resolve:
dref(m,hr,r)  = D.L(m,hr,r);
pref(m,hr,r)  = mobj*sum(k,thetad(r,k)*nodebal.m(m,hr,k));
solve network using qcp minimizing OBJ;

*       Include the results report for the network model
*       Here we already define extension for the interfaced pe model defined in pege.gms
*       such that we can use the peaccounting throughout
set             ds                      Electricity demand segments /
                                        fd      final demand,
                                        ind     industrial sectors,
                                        srv     service sectors /;


*       Define PE cost indices (multipliers) updated from the GE solves
parameter       costindex(r)            Index of relative prices of variable inputs (BMK = 1),
                priceindex(r,ds)        Price index of wholesale electricity (BMK = 1),
                adindex(r,ds)           Aggregate electricity demand index (BMK = 1);


*       Initially all PE cost indices are set to unity
costindex(r)      = 1;
priceindex(r,ds)  = 1;
adindex(r,ds)     = 1;


display "PE results for network model:";
$include peaccounting


RP.L(m,hr,g)  = RP.L(m,hr,g) - smin(month, RP.L(month,hr,g));
RL.L(m,g)     = RL.L(m,g) - smin(month, RL.L(month,g));
RS.L(m,g)     = RS.L(m,g) - smin(month, RS.L(month,g));

$set mdl network
```

Appendix E: Reporting of the model results

PE reporting (see spreadsheet –pe_results.xlsx):

Parameters:

rep_quant(*,*,*,*)	Physical electrictiy market statistics (GWh)
rep_econ(*,*,*)	Economic values (1000 CHF)
rep_price(*,*,*)	Prices (CHF per MWh)
rep_acct(*,*,*)	Decomposition of revenues and cost (incl capital cost = rents)

Sets (dimension of report parameters):

Regional resolution:	cantons, neighboring regions, “total” (sum across all regions)
Time resolution:	months, hours, “annual”

Items in rep_quant:

et.tl	Power generation by technology (text-labeled with technology name)
Y:	Total generation (note: includes generation from new power plants)
YN:	Total generation from new power plants
C:	Electricity consumption
E:	Exports
M:	Imports
“M-E”:	Imports minus exports

Items in rep_econ:

VE:	Value of exports
VM:	Value of imports
CS_e:	Consumer surplus from exports (integral under export demand function)
CS_d:	Consumer surplus from domestic consumption (integral under consumer demand function),

PS_m: Producer surplus from imports

dmargin: Distribution margin (cost),

"gc*Y": Variable cost of dispatch from preexisting capacities (i.e. Y without YN)

"dc*YN": Variable cost of dispatch from new power plants capacities

"kc*KN": Capital (investment cost) of new power plants capacities

"d_surplus": Domestic surplus = CS_d - "gc*Y" -"dc*YN"-"kc*KN") -dmargin

"t_surplus": Total surplus = “d_surplus” + CS_e – PS_m

Items in rep_acct::

"P*MS": Value of import supply (cost)

"gc*Y": Dispatch cost of extant generation

"dc*YN": Dispatch cost of generation from new power plants

"kc*KN": Capital cost of new power plants capacities

"dmargin": Distribution margin (cost)

"inflow": Scarcity rents on water inflow

"Y.UP": Scarcity rents on upper generation (capacity) bounds for extant power plants

"KN.UP": Scarcity rents on upper bound for new power plants capacity

"RL.UP": Scarcity rents on capacity of primary reservoir for storage plants

"RS.UP": Scarcity rents on capacity of secondary reservoir for pump-storage plants

"RP.UP": Scarcity rents on water reservoir capacity for circular-pump-storage plants

"Z.UP": Scarcity rents on upper bound for dispatch from circular-pump-storage plants

"H.UP": Scarcity rents on upper bound for hydro-pumping of pump-storage plants (from secondary to primary reservoir)

"HS.UP": Scarcity rents on upper bound for circular pumping

"X.UP": Scarcity rents on transmission line capacity constraints

"PROD_tgt": Negative rents on enforced production/generation targets (subsidies)

"netimports": Negative rents on import constraints

"P*D": Value of domestic sales (sales)

"P*ED": Value of export sales (sales)

Cost: Cost components include: /"P*MS", "gc*Y", "dc*YN", "kc*KN", "dmargin"/

Rents: Rent components (which are interpreted as capital cost) include: /"inflow", "netimports", "Y.UP", "KN.UP", "RL.UP", "RP.UP", "RS.UP", "Z.UP", "H.UP", "HS.UP","X.UP", "PROD_tgt"/

Sales: Sales components include: /"P*D", "P*ED"/

Net: We compute a net economic handshake between cost and revenues as follows: Net = sales – cost – rents. The “Net” amount should be zero.

Net%: Handshake on Net accounting expresses as the ration of “net” over the total benchmark value of the retail electricity consumption value (“P*D”)

Format of reporting:

We report results of physical and economic indicators in different formats:

“scn”: absolute values (e.g. in GWh or 1000 CHF) for scenario values

“bau”: absolute value in BaU

“diff”: difference in absolute values between “scn” and “bau”

“pct”: the percentage change of the scenario value as compared to the bau value – note that percentage changes can be huge if the denominator in the BaU is very small (in this case it is even more important to look up absolute values as well (“bau”, “scn”,“diff”)

GE reporting (see spreadsheet –ge_results.xlsx):

Parameters:

rep_macro(*,*,*)	Report of macroeconomic results,
rep_sector(*,*,*,*)	Report of sector-specific results,
rep_ele(*,*,*,*)	Report of electricity market results,
rep_inc(*,*,*)	Report of income effects (decomposition);

Sets (dimension of report parameters):

Regional resolution: cantons (r), “total” (sum across all cantons)

Sector resolution: sectors of the dataset (incl. public good and investment production)

Commodity resolution: consumption goods of the dataset (cg)

Items in rep_macro:

Y: Total generation (note: includes generation from new power plants)

GDP: Gross domestic product

Consumption: Real consumption - (equivalent to welfare with fixed investment, fixed government demand and fixed labor supply)

Welfare: Welfare (HEV)

EV_GDP: Welfare loss stated as a fraction of BMK GDP (only in % changes)

Items in rep_sector:

Y: Production level

A: Armington supply

Z: Consumption good supply

LD: labor demand

YR: regional supply

YN: national supply

YX: international export supply

MN: national import

MM: international import

P: Price index for goods ("N" denotes the national pool price)

PA: Armington price index

PZ: Consumption good price index

PK: Rate of return

PL: Wage rate

Items in rep_ele:

PELE: Electricity price index by demand segment (r,ds)

PELESUP: Electricity supply price index

PELEGEN: Electricity generation cost index

FDELE: Electricity demand by consumption category (r,cg)

IDELE: Intermediate electricity demand (r,i)

Items in rep_inc:

BOBR	Adjusted "balance of payment" (vb0(r)+v0_ele(r))
OthRent	Capital earnings in sectors other than electricity (ke0(r,i))
IGS	Value of exogenous demands for investment, government, and stock changes
Wages	Wage earnings
EleRent	Rents in the electricity system
Taxes	Tax revenues
Eleinvest	Investment cost for new power plants expansion

Format of reporting: see pe_results.xlsx above

Appendix F: Storage power plants data

The data for the storage capacities and circulation mode operation comes from the following sources

- BFE (1974), Statistik der Wasserkraftanlagen der Schweiz 1.1.1973.
- BFE (1982), Statistik der Wasserkraftanlagen der Schweiz 1.1.1981.
- Margot André, Sigg Rudolf, Schädler Bruno, Weingartner Rolf (1992), Beeinflussung der Fliessgewässer durch Kraftwerke (>= 300 kW) und Seeregulierung. In: BAFU, Hydrologischer Atlas der Schweiz, Tafel 5.3 http:\\hydrologischeratlas.ch/downloads/01/data/Tafel_5_3.de.xls
- Various business documents on the larger storage power plants:
  - Chatelard Barberine
  - KWO
  - Emosson
  - Etzelwerk
  - PSW Limmern
  - Bortel
  - Robiei – Peccia
  - Grande Dixcence mit Bieudron Fionnay and Nendaz

Table 7: Storage power plants: storage capacities and pump resp. circulation mode

bfe_id	Name	GWh winter pump demand	GWh summer pump demand	GWh storage capacity	CircMode GWh winter production	CircMode GWh summer production	CircMode GWh winter pump demand	CircMode GWh summer pump demand	CircMode GWh storage capacity
100200	Sedrun 1	-	-	191.0	-	-	-	-	-
100300	Tavanasa (KVR)	-	-	153.3	-	-	-	-	-
101000	Ilanz 2	-	-	43.0	-	-	-	-	-
101100	Zervreila	-	4.4	18.0	-	-	-	-	-
101200	Safien Platz	-	-	95.0	-	-	-	-	-
101300	Rothenbrunnen (KWZ)	-	-	151.0	-	-	-	-	-
101900	Ferrera 1	26.0	72.0	225.0	3.6	3.6	4.5	4.5	4.3
102100	Bärenburg	-	-	149.0	-	-	-	-	-
102300	Sils (KHR)	-	-	191.0	-	-	-	-	-
103100	Tinizong	-	-	65.2	-	-	-	-	-
103200	Tiefencastel Ost	-	-	54.3	-	-	-	-	-
103600	Rothenbrunnen (EWZ)	-	-	22.6	-	-	-	-	-
104200	Klosters	-	-	7.7	-	-	-	-	-
104600	Mapragg	-	-	32.9	84.7	83.3	105.9	104.1	2.8
104700	Sarelli	-	-	25.6	-	-	-	-	-
106300	Engeweiher	-	-	0.2	5.1	5.0	6.3	6.2	0.2
107400	Wasserauen	-	-	0.6	-	-	-	-	-
200800	Grimsel	5.1	25.7	590.0	133.7	290.3	167.1	362.9	26.9
201900	Isch	-	-	0.5	-	-	-	-	-
202600	Klusi	-	-	1.0	-	-	-	-	-
203600	Innergsteig	-	-	5.3	-	-	-	-	-
204400	Hauterive	-	-	37.1	-	-	-	-	-
204600	Oelberg	-	-	24.5	-	-	-	-	-
204700	Schiffenen	-	-	4.5	-	-	-	-	-
205200	La Dernier	-	-	16.5	-	-	-	-	-
300400	Göschenen (Göscheneralp)	-	-	110.0	-	-	-	-	-
302800	Engelberg	-	-	1.3	-	-	-	-	-
303300	Oberrickenbach	-	-	2.2	-	-	-	-	-
303650	Unteraa (Melchaa)	-	-	2.0	-	-	-	-	-
303700	Unteraa (Lungerersee)	-	-	21.5	-	-	-	-	-
303800	Hugschwendi	-	-	5.6	-	-	-	-	-
400200	Tierfehd (Limmern)	10.0	47.5	201.0	59.2	58.1	74.0	72.7	0.5
400400	Linthal (Limmern)	-	-	34.9	-	-	-	-	-
401500	Schwanden (Niederenbach)	-	-	7.2	-	-	-	-	-
401900	Am Löntsch	-	-	33.0	-	-	-	-	-
403000	Merlen	-	-	2.7	-	-	-	-	-
404100	Rempen	-	23.0	49.0	4.7	4.6	5.8	5.7	0.8
404200	Siebnen	-	-	36.0	-	-	-	-	-
404400	Etzelwerk Altendorf	-	-	91.8	5.4	11.4	6.8	14.2	2.6
500100	Altstafel	-	-	14.0	-	-	-	-	-
501200	Bitsch (Biel)	-	-	14.0	-	-	-	-	-
501350	Bortelalp	-	1.1	0.1	0.8	0.8	1.0	1.0	0.1
501375	Ganterbrücke	-	-	0.5	-	-	-	-	-
501500	Zermeiggern	2.2	23.0	97.9	15.8	15.5	19.7	19.4	2.6
501800	Stalden (KWM)	-	-	233.0	-	-	-	-	-
502600	Oberems (Argessa)	0.4	11.1	10.3	0.3	0.3	0.4	0.4	0.1
502800	Turtmann	-	-	13.3	-	-	-	-	-

bfe_id	Name	GWh winter pump demand	GWh summer pump demand	GWh storage capacity	CircMode GWh winter production	CircMode GWh summer production	CircMode GWh winter pump demand	CircMode GWh summer pump demand	CircMode GWh storage capacity
503200	Mottec	1.0	30.0	111.0	10.4	10.2	13.0	12.7	1.7
503300	Vissoie	-	-	76.0	-	-	-	-	-
503400	Navisence	-	-	98.0	-	-	-	-	-
503500	Croix	-	-	95.0	-	-	-	-	-
503700	St-Léonard	-	-	50.0	-	-	-	-	-
504950	Dixence	24.3	364.8	1'659.0	-	-	-	-	-
505300	Fionnay (Mauvoisin)	-	-	170.0	-	-	-	-	-
505400	Riddes	-	-	400.0	-	-	-	-	-
505900	Pallazuit	-	-	22.0	-	-	-	-	-
506700	Châtelard-Barberine 1 + 2	3.5	8.5	151.0	9.4	9.2	11.7	11.5	1.5
506800	Emosson	25.1	100.2	288.8	-	-	-	-	-
507200	Vernayaz (CFF)	-	-	70.0	-	-	-	-	-
507300	La Bâtiaz	-	-	246.5	-	-	-	-	-
507500	Miéville	-	2.4	120.0	-	-	-	-	-
508700	Diablerets	-	-	8.4	-	-	-	-	-
509000	Vouvry	-	-	3.8	-	-	-	-	-
509100	Veytaux I	-	-	104.0	74.8	73.5	93.5	91.9	43.0
600050	Sella	-	-	2.0	-	-	-	-	-
600100	Airolo	0.3	1.6	70.0	-	-	-	-	-
600400	Ritom	-	-	80.4	-	-	-	-	-
600600	Tremorgio	-	-	15.6	-	-	-	-	-
601200	Olivone	-	-	102.0	-	-	-	-	-
601300	Biasca	-	-	139.0	-	-	-	-	-
601400	Spina (Isola)	-	-	5.3	-	-	-	-	-
602200	Gordola	-	-	48.8	-	-	-	-	-
602400	Peccia (Sambuco)	1.5	10.5	56.7	6.4	6.3	8.0	7.9	0.1
602500	Robiei	-	24.0	20.9	43.8	43.1	54.8	53.9	6.1
602700	Cavergno / Bavona	-	-	234.9	-	-	-	-	-
602800	Verbano 1	-	-	3.0	-	-	-	-	-
602900	Verbano 2	-	-	0.1	-	-	-	-	-
700100	Palü	0.3	4.0	11.4	-	-	-	-	-
700300	Cavaglia	-	-	8.1	-	-	-	-	-
700400	Robbia	-	-	24.3	-	-	-	-	-
700500	Campocologno 1	-	-	33.5	-	-	-	-	-
700600	Campocologno 2	-	-	1.0	-	-	-	-	-
701400	Castasegna / Löbbia	-	14.8	123.5	-	-	-	-	-
800800	Ova Spin	5.8	41.9	50.0	14.7	14.4	18.3	18.0	2.9
801000	Pradella	-	-	252.7	-	-	-	-	-
801100	Martina	-	-	70.8	-	-	-	-	-
Total		105.5	810.5	8'113.6	472.8	629.6	591.0	787.0	96.3

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