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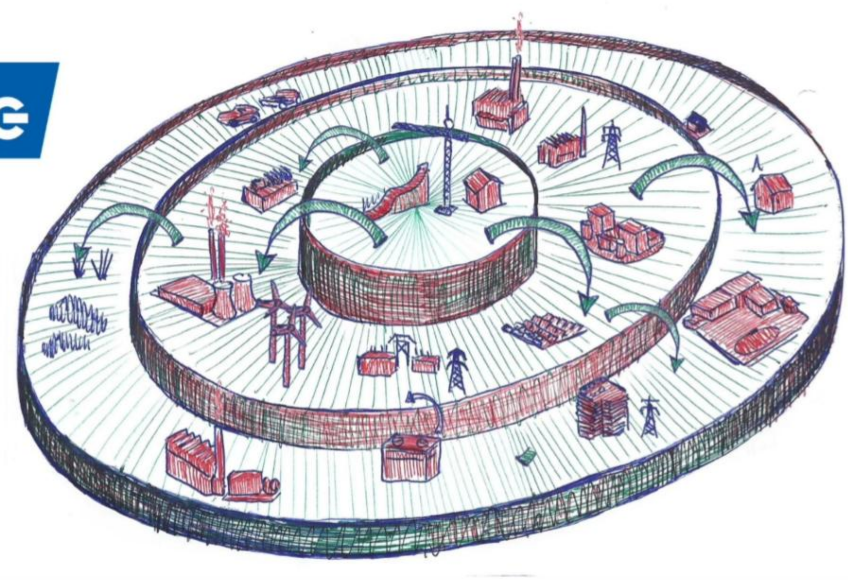
Final report

Assessing the Feasibility of Scenarios for the Swiss Electricity System

Roadmaps by Swissolar, Helion, and Grossen

Nexus-e



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Zusammenfassung

Das Unternehmen Helion, der Schweizer Branchenverband Swissolar und Nationalrat Jürg Grossen haben jeweils Roadmaps für das Schweizer Stromsystem bis 2050 entwickelt. Diese Szenarien zeichnen sich durch einen raschen und starken Ausbau der Photovoltaik (PV) aus, der den Ausstieg aus der Kernenergie kompensieren und einen grossen Teil des steigenden Strombedarfs decken soll. In dieser Studie untersuchen wir die Machbarkeit dieser Roadmaps und vergleichen sie mit dem Szenario "Weiter Wie Bisher" (WWB) der Energieperspektiven 2050+. Zu diesem Zweck verwenden wir Nexus-e, eine von der ETH Zürich entwickelte Plattform zur Modellierung von Energiesystemen.

Unsere Ergebnisse liefern fünf wichtige Erkenntnisse über die Roadmaps:

1. Alle Roadmaps und das WWB-Szenario sind machbar – sowohl im Referenzszenario als auch in den Sensitivitäten. "Machbar" heisst hier, dass in jeder Stunde der untersuchten Jahre (2030, 2040 und 2050) die Schweizer Stromnachfrage mit der inländischen Erzeugung und den verfügbaren Importen gedeckt werden kann.

2. Die Roadmaps weisen geringere Stromgestehungskosten auf als das WWB-Szenario (siehe Abbildung 1). Der Vergleich auf der Basis der Stromgestehungskosten ist wichtig, da der Strombedarf in den Roadmaps deutlich höher ist als im WWB-Szenario, welches eine geringere Elektrifizierung im Wärme- und Mobilitätssektor aufweist und stattdessen auf fossile Energieträger wie Heizöl und Benzin zurückgreift.

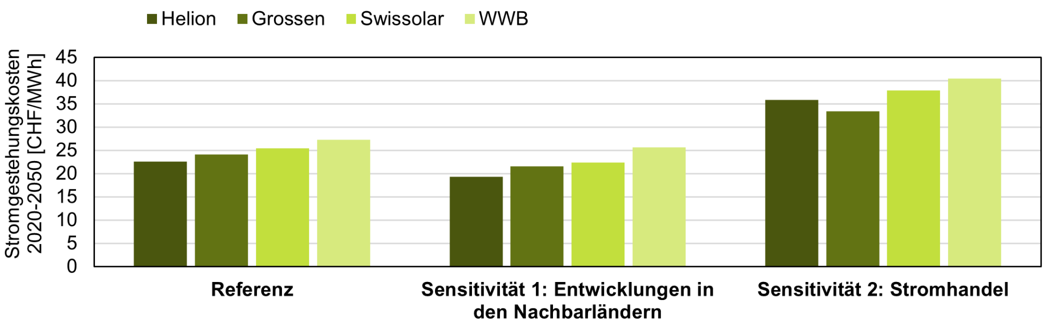
3. Das Helion-Szenario weist im Referenzfall mit 51 Mrd. CHF bis 2050 die niedrigsten Stromsystemkosten auf, während das Swissolar-Szenario mit 59 Mrd. CHF die höchsten Kosten verursacht. Das Grossen-Szenario liegt mit 56 Mrd. CHF dazwischen. Die erhöhten Gesamtkosten im Swissolar-Szenario sind hierbei auf die kürzere Laufzeit der Kernkraft zurückzuführen.

4. Das Grossen-Szenario enthält eine hohe inländische Wasserstoffproduktion und Investitionen in Gas-to-Power Kapazitäten, was das Szenario im Vergleich zu den anderen Roadmaps teurer macht. Wenn der Stromhandel mit den Nachbarländern jedoch eingeschränkt werden sollte (Sensitivität 2), wird das Grossen-Szenario zum günstigsten, da es diese Reservekapazitäten nutzen kann, wenn die Importe begrenzt und teuer werden. Generell sehen wir, dass alle Roadmaps sowie das WWB-Szenario deutlich teurer werden, wenn der Stromhandel mit den Nachbarländern eingeschränkt wird.

5. Ein noch stärkerer Ausbau von Erneuerbaren in den Nachbarländern, besonders von PV (Sensitivität 1), führt dazu, dass die Schweiz weniger PV-Strom im Sommer exportieren kann und die Stromerzeugung im Inland häufiger abregeln muss. Die bestehenden Flexibilitätsoptionen im Schweizer Stromsystem wie Pumpspeicher, Staudämme und Batteriespeicher hingegen werden umso wertvoller, je höher der Anteil der schwankenden Stromerzeugung in den Nachbarländern ist.

Die Plattform Nexus-e ermöglicht es uns, den stündlichen Einsatz von Stromerzeugungseinheiten, die Abregelungen bei den erneuerbaren Energien und die Gesamtkosten der Stromversorgung im Detail zu untersuchen. Für alle Szenarien testen wir zwei Sensitivitäten. Wir bewerten die Auswirkungen der Entwicklungen in den Nachbarländern sowie die Auswirkungen von Stromhandelsbeschränkungen, wobei wir die möglichen Auswirkungen des EU-Pakets für saubere Energie berücksichtigen.

Die Ergebnisse dieser Studie sollen quantitative Einblicke in die Unterschiede der Szenarien bieten, dienen jedoch nicht als Prognosen. Die Modellierung des Schweizer Stromsystems unterliegt vielen Annahmen und Vereinfachungen. In den Gesamtkosten der Szenarien sind die Kosten für den benötigten Ausbau des Übertragungs- und Verteilnetzes nicht berücksichtigt.



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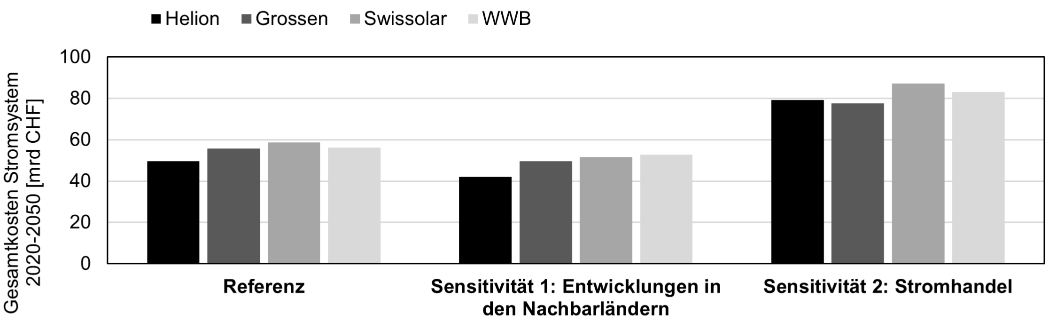


(b)

Figure 1: Stromgestehungskosten (1a) und Gesamtkosten des Stromsystems (1b) von 2020-50. Kosten beinhalten Betriebs- und Unterhaltskosten, Investitionskosten und Kosten/Erlöse für Stromimport/-export.

Summary

The company Helion, the Swiss industry association Swissolar and National Councilor Jürg Grossen have each developed roadmaps for the Swiss electricity system up to 2050. These scenarios are characterized by a rapid and strong expansion of photovoltaics (PV) to compensate for the phase-out of nuclear energy and to cover a large part of the increasing electricity demand. In this study, we investigate the feasibility of these Roadmaps and compare them with the "Business as usual" ("Weiter Wie Bisher", WWB) scenario of the Energy Perspectives 2050+. For this purpose, we use Nexus-e, an energy system modeling platform developed by ETH Zurich.

Our results provide the following five main conclusions:

1. All roadmaps and the WWB scenario are feasible – both in the reference scenario and in the sensitivities. "Feasible" here means that in every hour of the years studied (2030, 2040, and 2050), Swiss electricity demand can be met with domestic generation and available imports.

2. The Roadmaps show lower LCOE than the WWB scenario (see Figure 2). The comparison based on electricity generation costs is important because the electricity demand in the Roadmaps is significantly higher than in the WWB scenario, which has lower electrification in the heat and mobility sectors and instead has to import fossil fuels such as heating oil and gasoline.

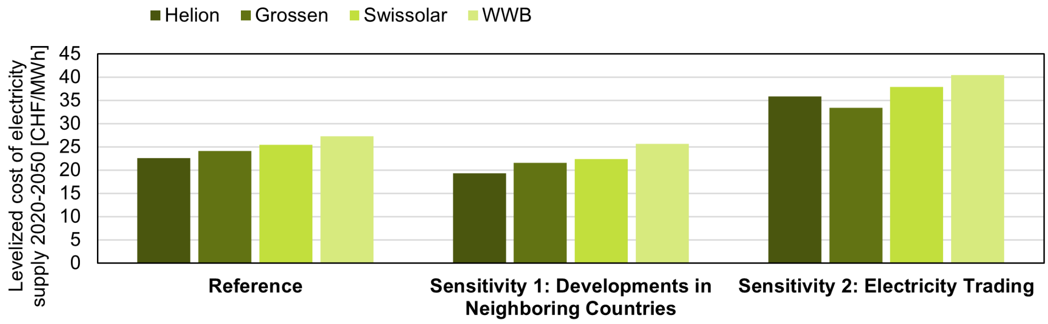
3. The Helion scenario has the lowest electricity system costs in the reference case with CHF 51 billion by 2050, while the Swissolar scenario has the highest costs with CHF 59 billion. The Grossen scenario lies in between with CHF 56 billion. The increased total costs in the Swissolar scenario are due to the limited lifetime of nuclear power.

4. The Grossen scenario includes high domestic hydrogen production and investments in gas-to-power capacities, which makes the scenario more expensive compared to the other Roadmaps. However, if electricity trade with neighboring countries were to be curtailed (Sensitivity 2), the Grossen scenario is the least expensive because it can use this spare capacity if imports become limited and expensive. In general, we see that all Roadmaps as well as the WWB scenario become significantly more expensive if electricity trade with neighboring countries is restricted.

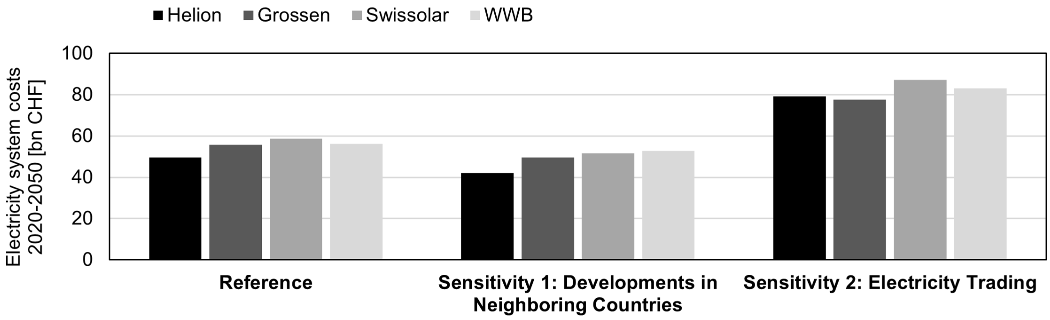
5. An even stronger expansion of renewables in neighboring countries, especially PV (Sensitivity 1), leads to Switzerland being able to export less PV electricity in summer and having to shut down domestic electricity generation more often. In contrast, the existing flexibility options in the Swiss electricity system, such as pumped storage, dams and battery storage, become more valuable the higher the share of fluctuating electricity generation in neighboring countries.

The Nexus-e platform allows us to examine in detail the hourly deployment of power generation units, renewable curtailments, and the total cost of power supply. For all scenarios, we test two sensitivities. We evaluate the impact of developments in neighboring countries and the impact of electricity trade restrictions, considering the potential impact of the EU clean energy package.

The results of this study are intended to provide quantitative insight into the scenario differences but do not serve as forecasts. The modeling of the Swiss electricity system is subject to many assumptions and simplifications. The total costs of the scenarios do not include the costs of the required expansion of the transmission and distribution grid.



(a)



(b)

Figure 2: Levelized costs (2a) and cumulative costs (2b) of electricity supply from 2020-50. Costs include operating and maintenance costs, investment costs, and costs/revenues for electricity import/export.

Contents

Abbreviations

CentIv	Centralized Investments Module
ENTSO-E	European Network of Transmission System Operators for Electricity
EV	electric vehicle
FOM	fixed operation and maintenance
NTC	net transfer capacity
PV	photovoltaic
TYNDP	ten-year network development plan
V2G	vehicle to grid
VOM	variable operation and maintenance
WWB	"Weiter Wie Bisher"

List of Figures

1 Introduction

The company Helion, the Swiss trade association Swissolar, and National Councillor (Nationalrat) Jürg Grossen have drawn up Roadmaps for the development of the Swiss electricity system until 2050. These scenarios are characterized by a rapid and strong expansion of solar photovoltaic (PV), which should compensate for the phase-out of nuclear power and cover a large share of the increasing electricity demand. In addition, the winter supply should be ensured with a mix of PV, wind power, battery storage, demand-side management, hydropower extension, and gas-to-power. Solar surpluses in summer and midday hours are planned to be converted into hydrogen or exported to the neighboring countries.

However, it remains to be seen whether an electricity system that relies so heavily on hydropower and PV can provide a secure supply of electricity. In this study, we examine the feasibility of the three Roadmap scenarios and compare them to the "Weiter Wie Bisher" (WWB) scenario of the Energy Perspectives 2050+ provided by the Swiss Federal Office of Energy. In particular, we examine all scenarios concerning the questions of whether demand can be met every hour, what the hourly dispatch of power generation units looks like for Switzerland and neighboring countries, how much renewable energy has to be curtailed, and what the resulting total costs of the power system are.

For this purpose, we use Nexus-e, an energy system modeling platform developed by ETH Zurich. The information for the developments of the installed capacities for electricity generation units (rooftop PV, wind, hydro, biomass, gas-to-power, geothermal, nuclear, and fossil power plants) and the electricity demand (conventional, electric vehicles, hydrogen, heat pumps) in Switzerland is defined by the Roadmaps themselves. All other assumptions and input data required to run Nexus-e remain similar across the scenarios to ensure their comparability. For example, for the installed generation capacities and electricity demand in neighboring countries, we use the "Global Ambition" scenario of the ten-year network development plan (TYNDP) published by European Network of Transmission System Operators for Electricity (ENTSO-E).

2 Method and Data

2.1 Nexus-e

Nexus-e is an energy system modeling platform consisting of multiple modules. For this study, we use the Centralized Investments Module (CentIv). CentIv is a linear optimization problem aimed at identifying the optimal investments into electricity generation capacities and the operations thereof to meet electricity demand, taking a centralized system perspective. As for this study, the capacities are defined already by the Roadmaps, CentIv is optimizing only the operations of these units. Detailed information about Nexus-e and CentIv can be found in [1] and [2], respectively.

We simulate the years 2020, 2030, 2040, and 2050. Optimal dispatch is computed for every hour of every second day of these years to reduce runtime and computational complexity. All generation technologies are modeled considering their operation limits and characteristics. We assume historical power generation profiles for renewable energies with hourly and cantonal resolution. The use of dispatchable power generation units such as gas-to-power plants is optimized in the model, taking into account technical constraints. The Swiss extra-high-voltage grid, corresponding to grid level 1, is modeled and its grid constraints are taken into account. Neighboring countries are aggregated into a few synthetic nodes, which allows representing all Swiss cross-border lines and synthetic cross-border lines between neighboring countries (e.g., Germany-France).

2.2 Input Data

For the three Roadmaps and the WWB scenario, data on the installed generation capacities and electricity demand is directly provided by Helion, Swissolar, Jürg Grossen, and the Energyperspectives 2050+. All other input data and assumptions required to run Nexus-e can be found in [3].

To make use of the Roadmap data in Nexus-e, we processed it as follows: First, since the scenarios do not provide information on where in Switzerland the addition of new power generation units will take place, we need to define this in Nexus-e. This is important as Nexus-e represents the transmission grid in detail. Loads and generation units have thus to be assigned to a respective grid node so emerging load flows can be calculated. We allocate distributed technologies (e.g., PV, wind, stationary batteries, and electric vehicle (EV) batteries) to the grid nodes proportionally to the node's annual demand. For the other power generation units, we manually allocate the capacities.

Second, the scenarios include geothermal generation as part of the future electricity mix. Nexus-e, however, has no detailed representation of geothermal technologies yet. We, therefore, model the geothermal as a baseload technology with constant power output. Values for investment and variable operation and maintenance (VOM) costs are taken from [4]. We set fixed operation and maintenance (FOM) costs to 0 EUR/MW due to a lack of information available. The installed geothermal power plant is geographically allocated to the Mühleberg node to which the dismantled nuclear site was connected until 2019. The node thus has some free transmission capacity.

Third, the increase of biomass generation is implemented by increasing the installed capacity of existent biomass power plants proportionally to their current installed capacity. The construction of biomass power plants in new locations is therefore not considered. Additionally, the distinction between biomass power plants with and without CCS/CCU technology is not taken into account, due to a lack of information on investment and operational costs.

Fourth, to account for the variations in the installed capacity for fossil-fueled power plants, we adjust the installed capacities of all currently available fossil-fueled power plants proportionally. The CCS technology and its costs are considered. In previous studies, possible locations for new gas power plants were identified.[1] These grid nodes are used for the H2-fired power plants.

Fifth, for all types of hydropower plants (i.e. run of river, storage hydro and pumped storage hydro), detailed information from previous studies with Nexus-e is used. The original information on installed capacity is kept unchanged for all scenarios. Investment cost values for new hydropower plants are taken from [4]. However, there is a large variability in values. This is due to the dependence on the power plant type and its size, location, and reservoirs. For these simulations, an average value of 7500 EUR/kW is considered for run-of-river and storage hydropower plants. For pumped storage plants, however, a value of 2300 EUR/kW is considered, which is equal to the investment costs of the most recent Swiss hydropower plant of Nant De Drance [5].

Sixth, whereas the Roadmaps and the WWB scenario provide the developments of the annual, Swiss-wide demand, we have to make assumptions on its spatial and temporal distribution. The scenarios split the annual demand data into the four categories e-mobility, heat pumps, hydrogen production, and conventional demand. For each category, we use typical hourly load curves and then scale them according to the annual demand. Summing the load curves for all demand categories gives us the hourly Swiss-wide demand curve. We then allocate this curve proportionally to the population.

Lastly, as parts of the demand such as EV and heat pump load are flexible, we include demand-side management in all scenarios. Demand-side-management is subject to a power and an energy constraint. The power constraint limits the shifted power for each hour, while the energy constraint limits the total amount of energy being shifted during one day. Additionally, daily up and downwards regulation of demand are equal to each other, resulting in a shift of the demand without varying the daily power consumption. We also consider V2G. We do not assume investment and operating costs for V2G. Vehicles participating in vehicle to grid (V2G) are considered to be privately owned, which is why we assume that, from a system perspective, there are no investment costs for EV. Additionally, due to the lack of literature and business cases on remuneration for the V2G service offered by EV, we assume 0 VOM and FOM costs for V2G.

2.3 Scenarios

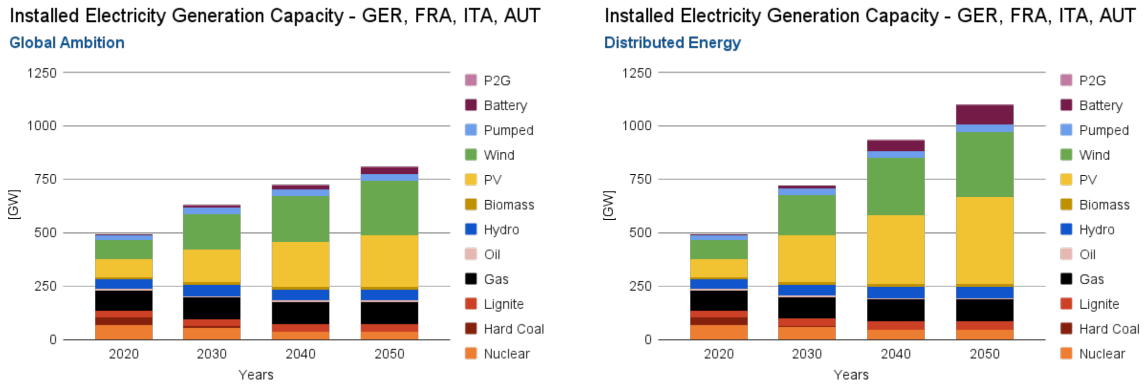
We run three Roadmap scenarios: the Swissolar scenario, the Helion scenario, and the Grossen scenario. These scenarios are characterized by a rapid and strong expansion of PV, which should compensate for the phase-out of nuclear power and cover a large share of the increasing electricity demand. In addition, the scenarios aim to ensure winter supply with a mix of PV, wind power, battery storage, V2G integration, and gas-to-power as a backup. Solar surpluses in summer and midday hours are planned to be converted into hydrogen or exported to neighboring countries.

We compare these Roadmaps with the WWB scenario, published by the Swiss Federal Office of Energy in their "Energy Perspectives 2050+". The installed capacities for all scenarios are visualized in Appendix A.

Next to running the four scenarios in the reference case, we also conduct two sensitivity assessments. First, we test the impact of the developments in the neighboring countries on the feasibility of all scenarios. While in the reference case, we base the installed generation capacity and the demand in the neighboring countries on the ENTSO-E TYNDP "Global Ambition" scenario, here we test the impact of switching to the "Distributed Energy" scenario [6] (see Figure 3). The "Global Ambition" scenario

[1] see "Konzept Spitzenlast-Gaskraftwerke zur Sicherstellung der Netzsicherheit in ausserordentlichen Notsituationen - Bericht zuhanden Bundesrat"

is based on an energy transition where the power supply is mainly based on centralized production facilities such as offshore wind. The "Distributed Energy" scenario, on the other hand, is based on a decentralized energy transition with a high level of electrification and investments in rooftop PV and battery storage. It also includes a substantially higher CO2 price.



(a) (b)

Figure 3: Installed generation capacities in ENTSO-E scenarios (3a) "Global Ambition" and (3b) "Distributed energy"

Second, we want to test the impact of electricity trading limitations on the feasibility of the four scenarios. The EU Clean Energy Package, which came into force in 2020, sets the rules for electricity trading and technical grid operation. It requires that by the end of 2025, all European transmission system operators make at least 70 percent of relevant electricity network capacity available for cross-border trading. However, it has not yet been regulated how third countries such as Switzerland are to be included in the 70 percent criterion. In an extreme case, this could limit cross-border capacities towards Switzerland and thus also electricity trading. Here we reduce the net transfer capacities by 70 percent to illustrate such an extreme case.

3 Results

The results of the simulated scenarios are analyzed with respect to their hourly dispatch of power generation units, curtailment of renewables, and total costs of electricity supply. Results for all scenarios are visible on the Nexus-e Webviewer at the following web address: `https://nexus-e.org/results_v2/roadmap`.[2] The different scenarios can be selected from a drop-down menu and compared to each other.

Scenarios in the reference case:

- Helion: *helion*
- Grossen: *grossen*
- Swissolar: *swissolar*
- WWB: *wwb*

Sensitivity on developments in the neighboring countries:

- Helion with Distributed Energy: *helion_de*
- Grossen with Distributed Energy: *grossen_de*
- Swissolar with Distributed Energy: *swissolar_de*
- WWB with Distributed Energy: *wwb_de*

Sensitivity on restricting electricity trading

- Helion with reduced net transfer capacity (NTC): *helion_30ntc*
- Grossen with reduced NTC: *grossen_30ntc*
- Swissolar with reduced NTC: *swissolar_30ntc*
- WWB with reduced NTC: *wwb_30ntc*

In the following, we present the results for the scenarios in the reference case (section 3.1). We then highlight the most important insights from the sensitivities on the developments in neighboring countries (section 3.2) and electricity trading (section 3.3).

3.1 Scenarios in the Reference Case

3.1.1 Electricity Generation

First of all, all Roadmaps (Helion, Grossen, and Swissolar) and the WWB scenario are feasible in our simulations. "Feasible" here means that in every hour of the scenario years (2030, 2040, and 2050) the Swiss electricity demand can be covered with inland generation and available imports. In our model, imports are only possible if neighboring countries have export capacities, meaning that their generation exceeds their demand. The same holds true for exports. Switzerland can only export to the neighboring countries if they have the need for additional (or lower-cost) electricity generation.

To exemplify how the technologies are dispatched in our results, Figure 4 illustrates the installed capacity and Figure 5 the electricity generation for the Helion scenario. The installed capacity in the Helion scenario is dominated by PV starting in 2030. Striking is also the substantial capacity addition of mobile and stationary battery storage. Due to the strong expansion of PV, Switzerland becomes a net exporter in 2030 despite phasing out its nuclear power.

[2] Please note that the technology "geothermal" is listed as "wind offshore" due to the current limitations of the webviewer.

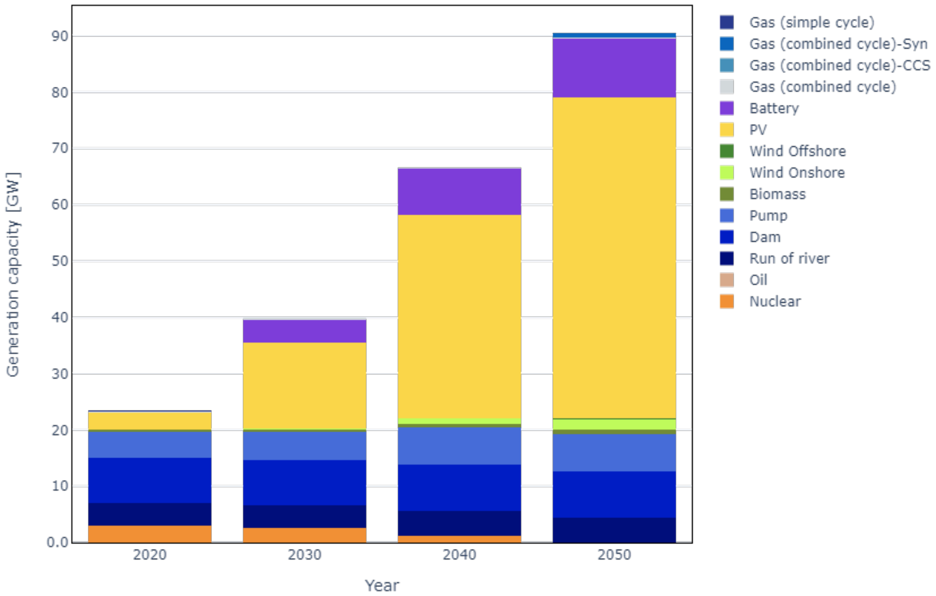


Figure 4: Installed capacity from 2020-50 in scenario Helion. Please note that the technology "geothermal" is here shown as "wind offshore".

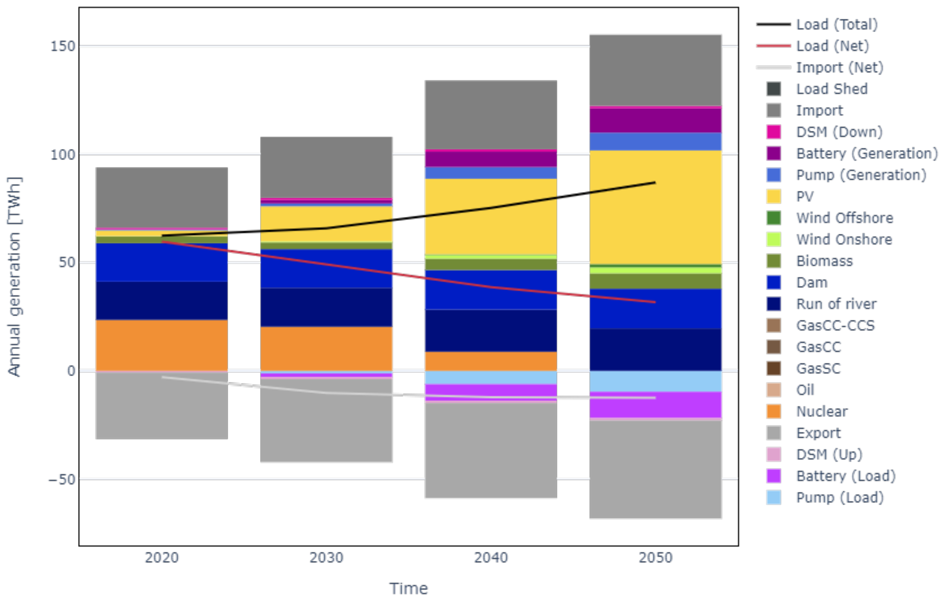


Figure 5: Electricity generation from 2020-50 in scenario Helion. Please note that the technology "geothermal" is here shown as "wind offshore".

3.1.2 Curtailment

The Roadmaps are characterized by a substantial uptake of PV between 2020 to 2050. In our results, such an increase in intermittent generation causes higher levels of curtailment. Figure 6 shows the annual curtailment of electricity generation from 2020-50 for the four scenarios. We can see that the Helion scenario has the highest level of curtailment, whereas the WWB scenario has almost no curtailment. This can be mainly explained by the installed PV capacity, which is highest in the Helion scenario (57 GW in 2050), followed by the Swissolar scenario (50 GW in 2050), the Grossen scenario (44 GW in 2050), and the WWB scenario (12.24 GW in 2050).

It is striking, however, that the Grossen scenario with such high PV capacity has an annual curtailment of below 2 TWh (less than 5 percent of the annual PV electricity generation). It seems that the included flexibility (hydro damns, hydro pumps, battery storage, demand-side management) in the modeled electricity system can integrate around 40 GW and then begins curtailing with higher PV installations. Please consider that we do not model the distribution grid. Constraints set by the distribution grid could increase the curtailments substantially.

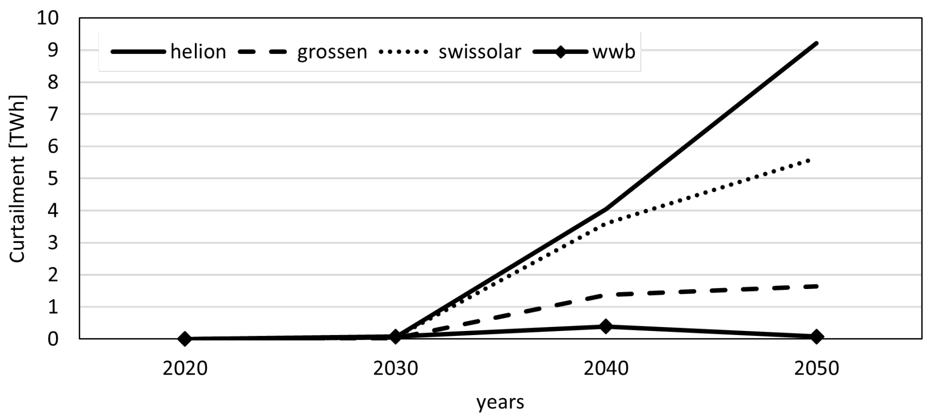


Figure 6: Annual curtailed electricity in TWh

3.1.3 Costs

The costs of the electricity system include VOM, FOM, investment costs, and costs/revenues related to the import/export of electricity from/to neighboring countries.[3]

Figure 7 shows the electricity system costs for the four scenarios. The scenario with the lowest electricity system costs is the Helion scenario with 50 bn EUR until 2050. The most expensive scenario with 59 bn EUR is the Swissolar scenario. The main driver of this cost difference is the timing of the nuclear phase-out. While in the Swissolar scenario, nuclear power is already phased-out after 50 years lifetime, in the Helion scenario nuclear reactors have a lifetime of 60 years. Based on historic investment costs for the renewal and safety of nuclear plants in Switzerland, we assume that extending the lifetime of one nuclear reactor by 10 years comes at additional investment costs of 1 bn EUR per reactor. Despite these costs, the additional exports and avoided imports due to nuclear electricity result in overall lower electricity system costs.

[3]Annual values are provided by the model for all simulation years. VOM and import/export costs for the not-simulated intermediate years are obtained through interpolation. FOM costs are considered to be constant for the intermediate years since investments are assumed to happen only in the simulation years. Investment costs are spread out over the installed generator's lifetime.

However, comparing absolute electricity system costs between the scenarios is problematic as the level of electricity demand differs between the scenarios. Especially the WWB scenario has a lower level of electrification for the heating and mobility sector, leading to an electricity demand of 70 TWh (including line losses and demand for hydrogen generation, excluding pump storage and battery demand). The other three scenarios all have a similar demand ranging from 87 TWh to 91 TWh. The higher rate of electrification reduces expensive imports of fossil fuels such as heating oil and gasoline. In 2020, Switzerland imported more than 130 TWh of energy via fossil fuels, leading to costs of around 10 bn EUR. Electrifying mobility and transport reduce the costs of importing fossil fuels heavily. To be able to compare the scenarios in terms of total costs we calculate the levelized cost of electricity supply, which can be understood as the average cost of the system to supply one MWh of electricity. Figure 7 depicts such levelized cost. We see that the WWB scenario has the highest levelized costs whereas the Helion scenario has the lowest levelized costs.

Important to mention is that the Grossen scenario has substantially higher costs despite a similar nuclear phase-out timing. This can be explained by the lower installed PV capacity (and therefore fewer exports) and expensive investments in backup gas-to-power capacities. These backup capacities are not used in the reference case (see section 3.3 for a scenario in which the backup capacity is leveraged).

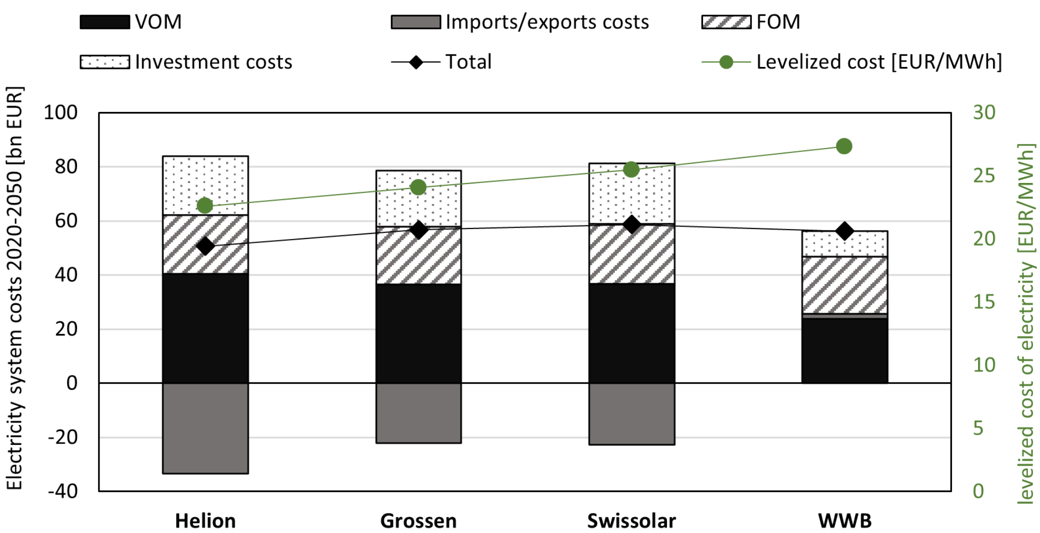


Figure 7: Cumulative costs (left axis) and levelized costs (right axis) of electricity supply in the reference cases for the years 2020-50.

3.1.4 Dependence on Electricity Imports

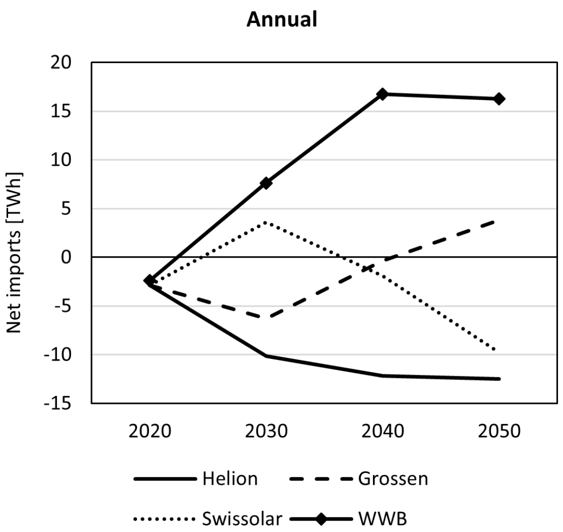
All scenarios are characterized by substantial electricity trading between Switzerland and its neighboring countries. Figure 8 depicts the annual and winter net imports for the Roadmaps and the WWB scenario.

In the Helion and Swissolar scenarios, which also have the largest installed capacities of PV, Switzerland becomes a net exporter latest in 2040. By 2050, in both scenarios, Switzerland has annual net exports of around 10 TWh. In the Grossen scenario, however, Switzerland is a net exporter until 2040 but then shows net imports in 2050 (4 TWh). The WWB scenario shows by far the highest annual imports for all years and exceeds annual net imports of 15 TWh in 2040 and 2050.

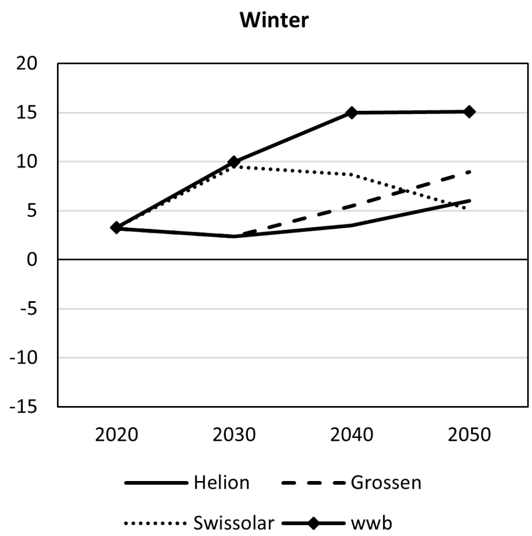
Despite having a positive electricity balance over the year, imports in winter are required in all scenarios. In the Helion scenario, winter imports can be kept at today's level with around 5 TWh. In the

Grossen scenario, winter imports increase substantially starting in 2030, reaching almost 10 TWh in 2050. The Swissolar scenario shows a different pattern. Due to the early nuclear phase-out winter imports shoot up in 2030 before then gradually decreasing until 2050 to a similar level as the Helion scenario. In the WWB scenario imports also shoot up by 2034 due to the nuclear phase-out and then remain almost constant as PV capacity additions are lacking.

It is, however, important to note that the net import values in the main scenarios provide no direct insight into the security of supply provided by the scenarios. In our model, Switzerland imports if it is the economically better solution instead of generating electricity itself. For example, in the Grossen scenario, the gas-to-power units are not utilized in the reference case as their operation is more costly than importing electricity from the neighboring countries. So although the Grossen scenario shows higher net imports compared to the Helion and Swissolar scenarios, it might have a higher security of supply as it can provide additional electricity in extreme situations.



(a)



(b)

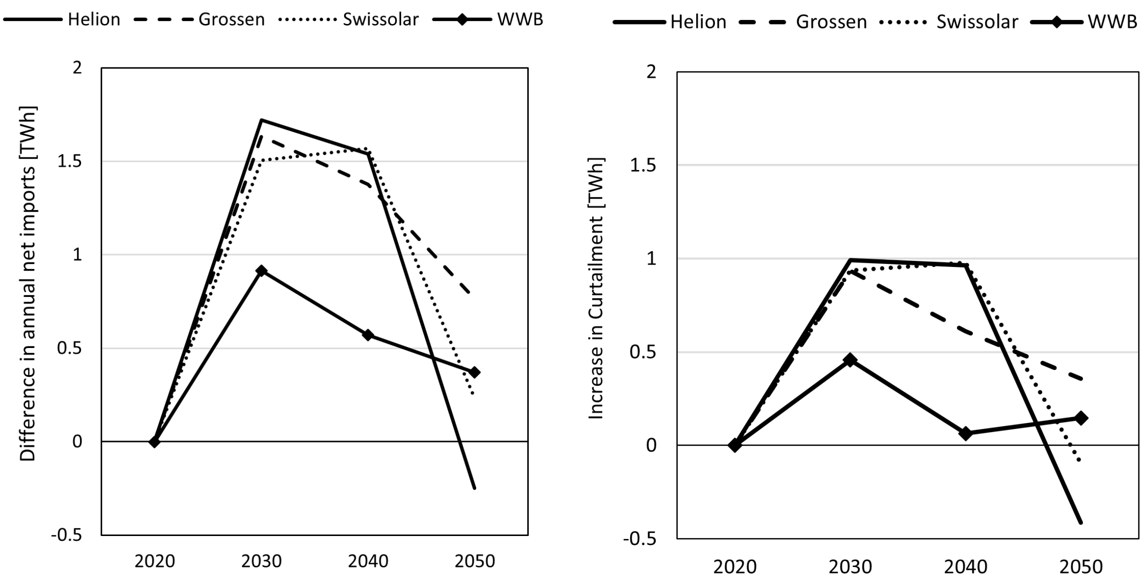
Figure 8: (8a) Annual and (8b) winter net imports for the scenarios Helion, Grossen, Swissolar, and WWB

3.2 Sensitivity on Developments in Neighboring Countries

In this sensitivity, we test the impact of the developments in the neighboring countries on the feasibility of the three scenarios. While in the reference case, we base the installed generation capacity and the demand in the neighboring countries on the ENTSO-E TYNDP "Global Ambition" scenario, here we test the impact of switching to the "Distributed Energy" scenario [6]. The "Distributed Energy" scenario shows higher electricity demand which is covered mostly by wind and solar. The share of renewables and especially PV and batteries in the electricity mix is larger while the share of gas units is smaller. The CO2 price is also higher.

Also under different developments in neighboring countries, in our results, all scenarios are feasible. Electricity trading remains important. We observe a slight change in net imports due to higher levels of curtailment (see Figure 9). As neighboring countries have a higher share of PV in their electricity mix exporting PV in hours of excess generation becomes more difficult.

The stronger focus on PV in the neighboring countries makes it also more difficult for Switzerland to import electricity in winter. Contrary to the scenarios based on "Global Ambition", here Switzerland makes also use of their backup gas-to-power capacities. The Grossen scenario makes the most use of it and generates 120 GWh of electricity in winter 2050.



(a) (b)

Figure 9: Change in annual net imports (9a) and annual curtailment (9b) in "Distributed Energy" scenario compared to "Global Ambition" scenario

Despite more annual net imports, curtailments, and the use of expensive power-to-gas technologies, total electricity system costs and the levelized cost of electricity supply are lower than in the reference case. In our results, total costs are reduced by 6 to 15 percent, with the highest reduction in the Helion scenario and the lowest reduction in the WWB scenario. Figure 10 depicts the difference in total costs and levelized costs between scenarios based on the "Global Ambition" and the "Distributed Energy" scenarios.

The main reason for the decrease in system costs are the higher and stronger fluctuating electricity prices in the neighboring countries, a result of higher CO2 prices. These high electricity prices result in more profitable exports for Switzerland, also indicated by the higher utilization of batteries and hydro pump storage in all four scenarios.

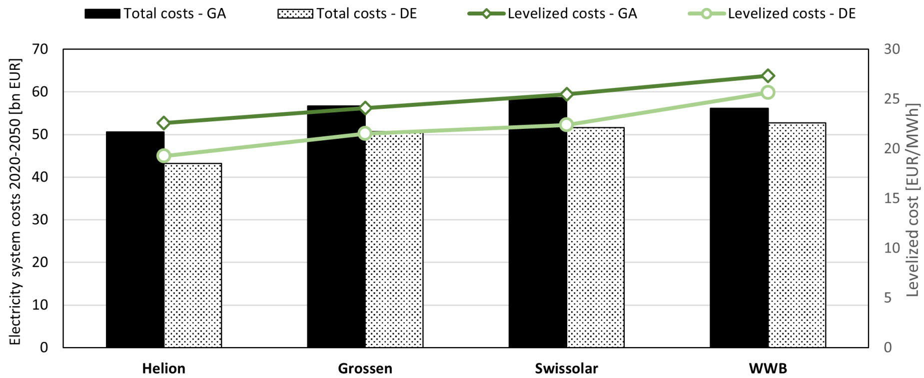


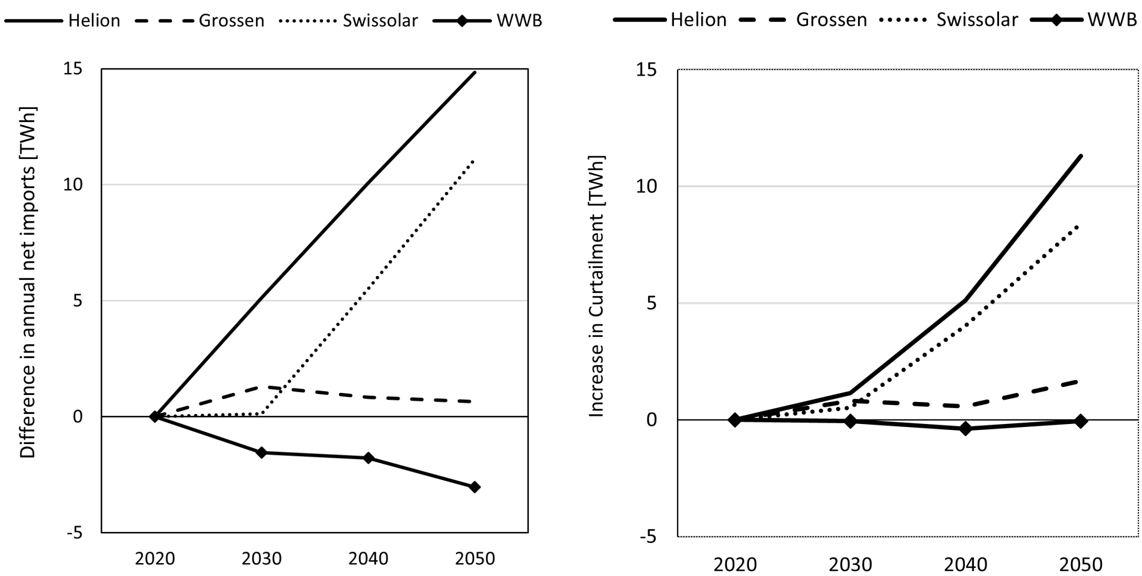
Figure 10: Difference in cumulative electricity system costs for the years 2020-50 (left axis) and levelized costs of electricity supply (right axis) between the "Global Ambition" and "Distributed Energy" scenario.

3.3 Sensitivity on Electricity Trading Restrictions

In the second sensitivity, we test the impact of electricity trading limitations on the feasibility of the three Roadmaps and the WWB scenario. To do so, we reduce the net transfer capacities (NTC) to 30 percent of the values in the reference scenario. Assessing a system with restricted NTCs became relevant with the introduction of the EU Clean Energy Package in 2020, which requires that by the end of 2025, all European transmission system operators make at least 70 percent of the relevant electricity network capacity available for EU cross-border trading. In an extreme case, this could limit cross-border capacities towards Switzerland by 70 percent.

In our results, even with reduced NTC values, all analyzed scenarios are feasible and all electricity demands can be served with inland generation and remaining imports. However, the NTC reduction has a substantial impact on the exchange between Switzerland and its neighboring countries and thus on the operation of the Swiss electricity system. Figure 11 depicts the changes in annual net imports and curtailment. We see that, compared to the reference case, annual net imports are increasing for the three Roadmap scenarios. This is mainly because of additional curtailment that is caused by export limitations. Curtailments are especially increasing in the Helion and Swissolar scenarios due to their large installed PV capacities. In fact, in these scenarios, the curtailed electricity is almost twice the amount compared to the reference scenarios. Only in the WWB scenario curtailment is not affected by restricted trading in all years due to the low shares of PV. This and the dispatching of gas units to cover electricity demand in winter results in decreasing annual net imports in the WWB scenario.

It is important to highlight that in all scenarios and all years, imports and exports are decreasing heavily. In the Helion and Swissolar scenarios, the exports decrease more than the imports, which is why we see net imports increasing. In the WWB scenario, however, imports are decreasing more than exports and thus annual net imports are also decreasing by 2050.



(a) (b)

Figure 11: Change in 9a annual net imports and 9b annual curtailment in "Distributed Energy" scenario compared to "Global Ambition" scenario

Restricting trading not only challenges the operation of the Swiss electricity system but also makes it more expensive. In all scenarios total system costs and levelized cost of electricity increase by at least 40 percent. Such an increase in costs is most pronounced in the Helion scenario as heavy curtailments reduce export revenues. On top, with reduced NTCs, Switzerland's flexible units (pump storage, hydro dams, batteries) have less trading capacity to make use of electricity price volatility. Interestingly, no gas-to-power is utilized in the Helion and Swissolar scenarios despite NTC restrictions.

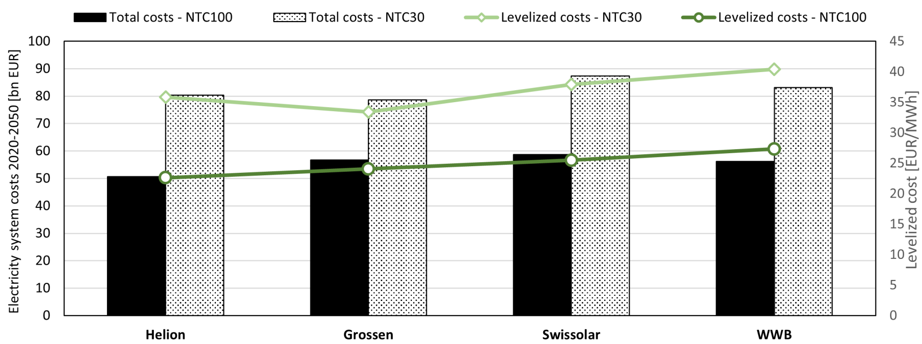


Figure 12: Difference in cumulative electricity system costs for the years 2020-50 (left axis) and levelized costs of electricity supply (right axis) between the "Global Ambition" and "Distributed Energy" scenario.

4 References

[1] Blazhe Gjorgiev, Jared B. Garrison, Xuejiao Han, Florian Landis, Renger van Nieuwkoop, Elena Raycheva, Marius Schwarz, Xuqian Yan, Turhan Demiray, Gabriela Hug, Giovanni Sansavini, and Christian Schaffner. Nexus-e: A platform of interfaced high-resolution models for energy-economic assessments of future electricity systems. *Applied Energy*, 307, 2 2022.

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[6] ENTSO-G and ENTSO-E. Tyndp 2020 scenario report, 2020.

Appendices

A Installed Capacities in the Reference Case

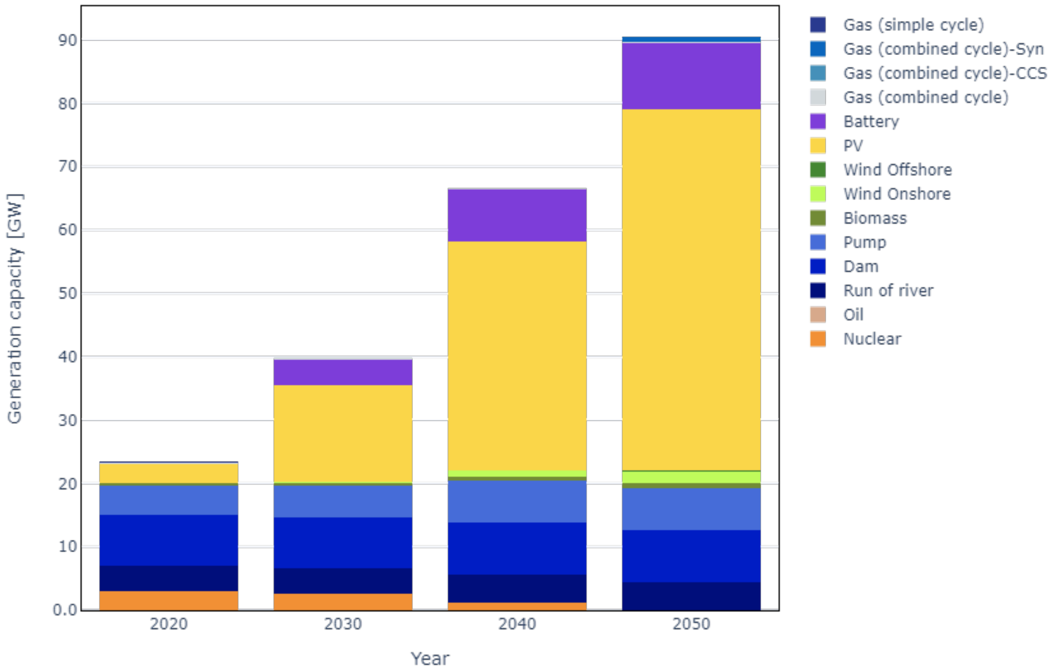

Figure 13: Installed generation capacity Helion. Please note that the technology "geothermal" is here shown as "wind offshore".

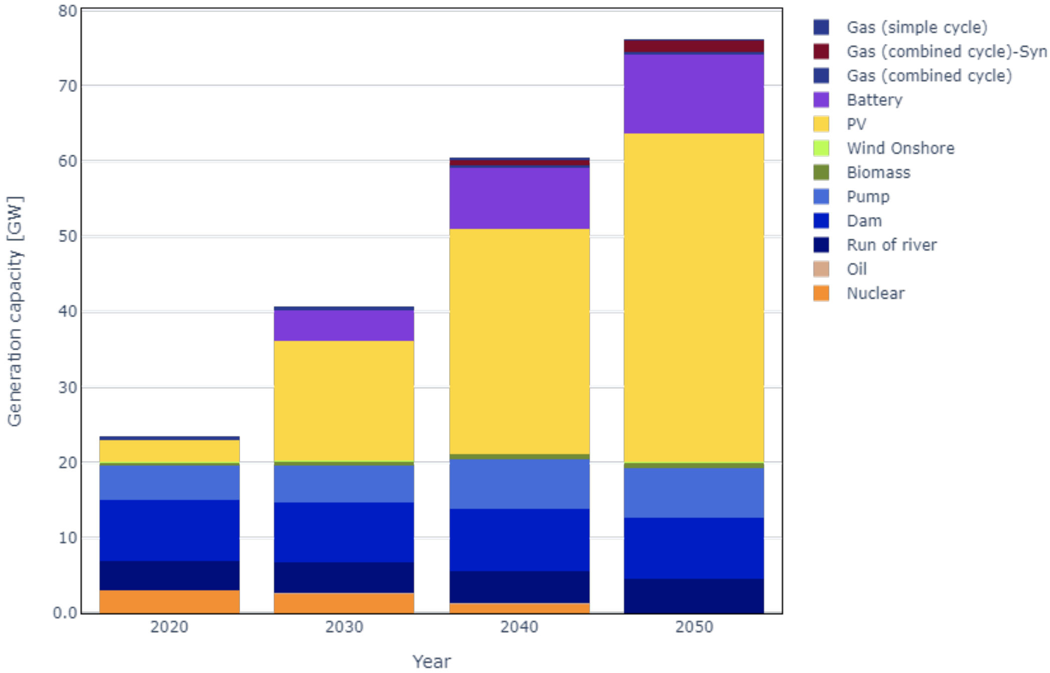

Figure 14: Installed generation capacity Grossen. Please note that the technology "geothermal" is here shown as "wind offshore".

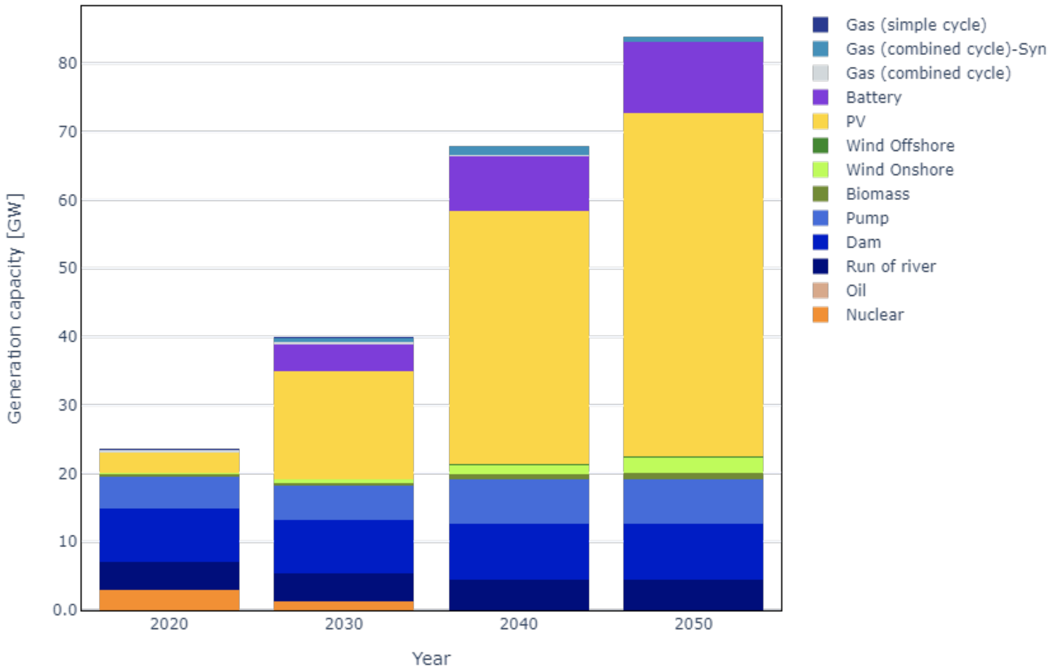

Figure 15: Installed generation capacity Swissolar. Please note that the technology "geothermal" is here shown as "wind offshore".

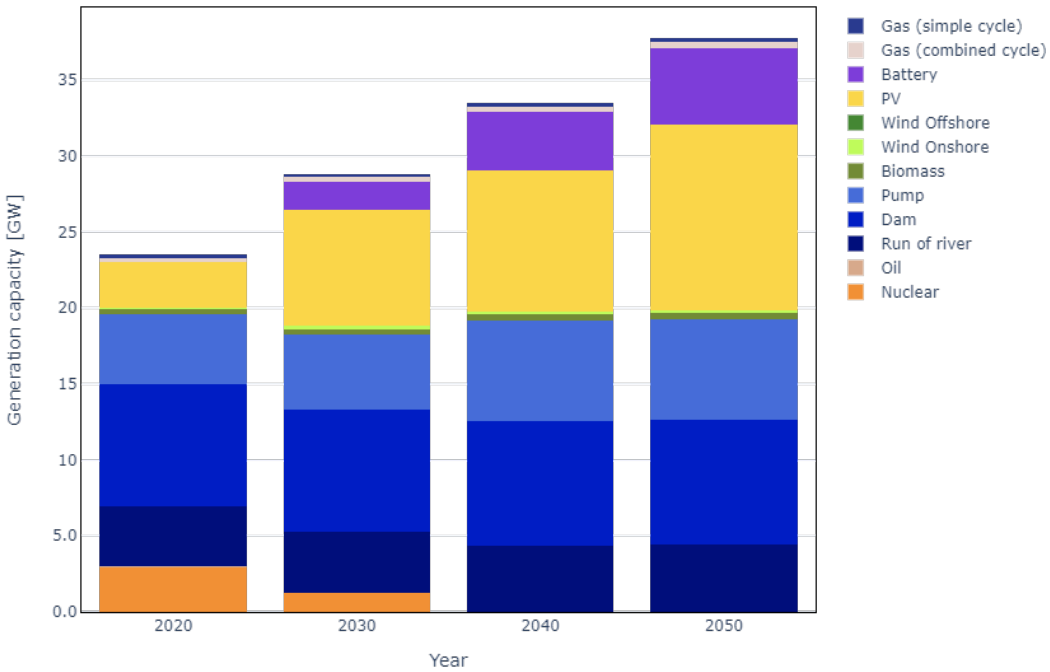

Figure 16: Installed generation capacity WWB. Please note that the technology "geothermal" is here shown as "wind offshore".