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An Island in the Middle of Europe? The Costs of Swiss Electricity Autarky

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***Abstract*— Independence has always been an important topic within Switzerland. The ongoing energy transition is no exception. The negotiations between Switzerland and the European Union about the Swiss integration in the European electricity market are currently on hold. Consequently, a more self-sufficient electricity future for Switzerland may become a relevant debate in the near future. In this paper the consequences of a potential self-sufficient future of the Swiss electricity supply are quantified making use of the Swiss electricity market model 'Swissmod'. Three scenarios for the year 2035 with different degrees of self-sufficiency in the Swiss electricity supply are analyzed. The results show that Switzerland has to bear the bulk of the costs of a self-imposed Autarky, while the European countries incur a smaller loss.**

***Index Terms*-- Self-sufficiency, electricity markets, Switzerland, Swissmod, capacity investments.**

I. Introduction

The Swiss electricity market is subject to profound changes after the decision to phase out the existing nuclear plants at the end of their life-time and not to replace them with new ones. With the questions whether and how to replace the ca. 40% nuclear generation share the aspect of a self-sufficient Swiss electricity system has emerged within the debate. Albeit, autarky is not the envisioned political direction of the Swiss Energy Strategy 2050 the issue is likely embedded in the strong desire for independence in Switzerland. A second, more pressing issue, in this context is the integration of Switzerland into the European electricity market. Due to political debates following the Swiss immigration referendum in February 2014 the Swiss future within the European institutional framework is not clarified so far. This has feedback effects on the negotiations about the Swiss integration in the European electricity market [1].

Thus, a more self-sufficient electricity future for Switzerland may become a relevant debate once investments for new power plants and further support for renewables have to be decided. In general Switzerland is already partly self-sufficient in its electricity supply since Swiss electricity imports and exports are nearly balanced over a year. However, seasonally, Switzerland is highly dependent on electricity imports from its neighboring countries due to the seasonality of the hydropower dominated electricity supply. In general Switzerland is import dependent during the winter months and a net exporter during the summer months [1].

From an economic perspective a Swiss electricity island is a costly endeavor (e.g. see [2]). Especially, if not only the current status-quo of balanced yearly demand and generation is the objective but a fully self-sufficient electricity system with zero electricity imports. In this paper, we analyze the consequences of a potential self-sufficient future of the Swiss electricity supply. We quantify the cost of self-sufficiency for the Swiss electricity system making use of the Swiss electricity market model 'Swissmod' developed by [3] and extending it to cover investment decisions. By enabling Switzerland and its neighboring countries to invest in generation capacity, three self-sufficiency scenarios with different electricity import restrictions are analyzed: A benchmark scenario with no self-sufficiency restrictions, a scenario in which Switzerland needs to supply its own demand in all hours, and a scenario in which Swiss electricity trade over the year must be balanced.

The remainder of this paper is structured as follows. Section 2 presents the extension to 'Swissmod' to include investments into the dispatch framework and the restrictions for the different autarky scenarios. In Section 3 the data for calibrating the model is described. Section 4 discusses the results of the self-sufficiency scenarios and section 5 concludes.

II. Model and Autarky Scenarios

In order to analyze the cost of self-sufficiency for the Swiss electricity system, 'Swissmod', a bottom-up electricity market model for Switzerland by [3] is used. 'Swissmod' is a numerical linear cost minimization model with nodal pricing which makes use of a DC load flow approach to model the electricity transmission system of Switzerland and its interconnections to neighboring countries. Since the Swiss electricity system is dominated by hydropower the model includes a detailed representation of the hydraulic network of Switzerland capturing all forms of Swiss hydropower generation. In order to analyze the cost of self-sufficiency for Switzerland in this paper, 'Swissmod' is extended to an investment model by allowing Switzerland and its neighboring countries to invest in generation capacity. As in [4] the basic model setup of 'Swissmod' is changed from cost minimization to welfare maximization. Therefore, an elastic linear demand function is used instead of an inelastic demand. To analyze the consequences of a self-sufficient electricity system for Switzerland three autarky scenarios with different electricity import and export constraints are modeled. The model is coded in GAMS with an hourly resolution over a one-year horizon and solved using the IBM CPLEX solver.

A. Model

The objective of the model is to maximize welfare of the modeled electricity system (Eq. 1) subject to technical constraints covering investment, dispatch, hydro and network restrictions.[1] Welfare *W* is expressed as the sum of producer rent and consumer rent over all electricity nodes and a time horizon of one year considering different generation technologies:

$$max\ W = \sum_{t,n} \int_0^{D_t^n} P(D_t^n) dD_t^n - \sum_{i,t,nEffBlock} vc_{i,n,EffBlock} E_{i,t,EffBlock}^n - \sum_{i,n} c_i^{inv}\, ann_i\, Cap_{i,n}^{new} \quad (1)$$

The sum of producer and consumer rent is calculated as the area below the elastic linear demand function *P(D)* expressed as an integral less the sum of the variable generation cost *vc* of electricity generation *E* of technology *i* and the sum of the investment costs c^{inv} for new generation capacity Cap^{new} of a specific technology. Investment costs are expressed as annualized costs by multiplying the capital cost of technology *i* with annuity factor *ann*.

Since the investment potential for some technologies is limited due to feasibility constraints such as resource availability or country-specific climate policy the investments in new capacity are limited for some technologies (Eq. 2).

$$\sum_{n} Cap_{i,n}^{new} \leq invest_i^{max} \quad (2)$$

Therefore, the new generation capacity has to be lower or equal than its maximum capacity $invest^{max}$. For renewable generation the locational conditions define the production costs as well as the available potential. For the potential we make use of data from Meteotest [9]. Given the suitability and potential for solar and wind on municipality level we derive an aggregate cantonal investment cost curve, while the resource availability constraint (Eq. 2) is defined for each canton separately.

The total generation capacity is constraining the amount of electricity which can be generated given the seasonal plant availability (Eq. 3).

$$E_{i,t,EffBlock}^n \leq cap_{i,n,effBlock}^{exist} * avail_{i,t,n,EffBlock} + Cap_{i,n}^{new} * avail_{i,t,n} \quad \forall\, n,i,t \quad (3)$$

B. Autarky Scenarios

We run three autarky scenarios for the year 2035, the first year after the final nuclear plant has to go offline. The scenarios differ in constraining the electricity imports and exports of Switzerland:

- In the '**no autarky**' scenario Swiss imports and exports are only restricted with respect to the underlying cross-border network capacities. Thus, Switzerland can either generate enough electricity to cover Swiss demand by itself which may require investments in generation capacity or import electricity from its neighboring countries. Overproduction can be exported to the neighboring countries.

- In the '**yearly autarky**' scenario the Swiss electricity supply and demand has to be balanced over the year:

  $$\sum_{i,t,n^{CH}} E_{i,t}^{n^{CH}} - \sum_{t,n^{CH}} D_t^{n^{CH}} \geq 0 \quad (4)$$

  Thus, the yearly Swiss electricity generation of all technologies has to be at least as large as yearly electricity demand of Switzerland. However, the balance only has to hold over a year. Within a year Switzerland is still able to import and export electricity as long as their intra-annual electricity exports are at least as high as the imports.

- In the '**full autarky**' scenario Swiss cross-border lines are cut off. Thus, Switzerland is completely isolated:

  $$\sum_{i,n^{CH}} E_{i,t}^{n^{CH}} - \sum_{n^{CH}} D_t^{n^{CH}} = 0 \quad \forall\, t \quad (5)$$

  Since electricity imports and exports are not possible any more Switzerland has to cover its domestic electricity demand at any time by itself.

Given the dependency of the investment results on the underlying costs and price assumptions for each of the scenarios we perform a sensitivity analysis by adjusting the investment costs for wind and solar capacities. Starting with the 2015 reference values we reduce the cost level in 20% steps.

[1] We do not report all equations of 'Swissmod' here. See [3] for a detailed description of the 'Swissmod' model, especially with respect to network and hydro representation. Note that we use capital letters for endogenous variables and lower case letters for exogenous parameters.

Albeit limiting the sensitivity to the renewable side this can easily be translated into capturing an equivalent increase in fossil fuel prices or emission price levels. The results aim to provide an indication of the direction of changes the relative cost advantage of fossil and renewable technologies will induce.

III. DATA

To calibrate the model, data from 'Swissmod' by [3] and [4] are used. The model includes a detailed hydrology representation for the largest hydro power plants in Switzerland and a nodal representation of the transmission system in Switzerland as well as an aggregated representation for neighboring countries.

Demand is distributed to nodes using cantonal GDP and population as proxy. Fossil generation is modeled in an aggregated manner. For each plant type three power plant blocks are introduced, one with a high efficiency, one with a medium one, and one with a low efficiency value. This stepwise structure aims to capture the increasing structure of the merit order. For new power plants the highest efficiency was assumed.

Investment related data such as years of depreciation and capital costs for specific generation technologies as well as the annual fixed operation and maintenance costs are taken from the 'DIW Data Documentation 68' [5], a comprehensive literature survey regarding the current and future cost of electricity generation. The capital costs for the year 2035 and the years of depreciation, which are used in calibrating the model, are represented in TABLE I. For wind and solar investment costs, we conduct a sensitivity analysis starting from 2015 investment cost and reducing them to 80, 60 and 40% of 2015 costs. Capital costs are annualized assuming an interest rate of 7% as in [6] and making use of technology-specific years of depreciation. Base case fuel price assumptions are taken from [7].

TABLE I: CAPITAL COSTS AND YEARS OF DEPRECIATION OF DIFFERENT GENERATION TECHNOLOGIES IN OUR SCENARIOS.

Technology	**Capital cost in EUR/kW**	**Years of depreciation**
CCGT	800	31
Wind	508-1269	24
Solar	380-950	24
Oil Steam	400	35
Geothermal	3216	33
Gas Steam	400	31
Biomass	2141	27

Beside the generation technologies contained in TABLE II Swiss hydropower technologies are modeled in a more disaggregated way by regarding specific hydropower projects which were used by the [8] in considering the future Swiss hydropower potential within the Swiss Energy Strategy 2050.

Planned hydropower sites are introduced into the hydraulic network of 'Swissmod' by using a geographic information system while site-specific investment costs are taken form the project web sites or project reports. Thus, the model decides whether a specific hydropower project is realized and becomes part of the Swiss hydraulic network or if it is not realized.

The monthly availabilities of the generation technologies are based on fitted values from a kernel-weighted local polynomial regression based on historical data from neighboring countries' monthly conventional power plant availabilities. We use the resulting smoothed availability values for newly invested power plants in Switzerland.

For the variable renewable energies wind and solar, hourly availability values from [6] are used. For the maximum potential of geothermal and biomass capacity in Switzerland we use the assumed capacity from the Swiss Energy Strategy 2050 as a proxy. To determine the regional potentials of wind and solar on municipality-level, data from [9] were used to derive the relationship between installed capacity and output. Under the assumption that best sites are used first the values were aggregated to cantonal yield curves and translated into increasing costs.

To derive reasonable estimates for the elastic demand we rely on the 2012 demand profile and scale the values according to the forecast in [1] and [7]. The reference price level, at which we calibrate the resulting hourly demand is generated from running the model two times before the actual model run, once with fixed demand and once with elastic demand. Using this price as reference price level we obtain the linear demand assuming an elasticity at the reference point of 0.1.

IV. RESULTS

In TABLE III, we provide an overview about the different investments realized in each scenario and cost assumption. First, the total investments in geothermal and biomass remain fixed at the defined upper limit for each case. This is based on the cost assumptions for those technologies that make them a profitable investment in all settings. Second, we don't observe investments into any of the allowed new hydro power projects. This is also based on the underlying cost assumptions but this time making them unprofitable in all possible settings.

The split between gas fired CCGT, wind and solar plants depends on the respective autarky restrictions and the investment costs. We observe significant investments into capacities even in case of no specific requirement for Swiss based production (*No Autarky*). This is a simple effect of the underlying cost assumptions and the fact that we take most of the European electricity capacities as given. To counter part of the bias we obtain with this approach we allowed neighboring countries to also invest into additional conventional power plants. However, only Germany invests into further gas CCGT units of roughly 4GW in addition to their 20.85GW existing capacities in 2035.

In case of relatively costly renewable capacities only the best wind and solar sites are exploited and about 1GW of gas generation is built to benefit from the European price level. With decreasing renewable investment costs wind and solar capacities are increased and in the gas units are reduced. The results show that with a significant further cost reduction for renewables the respective investments become highly profitable.[2]

TABLE II: SWISS GENERATION INVESTMENTS [GW]

Scenario	RES Cost Level	Geo/Bio	Wind	Solar	Gas CCGT
No Autarky	100%	1.1	1.0	0.8	0.9
	80%	1.1	1.7	14.8	0.6
	60%	1.1	3.1	25.6	0.3
	40%	1.1	5.0	26.1	0.0
Yearly Autarky	100%	1.1	1.0	1.0	3.1
	80%	1.1	1.7	15.3	0.7
	60%	1.1	3.1	25.6	0.3
	40%	1.1	5.0	26.1	0.0
Full Autarky	100%	1.1	1.3	1.3	4.1
	80%	1.1	2.1	2.8	3.9
	60%	1.1	3.3	5.1	3.5
	40%	1.1	4.8	6.0	3.2

This pattern translates into the *Yearly Autarky* scenario. In case of costly RES investments the requirement is fulfilled with dispatch able gas fired units. With decreasing cost levels wind and solar become more attractive making fossil generation completely obsolete to achieve a balanced import/export over the year. Actually, in the 60% and 80% cases Switzerland becomes a net-exporter. Thus, only for high renewable investment costs will the desired autarky level need investments that would not happen anyway given the market prices.

Finally, in the *Full Autarky* case the only way to achieve an hourly balanced Swiss system is to invest into dispatch able gas units. Albeit renewable generation is integrated with decreasing investment costs a base level of gas plants will remain to counteract the intermittent nature of wind and solar.[3] The infeasibility to export surplus energy to Europe furthermore limits the amount of RES that can be incorporated into the Swiss system. Consequently, the total installed amount of RES capacities is the lowest of all scenarios.

This also translates into respective welfare effects (Figure 1). While the *Yearly Autarky* only shows modest welfare losses in case of costly renewable investments the effects are significant for the *Full Autarky* case.

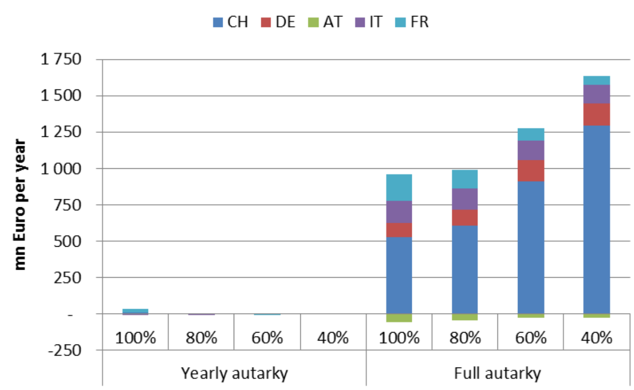

Figure 1. Welfare loss compared to 'No Autarky' [mn Euros]

The overall Swiss welfare loss rises to up to 1.25 billion Euro in case of low investment costs (ca. 3% of the Swiss welfare). This is a direct effect of the reduced profit possibilities due to the impossibility to sell excess generation on the European market and the resulting lower RES investments. In the 40% case the producer profit is only 60% of the obtainable profit in the *No Autarky* scenario. Albeit consumers benefit from lower local electricity prices the loss of producers leads to a general welfare loss.

This is a typical effect in situations with changes in export possibilities. In regions with cheap production possibilities, like Switzerland's hydro and the assumed RES capacities, producers benefit from the possibility to sell to higher priced foreign regions. On the other hand consumers benefit from limited export capacities as this keeps local prices low.

Examining the overall welfare effects we see that Switzerland has to bear the bulk of the costs of the self-imposed Autarky. Albeit the decoupling of the Swiss system impacts the exchange between the other European countries their loss is far less than the Swiss one.

[2] Note that we do not allow additional RES investment in neighboring countries beyond the capacities projected for 2035 in [7].

[3] Note that we have not included any storage technologies beside few potential pump storage sites. Consequently, the share of gas could also be replaced by more RES and additional storage investments under respective technology and cost assumptions.

V. CONCLUSION

In this paper we aim to quantify the costs of a Swiss strive for electricity autarky following the suspended negotiations about the Swiss integration in the European electricity market. Based on an investment model we derive different scenarios of self-sufficiency for varying investment costs assumptions.

The results indicate that with the current expectations on the future European electricity market and renewable cost developments, Switzerland will keep its yearly import/export balance by replacing its nuclear plants with renewable capacities. This will likely exaggerate the current split between import dependency during winter and export surplus in summer months as solar and hydro generation amplify this trend.

A full autarky on the other hand will be extremely costly for Switzerland and require dispatch able generation possibilities. In our simulations those were provided by gas plants. The complete decoupling from Europe comes at the expense to not being able to sell surplus energy to neighboring markets; a solid income for Swiss generators in the other scenarios. Albeit the full autarky also leads to welfare losses for neighboring countries the bulk of the loss is to be borne by Switzerland.

The results indicate that both Switzerland and the European Union should have an incentive to ensure a proper integration of the Swiss system into the European electricity markets.

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