Joint Activity Scenarios and Modelling

JASM Transmission Adequacy Assessment

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Chapter 1

Introduction

In the context of the Joint Activity Scenarios and Modeling (JASM), the energy systems models SES (ETH and EPFL) and STEM (PSI) are used to model the overall energy system including investment choices in different energy generation and usage technologies to arrive at annual figures of energy usage in different sectors and energy carriers. While these energy system models consider some intra-annual patterns, their large model scope limits the degree of detail these models can capture.

In this report on system adequacy within the framework of JASM, we analyze whether the results from the overall energy system models are robust from the perspective of the electricity system with regard to high-resolution temporal, spatial and structural patterns. These patterns are, amongst others, the time-variability of weather (with respect to solar and wind infeed, hydropower resources, as well as demand), the spatial specificity of the nodal electricity grid, and the structural dependence of hydropower within cascade structures. We also put the Swiss results from the energy system models into the context of the overall European electricity market and assess the resulting security of supply for the Swiss electricity consumption.

We use the Swiss electricity market model Swissmod for our analysis. Swissmod is a DC load-flow electricity market model with a detailed representation of Switzerland on transmission grid level and a high degree of detail on hydropower. Each model run captures one year in hourly resolution.

We base our work on the ENTSO-E TYNDP scenarios, which lay out data for the European electricity system until 2040. Thus, we model the two overlapping years between the JASM STEM results and the TYNDP, namely 2030 and 2040. The year 2050 is not included in our analysis, as there are no ENTSO-E TYNDP scenarios available for that year yet and it would be too early to assess grid adequacy at this point. While transmission grid investments have a long lead-time, the 2050 time horizon still has many uncertainties on the grid level so a detailed analysis will only make sense at a later stage and the broader results from the energy system models are sufficient at this stage.

Additionally to providing insights on system adequacy, we also provide a data package available on the JASM data platform that provides high-resolution price data that is consistent with the broader STEM results.

The remainder of the paper is structured as follows. First, we present the Swissmod model that we use for our analysis, including the specific system adequacy indicators we use in the result section below. Second, we present our scenarios and the underlying input data. Third, we present the model results, discuss them in the wider context of system adequacy studies and thus put them into perspective. The final section concludes and points out the implications of the results.

Chapter 2

The Swissmod model

Swissmod (Schlecht and Weigt, 2014, Abrell et al., 2019) is a technology-rich, bottom-up, DC load-flow electricity market model of Switzerland and its neighboring countries.

2.1 Model description

Swissmod is based on a detailed electricity transmission network for Switzerland (Figure 2.1) and aggregated representations of 18 further European countries including the Swiss neighboring countries and again their neighbors. As a conservative assumption, the transmission grid is assumed to be static, which means we ignore the switching actions that transmission system operators could do in real-time to ease grid constraints in situations where the static grid would not be optimally suited to transport the maximum of electricity. Electricity generation plants are modeled at unit-level for Switzerland and at technology-level for the remaining European countries. Swissmod uses a nodal pricing approach that helps identify congestion of the transmission system and the differential value of energy at different places and at different points in time. It has a time horizon of one year in hourly resolution.

For the analysis at hand, demand is considered as inelastic while system costs are minimized. The model is deterministic and assumes a perfect competitive market with perfect foresight

The model details the natural rivers and streams and man-made hydropower components of the Swiss hydrological network. This modeling approach allows Swissmod to capture the inputs, constraints, and interconnections of run-of-river, yearly storage, and pumped storage facilities. As Switzerland relies on hydropower for a majority of its electricity production (approximately 60% in 2019), Swissmod was developed to model this source as accurately as possible due to its high importance for Swiss electricity supply. Figure 2.2 shows the modeled hydro power plants in Switzerland as well as an exemplary hydro cascade structure. In total, 260 hydro power cascades and 400 hydro power plants are modeled in detail. In addition, all other electricity generating technologies are explicitly modeled.

Loss of load is modeled as a variable equivalent to generation that is available at all nodes up to the level of load and has a marginal cost of 10’000 EUR/MWh.

Swissmod is a quadratic (due to linearly increasing marginal costs per technology in neighboring countries) cost optimization model subject to generation, transmission and hydrologic constraints. Swissmod is coded using GAMS and the IBM CPLEX solver. A detailed model description can be

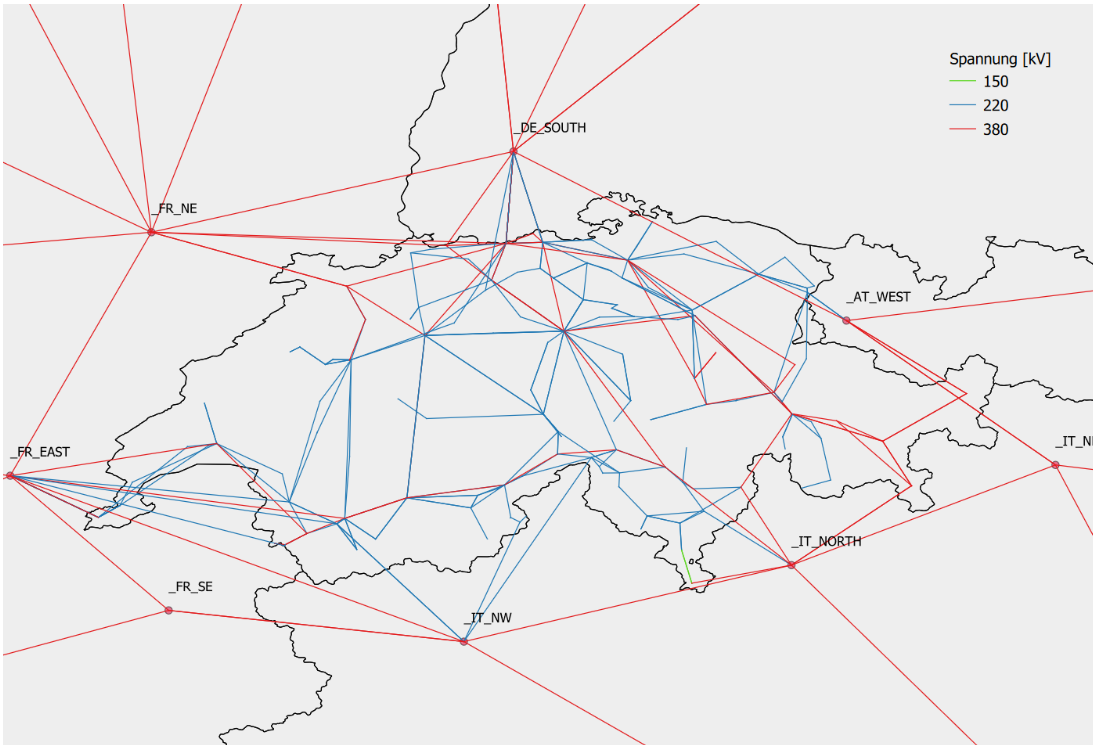

Figure 2.1: Grid structure

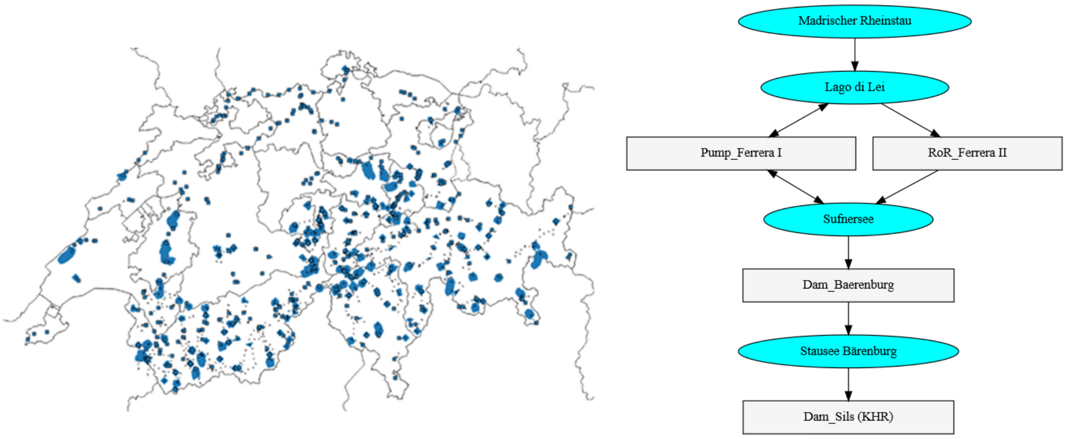

Figure 2.2: Hydro structure

found in (Schlecht and Weigt, 2014, Abrell et al., 2019).

2.2 System adequacy indicators

For the adequacy analysis within this paper, we use a number of adequacy indicators that are known from various resource adequacy assessments in Europe such as by ENTSO-E in their short-term adequacy analyses as well as for Switzerland in the last two system adequacy studies that were also carried out using Swissmod (BFE, 2019).

As indicators, we take into account:

- Energy Not Served (ENS), in GWh per year, describes the part of demand which could not be served by the electrical system due to shortage of generation or transmission capacity. It is calculated as follows:

$$ENS = \sum_{h=1}^{8760} LostLoad(h) \tag{2.1}$$

  where $LostLoad(h)$ is the amount of load that could not be served in a particular hour.

- Loss of load (LOL), in hours per year, describes the number of hours in the year where at least some load greater zero could not be served.

$$LOL = \sum_{h=1}^{8760} LOLF(h) \tag{2.2}$$

  where the Loss of load flag (LOLF), is the indicator for a loss-of-load event in the h^{th} hour. It equals 1 if $LostLoad(h) > 0$ and is zero otherwise.

- Remaining Capacity Margin (RCM), in GW, describes the remaining capacity in the system in the h^{th} hour:

$$RCM(h) = C_{conv}(h) - L(h) - E_{RES}(h) \tag{2.3}$$

  where $C_{conv}(h)$ is the available conventional dispatchable capacity, $L(h)$ is load (demand) at a given hour and $E_{RES}(h)$ the infeed of non-dispatchable plants (mostly PV and wind, but also biomass, some run-of-river power plants and small fossil-fueled power plants).

Chapter 3

Scenarios and data

To parameterize our model, we take different input data that are varied across different scenarios. In this section, we first describe the input that remains fixed in all our scenarios and in the following subsection the input data that is varied across scenarios.

3.1 Input data

We mainly base our model runs on the data underlying the ENTSO-E's Ten-year network development plan (TYNDP) (ENTSO-E, 2018). From the TYPDN, we take European power plant capacities, fuel prices, availabilities, and load time series. The TYNDP data is available from and described at ENTSO-E (2018). We base our model on the Sustainable Transition scenario of the TYNDP.

On the hydropower side, we base our model on our own Swissmod data base, which is described in detail in Abrell et al. (2019) and Schlecht and Weigt (2014).

3.2 Scenarios

The scenarios are set up from the scenario definitions used in the STEM model for the JASM framework. The JASM scenarios analyzed are thus the business-as-usual scenario (BAU), the energy policy scenario (EPOL) as well as the stringent climate policy (CLI) scenario. We analyze all of these scenarios across the three weather year scenarios that TYNDP ships with for the load time series and corresponding solar and PV time series from the Renewables.ninja database (Pfenninger and Staffell, 2016).

The main variance across the STEM scenarios for the electricity system concerns the differences in total electricity demand (i.e. total load including losses and demand from electrolyzers, but not from batteries and hydro pumped storages which are modeled endogenously). The different demand levels across the STEM scenarios and target years can be seen in Figure 3.1 . While the EPOL scenario has a lower electricity demand compared to the BAU scenario, the CLI scenario, with its large-scale electrification of transport and heating, has a significantly increased load.

Besides the demand level, there are also differences in the electricity generation across the STEM scenarios. These are depicted in Figure 3.2. While hydropower and nuclear capacities remain relatively constant across scenarios, nuclear decreases significantly from year 2030 to year 2040 according to

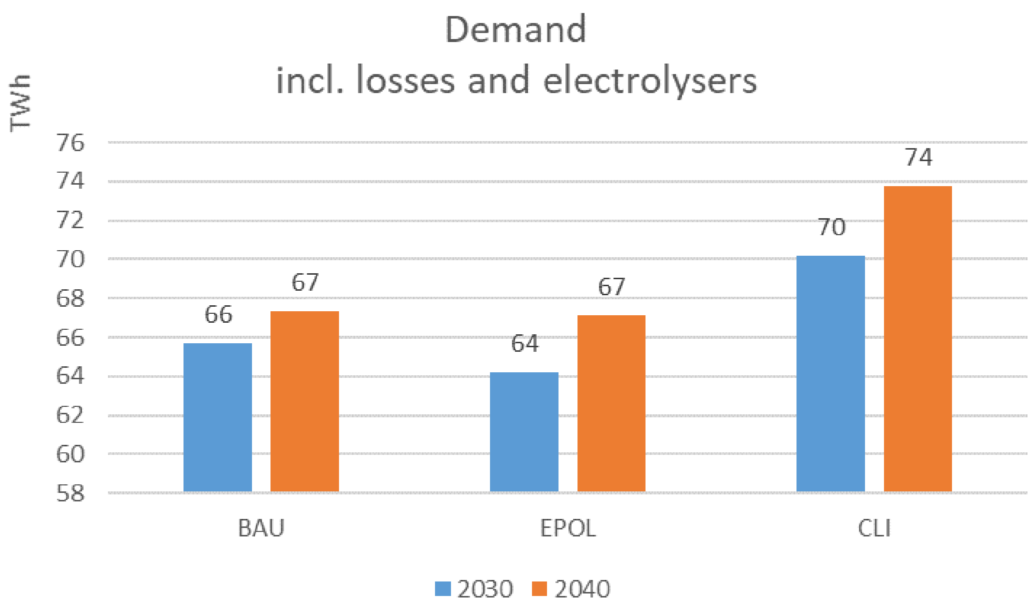

Figure 3.1: Electricity demand across the scenarios and target years including losses and demand from electrolyzers

the STEM life-expectance for nuclear plants of 60 years and the according decommissioning of the Gösgen and Beznau plants before 2040. The CLI scenario builds significant additional solar capacity compared to the other scenarios until 2040. Wind does not play a significant role in all scenarios, although the CLI scenario does build wind generation capacity to generate approximately 2 TWh of wind energy.

A further change can be observed with regard to the amount of batteries supplied to the system, with the CLI scenario seeing 300 MW of battery storage deployed across the different grid levels, while in the BAU scenario batteries remain below 60 MW even in 2040 – thus only contributing to system adequacy in a negligible way.

The other dimension across which we vary our scenarios is the weather year dimension. In total, we look at three different weather years that correspond to three clusters of 30 weather years that were found to be maximally different according to the ENTSO-E TYNDP and for which the TYNDP ships with hourly load curves for all modeled European countries. We complement the hourly load curves with solar and wind profiles from the Renewables.ninja database (Pfenninger and Staffell, 2016) that match the same weather years. Figure 3.4 shows the overall European sum of the weather dependent inputs. While the difference in weather years in the yearly perspective is little, it is important to keep in mind that the hourly profiles from these considered weather years vary significantly and can thus cause a very different degree of stress to the system in terms of adequacy relevant outcomes.

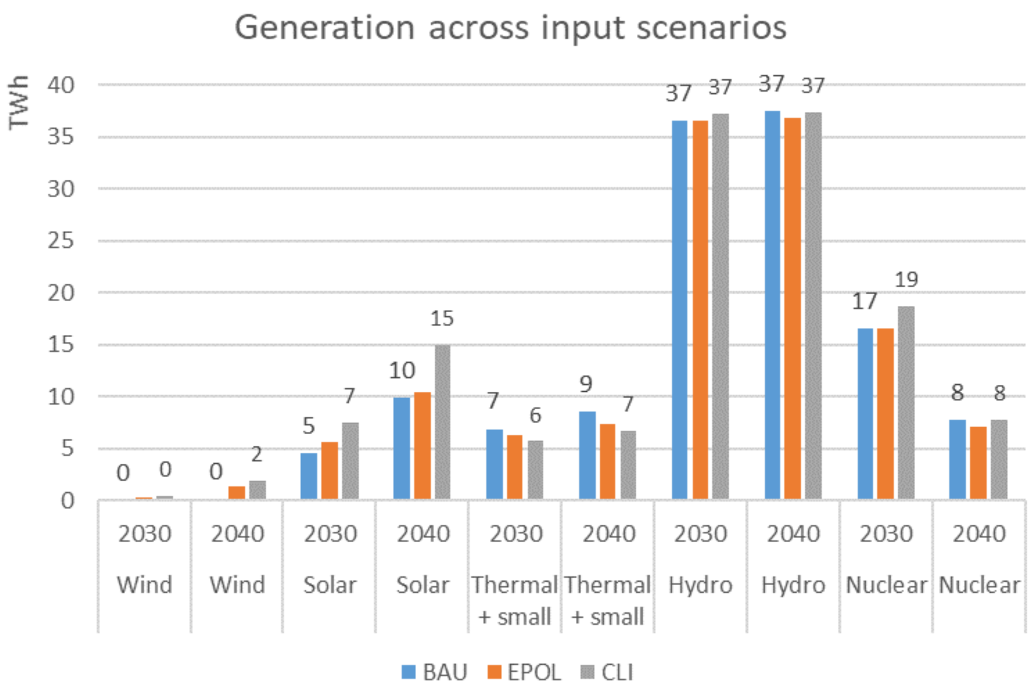

Figure 3.2: Electricity generation (input) across the scenarios and target years

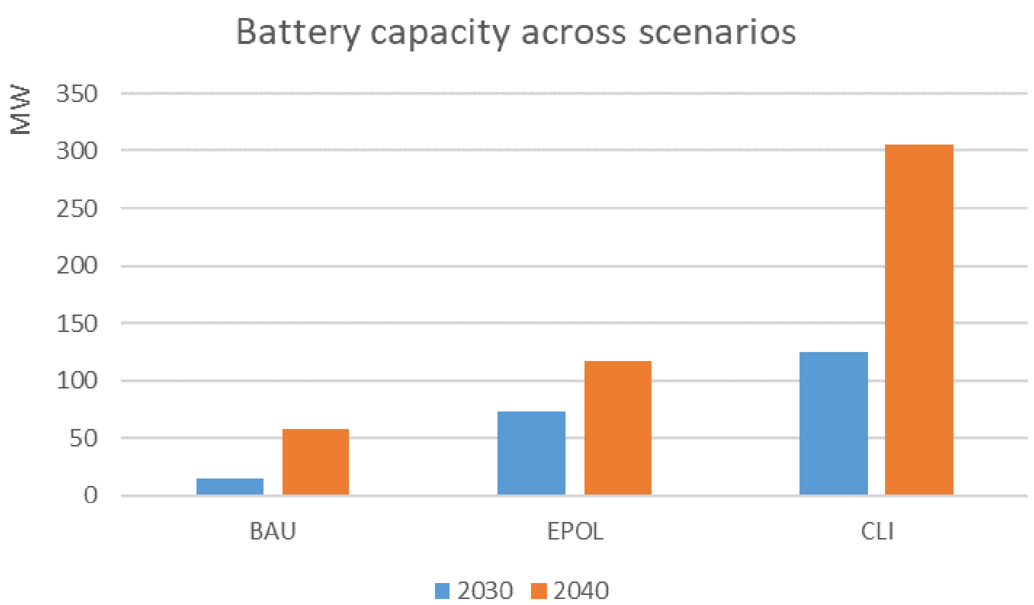

Figure 3.3: Battery capacity across scenarios

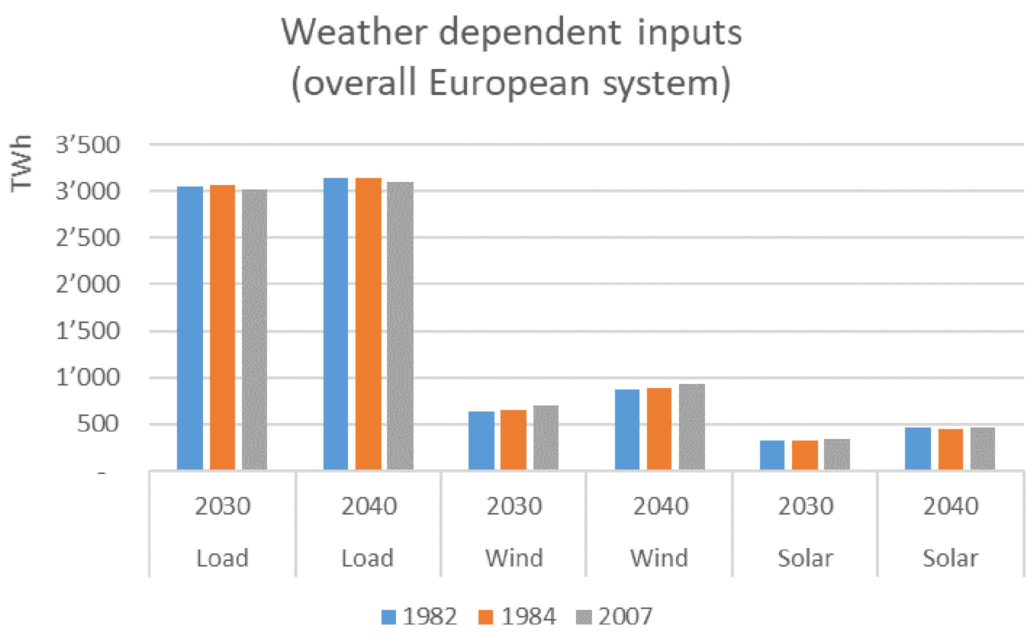

Figure 3.4: Weather dependent inputs

Chapter 4

Results and discussion

This section presents and discusses the model results across the different scenarios. We first discuss the system adequacy indicators introduced above in Section 2.2, before taking a detailed look at the most critical scenario to assess whether the indications of supply problems in that scenario are of importance for the overall scenario outlet.

4.1 Remaining capacity indicator

To put any further results in perspective, it is important to consider the minimum remaining capacity margin. The Remaining Capacity Margin (RCM) is expressed in GW and shows the minimum available spare capacity (i.e. after serving load) across all hours of the modeled year. We only consider the minimum value of this time series which varies over the year (due to renewable as well as load variability), as the minimum value shows where problematic situations can occur. We consider this indicator both on a European level and on the Swiss level. From the results shown in Table 4.1, it becomes apparent that on both geographic levels there is never a capacity shortage, i.e. remaining capacity always remains positive. It is important to note that this result is on a generation capacity level only, i.e. it does not mean that the available generation is placed at the right nodes where it is needed or whether the grid can always transport the energy.

On the European level, the most critical scenario is the 2040 CLI scenario, where the number drops to 25 GW in one hour - which is still a high and comforting number. The assumed scenarios from the TYNDP thus do not signify supply shortages on the European level.

On the Swiss level, the most critical scenario is the 1982 weather year in the 2040 CLI variant, where the value drops to approx. 1.9 GW. Given the size of the Swiss electricity system, this is still a comforting number – yet only the full system analysis and the energetic loss of load indicators show whether transmission and hydro constraints always allow this capacity to be used when needed. Yet from the capacity point of view, Switzerland is well equipped in these scenarios up to 2040.

4.2 Load shedding indicators

The main results of the system adequacy analysis are the indicators on necessary load shedding as measured by the Energy Not Served (ENS) and the Loss of Load (LOL) indicators. The results depicted

	Weather years:		1982	1984	2007
CH	2030	BAU	5.33	5.18	4.67
CH	2030	CLI	4.5	4.53	3.83
CH	2030	EPOL	5.48	5.36	4.86
CH	2040	BAU	4.12	3.88	2.65
CH	2040	CLI	1.89	2.54	2.2
CH	2040	EPOL	4.03	3.82	2.69
EU	2030	BAU	78.69	72.25	78.33
EU	2030	CLI	77.98	71.3	77.49
EU	2030	EPOL	78.79	72.45	78.53
EU	2040	BAU	33.44	25.96	40.5
EU	2040	CLI	31.33	25.04	40.1
EU	2040	EPOL	33.38	25.96	40.5

Table 4.1: Minimum Remaining Capacity Margin (RCM) resulting from the scenarios

	Weather years:		1982	1984	2007
CH	2030	BAU	0	0	0
CH	2030	CLI	0	0	0
CH	2030	EPOL	0	0	0
CH	2040	BAU	0	4	4
CH	2040	CLI	20	27	40
CH	2040	EPOL	0	4	4

Table 4.2: Number of Loss of Load (LOL) hours resulting from the scenarios

	Weather years:		1982	1984	2007
CH, GWh	2030	BAU	0.05	0.06	0.06
CH, GWh	2030	CLI	0.06	0.08	0.07
CH, GWh	2030	EPOL	0.04	0.06	0.06
CH, GWh	2040	BAU	0.05	0.18	0.3
CH, GWh	2040	CLI	1.43	1.49	1.9
CH, GWh	2040	EPOL	0.06	0.21	0.32
CH, % of load	2030	BAU	0.000%	0.000%	0.000%
CH, % of load	2030	CLI	0.000%	0.000%	0.000%
CH, % of load	2030	EPOL	0.000%	0.000%	0.000%
CH, % of load	2040	BAU	0.000%	0.000%	0.000%
CH, % of load	2040	CLI	0.002%	0.002%	0.003%
CH, % of load	2040	EPOL	0.000%	0.000%	0.000%

Table 4.3: Energy Not Served (ENS) resulting from the scenarios

in Table 4.3 show that overall the system is very robust and hardly any load shedding occurs. The indicated load shedding in the 2040 CLI scenario is in the range of 0.002%, i.e. a tiny fraction of overall load that is close to the model precision. However, it gives an indication of which scenario causes the largest strain to the system, namely the CLI scenario in 2040, especially in the weather conditions of 2007. In that scenario, over the course of the year, 1.9 GWh or 0.003% of load are shed in Switzerland. We provide a detailed analysis of the reasons for the minimal amount of load shedding occurring in this scenario in Section 4.4.

The LOL indicator (Table 4.2) shows that this load shedding in the most severe scenario occurs over 40 hours in total, resulting in an average of 47 MW of ENS for the hours where load is shed. This would likely be well within the range that is manageable by short-term operations or deliberate temporary (industrial) load shedding.

4.3 Import dependence and seasonality of imports

In the Swiss discussion on system adequacy, a key factor that is often named is the import dependence of Switzerland. Our results show that in the modeled weather years, Switzerland is mostly a net importer 4.4. While the BAU and EPOL scenarios for 2030 feature a net exporting Switzerland, all remaining scenarios are net importing.

	Weather years:		1982	1984	2007
CH	2030	BAU	-949	4643	4152
CH	2030	CLI	3378	9974	8216
CH	2030	EPOL	-2970	2449	2100
CH	2040	BAU	5946	10796	17222
CH	2040	CLI	15714	13943	13227
CH	2040	EPOL	5702	10470	16819

Table 4.4: Net imports in GWh on annual basis

A closer look at the seasonality of these imports (Table 4.5) show that the current picture of exports in summer and imports in winter is largely bound to stay. Only in the EPOL and BAU scenarios for 2040 the summer switches to being import-dependent while in the CLI scenario it is almost balanced. Winter imports increase to up to 15.8 TWh.

Given the results on ENS and RCM shown above, the increased import dependence does not seem to cause system adequacy problems. The model shows that despite large increases in the import dependence the system remains stable.

	Weather years:			winter	summer
CH	2030	BAU	1982	6178	-7128
CH	2030	BAU	1984	7711	-3068
CH	2030	BAU	2007	7826	-3674
CH	2030	CLI	1982	9243	-5865
CH	2030	CLI	1984	10797	-823
CH	2030	CLI	2007	10801	-2585
CH	2030	EPOL	1982	5174	-8145
CH	2030	EPOL	1984	6725	-4276
CH	2030	EPOL	2007	6731	-4631
CH	2040	BAU	1982	9811	-3864
CH	2040	BAU	1984	11450	-654
CH	2040	BAU	2007	14073	3149
CH	2040	CLI	1982	15771	-57
CH	2040	CLI	1984	13982	-39
CH	2040	CLI	2007	13666	-439
CH	2040	EPOL	1982	9676	-3975
CH	2040	EPOL	1984	11297	-827
CH	2040	EPOL	2007	13860	2959

Table 4.5: Net imports in GWh on a seasonal basis

4.4 Detailed analysis of most critical scenario

In the overview of system adequacy indicators above, the CLI scenario for year 2040 and the weather year 2007 has come out as the one where most load is shed. Therefore, to understand the reasons for this result and to assess whether this result is reason for concern, we take a closer look at this scenario. Figure 4.1 shows the amount of load shed in the scenario across the year as well as the corresponding percentage values. The small amount of the loss of load hints at the problems being likely caused by model issues (i.e. the assumed absence of switching actions in the transmission grid) rather than real generation adequacy concerns.

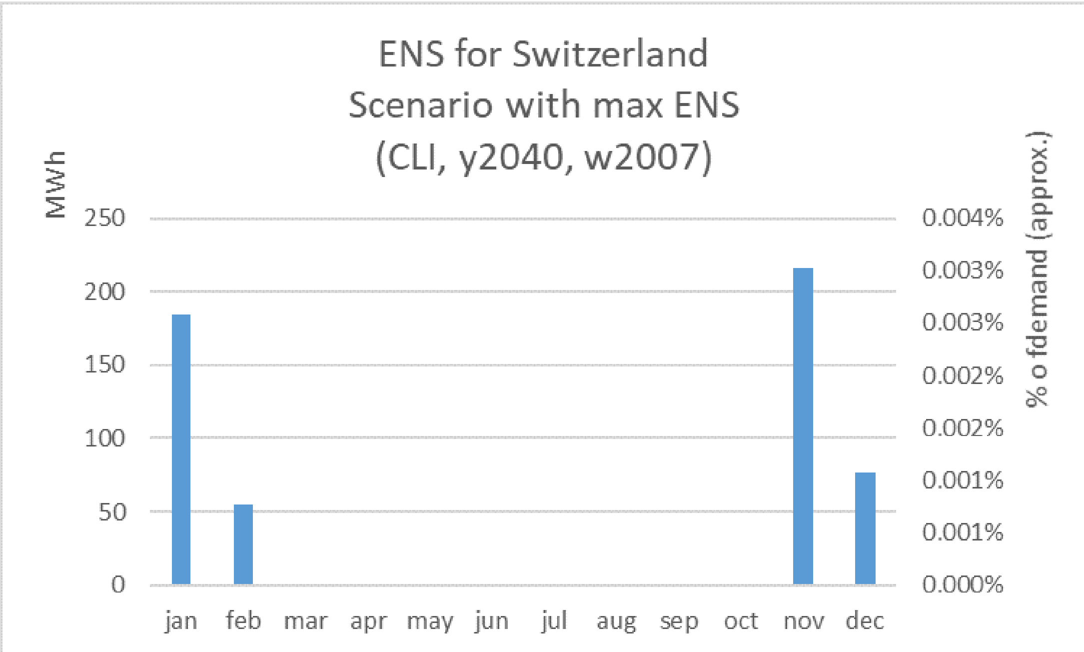

Figure 4.1: Detail analysis: ENS in the scenario

Figures 4.2 shows the time incidence of loss of load across the year and the corresponding Remaining Capacity Margin (RCM). The fact that the RCM is always well in the positive region makes clear that the loss of load events do not occur for a lack of capacity

In order to assess whether the reason for the loss-of-load can be low storage levels or instead high European load, Figure 4.3 depicts the storage curve, European load and again the time indicator of the loss-of-load hours. This shows that at the times when the loss-of-load event occurs, there is still plenty of hydro storage remaining in Swiss hydro storage lakes, ruling out hydro shortages as potential LOL reason. At the same time, it is apparent that loss of load coincides with high levels of European load. However, the early November LOL event has a lower load level than some months in March which do not see LOL events.

Another important indicator to find clues for loss of load events are the nodal prices. Figure 4.4 shows the nodal prices in a critical hour in November. The picture indicates that the hour is influenced by extreme nodal prices, which means there are heavy transmission grid issues at work. While some nodes in Switzerland feature negative prices, at the same time other nodes feature prices up to the loss-of-load price level of 10’000 EUR/MWh. This indicates that there is enough generation at one end of the grid (with even negative prices there) while at the other end of the Swiss grid there is a

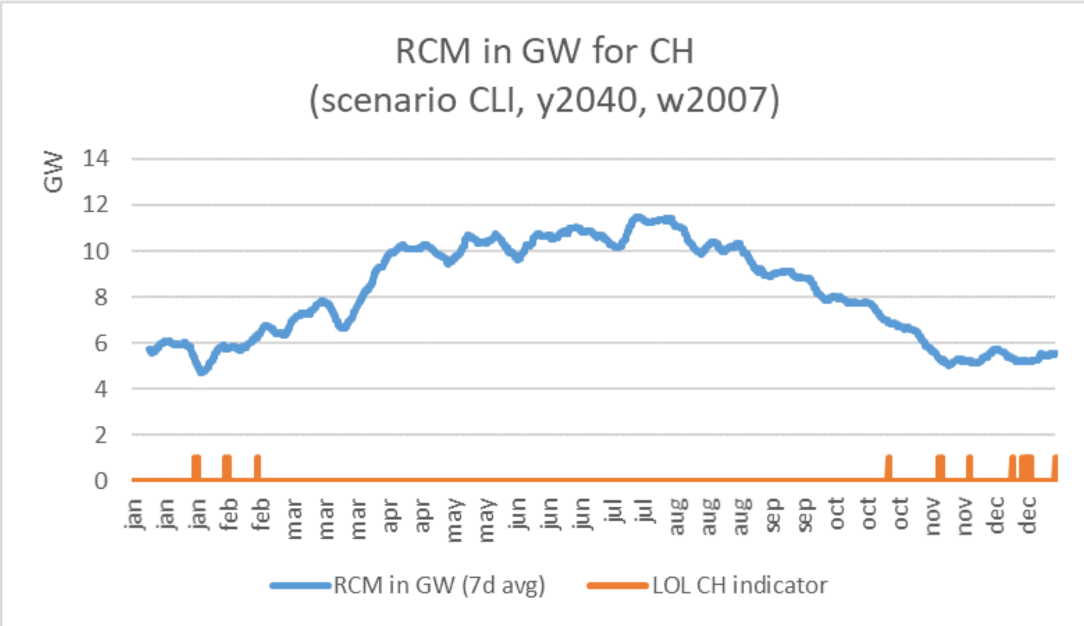

Figure 4.2: Detail analysis: RCM in the scenario

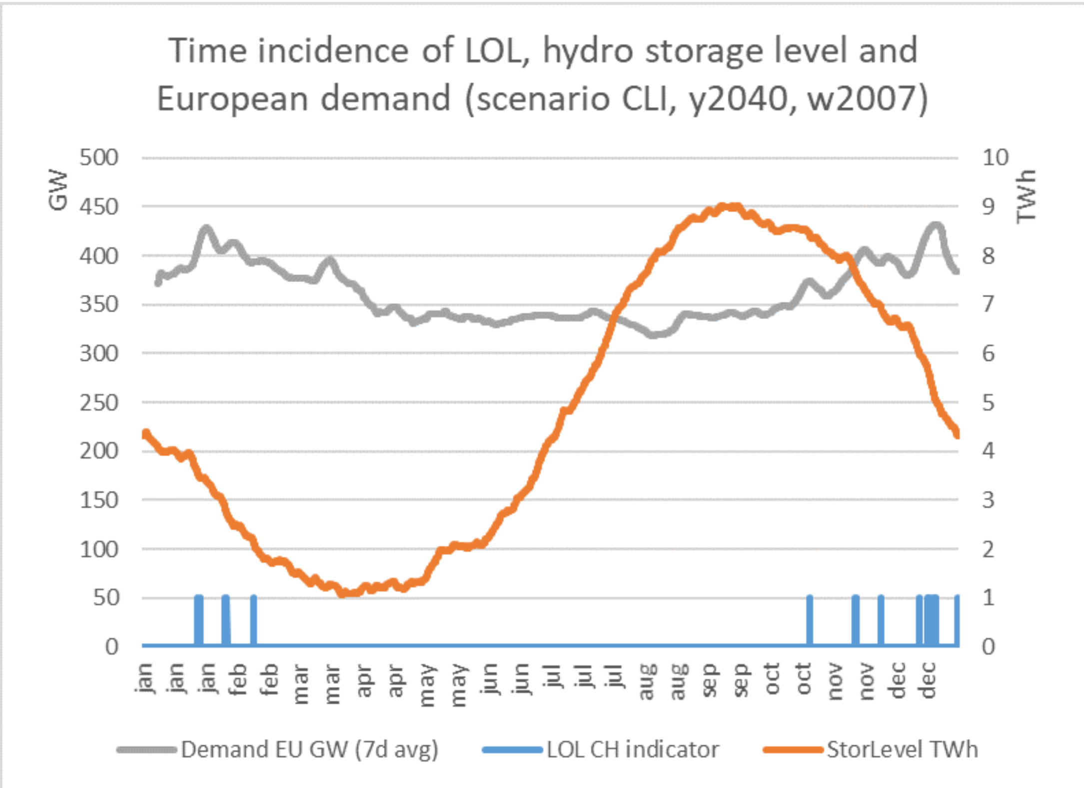

Figure 4.3: Detail analysis: Timing of loss-of-load events, storage and European demand

shortage of electricity, so that (small) amounts of load are shed.

This shows that the issue is a grid issue where electricity cannot be transported in full to the desired destinations. Figure 4.5 shows the dispatch during the critical day. Loss of load is indicated by the yellow bars in hours h18 to h20. As the difference between the load curve and the generation area

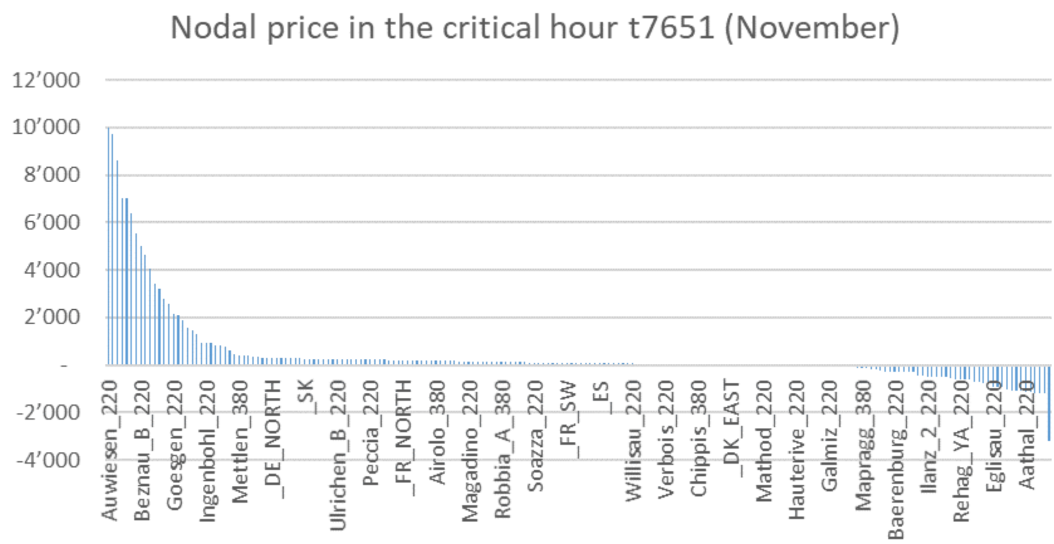

Figure 4.4: Detail analysis: Nodal prices in the scenario in the most critical hour

shows, Switzerland is heavily importing in that hour. But again, the dispatch picture shows the stark divide in scarcity and surplus respectively in Switzerland during these hours: While load is shed in one part of Switzerland, the dispatch picture also shows there is pump demand (i.e. the difference between the two load curves) occurring in that hour, so that some pump storage power plants apparently face cheap (or even negative) nodal prices while other nodes face a shortage of supply. Thus is again evidence for a grid inadequacy during that day.

Overall the detailed results indicate that there exists a local network bottleneck that leads to the need for load shedding. However, the overall cope of this bottleneck is rather limited as the low level of lost load indicate.Even though we cannot test this with our model, the small size of the energy amount shed in this situation could mean that likely in reality this event would not occur: The grid operator could use the grid to a larger extent than the 80% that our model assumes as maximum. We assume the maximum of 80% to keep a security margin of 20% and account for the lack of n-1 analysis in our model.

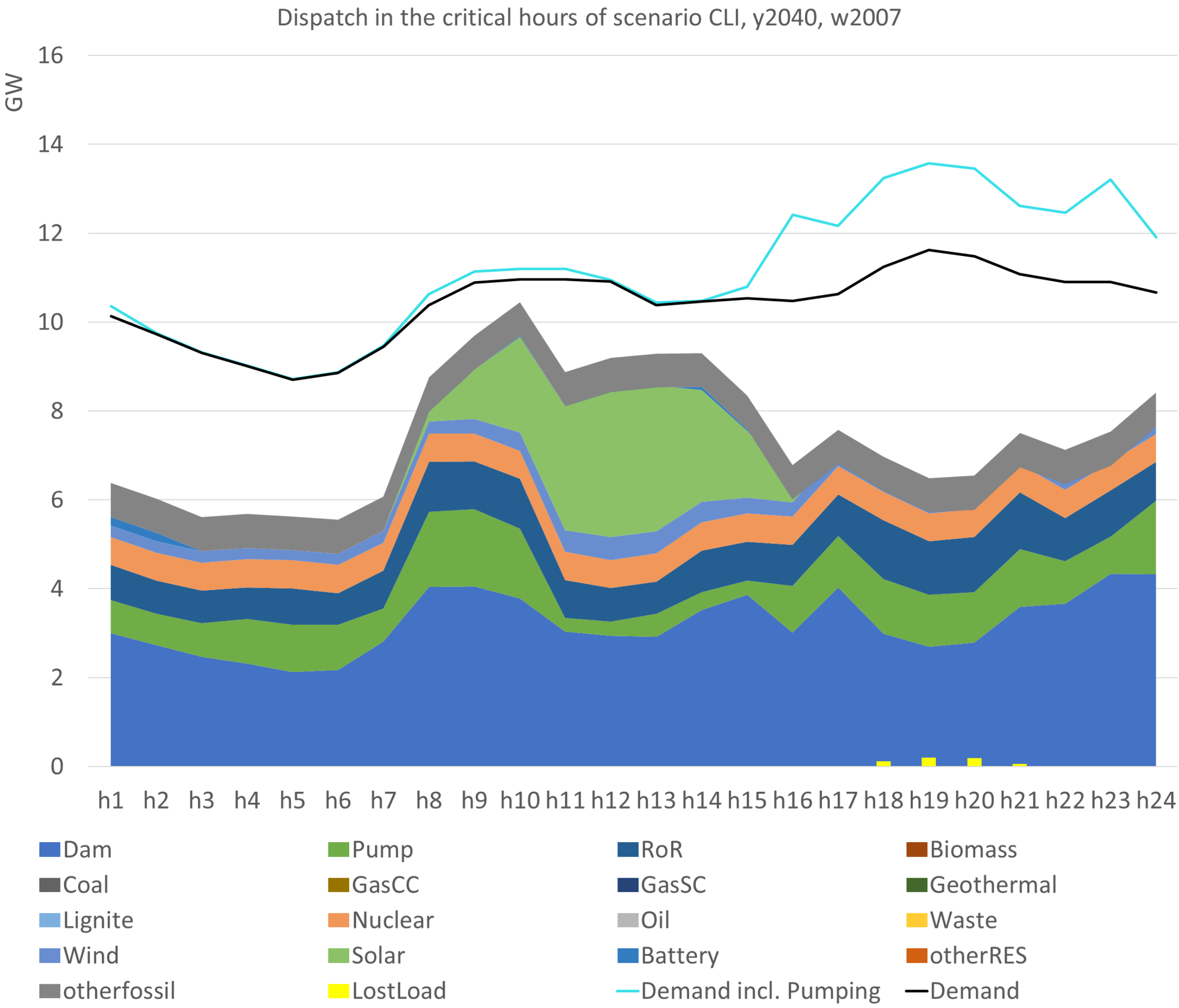

Figure 4.5: Detail analysis: Dispatch during the critical day

Chapter 5

Conclusions and implications

To conclude, our main result is that the proposed configurations of the Swiss system from the STEM model do not result in any significant loss-of-load for Switzerland. Therefore, even the scenarios with increased demand from added electrolysis and e-mobility in the CLI scenario are largely feasible within the currently planned transmission grid and hydropower structure and are robust to different high-resolution weather scenarios.

The fact that even the more ambitious Swiss scenarios do not have significant detrimental effects for Swiss security of supply is evidence again for a core finding from earlier adequacy studies (SA 2017, SA 2019), namely that Swiss security of supply is more impacted by neighboring countries' rather than by domestic developments. This is because its large hydropower capacity is successfully able to manage critical short-term situations and leads to Switzerland even exporting during many of these critical hours.

Therefore, according to the provided data from the STEM model, on the capacity-side Switzerland is well equipped until 2040 and can successfully manage the critical short-term situations arising. Only very small loss of load can be observed in the CLI scenario for 2040. A detailed analysis shows that this is due to transmission grid constraints and likely in a range that could be managed by the TSO using short-term switching actions or by allowing temporary violations of the 20% grid security margin that we consider in our model.

The adequacy assessment highlights the importance of European developments and thereby the importance of both sufficient cross-border transmission capacities as well as an integration of the Swiss energy system into the European market and system structure. While the existing and projected transmission and generation capacities are large enough to ensure system adequacy, the ongoing negotiations about the electricity agreement between Switzerland and the European Union (which has impacts on Switzerland's electricity exchange possibilities with its neighbors) put the main focus of the Swiss system adequacy into the political dimension and not the physical energy dimension.

Additionally to providing these insights on system adequacy, we also provide a data package available on the JASM data platform that provides high-resolution price data that is consistent with the broader STEM results.

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