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A quantitative assessment of the Axpo Power Switcher

A collaboration between ETH Zurich and Axpo

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Executive Summary

This report evaluates the results of [Axpo's Power Switcher] on the security of electricity supply. We operationalize security of supply with the electricity demand that cannot be served (DNS). The report assesses whether the Power Switcher's methodology of using a monthly electricity balance (and the consequential simplifications in the modeling) – instead of hourly power balances – is sufficient to make accurate statements on the security of supply. The rationale behind using monthly energy balances for evaluating the security of supply is that in Switzerland, a possible shortage of generation capacity in individual hours is not critical due to the high amount of existing (pumped hydro storage, hydro dams) and expected (battery storage, electric vehicles) flexibility options; security of supply is instead jeopardized by energy shortage over a longer period when fill levels of large storage reservoirs run low. However, due to using monthly energy balances, the Power Switcher, by definition, cannot make any statements on demand and supply on an hourly or daily resolution.

To assess the accuracy of Power Switcher's statements on the security of supply, we develop four scenarios and compare the results of the Power Switcher and Nexus-e, a platform of ETH Zurich for detailed modeling of the Swiss energy system. In all four scenarios, we find strong similarities between the two models regarding their results on DNS and can explain the remaining mismatches by outlining differences in input data and modeling assumptions. The monthly energy balance provides an accurate assessment of the DNS in most cases and can identify the critical events that jeopardize the security of electricity supply. However, the results become less accurate the more extreme the scenarios become (i.e., the more critical events are included in the scenario). Figure 1 depicts the DNS for 2030, 2040, and 2050 for the four scenarios and both models.

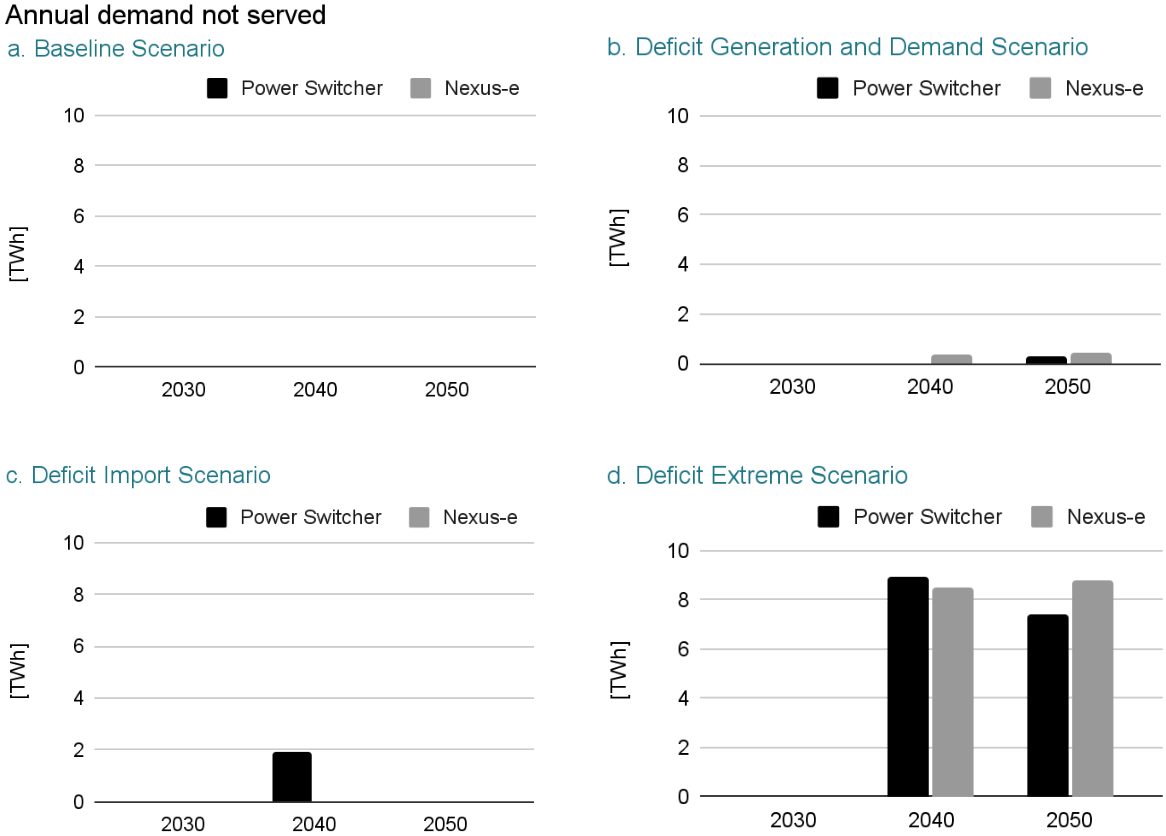

Figure 1: Overview of annual DNS in 2030, 2040, and 2050 for the scenarios **a. - d.**

While both models demonstrate a high level of electricity supply security in the "*Baseline*" scenario, they both have a small amount of DNS in the "*Deficit Generation and Demand*" scenario, which is defined by not allowing new installation capacities for wind and gas units, a 14-day extreme weather event in February with no solar and wind power in Europe, and a higher inland electricity demand. In this scenario, however, Nexus-e indicates DNS already from 2040 onwards, while the Power Switcher only in 2050. This mismatch results from the difference in how DNS in one country can create DNS in another country despite sufficient supply. While the Power Switcher defines national electricity systems that interact only if one country has insufficient inland generation, Nexus-e represents Switzerland's and its neighboring countries' transmission grid, including nodes and lines. Since electricity flows between the nodes defined by Kirchhoff's law – rather than staying within national or regional borders – electricity can flow to a neighboring country's node to cover the demand, even if there is another Swiss node with DNS.

Reducing the NTCs by 70% in the "*Deficit Import*" scenario causes a substantial DNS in the Power Switcher but none in Nexus-e – and thus the most substantial mismatch between the models observed in the scenarios. Both a higher electricity load and fewer net imports during the winter months are the main drivers of the DNS in the Power Switcher. The Power Switcher assumes the utilization, and thus the load, for pump storage being equally distributed over the year, while Nexus-e tends to utilize pump storage for seasonal load shifting in extreme scenarios (and thus, pump storage load is concentrated in the summer months and generation in the winter months). The lower net imports in the Power Switcher result from differences in the input data on the development of electricity demand and supply in the neighboring countries. Despite these differences, Nexus-e only narrowly avoids DNS in the "*Deficit Import*" scenario. Reducing the NTC by an additional 10% causes DNS in Nexus-e in 2040 to a similar extent as in the Power Switcher. Both models thus come to the same conclusion that import reductions jeopardize the Swiss electricity system predominantly in the mid-term.

The "*Deficit Extreme*" scenario, which combines the scenario assumption of the two other deficit scenarios, causes a severe amount of DNS in 2040 and 2050. It is important to note that combining the scenario assumptions of the two other deficit scenarios does not result in their combined DNS but instead has a compounding effect and is much higher. The impact of critical events is thus not linear. As soon as a critical situation is triggered, any additional critical event has a substantially larger impact than when occurring individually. This is because inland flexibility and imports from neighboring countries are already utilized to their maximum. The slight difference in the 2050 values between the two models is due to a higher import potential in the Power Switcher. In this extreme scenario, the less stringent grid restrictions in the Power Switcher resulting from the monthly balancing come into play.

The two models also agree to a large extent on the seasonal patterns of DNS. Both models show DNS only during the winter months, and in the "*Deficit Generation and Demand*" scenario, all DNS even occurs in the same months. Only in the "*Deficit Extreme*" scenario are seasonal patterns not congruent as the models differ in how they utilize the available flexibility in hydro dams' electricity generation. While the Power Switcher utilizes a hydro reserve as early as possible in the year to avoid DNS, in Nexus-e, the use of hydro dams is optimized across the year to minimize the system dispatch costs.

In general, three points have to be balanced in modeling: user-friendliness (particularly for non-professional users), computational speed, and accuracy of the results. The Power Switcher prioritizes the former two and thereby has to make methodological simplifications. The model …

- … limits NTCs on a monthly and not hourly basis. NTCs are thus less stringent.
- … does not consider marginal costs, important for the dispatch of flexible units.
- … neglects the national electricity grid and its impact on inland and cross-border flows.

However, despite these simplifications, the results of this report show that the Power Switcher can make statements on the security of supply with reasonable accuracy.

Future work in the Power Switcher could focus on providing more insights into the neighboring countries' installed capacities, electricity generation, and load. In addition, the model could indicate from where Switzerland is already importing and from where it could import even more. The Power Switcher could also account for the trade balance of Switzerland’s neighboring countries with the remaining European countries and include the option to use gas-fired power plants as a reserve only, similar to the hydro reserve.

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Background

The Axpo Power Switcher provides predefined scenarios and the option to create individual pathways for the development of the Swiss electricity system. Based on today's electricity mix, the pathways include multiple technologies for electricity generation, such as solar photovoltaics (PV), wind, hydropower, nuclear power, and gas-fired power plants. The electricity demand comprises demand for conventional uses, electromobility, hydrogen, and heat pumps. The Power Switcher calculates monthly energy balances based on electricity generation and demand. If inland electricity generation is insufficient to meet inland demand, the model checks whether importing electricity from the neighboring countries (Germany, France, Italy, and Austria) is possible. If both inland generation and available imports fall short of inland demand – and thus some demand cannot be served – the month is marked as an electricity deficit month. The website of the Axpo Switcher provides a detailed description of the methodology.

This report evaluates the Power Switcher's results on the security of electricity supply which we operationalize with the demand not served (DNS). The main question is whether the methodology of using a monthly electricity balance – instead of hourly power balances – is sufficient to make statements on the security of supply. The rationale for monthly energy balances is that in Switzerland, unlike in many other European countries, a possible shortage of generation capacity in individual hours is not decisive for security of electricity supply. This is because a high number of existing pumped hydro storage and hydro dams but also new flexibility options such as battery storage and electric vehicles make it possible to compensate for hourly or daily fluctuations in electricity production. The trigger for a possible interruption in the power supply is rather an energy shortage over a longer period when large storage reservoirs run dry.

To do so, we use Nexus-e, a platform of ETH Zurich for modeling the Swiss energy system. A detailed description of the modeling platform can be found on the Nexus-e website and recent publication.

Methodology & Scenarios

To compare the results on the security of electricity supply between the Axpo Power Switcher and Nexus-e, we develop four scenarios (see Figure 2).

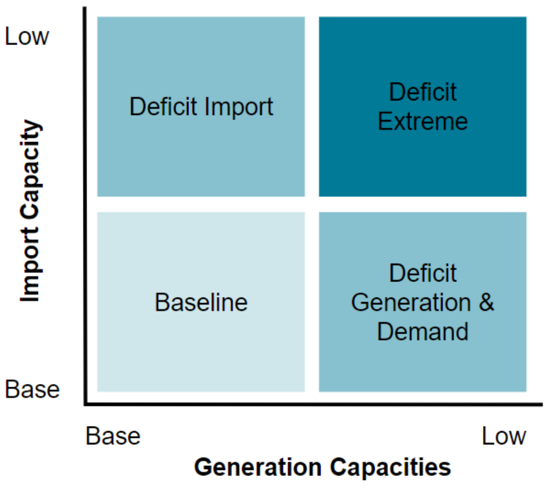


Figure 2: Scenario overview

Baseline Scenario

First, we develop a Baseline scenario with Nexus-e. Based on defined model inputs, we run the scenario in Nexus-e to obtain the “optimized” electricity generation capacities. Finally, we include the defined model inputs and the optimization results from Nexus-e in the Power Switcher.

The optimization in Nexus-e suggests an expansion path for the Swiss electricity system that leads to the lowest total costs of power supply. The system costs comprise investment, maintenance, CO_2, and fuel costs. The optimization considers learning effects (decreasing prices of the technologies over time) and current subsidies (for example, return tariffs and one-time payments for photovoltaic systems). The included technical potential of photovoltaics for rooftop installations is 53 GW by 2050 (not all potential is installed in the cost-optimal expansion path). The expansion of wind power is limited to 2 GW due to permits and financing, and biomass to 0.4 GW. Electricity generation from run-of-river power and pumped storage power plants remain at today's levels. The scenario assumes a general phase-out of nuclear power after 50 years, except for already confirmed lifetime extensions. Beznau 1 and Beznau 2 (both extended) will, therefore, remain online until 2029 and 2031, while Gösgen and Leibstadt remain until 2029 and 2035. The scenario also allows for the installation of gas-fired power plants with Carbon Capture & Storage (CCS) but excludes geothermal power for electricity generation and ground-mounted photovoltaic plants in the alpine region.

Electricity demand assumptions follow the "Zero Basis" scenario of Energy Perspectives 2050+, which considers increasing electricity demand mainly due to the electrification of the transportation and heating sectors with electric vehicles and heat pumps. Figure 3 depicts the development of the electricity generation capacities in the neighboring countries based on the ENTSO-E TYNDP “Global Ambition” scenario. Table 1 lists the current Net Transfer Capacities (NTC) and their development until 2050. Based on the latest ENTSO-E ERAA study and due to the lack of a framework agreement between Switzerland and the EU, in the Baseline scenario, there is no increase in import capacity between 2030 and 2050.

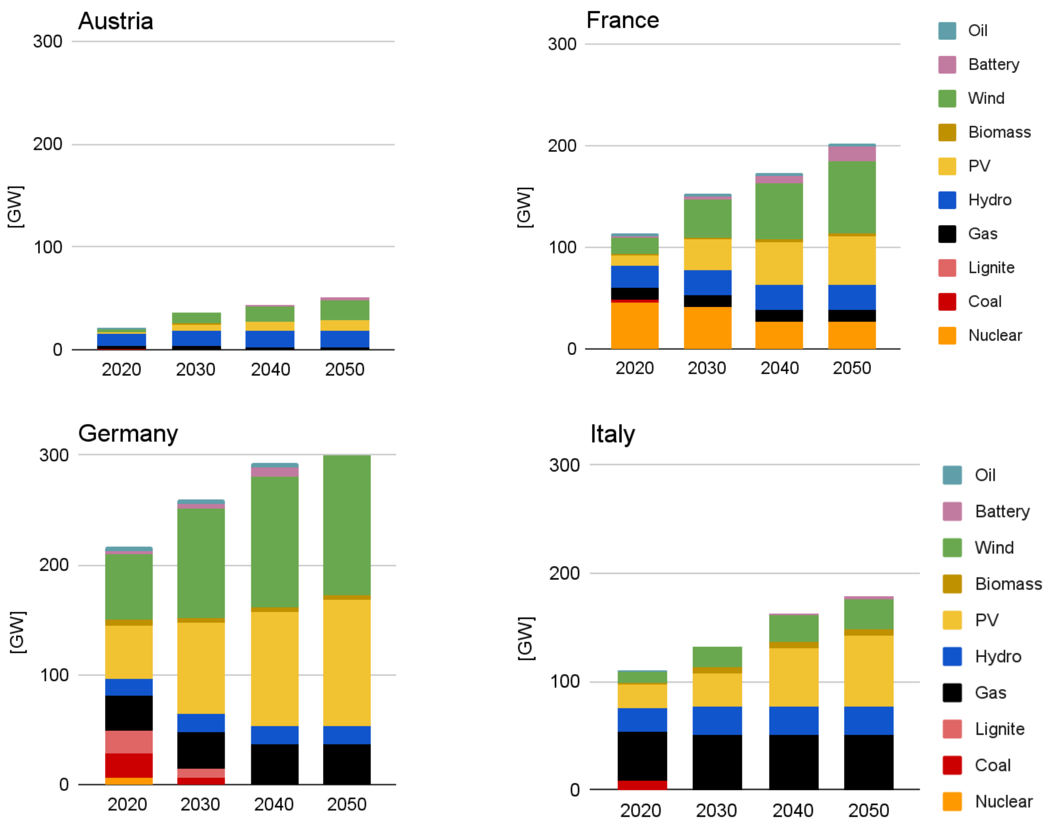


Figure 3: Installed electricity generation in neighboring countries

Table 1: Import NTC Values for the Baseline and the Deficit Import scenario [MW]

	Baseline Scenario				Deficit Import Scenario			
	2020	*2030*	*2040*	*2050*	*2020*	*2030*	*2040*	*2050*
France	2600	3700	3700	3700	780	1110	1110	1110
Germany	3150	3800	3800	3800	945	1140	1140	1140
Italy	1910	1910	1910	1910	573	573	573	573
Austria	1200	1200	1200	1200	360	360	360	360

Deficit Scenarios

Second, we define "deficit scenarios" using the Power Switcher. A scenario has a "deficit" when part of the electricity demand cannot be served with inland generation and imports in any month of any year. Beginning from the Baseline scenario, we define the deficit scenarios by adjusting the parameters in the Axpo Power Switcher as follows:

"*Deficit Generation & Demand" Scenario*: This scenario includes three changes. First, new installations of wind and gas-fired power plants in Switzerland are not allowed. Wind power currently has only a 0.2% share of the Swiss electricity mix. Besides high installation costs in Switzerland, long planning and approval processes can increase the time between the start of the project and its realization by up to 20 years. Although the Swiss government aims to improve the efficiency of planning and approval access for wind power, this scenario assumes that high barriers to new wind power installations and, therefore, no additional wind plants are finalized before 2050. Similarly, whether Switzerland should build domestic gas-fired generation capacity remains controversial. With the Ukraine-Russia war, dependence on Russian gas threatens Europe's energy security. Uncertainties about future availability are leading to gas prices at record levels. It is also unclear whether efforts to minimize dependence on Russian gas in the short-to-medium term can stabilize prices. For example, a renaissance of CO_2-intensive coal-fired power could cause CO_2 certificate prices to rise further. While the Swiss Federal Office of Energy has announced plans to build power-to-gas capacity, it is unclear whether these can be realized. Therefore, this scenario assumes that the social acceptance of gas-to-power electricity generation is too low for new installations. Furthermore, we account for an additional generation deficit with an extreme weather event by assuming 14 days in February of no wind blowing and no sun shining in Switzerland and neighboring countries. Lastly, we also assume a higher electricity demand in Switzerland due to stronger electrification of the transport and heating sectors, following the EP2050+ scenario Zero A.

"*Deficit Import" Scenario*: This scenario includes a reduction of the NTCs for the electricity trading between Switzerland and its neighboring countries by 70% compared to the Baseline scenario (see Table 1). Such a restriction of electricity trading reflects the ongoing discussion of the potential impact of the EU Clean Energy Package, which enforces EU member states to withhold 70% of grid capacity for EU cross-border flows

"Deficit Extreme" Scenario: This scenario combines the changes from the previous two scenarios that had already individually caused a deficit.

After defining the three deficit scenarios using the Axpo Power Switcher, we run these scenarios using Nexus-e. Please note that the installed electricity generation capacity is usually a model output of Nexus-e; however, for the three deficit scenarios, we fix the installed capacity to the Baseline scenario and adjust them according to the assumptions in the deficit scenarios.

Comparison of scenario results

In the following, we compare the results of the Power Switcher and Nexus-e on the electricity deficit.

Overview

Figure 4 depicts the demand not served (DNS) in each of the four scenarios for the years 2020, 2030, and 2040. The Axpo Power Switcher results show (per definition) no DNS in the Baseline scenario but in the other three deficit scenarios. The "*Deficit Generation & Demand*" scenario results in the smallest amount of DNS of 0.3 TWh in 2050, followed by the "*Deficit Import*" scenario with 1.9 TWh in 2040, and the "*Deficit Extreme"* scenario with 8.9 TWh in 2040 and 7.4 TWh in 2050.

Nexus-e results point out similarities with and differences to the Power Switcher results. In Nexus-e, there is no DNS in the Baseline scenario (similar to Power Switcher) nor in the "*Deficit Import*" scenario (different from Power Switcher). In contrast, in the "*Deficit Generation & Demand*" scenario, Nexus-e results in a higher DNS than the Power Switcher. With DNS amounting to 0.4 TWh in 2040, there is DNS in Nexus-e while not in the Power Switcher. Also, the Nexus-e DNS in 2050 is amounting to 0.5 TWh and thus slightly higher in Power Switcher. In the "*Deficit Extreme*" scenario, Nexus-e shows a substantial DNS of 8.5 TWh in 2040 and 8.8 TWh in 2050, similar to the values obtained from the Power Switcher.

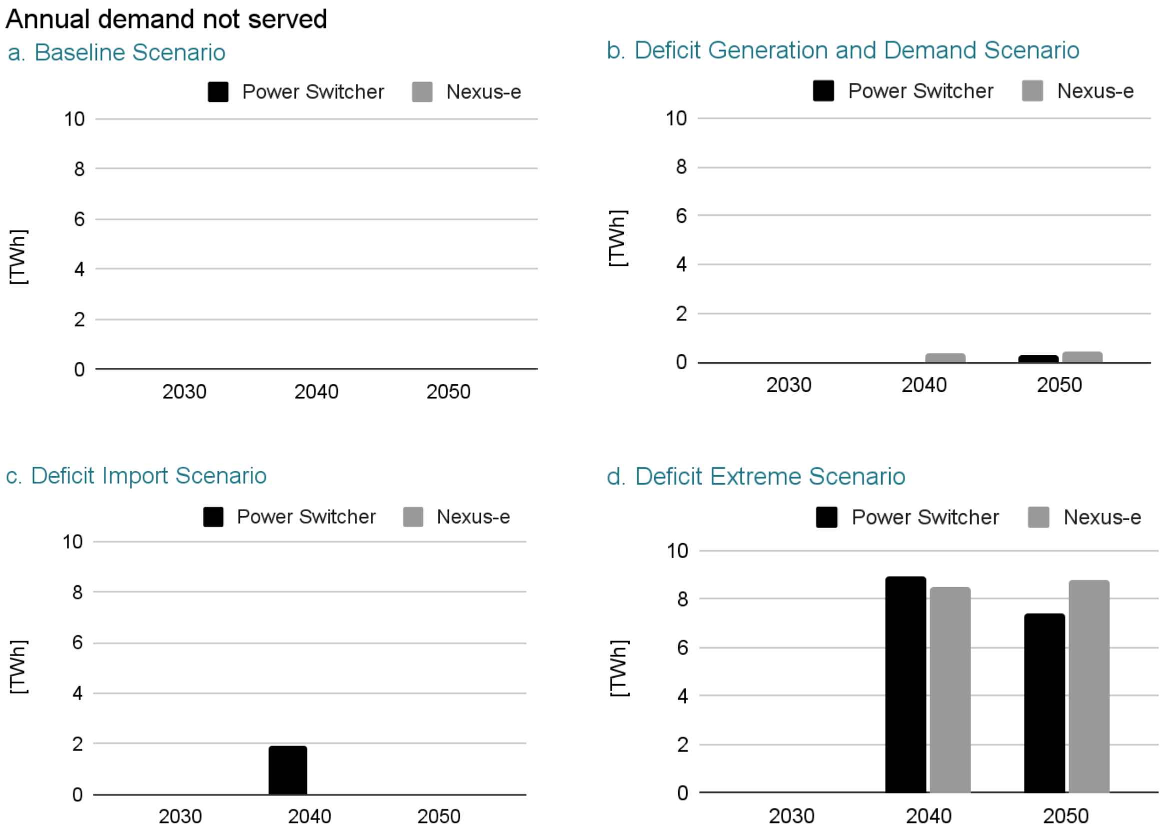


Figure 4: Overview of annual demand not served in 2030, 2040, and 2050 for the scenarios **a. - d.**

To improve our understanding of the differences in the modeling assumptions between the Power Switcher and Nexus-e, we assess the model outputs for each scenario in the following sections.

Baseline Scenario

Figure 5 depicts the annual electricity generation per technology in the Baseline scenario for the Power Switcher and Nexus-e. In both models, nuclear power is phasing out until 2040, and the annual electricity generation from hydropower and biomass remains similar from 2030 to 2050. Wind power is installed only from 2040 onwards, whereas solar PV is responsible for the largest share of new power generation installations. However, despite harmonizing most scenario inputs, such as the installed electricity generation capacities, electricity generation per technology differs substantially between the models, especially the use of gas-fired power plants with carbon capture and storage (CCS).

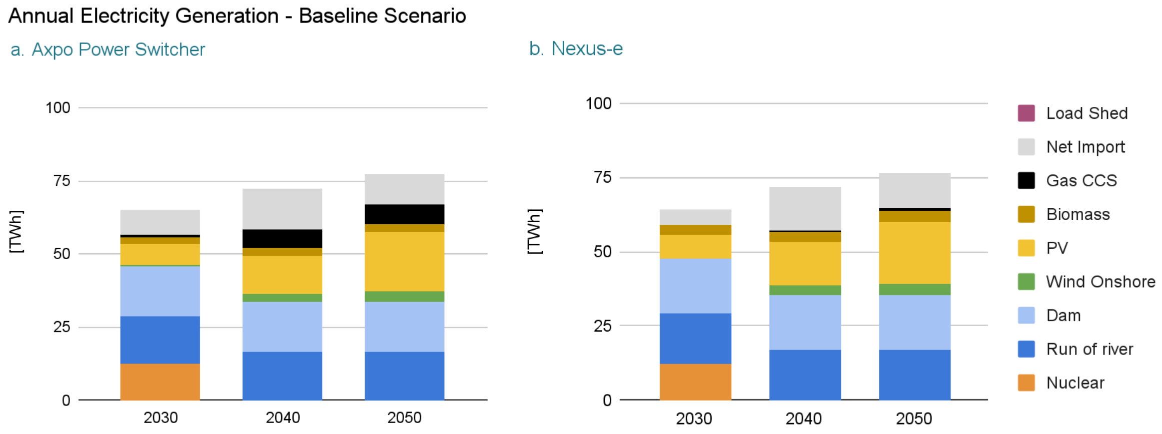


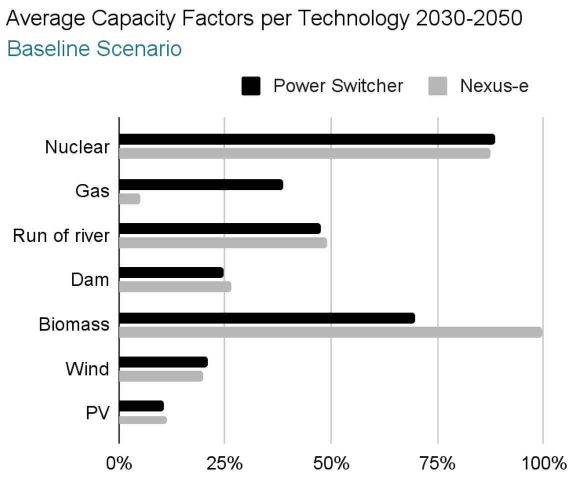
Figure 5: Annual Electricity Generation in Baseline Scenario in **a.** Power Switcher and **b.** Nexus-e

To better illustrate the differences, Figure 6 outlines the average capacity factors for each technology from 2030 to 2050. The capacity factors differ between the models for all technologies, especially gas and biomass units.

A methodological difference can explain the different capacity factors of gas units. In the Power Switcher, before importing, all inland power generation capacities, including gas units, are switched on to meet inland demand based on monthly energy balances. Only in case inland generation falls short, electricity is imported from neighboring countries. Conversely, in Nexus-e, electricity is imported when it is available in neighboring countries at a lower price compared to inland generation. With gas units having high variable costs (commodity price, CO_2 emission certificate), imports are often less expensive than running gas units in Switzerland. In the Baseline scenario, gas units are only used for a very few hours with very high electricity prices. Also, Nexus-e assumes only waste incineration for biomass, whereas in the Power Switcher, biomass is a generic term for a wide range of power plants that use biomass to generate electricity, including biogas, wood, and sewage gas plants, and the biogenic fraction in waste incineration. Generally, waste incineration has a higher capacity rate than other plants that use fermented, burned, or gasified biomass to produce electricity. The different capacity factors for wind, PV, and run-of-river result from using another historical weather year for creating the generation profile. Another methodological difference explains the different capacity factors for hydro dams. To allow for some flexibility in the electricity generation of hydro dams, the Power Switcher assumes a hydro reserve of 1.9 TWh. The reserve is only utilized if all other inland generation plus imports are insufficient to meet inland demand. In Nexus-e, electricity generation of dams depends on marginal dispatch costs, the actual storage level, and annual inflow pattern.

Table 2 lists both models' electricity generation, load, and imports in 2040. Due to lower capacity factors for PV and biomass in the Power Switcher, the electricity generation by renewable energies is 2.8 TWh lower. The difference in hydropower of 2.0 TWh is similar to the magnitude of the hydro reserve in the Power Switcher. The largest difference in 2040 is due to gas units that are providing baseload in winter in the Power Switcher while covering only peak loads in Nexus-e.

The load differs due to methodological differences. The Power Switcher assumes a fixed value for pumps' and batteries' annual efficiency losses as a model input that is similar across years and scenarios. In contrast, in Nexus-e, the efficiency losses depend on the actual utilization of both technologies in the scenario. With a higher utilization of pumps and batteries than expected in the setup of the scenario, Nexus-e overestimates loads from both technologies. The remaining difference can be explained by slightly lower imports in the Power Switcher and a minor rounding error in the calculation.



in TWh	Power Switcher	Nexus-e	Delta
Renewable Energies	18.4	21.2	-2.8
Hydropower	33.6	35.6	-2.0
Gas	6.2	0.6	5.6
*Load**	72.4	71.7	-0.7
Imports	14.1	14.3	-0.2
Sum			-0.1**

*: Includes efficiency losses from hydro pumps and batteries
**: Due to rounding error in calculation

Figure 6 (left)**:** Average Capacity Factor per technology from 2030-2050 in the Baseline Scenario

Table 2 (right)**:** Electricity generation in 2040 and the difference between the two models

With DNS occurring in the winter months, it is also important to understand the seasonality of electricity demand, load, and import. Figure 7 depicts the monthly electricity generation in 2040 in the Baseline scenario. In both models, Switzerland has insufficient inland electricity generation to meet its own demand in 9 out of 12 months and therefore relies on imports to close the gap between supply and demand. Only in June, July, and August renewable energies, including PV, biomass, wind, and hydro, are sufficient to meet inland demand.

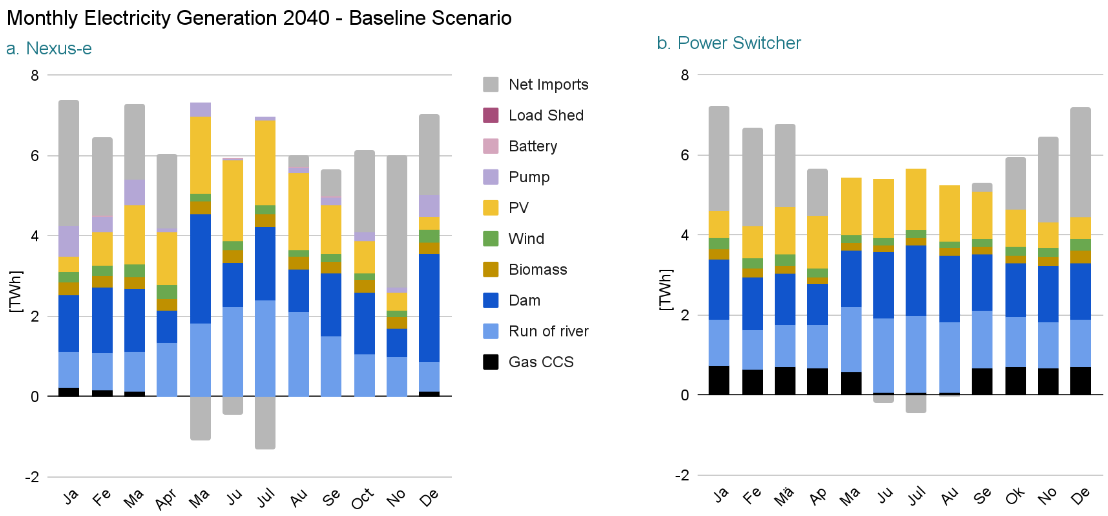


Figure 7: Monthly Electricity Generation in 2040 in the Baseline Scenario for **a.** Nexus-e and **b.** the Power Switcher (right)

As already discussed in the annual comparison, the Power Switcher has high utilization of gas units, which even run partly in the summer months. Conversely, in Nexus-e, where imports are typically cheaper than inland generation from expensive gas units, these thermal plants are dispatched only from December to March and only for a few hours. Also, the difference in the hydro profiles is striking. In Nexus-e, run-of-river demonstrates a more seasonal pronounced electricity generation than in the Power Switcher. Also, hydro dam generation fluctuates substantially between the month to reduce the dispatch of more expensive generators or imports.

Figure 8 compares the seasonal electricity generation for 2040 in the Baseline scenario, with "summer" including the months from April to September and "winter" from October to March". Interestingly, renewables have a higher annual electricity generation in Nexus-e (compare Table 2) but a higher winter generation in the Power Switcher. The capacity factors for non-dispatchable renewables (biomass, wind, PV) in the Power Switcher seem to be based on a historical weather year with a less pronounced seasonal pattern than in Nexus-e. Conversely, hydro production in winter is lower in the Power Switcher, mainly due to the hydro reserve that is not yet used in the Baseline scenario (as inland generation and imports are sufficient to meet inland demand). In a deficit scenario, the hydro generation in the winter months is thus likely to be similar in both models.

The electricity load is the same in summer but slightly different in winter. While the Power Switcher includes only the fixed annual efficiency losses of hydro pumps in the overall load (thus assuming that pump load and generation is balanced over a month), in Nexus-e, pumps also demonstrate a "seasonal storage behavior": While the pump load is higher in summer, the pump generation is higher in winter, meaning that part of the load is used to store electricity in summer for winter. To summarize, in winter, the lower electricity generation by hydropower and slightly higher load is balanced in the Power Switcher with higher utilization of gas units (which in turn also reduced the net imports).

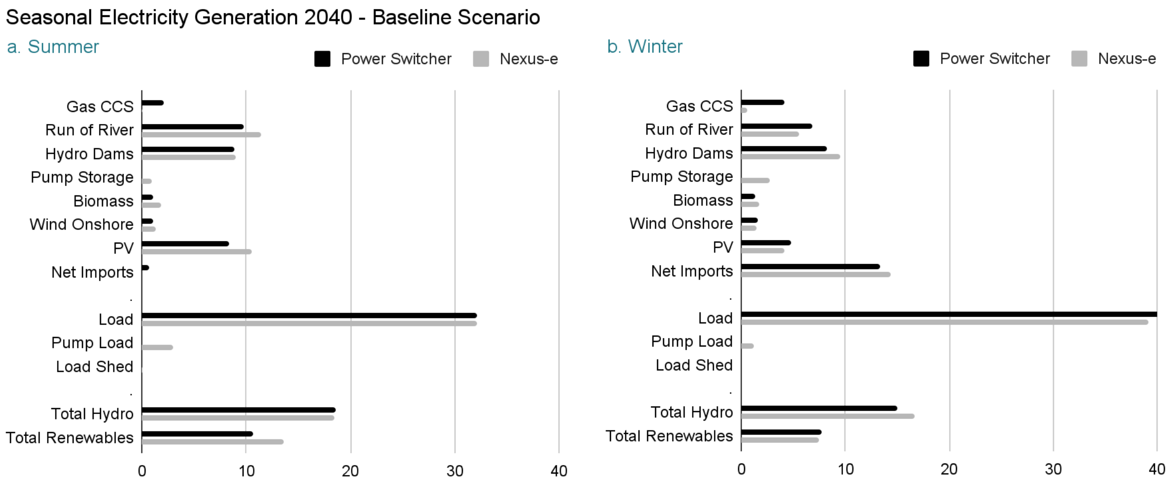


Figure 8: Comparison of seasonal electricity generation in 2040 in the Baseline Scenario in **a.** summer and **b.** Winter. The value for load presented here does not include efficiency losses for pumps and batteries.

Deficit Generation and Demand Scenario

This section evaluates the "*Deficit Generation and Demand*" scenario, which is defined by not allowing new installation capacities for wind and gas units in Switzerland, a 14-day extreme weather event in February with no solar and wind power in Europe, and a higher electricity demand in Switzerland.

Adjusting generation and demands results in 0.39 TWh and 0.47 TWh of DNS in 2040 and 2050 in Nexus-e. In the Power Switcher, there is DNS only in 2050, amounting to 0.27 TWh. Figure 1a. depicts the monthly DNS for 2030, 2040, and 2050 for both the Nexus-e and the Power Switcher results. In all cases, the annual DNS occurs entirely in February. Figure 1b. compares the electricity generation and imports for February 2050 between the "*Deficit Generation and Demand*" scenario and the Baseline scenario for both models. Following the "*Deficit Generation and Demand*" scenario definition, there is no electricity generation by gas and wind in both models, a slightly higher demand, and a reduced generation by PV. To counterbalance the impact, both models utilized the flexibility in hydropower to the maximum extent. In the Power Switcher, the entire hydro reserve (1.9 TWh) is utilized in February. Similarly in Nexus-e, hydro reservoirs for dams and pumps are depleted to avoid more DNS.

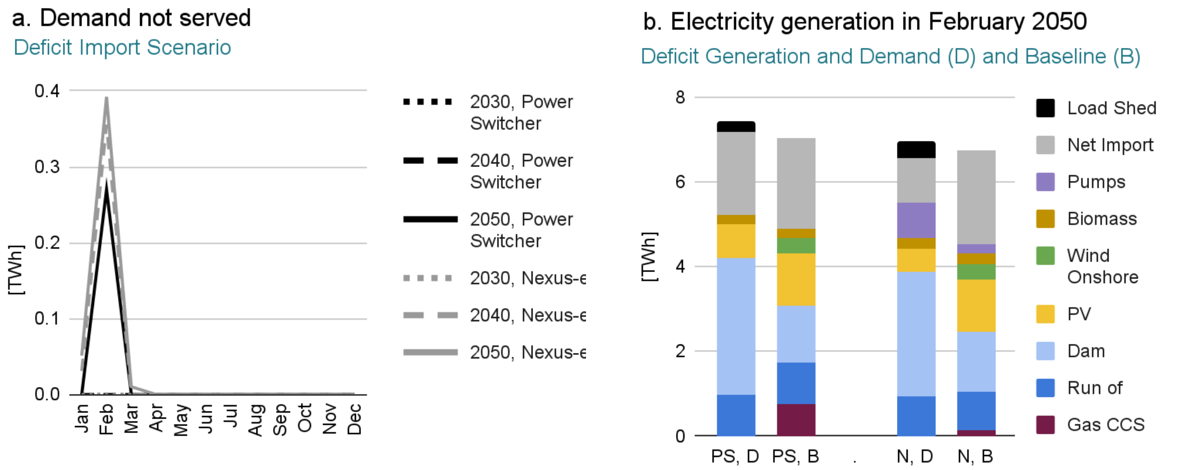


Figure 12: **a.** Monthly demand not served in the Deficit Import scenario. **b.** Electricity generation per technology in February 2050 in Power Switcher (PS) und Nexus-e (N) for the Deficit Generation and Demand (D) and Baseline (B) scenario.

In Nexus-e, Switzerland cannot import enough electricity to close the inland demand-supply gap. One reason for this is that electricity generation in neighboring countries is also affected by the 14-day extreme weather event. Figure 13 depicts the electricity generation in each neighboring country in February 2050 from Nexus-e for both scenarios. Wind and PV generation are lower in all countries compared to the Baseline case. This effect is partly mitigated by increasing gas, coal, and hydro shares. Nevertheless, also France and Germany see large amounts of DNS in February. Due to its large installed gas capacities, Italy has no DNS and shows a substantial amount of net exports. The neighboring countries export around 1 TWh to Switzerland, despite the critical weather event.

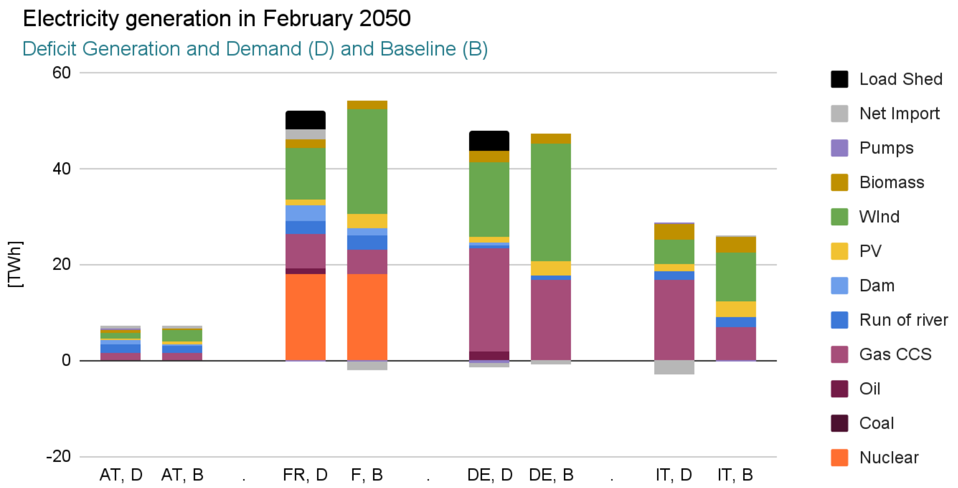


Figure 13: Electricity generation in February 2050 in the neighboring countries Austria (AT), France (FR), Germany (DE), and Italy (IT) for the Deficit Generation and Demand (D) and Baseline (B) scenarios from the Nexus-e model.

The February values for Germany are surprising as they depict both exports and DNS. Figures 14a and 14b show the hourly electricity generation and net imports in Nexus-e for February 1, the first day of the 14-day "no wind and sun" for Switzerland and Germany, respectively. During that day, Germany has both net exports and DNS from 08:00-12:00. Similarly, Switzerland also has both net exports and DNS for almost most of the hours. This behavior can be explained by Nexus-e's nodal representation of the electricity system of Switzerland and its neighboring country. Nexus-e does not separate between a "Swiss electricity system" and "neighboring countries' electricity systems," but rather considers them as one system with one electricity grid consisting of nodes (with electricity generation and demand) and lines between these nodes (with capacity restrictions). Electricity flows between the nodes defined by Kirchhoff's law – rather than staying within national or regional borders. Therefore, electricity generation in Switzerland can flow to a neighboring country's node to cover the demand, even if there is another Swiss node with DNS. This means that if electricity generation exceeds electricity demand in Switzerland, load shedding can also occur in Switzerland – especially in the case of heavy DNS in neighboring countries. What does this mean now for the model comparison? In Nexus-e, the results can show DNS for Switzerland, although inland electricity generation exceeds inland electricity demand, especially in the case when neighboring countries have DNS as well. This behavior is not included in the PowerSwitcher.

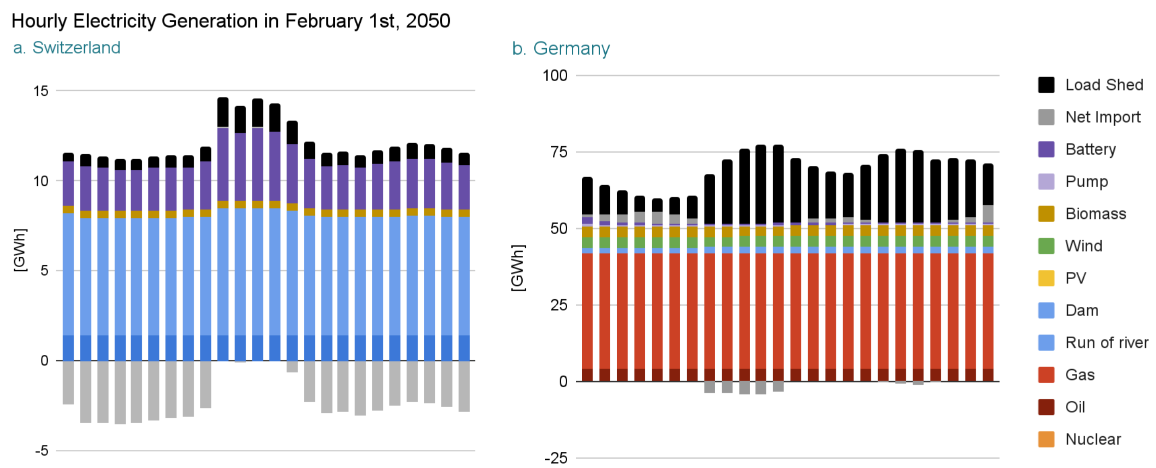


Figure 14: Hourly electricity generation on February 1st in 2050 for the Deficit Generation and Demand scenario in **a.** Switzerland and **b.** Germany.

Deficit Import Scenario

This section evaluates the "*Deficit Import*" scenario, which is defined by a reduction of the NTC values by 70% compared to the Baseline scenario.

Reducing the NTC by 70% results in 1.9 TWh of demand in 2040 that cannot be served in the Power Switcher. Contrary, there is no DNS when restricting the electricity trade in Nexus-e. Figure 9a depicts the monthly DNS for 2030, 2040, and 2050. DNS occurs in March, November, and December 2040, amounting to 0.36 TWh, 0.51 TWh, and 1.05 TWh, respectively. Figure 9b and Table 3 show the winter electricity generation, load, and imports for the deficit year 2040. The general picture remains unchanged compared to the Baseline scenario. The Power Switcher shows lower hydropower (0.3 TWh) and imports (0.8 TWh) that is compensated by more renewables (0.2 TWh) and gas (0.2 TWh) as well as a higher load (1.2 TWh).

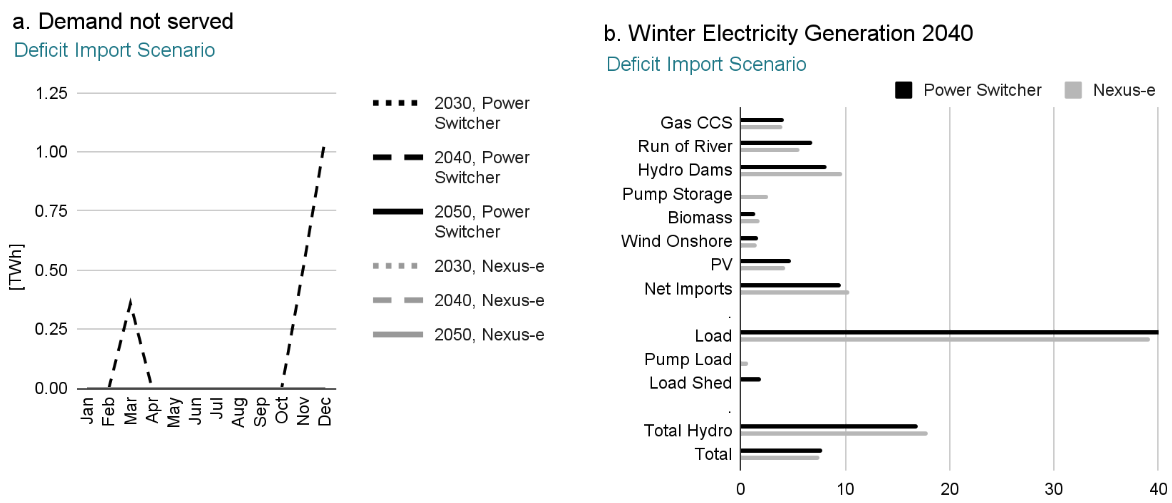


Figure 9: **a.** Monthly demand not served in the Deficit Import scenario. **b.** Winter electricity generation per technology in 2040 in the Deficit Import scenario

Important for the comparison is also to understand how the models react to the new scenario parameters, in this case, the reduction of the NTCs. Table 3 provides the changes compared to the same year in the Baseline scenario in parentheses. In both models, when reducing NTCs by 70%, net imports are reduced by around 40% but remain higher in Nexus-e (by 0.8 TWh). While there is no change in electricity generation by renewable energy and gas units, hydropower generation is increasing by 1.9 TWh in the Power Switcher and 0.6 TWh in Nexus-e. In Nexus-e, hydro pumps' "seasonal storage" behavior is even more pronounced with a lower load but similar production in winter. Combined with an additional shifting of dams, hydropower generation increases in Nexus-e (0.6 TWh) compared to the Baseline scenario. While gas CCS could not be further increased in the Power Switcher, in Nexus-e, it is dispatched to almost the same amount as in the Power Switcher. Figure 10 depicts the monthly electricity generation by hydropower in 2040 for both models. In the Power Switcher, in January and February, the hydro generation is higher in the "*Deficit Import*" scenario than in the Baseline scenario as the hydro reserve is being completely utilized during these months. In March, with an empty hydro reserve, hydroelectricity generation is similar again to the Baseline scenario. Comparing this behavior with the monthly DNS in Figure 9a, we see that the use of the hydro reserve in January and February was successful in avoiding DNS, but, after the reserve is depleted, DNS occurs in March (see Figure 9a).

In TWh	**Power Switcher**	**Nexus-e**	**Delta**
Renewable Energy	7.7 (0.0)	7.5 (0.0)	0.2
Hydro power	16.9 (1.9)	17.2 (0.6)	-0.3
Gas CCS	4.1 (0.0)	3.9 (3.3)	0.2
Net Imports	9.6 (-3.8)	10.4 (-3.9)	-0.8
Load Shed	1.9 (1.9)	0	1.9
Load	40.2 (0.0)	39.0 (0.0)	-1.2

Table 3: Comparison of winter electricity generation, load, and imports between Power Switcher and Nexus-e in 2040 in the Deficit Import scenario [TWh] (In brackets delta to Baseline 2040 values)

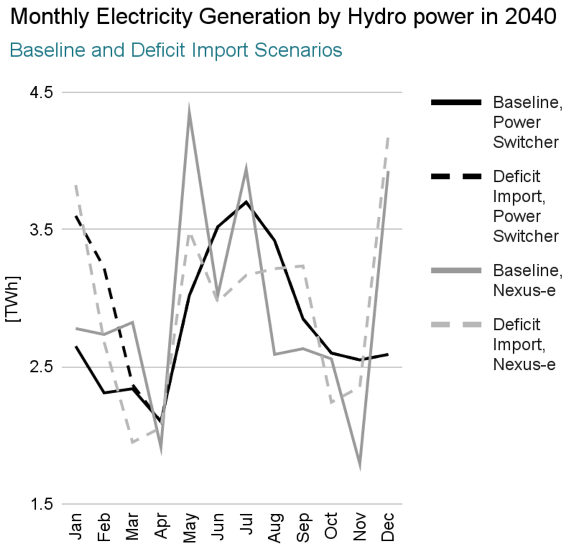


Figure 10: Monthly electricity generation by hydropower in 2040 for Baseline and Deficit Import scenario

Interestingly, the Power Switcher shows lower net imports in 2040 despite having DNS amounting to 1.9 TWh, indicating that the import assumptions in the Power Switcher might be more restrictive than those in Nexus-e. In both models, the option to import is affected by two restrictions: (i) excess electricity available in neighboring countries and (ii) sufficient grid capacities (i.e., NTC) for the required electricity trading.

The first assumption builds upon the development of electricity generation and demand in the neighboring countries until 2050. Both models use the TYNDP Global Ambition scenario for developments in neighboring countries (see Figure 2). However, not all technologies that are listed in the TYNDP scenario, such as combined heat and power units, are represented in the Power Switcher and Nexus-e. Therefore, there might be a mismatch in the installed capacities between the models. Also, the capacity factors for electricity generation in neighboring countries are not harmonized. Nexus-e also accounts for the neighboring countries' electricity trade with their neighboring countries while this is neglected in the Axpo Power Switcher. For the second restriction, both models use the projected net transfer capacities from ENTSO-E in the Baseline scenario (see Table 1). However, the two models fundamentally differ in how the NTCs are converted to electricity trading restrictions. In Nexus-e, the NTCs limit the power [MW] that can be imported from and exported to each neighboring country every hour. Instead, the Axpo power Switcher translates the NTCs into a monthly maximum of electricity [TWh] that can be used as imports in the energy balance. The monthly maximum is calculated by multiplying the NTC with the number of hours per month. The approach by Axpo can be considered the upper limit of the second restriction, which in Nexus-e would only be achieved if, in every hour of the month, the grid is fully utilized for imports. Therefore, restrictions for the grid capacities should be more binding in Nexus-e than in the Power Switcher.

Figure 11 depicts the net imports in winter for 2040 in the Baseline and “*Deficit Import*” scenario. It also provides the upper limit of the grid capacity restriction after reducing the NTC (black bars). Contrary to our initial hypothesis, in 3 out of the 6 winter months, net imports are lower in the Power Switcher than they are in Nexus-e when reducing the NTCs by 70%. In the following, each month is discussed individually. January behaves as expected: In the Baseline scenario, Nexus-e shows higher net imports as importing is cheaper than inland generation with gas units, whereas the Power Switcher only imports to avoid DNS. When reducing the NTC, the order changes and imports become lower in Nexus-e as the grid capacity restriction limits hourly imports rather than the monthly balance. February (and December) demonstrate similar behavior, with the only difference that net imports in the Baseline scenario are already higher in the Power Switcher. March demonstrates a surprising behavior in two ways: First, in Nexus-e, net imports are increasing when reducing NTCs. This is because hydro generation is reduced heavily in March and used instead in January (see Figure 10) to avoid DNS. Second, import restrictions seem to be more binding in the Power Switcher than in Nexus-e. In October, the reduced NTCs have no impact and as there is no DNS this month, imports might not be at their maximum. In November, the Axpo Power Switcher demonstrates lower net imports after reducing the NTCs – despite having DNS in that month.

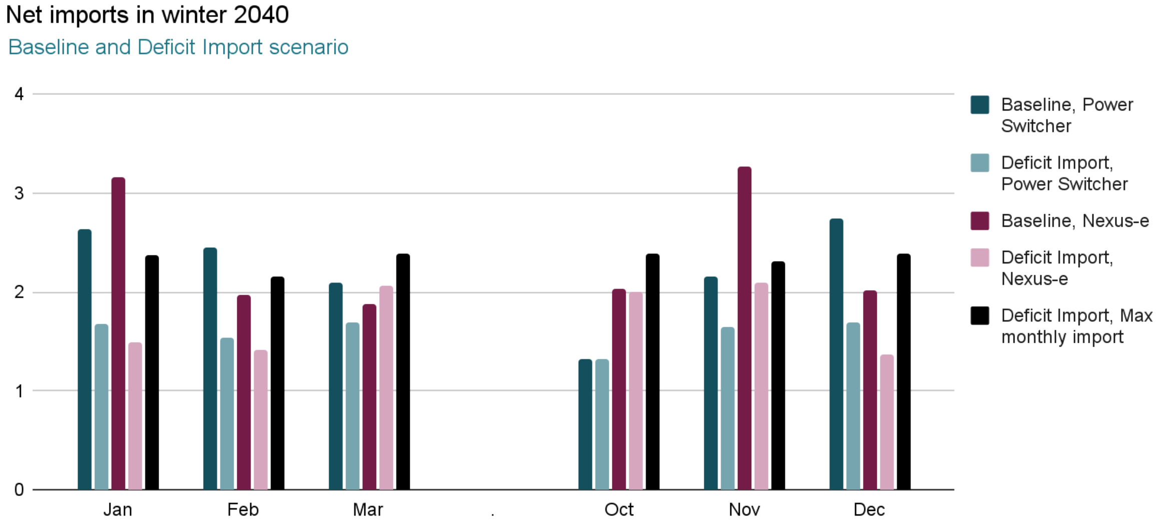


Figure 11: Net imports in winter for Baseline and Deficit Import scenario.

To test how close Nexus-e is to a deficit when reducing the NTCs, we also run a scenario with an 80% NTC reduction. In this scenario, there is a deficit in Nexus-e similar to the level observed in the Power Switcher – and also mostly in 2040. This shows that both models agree on import reductions being more challenging for the Swiss electricity system in the mid-term (2040) than in the long-term (2050).

Deficit Extreme

This section presents the results of the "*Deficit Extreme*" scenario, which combines the scenario assumptions of the two other deficit scenarios: a reduction of the NTC values by 70% compared to the Baseline scenario, no new installations of wind and gas units in Switzerland, a 14-day extreme weather event in February without wind and solar power in Switzerland and its neighboring countries, and an increase in electricity demand in Switzerland.

The combination of such extremes results in 8.9 TWh and 7.4 TWh of demand that cannot be served in 2040 and 2050 in the Power Switcher. Similarly, Nexus-e shows DNS amounting to 8.5 TWh in 2040 and 8.8 TWh in 2050. Figure 15a depicts the monthly DNS for both models. Nexus-e shows a more prominent DNS at the beginning of 2040, peaking in February with 2.6 TWh, whereas the Power Switcher values are higher at the end of 2040, peaking in December with 2.3 TWh. In 2050, the DNS follows a similar seasonal pattern. Figure 15b depicts the annual electricity generation and imports for 2040 and 2050. The annual higher DNS in 2040 in the Power Switcher results from a lower electricity generation by PV (-1.2 TWh) and biomass (-1.1 TWh) which is not fully compensated by higher imports (1.5 TWh) and lower load (-0.4 TWh). Differences in electricity generation by PV and biomass as well as in electricity load can be explained by varying input assumptions (compare with the section on the Baseline scenario). In 2050, the DNS is decreasing in the Power Switcher but increasing in Nexus-e, resulting in a higher annual DNS in Nexus-e. This is mainly because imports are increasing from 2040 to 2050 in the Power Switcher but decreasing in Nexus-e.

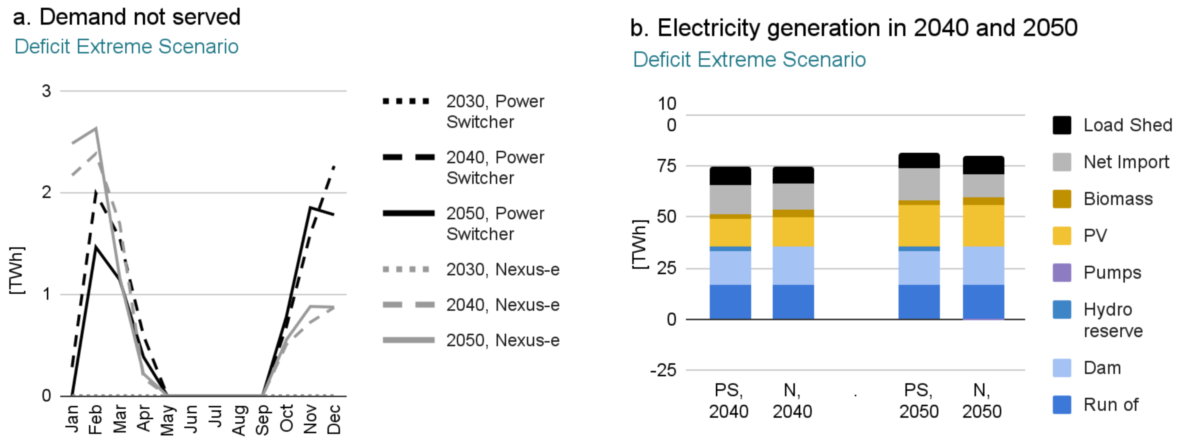


Figure 15: **a.** Monthly demand not served in the Deficit Extreme scenario. **b.** Electricity generation in 2040 and 2050 for both models Power Switcher (PS) and Nexus-e (N).

To better understand the 2040-to-2050 change in imports, Figure 16 depicts the winter imports for the "*Deficit Extreme*" scenario for both years. In the Power Switcher, the electricity imports are increasing from 2040 to 2050 in 4 out of the 6 months. The reason is that, from 2040 to 2050, new generation capacities are installed in neighboring countries (compare with Figure 3). Although electricity demand is also increasing in these countries, the new electricity generation outpaces new electricity demand, providing neighboring countries more options to export. However, imports stagnate in October and November. In Nexus-e, the increase in imports from 2040 to 2050 is less pronounced. Imports increase only slightly in January, March, and December. In January, imports can not further increase because France depends on imports during days with low wind power. Limited excess electricity available from France also reduces imports in December substantially and slightly in March, while limited excess electricity available from Italy reduces imports slightly in October.

In February, Nexus-e shows even negative net imports (i.e., net exports) for Switzerland. This is similar to the observation in the previous section on the "*Deficit Generation and Demand*" scenario: when neighboring countries face severe DNS, Switzerland can have DNS and simultaneously export electricity. In November, imports are only restricted by grid constraints.

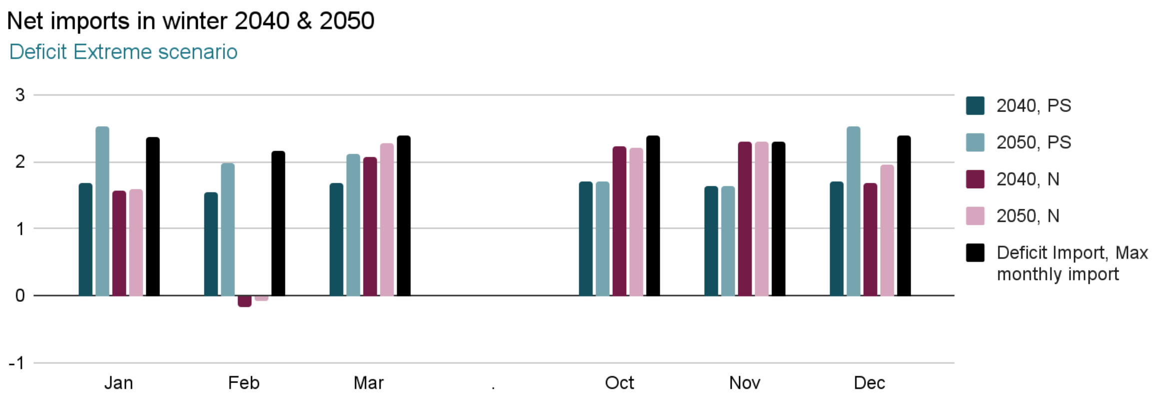
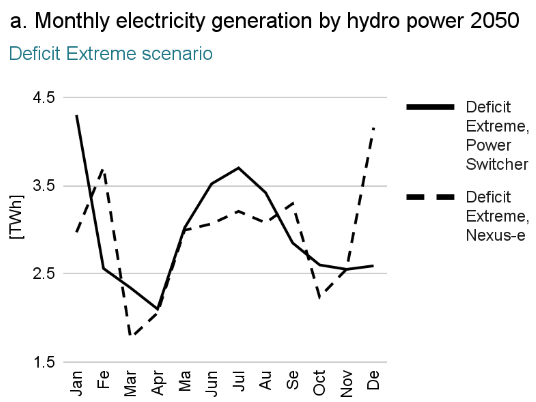


Figure 16: Net imports in the winter months in 2040 and 2050 in the Power Switcher (PS) and Nexus-e (N).

The two models also show different seasonal patterns. The lower amount of DNS at the beginning of the year in the Power Switcher can be partially explained by the dispatch of the hydro reserve, which is utilized for reducing DNS as early in the year as possible (compare with results on the "*Deficit Import*" scenario). Figure 17a depicts the monthly electricity generation by hydropower in 2050. 1.65 TWh of the hydro reserve in Power Switcher is used in January to avoid DNS, the remaining 0.25 TWh in February. Figure 17b compares the electricity generation for the 1st and 4th quarters between the Power Switcher and Nexus-e in 2050. The hydro reserve is fully utilized in the 1st quarter in the Power Switcher. Contrary, the pump storage in Nexus-e (which acts partly as seasonal storage in this scenario; compared with results on the Baseline scenario) is used similarly in both quarters. Additionally, the imports in the 1st quarter in Nexus-e are much lower than in the Power Switcher. 2040 demonstrates similar patterns.



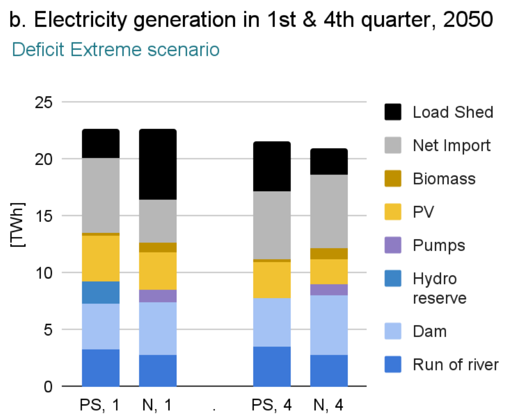


Figure 17: a. Monthly electricity generation by hydropower in 2050 **b.** electricity generation in the 1st and 4th quarter of 2050 in Power Switcher (PS) and Nexus-e (N).

Discussion and Conclusion

Comparing the results on security of electricity supply (i.e., demand not served, DNS) between Axpo Power Switcher and Nexus-e, we find that the methodology of using a monthly energy balance – instead of hourly power balances – is appropriate to make statements on the security of supply. Generally, we find strong similarities between the two models, especially when it comes to identifying the critical events that cause an electricity deficit. Still, deviations between the models occur when the scenario becomes more extreme (i.e., the more critical events included in the scenario).

In general, three points have to be balanced in modeling: user-friendliness (particularly for non-professional users), computational speed, and accuracy of the results. The Power Switcher prioritizes the former two and thereby has to make methodological simplifications. We discuss three of the methodological simplifications in the following: First, the Power Switcher limits NTCs on a monthly (i.e., hours per month multiplied with the NTC) and not an hourly basis. NTCs are thus less stringent. While monthly limits seem to be an appropriate simplification for identifying monthly net imports, the approach becomes less accurate when Switzerland depends substantially on imports for a longer duration (see, for example, winter 2050 in the "*Deficit Extreme*" scenario). For example, if Switzerland requires the maximum allowed imports (NTC restricted) every hour, and neighboring countries can only supply the electricity for half of the month, the monthly approach would result in twice the imports as the hourly approach.[1] Therefore, especially in those extreme situations, the Power Switcher overestimates monthly imports to Switzerland and becomes less accurate.

Second, the Power Switcher does not consider marginal costs for electricity generation per technology in Switzerland and the neighboring countries. Neglecting the costs, the modeler has to make assumptions on when to use flexible units, expensive inland generation, and imports. For example, the Power Switcher uses the hydro reserve as early in the year as possible as soon as imports and inland generation are insufficient.This might affect the timing of electricity deficits as hydropower is overestimated at the beginning while underestimated at the end of the year. Another example is that the Power Switcher always utilizes inland generation, including expensive thermal units such as gas-fired power plants, before importing. Due to the high commodity prices of natural and synthetic gas and high costs for CO_2 certificates and carbon capture and storage, it is unlikely these units would run when imports with lower costs from neighboring countries would be available. On the one hand, this might lead to an overestimation of the utilization of thermal power plants and thus CO_2 emissions in the scenarios with gas-fired power plants. On the other hand, this approach fits the question of security of supply and shows how much inland electricity generation is available to cover inland demand before using imports.

Third, the Power Switcher does not consider the electricity grid, including its nodes (with electricity generation and demand) and lines between these nodes (with capacity restrictions). While the results do not indicate a general bias due to this simplification, the models' results begin to diverge as soon as one country has a substantial deficit. In an electricity grid, electricity flows between the nodes are governed by Kirchhoff's law. Electricity generation in one country can thus flow to a neighboring country's node, even though the country itself has an electricity deficit. Therefore, the Power Switcher might underestimate the actual DNS in Switzerland in case of a large amount of electricity not being served in a neighboring country – and vice versa, overestimate the deficit in Switzerland if its deficit is much higher than those of its neighbors. However, for assessing whether demand and supply are matching from a market perspective, considering the actual physical flows and their impact on DNS is not necessary.

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[1] For example, in Nexus-e, France has excess electricity available in winter only in hours of strong wind but requires imports in hours of low wind. In an hourly resolution, imports from France are limited to the hours with high wind power, while the monthly balance considers the full excess electricity in hours with high wind power over the month.

Future work in the Power Switcher could focus on providing more insights into the neighboring countries' installed capacities, electricity generation, and load (instead of referring to the respective ENTSO-e scenario). In addition, the model could indicate from where Switzerland already is importing and from where it could import even more. From a methodological perspective, the Power Switcher could account for the trade balance of Switzerland’s neighboring countries with the remaining European countries and include the option to use gas-fired power plants as a reserve only, similar to the hydro reserve. As an alternative to the latter, the Power Switcher could include the option to switch between the current “security of supply perspective” and a “market perspective,” including a merit-order approach based on marginal costs of electricity generation.