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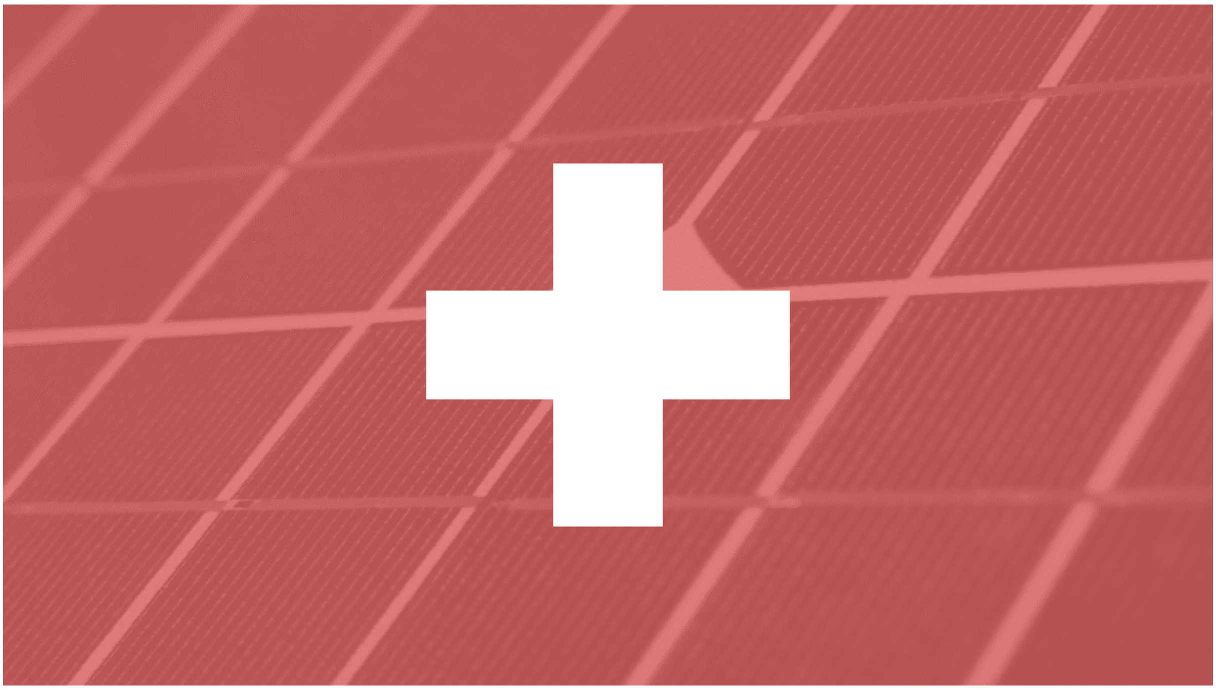
Final report

FiPPS

Firm PV power generation for Switzerland



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Summary

We investigate whether photovoltaics (PV) can effectively and economically contribute to a massively renewable energy (RE) power generation future for Switzerland. Taking advantage of the country's flexible hydropower resources, we determine the optimum PV/battery configurations that can meet the country's growing electrical demand firmly 24x365 at the least possible cost while entirely phasing out nuclear power generation. We examine several ultra-high RE scenarios where PV and hydro would meet the bulk of the country's demand. Depending on future cost predictions for PV and batteries, and a small contribution from domestic or imported dispatchable resources, we show that power production costs on the Swiss grid would range from 6 to 8 cents per kWh. This is well in line with market prices till mid-2021 and strongly below the current price levels. Also, scenarios with no or only marginal imports – either of electricity or e-fuels – would lead to only slightly higher costs – due to the effects of overbuilding and curtailment. Our analyses show that firm PV power is an enabler of the energy transition and can ease the energy trilemma – regarding security of supply, sustainability and affordability – existing also in Switzerland.

Zusammenfassung

Wir untersuchen, ob die Photovoltaik (PV) einen effektiven und wirtschaftlichen Beitrag zur zukünftigen Stromerzeugung aus erneuerbaren Energien (EE) in der Schweiz leisten kann. Unter Ausnutzung der flexiblen Wasserkraftressourcen des Landes bestimmen wir die optimalen PV-/Batteriekonfigurationen, die den wachsenden Strombedarf des Landes 24x365 zu den geringstmöglichen Kosten decken können, während die Stromerzeugung aus Kernkraft vollständig eingestellt wird. Wir untersuchen mehrere Szenarien mit extrem hohem EE-Anteil, bei denen PV und Wasserkraft den Großteil des Strombedarfs des Landes decken würden. Abhängig von zukünftigen Kostenprognosen für PV und Batterien und einem kleinen Beitrag von inländischen oder importierten regelbaren Ressourcen zeigen wir, dass die Stromproduktionskosten im Schweizer Netz zwischen 6 und 8 Rappen pro kWh liegen würden. Dies entspricht in etwa den Marktpreisen bis Mitte 2021 und liegt weit unter den gegenwärtigen Marktpreisen. Auch Szenarien ohne oder mit nur geringfügigen Importen – entweder von Strom oder von E-Treibstoffen – würden nur zu geringfügig höheren Kosten führen – aufgrund der Auswirkungen von Überdimensionierung und Abregelungen. Unsere Analysen zeigen, dass das Konzept der Überdimensionierung und der Abregelung von PV-Anlagen die Energiewende möglich machen und das Energie-Trilemma der Schweiz – bezüglich Versorgungssicherheit, Nachhaltigkeit und Bezahlbarkeit – entschärfen kann.

Résumée

Nous étudions si le photovoltaïque (PV) peut contribuer efficacement et économiquement à un avenir de production d'énergie massivement renouvelable (RE) pour la Suisse. En tirant parti des ressources hydroélectriques flexibles du pays, nous déterminons les configurations PV/batteries optimales qui peuvent répondre à la demande électrique croissante du pays, fermement 24x365, au moindre coût possible, tout en éliminant complètement la production d'énergie nucléaire. Nous examinons plusieurs scénarios d'ER très élevés dans lesquels le PV et l'hydroélectricité répondraient à la majeure partie de la demande du pays. En fonction des prévisions de coûts futurs pour le PV et les batteries, et d'une petite contribution des ressources dispatchables nationales ou importées, nous montrons que les coûts de production d'électricité sur le réseau suisse seraient compris entre 6 et 8 centimes par kWh. Cela correspond bien aux prix actuels du marché jusqu'à la mi-2021 et est fortement en dessous du niveau de prix actuel. De même, les scénarios ne prévoyant aucune importation ou seulement des importations marginales – que ce soit d'électricité ou de carburants électroniques – n'entraîneraient que des coûts

légèrement plus élevés – en raison des effets de la surconstruction et de la réduction des effectifs. Nos analyses montrent que l'énergie photovoltaïque « ferme » est un facteur de transition énergétique et qu'elle peut atténuer le trilemme énergétique (sécurité de l'approvisionnement, durabilité et prix abordable) qui existe aussi en Suisse.

Main findings

- Overall, the results of the Energy Perspectives 2050+ could be confirmed. The optimum PV installation for this scenario (in this report #1) is 41 GW instead of the 37 GW modelled in the perspectives including higher (14% instead of 9%) curtailment.
- The lowest costs result with about 40 GW PV, 15% curtailment and 15 GWh bat-teries, including 10% net imports (18 TWh during winter) a 10% rise of hydro power generation and storage (plus 1 TWh), a rise in pumped hydro (from 2.9 to 5.7 GW) and an import of 5 TWh of e-fuels (for electricity generation).
- In all cases, required battery storage is low, amounting to 0.3 hours of full PV capacity in the case of conservative cost assumptions, and ~1.2 hours in the case of optimistic cost assumptions.
- 10–85 GWh of batteries seem feasible compared to the expected electrical vehicle batteries, which will include about 200 GWh of battery storage. Accessing 10% of this storage with by-directional loading systems would reduce the need of extra storage significantly
- As unlikely as this configuration may be, stand-alone grid operation would only increase these costs by an average of 7% i.e., not constituting a showstopper.
- Without overbuilding and curtailment production costs would be an average of 63% higher across all scenarios for the net-zero interconnected configuration, and 450% higher in the autonomous grid configuration. The main factor for this cost difference is the amount of new battery storage required that would respectively be 1300% and 7500% higher without PV oversize/curtailment.
- Overbuilding and curtailment of PV is an enabler: different levels of security of supply can be reached without neglecting the net zero Co2 targets and still keeping electricity costs affordable. The higher the level of security the higher the installed PV and the higher the share of curtailment is needed.
- How to adopt the political and technical regulations to achieve the optimal values of overbuilt PV is an open question and needs to be investigated.

Firm PV Power Switzerland

Making energy transition possible

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Main contributions for this report were made by Marc Perez (Clean Power Research USA), who modelled the results as well as Richard Perez (State University of New York at Albany), who gave general advice and wrote main parts of the results chapter.

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1 Introduction

In a first and already historic phase of energy transition, wind and solar power were expensive and rare. In the current second phase, wind and PV have become cheap and normal. Production on country or transmission system level is in most cases still lower than load. Curtailment happens, but most often only to omit grid congestions. In the upcoming third phase, production will regularly be higher than load. Production capacity, timing and storage becomes important and curtailment will be a standard procedure.

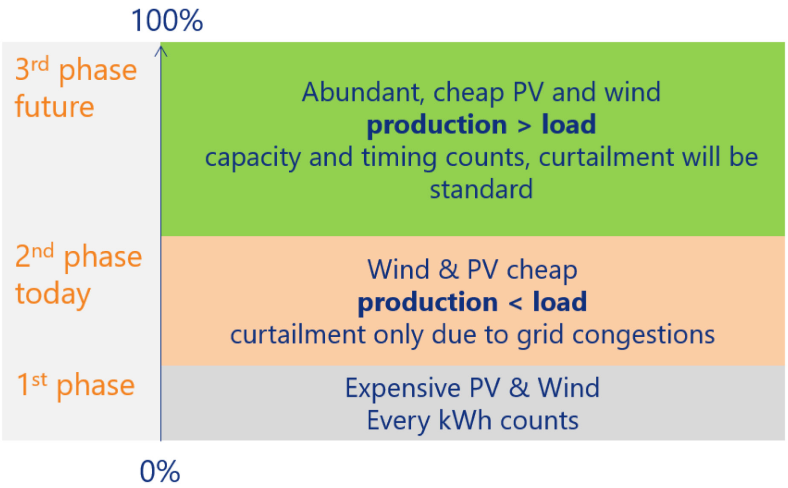

Figure 1: Three phases of the energy transition towards wind and PV power.

As PV and wind production costs are currently and – according to almost all studies – will also in the future be lower than short- and long-term storage costs, the main question is, which share of the energy should optimally be stored and which share curtailed.

This is the question analyzed in this study. The results of this study will show the amount of PV which is cost-optimally overbuilt (and curtailed) and stored in Switzerland for a fully renewable energy system.

The calculations are based on the Swiss Energy Perspectives 2050+ scenario net zero Basis (SFOE, 2021). The situation is modelled for 2050 only. This situation assumes a net PV production of 34 TWh, without nuclear production, but with enhanced hydropower generation, as well as pumped hydro storage resources for enhanced electricity load (electrified transport and building sector). The Energy Perspectives 2050+ assume full (heat-pump) electrification of the building sector’s heating requirements and large efficiency improvements (final consumption for heating will be 37% lower).

The calculation is based on the analysis of 3 years (2018–2020). In addition to exploring a fully Switzerland-based renewable scenario (PV, wind, hydro, pumped hydro and other storage technologies), we will also explore scenarios involving a degree of supply-side flexibility of up to 10–20% provided by e.g. dispatchable conventional generation (natural gas or e-fuels) and/or European grid imports.

For each scenario analyzed, the results will consist of: Least-cost firm power levelized cost of energy (LCOE), implied size of PV fleets, as well as implicit storage (overbuilding) and real storage (beyond existing hydropower storage resource) as defined in the Figure 2 below.

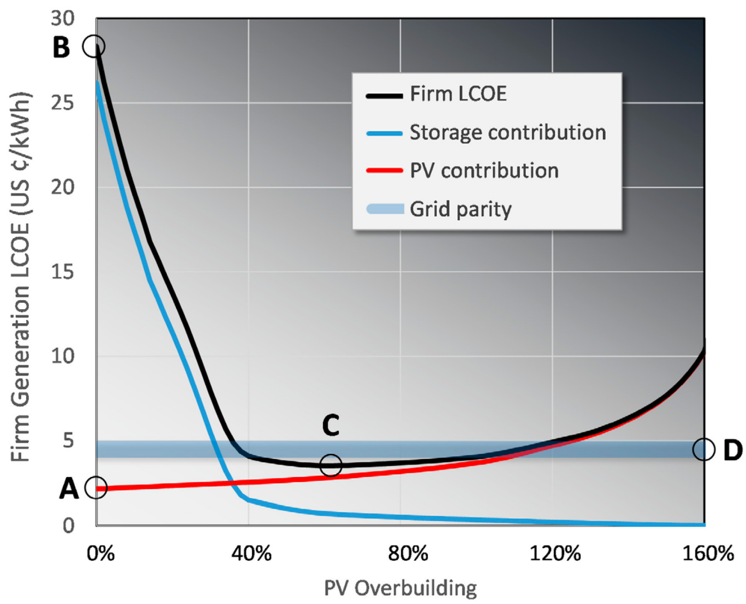

Figure 2: The influence of PV overbuilding on firm power generation LCOE. 100% overbuilding means, that 50% of the theoretical PV production is curtailed.

While unconstrained PV is inexpensive (apparently below grid parity), firming PV to meet demand 24/365 with storage alone (B) is unrealistically expensive. Overbuilding of PV fleets reduces storage requirements to the point (C) (sweet spot) where firm PV power generation can achieve true grid parity (D) (Perez et al., 2021; O'Shaughnessy et al, 2021, Tong et al., 2021).

This work is focused on the guaranteed supply of electricity in every hour of a year. It optimizes the costs in a macroeconomic viewpoint. There is no modelling of grid (costs) and no market (merit order) modelling. We would like to mention that to foresee the market model in 2050 is also highly uncertain. The current marginal costs-based model is presumably not adequate for a system based on marginal cost-free energy.

Results of previous investigations in the continental US (lower 48 states) and tropical island power grids indicate that a 95% renewable energy based, optimized wind/solar blend and an allowance for 5% supply-side flexibility via natural gas could yield firm 24/365 LCOEs below 4 cents per kWh by 2040, with a PV/wind overbuild of the order of 50% (Perez 2020; Perez et al., 2020, Tapaches et al., 2020).

2 Objectives

The results show how much PV is cost optimally built in Switzerland to fulfil the net zero 2050 goal of the Swiss Federal Council. This will help to define the needed policy changes – push and pulls i.e. regulations and subventions – to reach the targets regarding PV and storage. To know the amount of PV and storage required is also important in order to find an optimal solution for future remuneration models – which will have to change from energy to power based. The question of how to get enough incentives for PV and wind producers in case of significant curtailment has to be answered as well.

Our power and not energy focused method shows the value of flexibility. The results will also show the cost of isolation of Switzerland from the neighboring countries by calculating the option with limited or no electricity imports/exports to neighboring countries (scenarios #3 and #4 and scenarios "a").

Additionally, our results can show how much the option of building PV also on farmland (and not only on rooftops) will change the optimum and the costs (scenarios #5 and #6). The results are important for grid operators as well as for policy makers and especially the government.

The main question to be answered is how to optimally overcome intrinsic intermittency of PV.

2.1 Key questions

Optimal solutions are assessed in terms of:

- Optimum storage requirements — quantified in terms of installed PV capacity-hours.
- Optimum overbuilding — quantified as a percentage above unconstrained PV capacity needed to meet energy requirements without curtailment.
- "Bottom line" LCOE of optimally configured PV — quantified in cents per [firm] kWh.
- Different options to compare sensitivity of import and flexibility

We apply historical data from the Swiss transmission system operator (TSO) Swissgrid (load data) and from the European association for the cooperation of transmission system operators (TSOs) for electricity (ENTSO-E) (PV, hydro, nuclear, wind) as support to present and contrast the costs of achieving firm power generation capable of entirely displacing existing conventional generation (nuclear energy in particular) and including also future electricity needs for transportation and heating.

We analyze firm forecasts and firm power generation from the standpoint of existing distributed PV fleets. Current installations are scaled up based on this spatial distribution. The case study spans the years 2018–2020, for which we acquired ENTSO-E historical hourly load data as well as PV, wind, hydro and nuclear production as corrected for import and export by Swiss Energy Statistics from Swiss Federal Office of Energy (SFOE).

2.2 Firm Power Generation

We calculate the real and implicit storage (achieved via overbuilding) requirements, as well as the corresponding capital cost premiums, and levelized energy production costs (LCOE). In addition to the capital cost (CAPEX) of PV and storage, LCOEs are also a function of the considered life cycle, the operation and maintenance costs (OPEX) of PV and storage as well as the Weighted Average Cost of Capital (WACC).

Real storage and implicit storage (overbuilding/curtailment) requirements are calculated as a function of:

The capital costs of PV and storage.

- a future conservative scenario for 2050 with PV at CHF 860/kWp(stc) (CHF 660/kWp for PV on farm land) and battery storage at CHF 330/kWh (see chapter 3.3.1).
- An optimistic scenario based on US studies for bigger systems to model cost sensitivity CHF 390/kWp and 45 CHF/kWh for battery storage)

Further assumptions:

- The round-trip efficiency of storage. We assume 90%.
- Since the objective is to supply the demand 24/7 at high-penetration, there is no external battery recharge possibility at night or in off-hours. Storage can only be recharged when renewable production exceeds demand.
- We also consider flexibility defined in terms of the fraction of energy allowed from external, non-renewable sources and/or import. This external source could be supply-side, e.g., from legacy or new natural gas units, and/or demand-side from load management. We consider flexibility levels of 0% to 10%. The seasonal storage via e-fuels (H_2, methane) will be modelled via this flexibility (see below).

The financial specifics assume:

- A 30-year life cycle;
- Operation and maintenance costs of 1% of CapEx per year for PV;

- Operation and maintenance costs of 0.1% per full cycle for battery storage
- A 3% Weighted Average Cost of Capital, representative of the utility industry.

For a given time horizon, location, and PV fleet configuration, the cost of firm PV power generation is obtained by extracting the lowest life-cycle cost combination of storage and overbuilding, sufficient to meet the firm forecast requirements.

We calculate storage and implicit storage requirements to firmly supply the demand of Switzerland in its entirety. We apply the Clean Power Research Clean Power Transformation (CPT) model (Perez et al. 2019) to derive the optimum combination of real and implicit storage leading to the lowest possible firm generation cost.

2.3 Seasonal storage / flexibility

The implicit storage approach underlying the proposed study seeks the optimum solution between storage and over-build/curtailment given an allowable amount of flexibility (Perez et al., 2020). The required size and duration of storage are a direct result of this optimization. The ongoing investigations in the US show that the duration of storage (hence the need for seasonal reserves) is greatly influenced by both oversizing and allowed flexibility. In particular, supply-side flexibility (import/export, gas fired power plants with natural gas and renewable energy-based hydrogen or methane) alleviate the needs to build up long-term reserves for extreme low supply/high demand situations. Optimum solutions show that seasonal-duration storage is not needed to supply competitively priced firm power and meet demand year around.

The six simulation options outlined in chapter 3 will capture optimum requirements for Switzerland and characterize any long-term storage requirements if needed.

For hydro power we assume a growth of the seasonal storage of 2 TWh for scenario #1 and 1 TWh for scenarios #2–#6 (Table 3).

3 Definition of Swiss Energy system

3.1 Introduction

The Swiss Energy System is defined in Table 9 in the Annex. Here we give an explanation of the terms and values used.

The existing system is based on the Swiss electricity statistics and hourly data of ENTSO-E[1] between 2018 and 2020. The numbers can be used to be scaled up for future scenarios. As the ENTSO-E source includes some missing values, it has been corrected to the Swiss electricity statistics[2]. PV production had to be gap filled as well. This was done with the aid of Swissmetnet stations, averaged and modelled to a 15° tilted plane.

The future system (2050) is based on the Swiss Energy Perspectives 2050+ (SFOE, 2021). This includes several scenarios of possible future energy systems fulfilling the climate agreement of Paris (1.5°C target).

3.2 Today's system

Today's system is defined as the average of the years 2018–2020.

Yearly production in TWh is given as well as installed capacities and cost levels (in cts/kWh). Gross production is 70 TWh, net production 66 TWh. The losses are based on consumption of pumps for hydro power and on grid losses.

The system is defined by a high share of hydro power. This is separated into three types:

1. Hydro storage (large dams in the Swiss Alps mainly for seasonal storage),
2. hydro pumped storage (mid-sized dams often combined with large seasonal storage dams) to store energy for some hours or days and
3. run of river hydropower system (of the rivers flowing from the Alps to the borders).

New renewables are relatively small. PV is at 2.2 TWh, wind production at 0.15 TWh. PV installations are growing at a rate of about 30% annually; annual increment of installed PV needs to be enhanced by a factor of three (from 0.5 to at least 1.2 GW/year) to achieve the goals of net zero policy.

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[1] Source: https://transparency.entsoe.eu/

[2] https://www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/energiestatistiken/elektrizitaetsstatistik.html

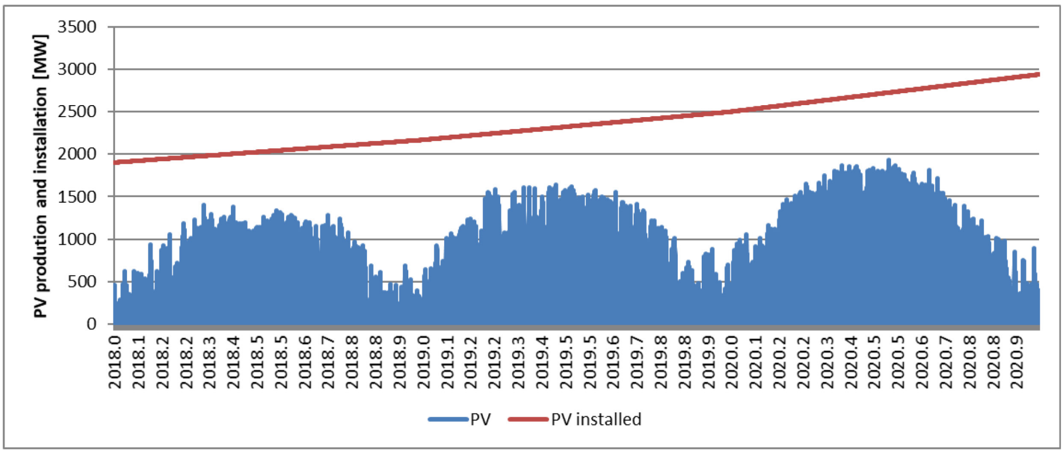

Figure 3: PV installed capacity (red line) and production (blue bars) 2018–2020.

Nuclear production is 24 TWh. Four nuclear power stations are running. The construction of new nuclear is forbidden by law. There is no fixed deadline for the phase out of the nuclear power stations. However, as they are built between 1969 and 1984, they are already relatively old. Life time is expected to be further extended and foreseen between 50 and 60 years. In 2050 the scenarios see no nuclear power stations and production.

Currently, electricity has a share about 25% of the energy consumption in Switzerland. 75% are non-renewables – all imported. In future (2050) this will change. The main scenario is highly based on electricity.

Since many years Switzerland is exporting electricity on the annual level. Those exports happen during summer time. In winter Switzerland is importing electricity. This imbalance will grow when nuclear power is replaced mainly with PV.

Swiss electricity production does not follow the Swiss load. Swiss hydro power plants (storage and pumped storage) are still exporting a certain amount of electricity to the surrounding countries during peak hours (morning and evening).

3.2.1 System data

The current system is defined by hourly values of three years 2018–2020 (Table 1) and includes the following parameters.

Table 1: Hourly parameters of the period 2018–2020.

Parameter	Abr.	Source	Remark
Load	L	ENTSO-E	Actual generation per production type
Nuclear	P_N	ENTSO-E	Actual generation per production type
Pumped hydro - storage	P_{Hp}	ENTSO-E	Actual generation per production type
Hydro storage (dams for seasonal storage)	P_{Hs}	ENTSO-E	Actual generation per production type
Hydro run of river	P_{Hr}	ENTSO-E	Actual generation per production type
Wind	P_W	ENTSO-E	Actual generation per production type
PV	P_{PV}	ENTSO-E Swissmetnet	Required a strong correction as in 2018 only a few PV installations were covered – and the coverage rose significantly till 2020 Gap filled with average of 20 Swissmetnet station data modelled to 15°S inclination
PV installed capacity	C_{PV}	SFOE	Modelled to hourly data
Import	P_I	ENTSO-E	Cross-border physical flow between Switzerland and the neighboring countries
Rest	R	Modelled	$R = L - P_N – P_{Hp} – P_{Hs} – P_{Hr} – P_W – P_{PV} - P_I$
Pumped hydro – consumption	L_{Hp}	Modelled	Negative part of rest (< -50 MW); sum of pump load & consumption < 2900 MW and scaled to match annual consumption
Hydro storage filling state	C_{Hs}	SFOE	Modelled from weekly to daily state
Inflow to hydro storage (net)	P_{HsiN}	Modelled	Delta of filling state. Shows approximately inflow due to snow melt
Inflow to hydro storage (gross)	P_{HsiG}	Modelled	Delta of filling state plus P_{Hs}, smoothed over 24 hours and scaled up to match yearly P_{Hs} production

Figure 4 shows the modelled inflow data – net and gross.

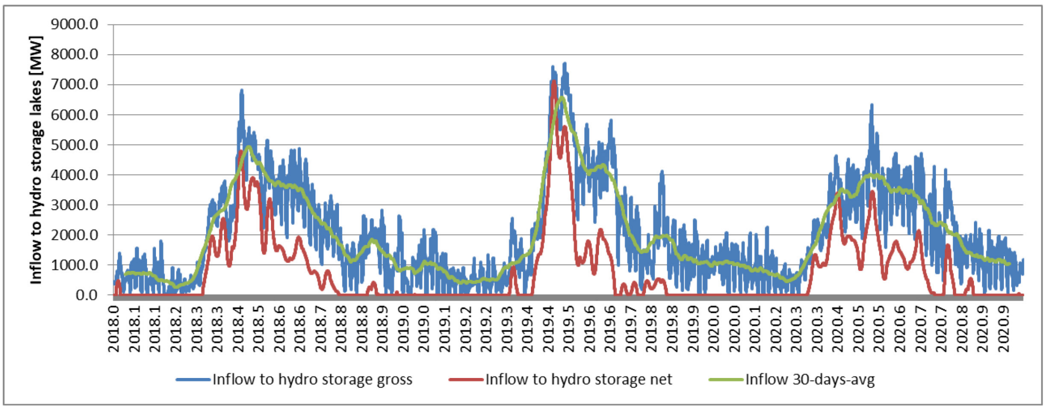

Figure 4: Modelled inflow to (seasonal) hydro storage expressed as potential electricity power in MW.

3.2.2 International grid connection

The European grid was started in 1958 on the Swiss border in Laufenburg. There the first lines were built between Germany, Switzerland and France. The Swiss grid is still highly interconnected with neighboring countries[3]. The electricity flowing through Switzerland is in the range of 50% of the electricity consumption within Switzerland. Italy depends heavily on the flow mainly from Germany. Electricity is generally imported in Switzerland during winter half year and exported during summer (up to 4.5 GW import and 8 GW export).

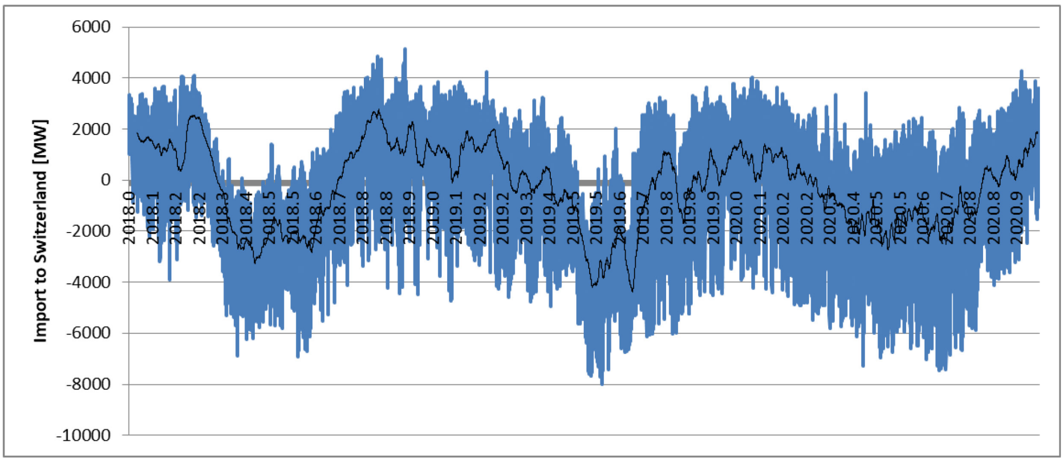

Figure 5: Import and export of electricity to Switzerland 2018–2020 (positive: import; negative: export). Black line: 15-days average.

Switzerland currently has no bilateral agreement with the EU regarding electricity due to a missing institutional agreement. Therefore, the market integration is lim-

[3] https://www.entsoe.eu/data/map/

ited and the outlook uncertain. Swiss utilities still take part in the day ahead market EEX[4]. However, a part of the electricity balancing market and renewable certificates market are not open for Swiss companies.

Historically, the electricity price is defined during summer by the German / French market (EEX) and during winter by the Italian market. End customers pay about 15–25 cts/kWh. Market price during the last 10 years was about 5 cts/kWh. However, during winter 2021/22 the prices for day ahead electricity rose up to 20 cts/kWh.

The market price is based on old, amortized power plants. During the last 20 years this price was too low to make investments for new power plants economically interesting (called missing money problem of the European market system).

The near future is relatively uncertain. The new regulation by the EU, to reserve 70% of the capacity to cross-zonal electricity trade, poses new challenges to Switzerland[5].

For all six scenarios (defined in chapter 3.3) we also modelled the extreme conditions of isolating Switzerland. Those scenarios are named with an “a” (e.g. 1a).

3.3 The situation in 2050

In 2021, the Swiss government published an update of the Energy Perspectives – called 2050+[6] (SFOE, 2021). This report shows possible pathways to a climate neutral energy system. In this study we use the main scenario "ZERO Basis".

New (non-hydro) renewables will grow from 3 to 40 TWh. PV has and shows the biggest potential with 33 TWh. According to the Swiss Federal Office of Energy (SFOE) and based on their solar cadaster, 67 TWh of electricity can be produced on buildings. In reality, the rooftop potential is presumably lower and in the range of 50 TWh / 50 GW[7]. In this study, a cap of 55 GW is applied which includes about 40 GW for rooftop and 15 GW of installations aside buildings (e.g. agri-PV, parking sites, floating PV). Wind energy potential would lie in the range of 8 TWh. However due to high population density this shrinks to 4.3 TWh, which even seems rather at the upper end of the possible contribution. Therefore, we used 50% lower values for wind power for scenarios #2–#6.

Also, hydro power is foreseen to grow. Mainly seasonal storage and hydro pumped storage capacities would be added. Seasonal storage is enhanced from 10 to 12 TWh (scenario #1) or 11 TWh (scenarios #2–#6) according to the official

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4 https://www.eex.com/en/market-data

5 https://www.swissgrid.ch/en/home/operation/market/european-market.html

6 https://www.bfe.admin.ch/bfe/en/home/policy/energy-perspectives-2050-plus.html

7 https://magazin.nzz.ch/nzz-am-sonntag/wirtschaft/solarenergie-ehrenrettung-ld.1679852?mktcid=smsh&mktcval=Twitter

targets and the Round Table discussions[8]. The price for these new systems is relatively high and would need special investments / securities by the government. As the scenarios show differences regarding to amount of new hydro the costs are also slightly varied.

PV off buildings is only included in one of the scenarios and discussions about feasibility just started in Switzerland. Main reasons for this are high population density, high price of land and the high importance of landscape protection in Switzerland. Most presumably Federal Act on Spatial Planning (RPG) and subvention regulations for agriculture need to be adopted. In scenario #6 a part of PV (around 30% or 13 TWh) is produced on farm land with agri-PV installations.

The official naming in the Energy Perspectives 2050+ is that 100% of the energy is produced within Switzerland. However, this isn't fully correct. The report includes 13.6 TWh of imported liquids based on Power to X technologies (PtL, based on renewables). Therefore, the share of energy produced in Switzerland is 84%. Additionally, the fuels for aircrafts are not included. About 20 TWh of renewable PtL is used for air transport at levels of 2019. Keeping the same levels of air transport, the real share of energy produced in Switzerland is 72%. Nonetheless, we use the term 100% in this report not considering the imported PtL and aside usage for air transport.

According the scenario ZERO Basis a small part of hydrogen is produced within Switzerland (1.9 TWh; to produce this 7.4 TWh of electricity is needed). The scenario is rather optimistic regarding efficiency measures. Total energy consumption will not grow much. One of the realistic reasons is that today many electric heating systems exist, which will be exchanged by heat pumps (saving 70% of the electricity). Oversizing was included in the modelling to a limited extent. In the scenario, 37 GW of PV is foreseen with 33.6 TWh of production. As 37 GW in Switzerland produce on average 37 TWh of energy peak shaving of 9% is included.

3.3.1 Cost levels 2050

There are no cost assumptions per technology published in the Energy Perspectives reports. The report only includes some general macro economical figures.

The definition of price levels 30 years ahead includes high uncertainties. Four different sources have been used as a basis: published papers (Figgener et al., 2019, NREL ATB[11]), Nexus-e reports (ESC, 2020[9]), conferences (EES 2021[10]) and selected Swiss experts, which have been interviewed. The reported values

[8] https://www.admin.ch/gov/de/start/dokumentation/medienmitteilungen.msg-id-86432.html

[9] https://nexus-e.org/documentation/

[10] https://www.ees-europe.com/

were included in the definition. As all PV (aside scenario #6) includes only rooftop PV and labor costs in Switzerland are high, the LCOE of PV will stay rather high.

The most comprehensive work on costs and cost perspectives exists in the Annual Technology Baseline (ATB) of the US National Renewable Energy Laboratory (NREL)[11]. Those figures are the main source for the state of 2050. They include also small-scale PV and batteries. We assume and apply a general security margin of 20%. To show the sensitivity, additionally lower costs assumptions based on US' studies with less conservative assumptions and for bigger installations are modelled.

Battery storage costs are currently still extremely high – especially for small storage at individual houses. In future there is a big potential for cost reductions. Often market prices are at +20% compared to Germany in well working markets.

Storage / H_2 prices have been updated based on EES 2021 conference (Oct. 21) and on ATB figures as well as in an IEA report[12]. We assumed a mix of 30% small installations (< 10 kW), 40% mid-sized installations (10–200 kW) and 30% bigger installations (for Swiss conditions).

Costs of imported and exported electricity today is in the range of 5 cts/kWh (a bit higher for exports as Switzerland gains some net income (SFOE, 2021). The forecast for 2050 is almost impossible especially when taking into account the turbulent situation on the electricity market during the last months. Generally, higher costs are foreseen[13]. We assumed slightly higher costs for import (6 cts/kWh) and constant costs for export (5 cts/kWh), as Switzerland will tend to export more in summer and import more in winter in future based on the switch from nuclear to PV.

11 https://atb.nrel.gov/electricity/2021/data

12 https://iea.blob.core.windows.net/assets/181b48b4-323f-454d-96fb-0bb1889d96a9/CCUS_in_clean_energy_transitions.pdf

13 https://www.handelsblatt.com/politik/deutschland/co2-und-erdgaspreise-studie-strompreis-steigt-bis-2030-um-50-prozent/27170486.html?ticket=ST-13976634-7m2L46hBf6kAVX9bDG0d-ap2

Table 2: Price assumptions for 2050. Round brackets: Lower costs based on US studies. Square brackets: costs including share of agri-PV. For PV and battery storage installation costs were used for modelling. For non-optimized production types, the energy costs.

Nr	Installation costs in CHF/kW	Approx. energy costs in cts/kWh
PV avg. on buildings	860 [786] (390)	6.9
Agri PV (farm land)	660	5.2
Battery storage[10]	330 (45)	9.2
Wind		11.0
Hydro		6.0 (mix of new and existing)
Hydrogen[11]		10.0
Gas power station (gas and investment)	2000 CHF/kW	8.5
ETS	100 CHF/tCO_2	
Thermal electricity cost incl. certification		11.1 – 16.8
Thermal electricity costs based on H_2 (e-fuels)		17.9 – 19.7
Imported electricity		6.0
Exported electricity		5.0

3.3.2 Six scenarios

Besides the main scenario based on ZERO Basis, five additional scenarios are modelled in this project. They are defined as follows (Table 3):

Table 3: Six scenarios used in this study.

No.	Scenario definition
1	100% renewable energy sources (RES) Switzerland with 0% net yearly import and no additional import/export capacity restrictions of electricity to neighboring countries
2	90% RES Switzerland with 10% net yearly import and no import/export capacity restrictions of electricity to neighboring countries
3	90% RES Switzerland with 10% net yearly import and limited import/export capacities (3 GW) and with gas fired power plants (natural gas with carbon price of 60 CHF/t CO_2)
4	90% RES Switzerland with 10% net yearly import and limited import/export capacities (3 GW) and with gas fired power plants (e-fuels)
5	84% RES Switzerland with 10% net yearly import/export, no import/export capacity restrictions and with 6% gas fired power plants (e-fuels)

No.	Scenario definition
6	84% RES Switzerland with 10% net yearly import/export, no import/export capacity restrictions and with 6% gas fired power plants (e-fuels) with 13 GW of PV on farm land

For all scenarios we also added the condition of isolating Switzerland and more optimistic costs assumptions. Therefore, we modelled 24 different scenarios in total.

In Tables 4–6 today's system as well as six future scenarios are defined. To reduce complexity the renewable and non-renewable thermal production is combined. Two additional major options were calculated:

1. Switzerland as an island with extremely limited transmission capacities to the surrounding countries. Only in scenarios #3, #5 and #6 7 GW of import would be allowed. Those scenarios are named with an “a” (e.g. “1a”).

2. Use of lower cost assumptions based on US studies. The source of the data is the same (NREL ATB[14]), but the costs are for bigger systems and include more optimistic outlooks.

Table 4: Annual electricity production in TWh 2018–2020 and 2050 with scenarios 1–6.

Type	2018–2020	2050 Sc. 1	2050 Sc. 2	2050 Sc. 3	2050 Sc. 4	2050 Sc. 5	2050 Sc. 6
PV	2.17	33.6	30.0	30.0	30.0	27.0	27.0
Wind	0.14	4.3	2.15	2.15	2.15	2.15	2.15
Hydro	39.5	43.3	40.8	40.8	40.8	40.0	40.0
Nuclear	24.2	0	0	0	0	0	0
Net import	0.77	0	8.25	0	0	8.25	8.25
Therm. production	3.0	3.1	3.1	11.35	11.35	6.9	6.9
Gross production	69.8	84.3	84.3	84.3	84.3	84.3	84.3
Net production	65.6	63.3	63.3	63.3	63.3	63.3	63.3

[14] https://atb.nrel.gov/electricity/2021/data

Table 5: Installed capacities in GW 2018–2020 and 2050 with scenarios 1–6. Opt. means: optimized in this project. Seasonal Hydro storage capacity is in TWh.

Type	2018–2020	2050 Sc. 1	2050 Sc. 2	2050 Sc. 3	2050 Sc. 4	2050 Sc. 5	2050 Sc. 6
PV	2.36	opt.	opt.	opt.	opt.	opt.	opt.
Wind	0.14	2.2	1.1	1.1	1.1	1.1	1.1
Hydro (all types)	15.3	20.0	19.5	19.5	19.5	19.0	19.0
Nuclear	2.96	0	0	0	0	0	0
Therm. production (all types)	0.97	0.97	0.97	3.75	3.75	2.25	2.25
Seasonal hydro storage [TWh]	10	12	11	11	11	11	11

Table 6: Overview of scenarios 1–6.

Type	2018–2020	2050 Sc. 1	2050 Sc. 2	2050 Sc. 3	2050 Sc. 4	2050 Sc. 5	2050 Sc. 6
Headline		E-Perspectives	10% import - no gas	10% gas - restricted import	restricted import - e-fuels	Import and e-fuels	Import, e-fuels and Agri-PV
Share of renewables*	64%	99%	89%	89%	90%	84%	84%
Net annual import	1%	0%	10%	0%	0%	10%	10%
Gas / E-Fuel fired pp.	0%	0%	0%	11%	11%	6%	6%

* does not include share of imported H_2 and share for air transport

3.3.3 Scenario #2 – 90% RES – 10% imported

The production of renewables is lowered (PV, wind, hydro) by 8.3 TWh to equal 10% of the electricity imported on an annual level. 10% are imported from neighboring countries. Limitation: 7 GW for import, 10 GW for export.

Sensitivity test for: Variability of costs with 10% import (enhancing flexibility and lowering price).

Background: The defined target for new renewables is relatively high. Therefore, lowering the target indicates a more realistic option.

3.3.4 Scenario #3 – 90% RES – 10% based on gas fired power plants – limited imports

The production of renewables is lowered (PV, wind, hydro) by 8.3 TWh. 10% are produced with new gas fired power plants based on methane with ETS.

Import and export are still allowed, but limited to 3 GW.

Sensitivity test for: Variability of costs with gas fired power plants (duration of usage) and with limitation to import and export of electricity.

3.3.5 Scenario #4 – 90% RES – 10% based on gas fired power plants run by renewable H_2 – limited import

The production of renewables is lowered (PV, wind, hydro) by 8.3 TWh. 10% are produced with new gas fired power plants based on renewable H_2.

Import and export are still allowed, but limited to 3 GW.

Sensitivity test for: Variability of costs with 10% electricity produced with gas fired power plants based on renewable liquids (H_2 or methane). How much do the costs vary when renewable liquids are used for the gas fired power plants?

3.3.6 Scenario #5 – 84% RES – 10% imported and 6% based on gas fired power plants

The production of renewables is lowered (PV, wind, hydro) by 12.1 TWh to equal approximately 84% of the electricity on an annual level. 10% are imported and 6% are produced with new gas fired power plants based on methane with ETS.

Sensitivity test for: Enhanced flexibility to 16% based on gas fired power plants and import.

3.3.7 Scenario #6 – 84% RES – 10% imported and 6% based on gas fired power plants – with option of agri-PV

The production of renewables is lowered (PV, wind, hydro) by 12.1 TWh compared to scenario 1. 10% are imported and 6% are produced with e-fuels / renewable liquids (H_2 or methane). PV on buildings is defined as 17 TWh and on agricultural land 10 TWh.

Sensitivity test for: Enhanced flexibility with gas fired power plants and 10% imports plus cost lowered by PV on agricultural land. What are the costs of not using PV on farm land?

Background: This scenario is assumed to lower the costs and will show a basic cost level.

3.3.8 Overview of the scenarios

Figure 6 summarizes the contribution of all supply-side energy sources in each scenario compared to the current situation. It clearly illustrates the central role to be played by new firm PV generation, ranging from 35% of total generation in scenarios #4 and #5 to 46% in scenario #1.

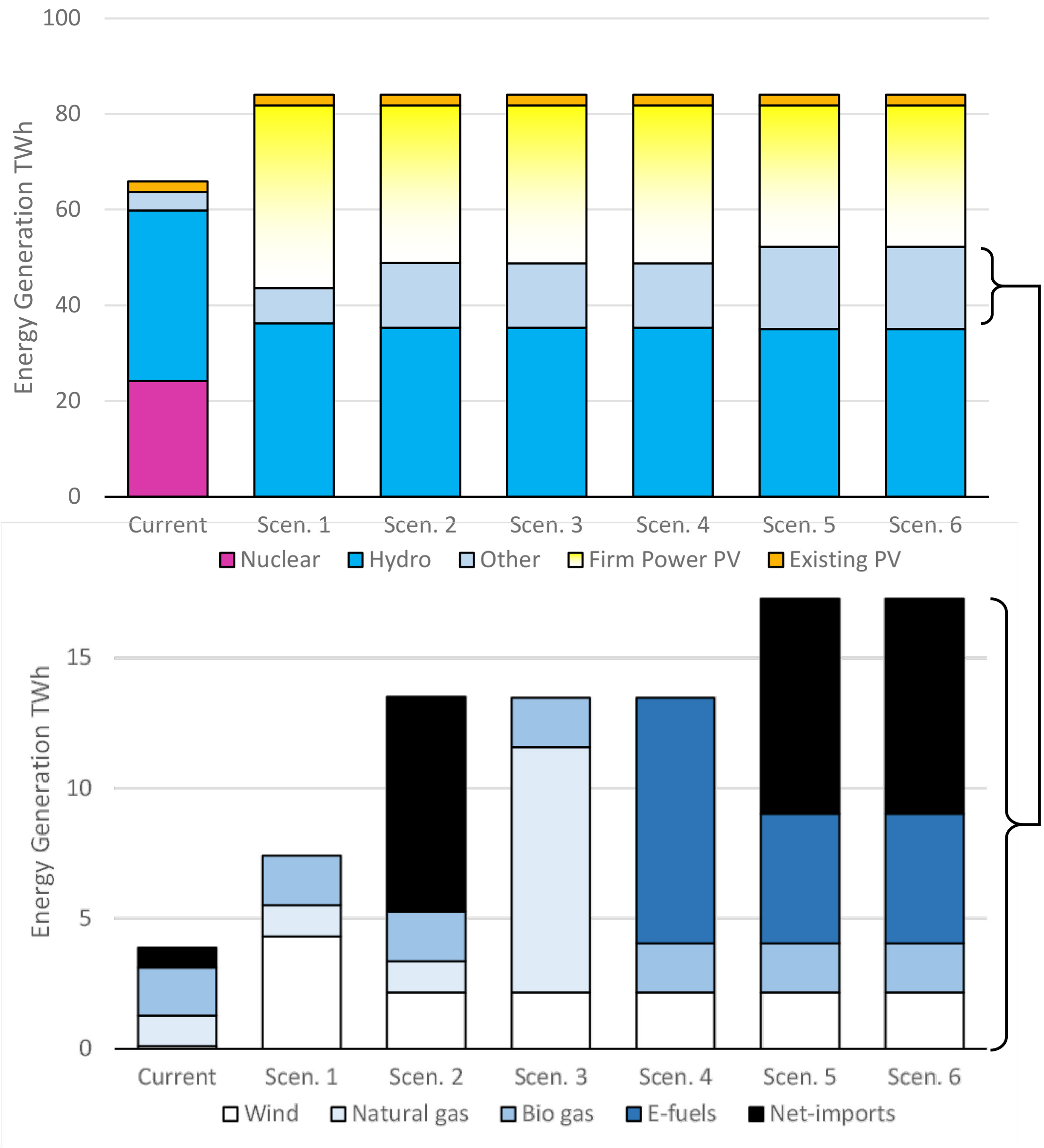

Figure 6: Supply-side electrical energy resources for all scenarios compared to the current situation. The bottom part of the figure provides details for the source labeled as 'other' in the top part. Note that scenario #4 is the only scenario that does not include non-renewable (natural gas) or possibly non-renewable (imports) resources.

3.4 Order of redispatch

The following Figure 7 shows the order of dispatch in the Clean Power Transformation (CPT) model for the basic scenario 1 not including any import / export.

PV capacity is deterministic and dependent on curtailment which is a driving independent variable. Optimization happens on curtailment / overbuilding in order to minimized cost while respecting capacity and energy limits/ setpoints.

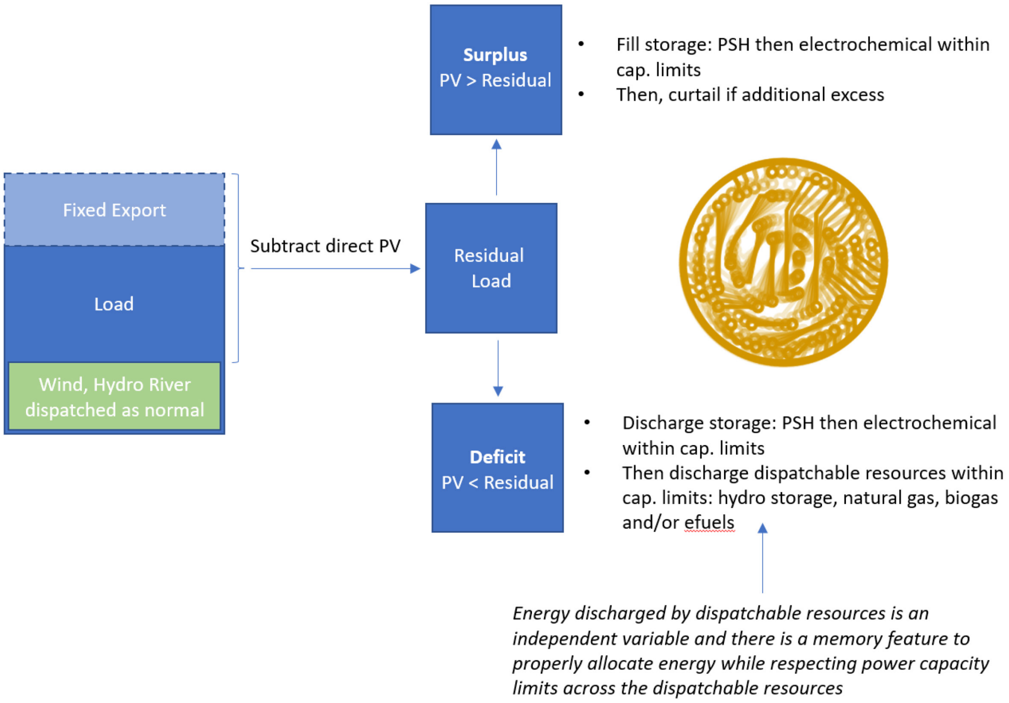

Figure 7: Dispatch model applied in the Clean Power Transformation (CPT) model. PSH stands for pumped hydro storage.

We apply the CPT model to determine the optimum PV and battery resources needed to meet demand firmly at the least possible cost while dispatchable resources are optimally deployed toward this minimum cost/firm power generation objective. The results of this optimization include the required quantities of new battery storage, new PV, curtailed PV output (implicit storage), the electricity generation cost of the optimum supply-side/storage blend that will supply Swiss demand 24x365.

Each meteorological year (2018, 2019 and 2020) is modelled alone to show the sensitivity of inter-annual variations.

The annual (2020) dispatching of these resources is illustrated in Figure 8. 30-day running means have been plotted to remove short-term fluctuations and improve visualization. The top edge of the graph represents demand on the Swiss grid. Note that the Swiss production is insufficient in winter and early spring, requiring imports from the rest of Europe. However, production exceeds demand in summer and is exported.

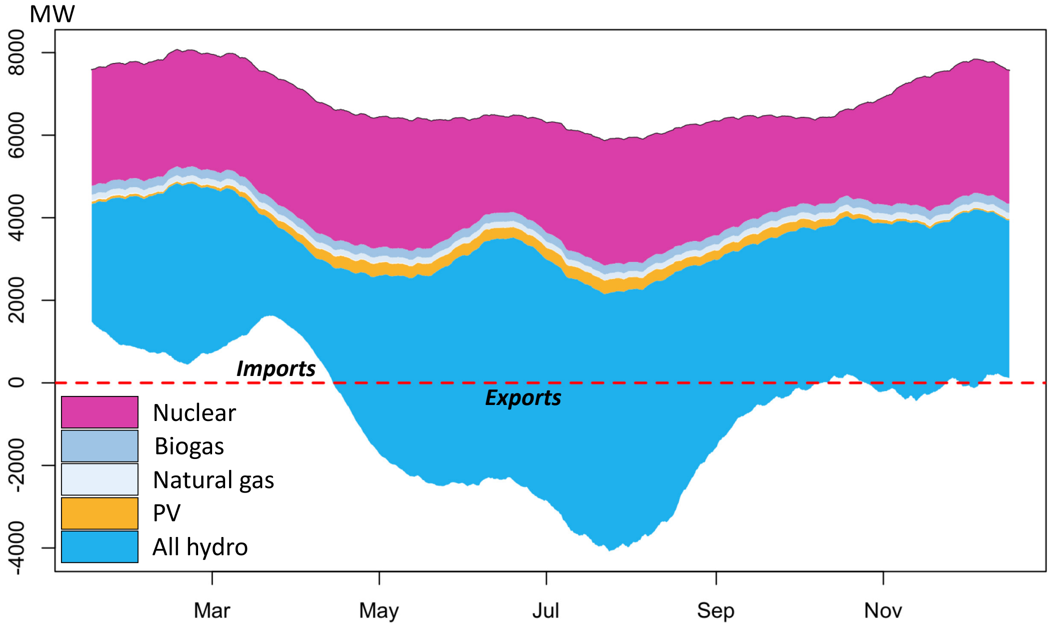

Figure 8: Annual dispatch of Swiss-based of supply-side resources for the year 2020. The top line of the stacked graph represents the Swiss grid load

Net imports over the winter half year summed up to about 5 TWh during the last 20 years.

3.5 Climate change

We use a conservative approach as we do not include any climate change effects:

1. Climate change will enhance the run of hydro production in winter and lower it in summer (a switch of about 0.6 TWh until 2050).

2. Climate change will lower the duration of winter. Therefore, the need for seasonal storage of hydro is lowered.

3. Climate change will lower the heating needs – and enhances the cooling loads (which will be much lower than the heating loads in 2050). Both would be positive for integration of PV.

All three effects will lower the seasonal unbalance.

4 Results

4.1 General overview

The upcoming figures are mostly based on the meteorological year 2020. The years 2018 and 2020 show very similar results, which is illustrated at the end of this chapter. In Figure 9, we report the new PV capacity, curtailed PV output (implicit storage), and battery storage required in each scenario to firmly meet demand on the Swiss power grid.

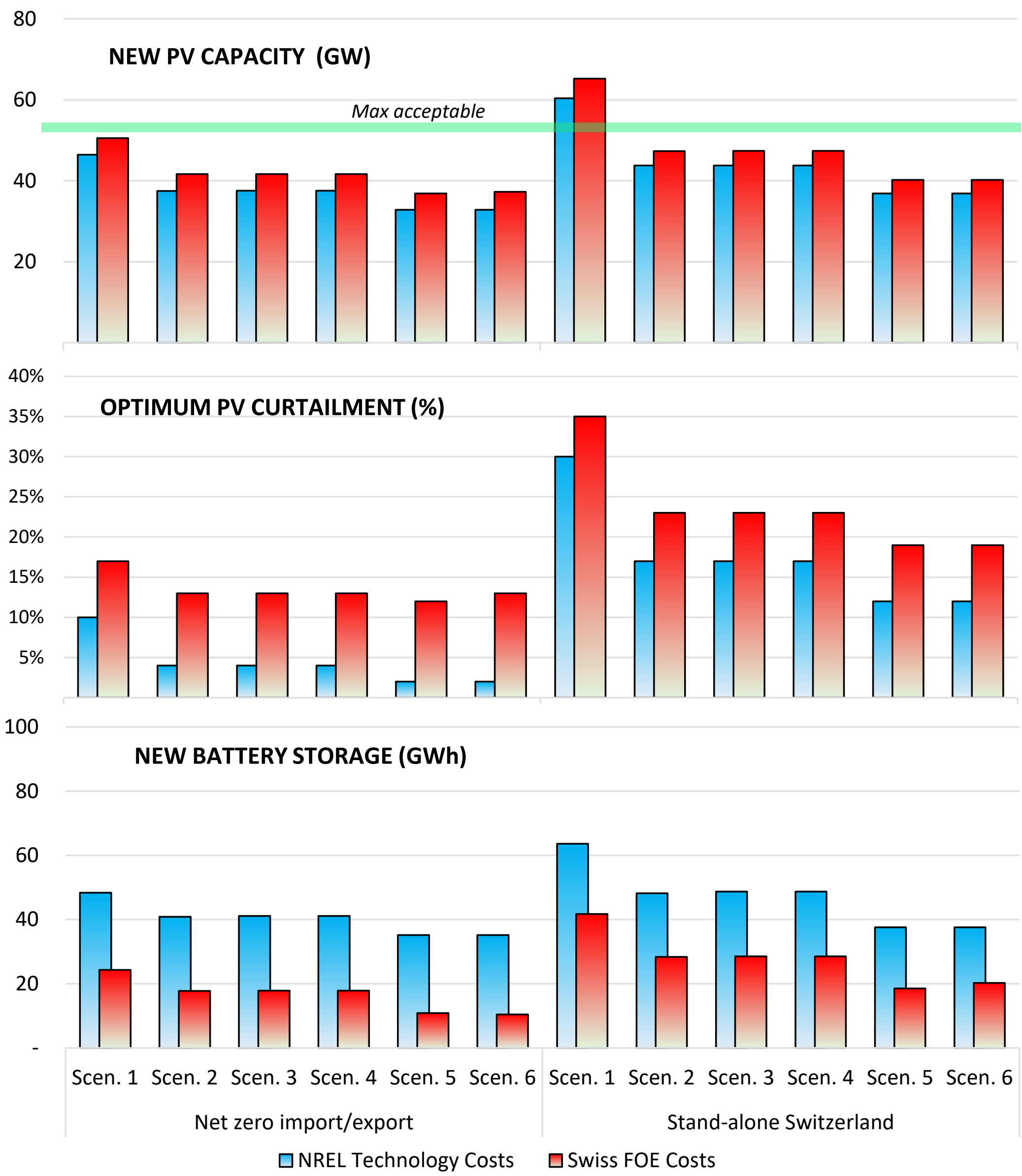

Figure 9: New PV capacities (top), optimal curtailment (middle) and new battery storage for scenarios 1–6 for connected (left) and stand-alone Switzerland (right). Max. acceptable shows the assumed maximum of acceptable PV in Switzerland (55 GW).

New PV capacities (Figure 9 top) range from 33.5 GW (scenario 5 & 6 with net-zero interconnectivity and optimistic technology costs) to 67 GW (scenario 1 without interconnectivity and conservative costs). Applying optimistic cost assumptions reduces new PV requirements by about 9% overall compared to conservative costs. Operating the Swiss grid stand-alone would require 17% more PV to be built than allowing net-zero interconnectivity. We plotted a “max acceptable” line indicating the maximum amount of new PV that could be reasonably deployed in the country. This amount is the result of a comprehensive analysis from the Remund et al. (2019) that considered all deployable options (including roof space, exclusion zones, farmland etc.) given current PV efficiencies. Importantly, all but one scenario (#1a – autonomous grid) falls under this upper limit.

PV output curtailment (Figure 9, middle) ranges from 2% (scenario 5 & 6 with net-zero interconnectivity and NREL costs) to 35% (scenario 1 without interconnectivity and Swiss FOE costs). Technology cost assumptions have a strong influence on required curtailment. Applying optimistic cost reduces the need for it by an average of 41%. Stand-alone grid operation, without net-zero flexibility would increase operational curtailment by 130%.

New battery storage requirements (Figure 9, bottom) range from 11.6 GWh (scenario #6 with net-zero interconnectivity and conservative cost assumptions) to 85 GWh (scenario #5 and #6 with stand-alone grid and optimistic tech costs). Applying optimistic cost assumptions leads to two times more battery storage overall. This significant difference is because future utility-scale NREL battery cost predictions are very low compared to the conservative small-scale estimates (8 times less) while the difference for PV between the two estimates amounts only to a factor of two. Interestingly, autonomous operation of the Swiss grid would only require 32% more battery storage than net-zero interconnected operation. In all cases, required battery storage is low, amounting to 0.3 hours of full PV capacity in the case of conservative cost assumptions, and ~1.2 hours in the case of optimistic cost assumptions. The bottom line is that no new long-term storage is required beyond the small addition to the existing buffer hydro system (+10% / 1 TWh for scenarios 2-6, +20% / 2 TWh for scenario 1), as is often assumed when envisaging ultra-high PV or wind penetration. This observation corroborates results obtained in the US (Perez, M., 2020). 10–85 GWh of batteries also seem feasible compared to the expected electrical vehicle batteries, which will include about 200 GWh of battery storage. Accessing 10% of this storage with by-directional loading systems would reduce the need of extra storage significantly.

Figure 10 reports the blended all-resources power generation LCOEs on the Swiss power grid.

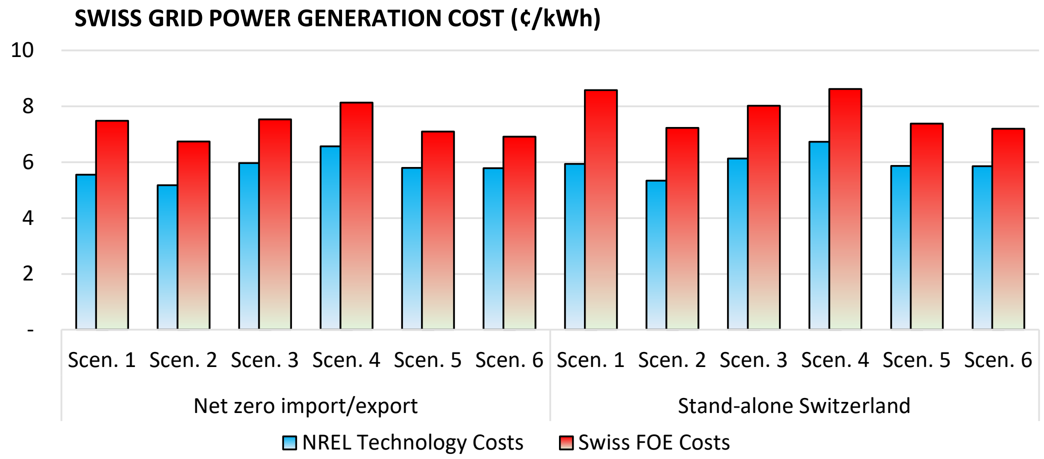

Figure 10: Swiss grid power generation costs for scenarios 1–6 and for connected and stand-alone Switzerland.

Electricity production costs range from 5.2 cts/kWh (scenario 2 with optimistic costs) to 8.6 cts/kWh (scenario 1 autonomous grid operation and conservative, small-scale tech costs). Applying optimistic utility scale storage/PV cost assumptions reduces generation costs by an average of 22%. Importantly, as unlikely as this configuration may be, stand-alone grid operation would only increase these costs by an average of 7% i.e., not constituting a showstopper.

Figure 11 illustrates the critical role of implicit storage on the bottom line. Without operationalizing PV overbuild and curtailment, production costs would be 71% higher on average in the net-zero interconnected case, and 600% higher in the stand-alone case.

The new annual dispatch of all resources is illustrated in Figure 11 for the 100% RE (e-fuel) scenario #4. The top graph illustrates the net-zero import/export grid configuration, while the bottom graph illustrates the autonomous grid configuration. As in Figure 1, 30-day running mean have been plotted to remove short-term fluctuations and improve visualization.

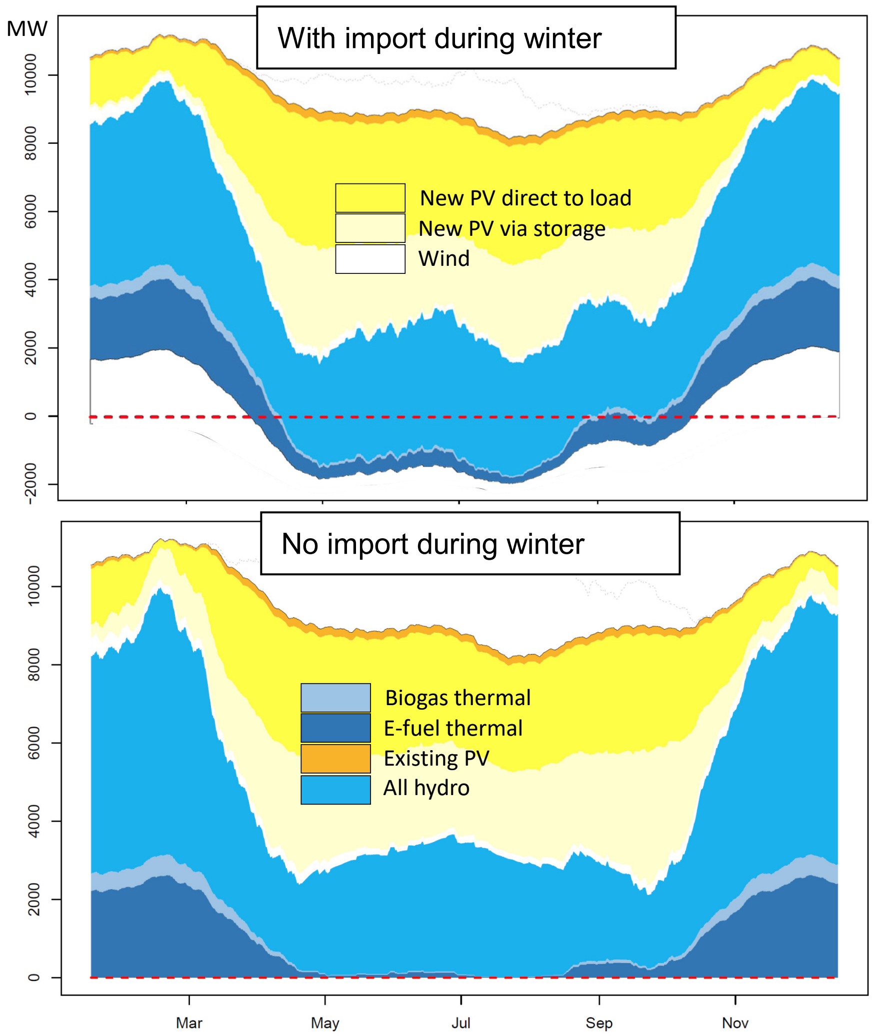

Figure 11: Annual dispatch of supply-side resources for the year 2020 illustrated for the 100% renewable scenario with e-fuels (#4). The top graph represents the net-zero interconnected configuration where winter imports are energetically matched to summer export amounting to net-zero. The bottom graph corresponds to the extreme stand-alone grid configuration.

Figure 12 shows the share of energy production in scenario #6.

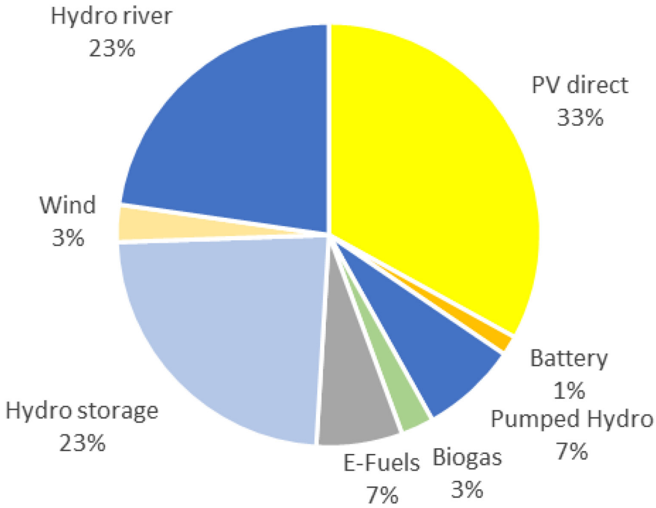

Figure 12: Share of energy production types for scenario #6 for 2050.

Electricity for battery charge and pumped hydro comes mostly from PV.

In Table 7 the main modelling results are concluded.

Table 7: Main results of the modelling for scenarios #1-#6 and #4a (no import).

Parameter	**Sc. 1**	**Sc. 2**	**Sc. 3**	**Sc. 4**	**Sc. 5**	**Sc. 6**	**Sc. 4a**
PV installed capacity [GW]	50.1	41.0	41.0	41.0	36.6	37.0	48.1
PV curtailment [TWh]	7.9	4.7	4.7	4.7	4.1	4.5	11.1
LCOE [cts/kWh]	7.5	6.7	7.5	8.1	7.1	6.9	8.6
Battery Capacity [GWh]	24.8	19.8	19.9	19.9	11.9	11.6	26.6
Imports [TWh]	10.0	18.3	10.0	10.0	18.3	18.3	0.0

Overall, the results of the Energy Perspectives could be confirmed. The optimum PV installation for this scenario (in this report #1) is 41 GW instead of the 37 GW modelled in the perspectives including higher (14% instead of 9%) curtailment. Results for all scenarios are given in Table 10 in the Annex.

4.2 Implicit storage impact

Figure 13 illustrates the importance of overbuilding and operationally curtailing the PV resource on the bottom line: production costs would be an average of 63% higher across all scenarios for the net-zero interconnected configuration, and 450% higher in the autonomous grid configuration. The main factor for this cost difference is the amount of new battery storage required that would respectively be 1300% and 7500% higher without PV oversize/curtailment.

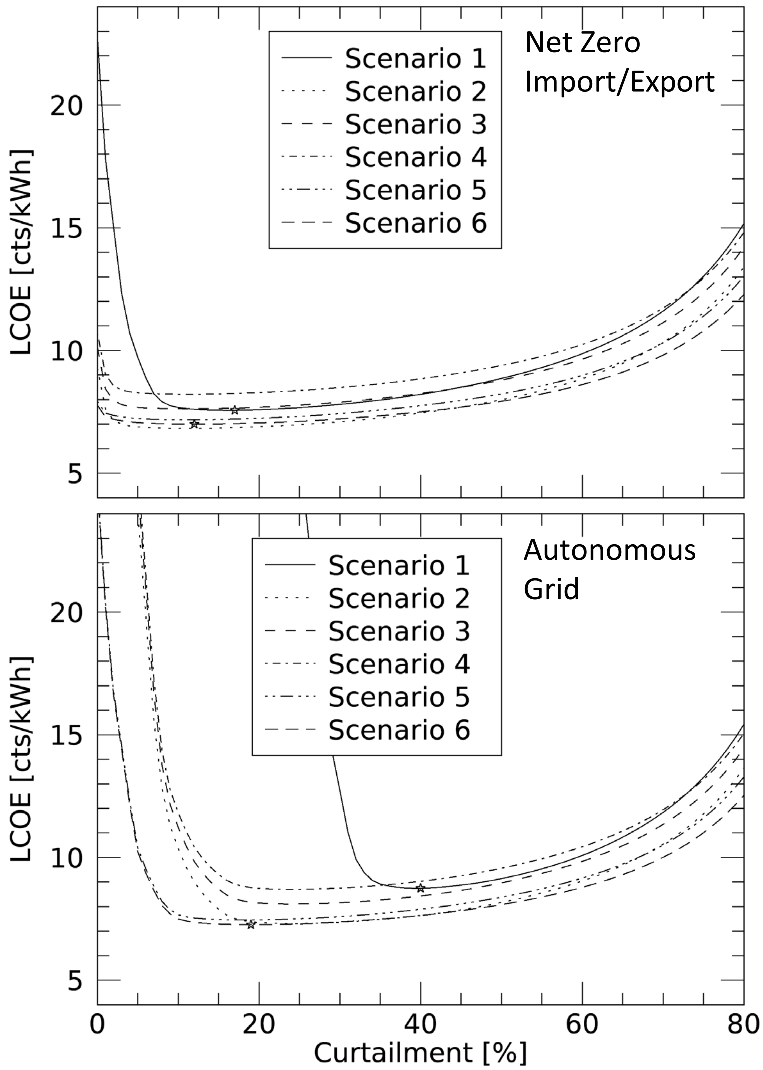

Figure 13: Electricity production cost on the Swiss power grid as a function of PV output curtailment for all scenarios. The top graph corresponds to the interconnected grid configuration with net-zero import/exports with the larger European grid. The bottom graph represents autonomous grid configuration. Scenarios: #1: E-Perspectives 2050+; #2: 10% net import; #3 and #4: 10% import, limited import capac., #5 and #6: 10% import, 6% gas & agri-PV.

4.3 Sensitivity analysis: differences of meteorological years

The three years (2018–2020), analyzed independently, lead to very comparable firm power production cost results overall as seen in in Figure 7 for the 100% renewable scenario #4.

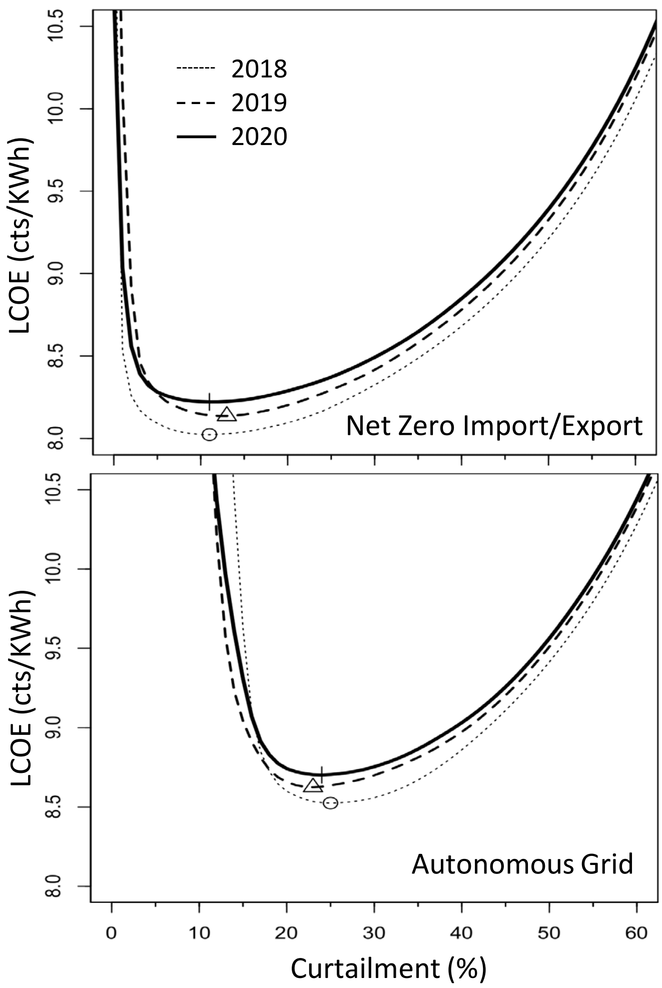

Figure 14: Comparing 2018, 2019 and 2020 electricity production cost on the Swiss power grid as a function of PV output curtailment for scenario #4. The top graph corresponds to the interconnected grid configuration with net-zero import/exports with the larger European grid. The bottom graph represents autonomous grid configuration.

4.4 Conclusions

Our investigation shows that high-RES solutions for Switzerland, with PV playing a central role as a complementary resource to the country's hydropower system, are both physically and economically reasonable, despite the minor role wind power can play, and the mediocre PV resource in winter months.

It is important to state that operational costs in all considered scenarios are reasonable compared to current wholesale market prices in Switzerland (these have been well above 20 cts/kWh the last couple of months[15]. The present ultra-high RE costs are even reasonable when compared to earlier pre-crisis wholesale prices (4–6 cts/kWh) noting that these earlier prices do not fully factor-in environmental or strategic externalities which, as we see today with international tensions, can be consequential.

Another particularly important observation is the result obtained for the 100% RES scenario (#4). Not only are operational generation costs reasonable (6.5–8.5 cts/kWh depending on technology and autonomy assumptions), but they show the supply-side flexibility catalyst role that e-fuels can play, even as expensive as they are expected to be at 18–20 cts/kWh.

Finally, we stress the importance of implicit storage (i.e., optimally overbuilding the PV resources). Not implementing this deployment strategy would result in higher prices on the network. It is therefore important to operationalize optimal overbuilding and curtailment early-on, by e.g., implementing appropriate regulations that would lead to firm power monetization, instead of current run-of-the-whether PV production.

4.4.1 Costs of isolating Switzerland

The amount of imported net energy was defined for each scenario to lie between 18.3 TWh (scenarios #2, #5 and #6) and 0 (scenario #1, #3 and #4 with isolation of Switzerland). Net imports are all taking place during the winter months. Table 8 shows the amount of electricity to be imported in 2050 for each scenario.

Table 8: Annual electricity imports in TWh with scenarios 1–6 with and without isolation.

Net annual import	Today	Sc. 1	Sc. 2	Sc. 3	Sc. 4	Sc. 5	Sc. 6
With imports	5.0	10.0	18.3	10.0	10.0	18.3	18.3
Isolation ("a")	-	0.0	8.3	0.0	0.0	8.3	8.3

[15] TNO & Fraunhofer ISE, (2022): Swiss Energy Charts. https://energy-charts.info/charts/price_spot_market/chart.htm?l=en&c=CH&interval=year&year=2022&legendItems=0000100000

Decoupling Switzerland from Europe increases costs by 5–15%. More PV, more curtailment and more storage are needed. Only scenario #1a with no import would induce PV capacities which are above the assumed threshold of 55 GW.

For a fully decoupled Switzerland with no additional imports of e-fuels (scenario #1a) PV on farm land or significantly more hydro or wind energy would be needed – all difficult to obtain due to political issues (landscape protection, food production, biodiversity). Therefore, not mainly the costs, but the natural resources and policy would be the main issues of decoupling Switzerland.

Just reducing imports (0% on annual bases and to 3 GW for power) and replacing them by natural gas or e-fuels would induce only minor changes regarding the costs. LCOE would rise slightly (about 15%). E-Fuels couldn't be produced largely in Switzerland but would have to be to imported (about 40% would be feasible based on curtailment).

4.4.2 E-Fuels

As stated above, electricity based on e-fuels is modelled at a high cost of 18–20 cts/kWh. Nonetheless, scenarios #4–#6 including electricity from e-fuels also show low overall LCOE costs (7–8 cts/kWh) because e-fuels have a low overall share.

4–8 TWh of PV production would be curtailed optimally in these scenarios. This could be used to produce e-fuels.

E-fuels are needed in the range of 9 TWh (scenario #4) and 5 TWh (scenarios #5–#6). Regarding the round-trip efficiencies of 0.4, 40–50% of e-fuels could theoretically be produced in Switzerland. How many e-fuel will effectively be produced in Switzerland will depend on technology costs, transport costs, storage available and costs of imported e-fuels.

4.4.3 Policy and Market

The lowest costs result with about 40 GW PV, 15% curtailment and 15 GWh batteries, including a 10% rise of hydro power generation and storage (plus 1 TWh), a rise in pumped hydro (from 2.9 to 5.7 GW) and an import of 5 TWh of e-fuels (for electricity generation).

How to obtain this optimum is another question. The current policy and regulatory framework most presumably will not induce enough investments to attain this: With bigger shares, PV will start to cannibalize itself. At noon there will be more PV than load and the prices will be zero or negative. Purely market-based models or power purchase agreements (PPA) will fail in this situation.

The electricity market in many Western countries and also in the EU and Switzerland is a copy of the market defined first in New England (USA) in the 1980s –

with no fluctuating renewable energies. It depends on marginal costs and the rule of merit order. Many countries added an incentive for renewables and a capacity market (Cramton et al., 2008) to reach more energy security as the energy only market did not induce enough investments into additional capacities. This debate is ongoing in Switzerland.

Germany, UK, Canada, USA and other major countries are targeting a 100% RES based by 2035. As this production portfolio will include only to a small part marginal costs a market based on marginal costs is at least debatable.

This shows the urgent need to develop new policies and new market models. A short literature review (IRENA, 2017; Peng & Poudineh, 2017) indicates that ideas exist, but the scientific foundation needs to be extended. Specifically, how to secure overbuilding and thus minimize the overall costs is an open question.

Another question is how to regulate the curtailment: Who is doing this on which level, based on which tools? IEA PVPS Task 14[16] started a study to describe existing models. More work is needed.

4.4.4 Comparison to other studies

Several studies in Switzerland pointed out lately that the energy transition is not easy to implement and that there are conflicting goals. The paper of Weiss et al. (2021) about the “Energy Trilemma” showed that sustainability (CO_2 emissions), affordability (consumers’ costs) and security of supply are competing objectives. Similar to this study, Thaler and Hofmann (2022) discussed the impossible energy trinity: energy security, sustainability and sovereignty.

In the paper about “Future Swiss Energy Economy” (Züttel et al., 2022) three approaches for the complete substitution of fossil fuels with renewable energy from photovoltaics were considered: a purely electric system with battery storage, hydrogen, and synthetic hydrocarbons. This study noted that either huge areas for PV or huge hydrogen storage or hydro power systems would be needed inducing high costs and sustainability problems. Conflicting goals clearly exist: integration in Europe, biodiversity, climate change and affordability of energy are competing challenges to a certain level. However, Züttel et al. modelled unrealistic extreme scenarios with 100% renewable energies (no imports also not for e-fuels) and no efficiency gains – which in reality exists based alone on electrification for heating and mobility and reduces the respective energy need by a factor of 2–3). In our study based on Energy Perspectives 2050+, a part of the energy is imported (28%) – PTL and e-fuels – and air transports aren’t included – to deliver those in Switzerland would indeed be difficult.

Additionally, all three referenced papers did not include curtailment of PV. With curtailment, a mostly isolated (with high security of supply) as well as e-fuels based scenarios (with low CO_2) lead to low costs of energy. As Table 10 shows,

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[16] https://iea-pvps.org/research-tasks/solar-pv-in-100-res-power-system/contacts_t14/

no optimum scenario for all objectives exists. Nevertheless, scenarios like #2a (import of 8 TWh of electricity) and #4a (import of e-fuels, but not electricity) would enhance electricity costs only marginally by 0.5 cts/kWh (to 8–8.5 cts/kWh) – costs affordable for the Swiss customers.

The effects of higher levels of energy security (and less integration in the EU) and climate protection is levelled out by higher PV installations and higher curtailments. The energy trilemma exists, but is solvable to a big extent by overbuilding PV which can be induced by suitable regulations and incentives.

4.5 Outlook

Four issues were not investigated in this study:

1. Nuclear power is not modelled as the study is based on the Energy Perspectives 2050+. The newest nuclear power station in Switzerland Leibstadt was built in 1984 and would be 66 years old in 2050, which is well above the planned lifespan. Building new nuclear power plants is forbidden in Switzerland by the current law. Nevertheless, in our optimization model a new nuclear power station could be added. It could deliver the answer to how the costs would change including a rather inflexible and expensive (15–20 cts/kWh) production method.

2. Alpine PV has not been included as well. PV installations in the Alps at altitudes of 1500–2500 m above sea level with steep inclinations (e.g. 70° South) would deliver almost the same electricity in winter as in summer. This would ease integration. However, the potential is regarded as rather small (3–5 TWh) which would be quite small compared to the required 33 TWh – and therefore would not change the seasonal distribution of the whole PV fleet significantly.

3. The load was raised linearly by the factor of existing and foreseen energy consumption (a growth from 70 to 84 TWh is modelled). No change regarding the seasonal distribution has been made. Linearizing the load and not taking into account that mainly winter electricity consumption will rise due to exchange of fossil heating systems with heat pumps, delivers too optimistic results regarding the winter load requirements.

4. The effects of climate change have been neglected. Neglecting climate change induces conservative results. Climate change reduces seasonal effects: shorter and warmer winters, more precipitation in winter and less in summer will be seen even if the Paris agreement limiting climate change to 1.5°C is reached.

5. Seasonal thermal storage isn't modelled; this would ease the integration additionally.

The effects of the simplified load modelling and neglecting climate change could level each other out to a certain degree.

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6 Annex

Table 9: Input definitions.

Energy production & import in TWh							
Type	**2018-2020**	2050 Sc. 1	2050 Sc. 2	2050 Sc. 3	2050 Sc. 4	2050 Sc. 5	2050 Sc. 6
PV	2.17	33.6	30	30	30	27	27
Wind	0.14	4.3	2.15	2.15	2.15	2.15	2.15
Hydro	39.5	43.3	40.8	40.8	40.8	40	40
Nuclear	24.2	0	0	0	0	0	0
Import	0.77	0	8.25	0	0	8.25	8.25
Therm. production	3	3.1	3.1	11.35	11.35	6.9	6.9
Gross production	69.8	84.3	84.3	84.3	83.4	84.3	84.3
Net production	65.6	63.3	63.3	63.3	63.3	63.3	63.3
Check sums							
Total	69.78	84.3	84.3	84.3	84.3	84.3	84.3
New renewables	5	39.8	34.05	34.05	34.05	31.05	31.05
All renewables	44.5	83.1	74.85	74.85	74.85	71.05	71.05
Reduced renewables			8.25	8.25	8.25	12.05	12.05
Gas fired pp				9.45	9.45	5	5
Import (annual share)	1%	0%	10%	0%	0%	10%	10%
Share of CH EE	64%	99%	89%	89%	90%	84%	84%

Installed GW							
Type	**2018-2020**	2050 Sc. 1	2050 Sc. 2	2050 Sc. 3	2050 Sc. 4	2050 Sc. 5	2050 Sc. 6
PV	2.36	50	41	41	41	37	37
Wind	0.14	2.2	1.1	1.1	1.1	1.1	1.1
Hydro	15.3	20	19.5	19.5	19.5	19	19
Nuclear	2.96	0	0	0	0	0	0
Import							
Therm. production	0.97	0.97	0.97	3.75	3.75	2.25	2.25

Scenario definition		2050 Sc. 1	2050 Sc. 2	2050 Sc. 3	2050 Sc. 4	2050 Sc. 5	2050 Sc. 6
Headline		E-Perspectives	10% import - no restrictions	No import - gas	No import - e-fuels	Import and e-fuels	Import, e-fuels and agri-PV
Share of renewables	64%	99%	89%	89%	90%	84%	84%
Net annual import	1%	0%	10%	0%	0%	10%	10%
Import restrictions	no (10 GW)	no (10 GW)	no (10 GW)	yes (3 GW)	yes (3 GW)	no (10 GW)	no (10 GW)
Share of gas fired pp.	0%	0%	0%	11%	11%	6%	6%
Thermal prod. [GW]	0.97	0.97	0.97	3.75	3.75	2.25	2.25
Thermal prod. [TWh]	3.1	3.1	3.1	11.35	11.35	6.9	6.9
Thermal prod. Renew. Share	61%	61%	61%	17%	17%	28%	28%

Fuel costs		2050 Sc. 1	2050 Sc. 2	2050 Sc. 3	2050 Sc. 4	2050 Sc. 5	2050 Sc. 6
Headline		E-Perspectives	10% import - no restrictions	No import - gas	No import - e-fuels	Import and e-fuels	Import, e-fuels and agri-PV
Natural gas	30	30	30	30			
Emission rate [t CO2/MWh]	0.4	0.4	0.4	0.4			
Efficiency (gas -> electricity)	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Power station (invest., o&m) [CHF/MWh]	35	35	35	35	35	35	35
CO2 emission certificates [CHF/tCO2]	60	100	100	100			
CO2 removal / sequestration [CHF/tCO2]		150	150	150			
E-Fuel (green H2) [CHF/MWh]					100	100	100
Total natural gas / certif [CHF/MWh]	100	111	111	141			
Total natural gas / sequestr [CHF/MWh]		124	124	168			
Total E-Fuel (H2) [CHF/MWh]					197	179	179
Natural gas without certif	85	85					

Renew. Costs		2050 Sc. 1	2050 Sc. 2	2050 Sc. 3	2050 Sc. 4	2050 Sc. 5	2050 Sc. 6
Headline		E-Perspectives	10% import - no restrictions	No import - gas	No import - e-fuels	Import and e-fuels	Import, e-fuels and agri-PV
PV install. Costs [CHF/MWh]		860	860	860	860	860	786
PV prod. Costs [cts/kWh]		6.9	6.9	6.9	6.9	6.9	6.3
Wind [cts/kWh]		11	11	11	11	11	11
Hydro [cts/kWh]		6.04	5.80	5.80	5.80	5.80	5.80
Battery install costs [CHF/MWh]		330	330	330	330	330	330
Battery [cts/kWh]		9.2	9.2	9.2	9.2	9.2	9.2
Import [cts/kWh]	5.0	6.0	6.0	6.0	6.0	6.0	6.0
Export [cts/kWh]	5.0	5.0	5.0	5.0	5.0	5.0	5.0

Table 10: Average results of modelling based on 2018, 2019 and 2020 meteorological years. Imports will happen during winter time (imports and exports are listed also in Table 9).

Costs	Scenario	PV installed	PV curtailed	Battery capac.	LCOE	Thermal prod.	Imports
		[GW]	[%]	[GWh]	[cts/kWh]	[TWh]	[TWh]
Swiss	1	50.1	14%	24.8	7.46	3.1	10
Swiss	2	41.0	11%	19.8	6.73	3.1	18.3
Swiss	3	41.0	11%	19.9	7.53	11.35	10
Swiss	4	41.0	11%	19.9	8.13	11.35	10
Swiss	5	36.6	11%	11.9	7.09	6.9	18.3
Swiss	6	37.0	12%	11.6	6.91	6.9	18.3
Swiss	1a	67.8	35%	34.8	8.60	3.1	0
Swiss	2a	48.0	24%	26.4	7.22	3.1	8.3
Swiss	3a	48.1	24%	26.6	8.02	11.35	0
Swiss	4a	48.1	24%	26.6	8.62	11.35	0
Swiss	5a	39.9	17%	19.5	7.38	6.9	8.3
Swiss	6a	40.2	18%	20.3	7.19	6.9	8.3
USA	1	45.9	9%	45.9	5.53	3.1	10
USA	2	37.4	3%	36.0	5.16	3.1	18.3
USA	3	37.4	3%	36.2	5.96	11.35	10
USA	4	37.4	3%	36.2	6.55	11.35	10
USA	5	33.5	0%	85.0	5.76	6.9	18.3
USA	6	33.5	0%	85.0	5.75	6.9	18.3
USA	1a	62.6	30%	55.6	5.99	3.1	0
USA	2a	43.9	18%	44.7	5.34	3.1	8.3
USA	3a	44.0	18%	45.4	6.13	11.35	0
USA	4a	44.0	18%	45.4	6.73	11.35	0
USA	5a	36.6	11%	35.2	5.85	6.9	8.3
USA	6a	36.6	11%	35.2	5.85	6.9	8.3