FIRM PV POWER SWITZERLAND

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Abstract

We investigate weather photovoltaic power generation 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 calculate 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 explore several ultra-high RE "net zero" scenarios where PV and hydro would meet the bulk of the country's demand. Depending on future battery storage and cost predictions for PV and batteries, and a small contribution from in-country or imported dispatchable resources, we show that power production costs on the Swiss grid would range from 6 to 9 EUR cents per kWh. While this is well in line with historic market prices, it is much lower than the current ones on the regional TSOs

Keywords: storage, implicit storage, firm power generation, photovoltaics, grid integration, high penetration renewables

1. Methodology

24/365 firm power availability is a prerequisite for intermittent solar and wind resources if they are to evolve from their current position at the margin of a core of dispatchable generation to a grid-dominant position.

It is now well understood that the least expensive way to transform intermittent renewables into firm power generators entails: (1) applying implicit storage – i.e., overbuilding and dynamically curtailing the resources (Perez et al., 2021, O'Shaughnessy et al, 2021, Tong et al., 2021) to keep real energy storage requirements at economically reasonable levels – and (2) optimally combining renewable resources that may have different daily and seasonal availabilities (Perez, 2020).

The Clean Power Research CPT model (Perez et al., 2021) we apply in the present investigation was designed to derive the least cost combination of intermittent renewables (PV, wind) and storage – real and implicit – for any location/region. The model also accounts for region or policy-specific operational contexts, such as any allowance for dispatchable supply-side generation (e.g., thermal generation from natural gas or e-fuels), the availability of other renewables (e.g., hydro), or the application of demand-side load management strategies.

Inputs to the model include the Capital Expenses (CapEx) and Operating Expenses (OpEx) of all considered generation, storage, and load management resources as well as multi-year hourly site/time-specific time series of renewable electrical production and demand. The main output of the model is the levelized production Cost Of firm Electricity (LCOE) of the optimized resources' blend. The model also produces the optimal amounts of real and implicit storage required to achieve this optimum LCOE.

Results of previous investigations in the continental US (CONUS) and tropical island power grids indicate that a 95% 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 PV/wind overbuild of the order of 50% [Perez, 2020, Perez et al. 2020, Tapaches et al. 2020]**.**

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2. The case of Switzerland

The situation in Switzerland is markedly different from our previous USA and tropical island case studies. It is characterized by both unique assets and unique challenges.

- Assets: Switzerland possesses a large existing hydro and hydro storage resource, including run-of-river hydropower and two types of storage systems: pumped hydro, and seasonal lakes, fed mainly by snow melt and holding large quantities of water released on demand. The storage systems are currently applied to maximize market economics (e.g., arbitrage in neighboring European markets). The specs of the hydropower assets are reported in Table 1 along with the other energy generating resources currently available in the country.
- Challenges: (1) it is environmentally difficult to deploy new wind, so large-scale natural wind-solar complementarities cannot be fully tapped. (2) The solar resource is highly seasonal with very low wintertime (Nov – mid Feb) solar production when electrical demand peaks.

Tab. 1: Current (2018-2020 average) power generation resources in Switzerland

	Installed capacity	Annual energy yield
Nuclear	3 GW	24.2 TWh
Run-of-river hydro	4.2 GW	17.6 TWh
One-way hydro buffer	8.2 GW	18 TWh*
Pumped hydro	2.9 GW	4.2Twh^
PV	2.4 GW	2.2 TWh
Wind	0.1 GW	0.1 TWh
Non-renewable thermal generation	0.42 GW	1.17 TWh
Renewable thermal generation	O.55 GW	1.84 TWh
Imports	7 GW	10.77 TWh
Exports	10 GW	-10 TWh

** the full-to-empty buffer system has a capacity of 10Wh.. Total output includes river-flow*
^ pumped hydro output -- net production in zero.

The annual (2018) dispatching of these resources is illustrated in Figure 1. 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 current production is insufficient in winter and early spring, requiring imports from the rest of Europe. However, production exceeds demand in summer and is exported, mainly to the summer-peaking Italian grid.

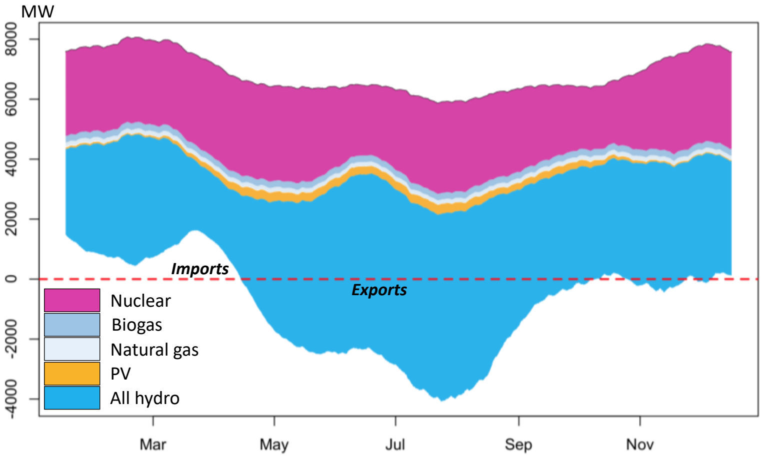

Fig. 1: Annual dispatch of Swiss-based of supply-side resources for the year 2020. The top line of the stacked graph represents the Swiss grid load [ENTSO-E, 2022]

3. Case study

We explore six scenarios at the 2050 horizon where the PV resource will be the central part of a high renewable energy (RE) firm power delivery system for the Swiss power grid. All scenarios include a phasing out nuclear power generation. All scenarios are based on the Energy perspectives 2050+ (SFOE, 2021). This matches net zero (carbon neutral) conditions, needed to fulfil the Paris climate agreement.

- •Scenario #1 –This scenario retains the current small contributions from thermal energy production and adds 2.1 GW of wind power generation amounting to a total wind energy production of 4.3 TWh/year. Pumped hydro capacity is increased from 2.9 to 5.7 GW with a commensurate increase in energy storage reserve. Seasonal hydro storage capacity is increased from 8.2 to 9 GW, with a 2 TWh increase in full-to-empty long term energy reserve.
- Scenario #2 – 10% imports, no restrictions. This scenario also retains the small current contributions from thermal production but adds only 1.0 GW of wind (2.15 TWh/yr). It allows for net imports from the European grid to total 8.25 TWh/yr. Pumped hydro capacity is only increased to 4.4 GW, while the buffer hydro storage capacity is increased to 8.5 GW with a full-to-empty energy reserve increase of 1 TWh.
- Scenario #3 – No imports, natural gas. This scenario is identical to scenario #2 but replaces the 8.25 TWh of imports with new thermal generation from natural gas (2.8 GW new capacity; prices including CO2 certificates). Net-zero import/export are limited to 3 GW with 10 TWh exchanged annually each way.
- Scenario #4 – No imports, e-fuels. This scenario is identical to scenario # 3, but replaces natural gas by e-fuels, produced either domestically or abroad. Note that this scenario is 100% renewable.
- Scenario #5 – Imports and e-fuels. This scenario retains the level of net imports from scenario # 2 and includes roughly half of the e-fuel thermal generation from scenario #4 (1.7 GW, 4.97 TWh/yr).
- Scenario #6 – Imports, e-fuels, and agri-PV. This scenario is identical to scenario #5, but with a slightly lower capital cost for new PV resulting from extensive agri-PV deployments (see below).

For all scenarios, the considered 2050 Swiss electrical demand is assumed to be 30% higher than current (from transportation/building electrification) and nuclear generation is eliminated. The new load demand profile is extrapolated upward from current load (+30% for all hours). The energy demand balance not met by hydro, or the wind/thermal/import resources identified above is met by new firm PV generation. Figure 2 summarizes the contribution all supply-side energy sources in each scenario compared to current. 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.

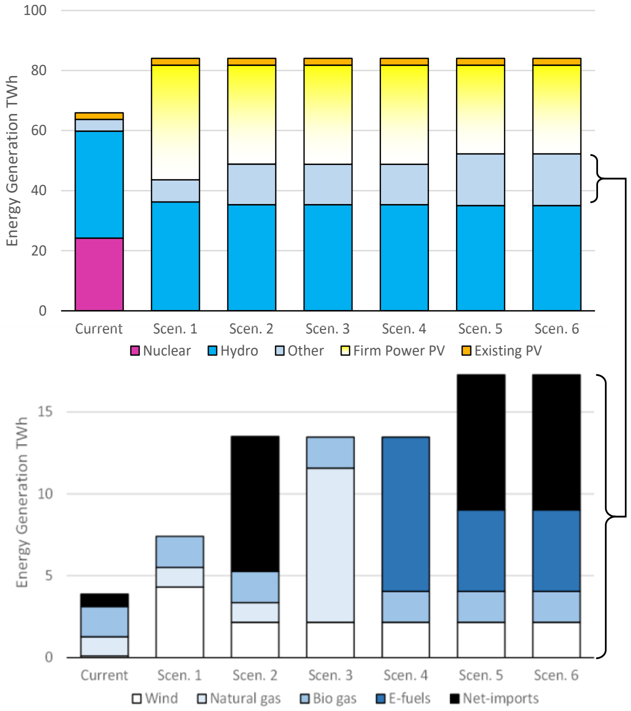

Fig. 2: Supply-side electrical energy resources for all scenarios compared to current. The bottom part of the figure provides details for the source labeled as 'other' in the top part. Note that scenario #4 is the only scenario that does not include non-renewable (nat. gas) or possibly non-renewable (imports) resources.

For each scenario, we investigate two sets of assumptions regarding (1) Switzerland interconnectivity with the larger European grid, and (2) the cost of new PV and electrochemical storage (battery) technologies.

For interconnectivity, we look at two configurations:

1. net-zero imports where the Swiss grid would continue to operate interconnected with the larger European grid and,
2. an extreme limit case where the grid would operate in full autonomy.

In the net-zero case, supply-side flexibility is provided by allowing 10 TWh/yr to be both exported from and imported onto the Swiss grid with a maximum capacity of 3 GW (note that this is above and beyond the supply-side-only imports identified in scenarios #2, 5, & 6) In the autonomous case, Switzerland would operate independently from the larger European grid to the exception of one-way imports considered in scenarios #2, 5 and 6. We note that this autonomous configuration is unlikely given the country's natural interconnectedness, but this limit case is nevertheless informative in quantifying extreme resiliency conditions.

Regarding technology, we consider two assumptions for PV and electrochemical storage CapEx at the 2050 horizon based conservative or optimistic predictions from the NREL technology roadmap[1].

1. The conservative assumption sets turnkey PV at $860/kW and electrochemical storage at $330/kWh.
2. The optimistic assumption prices these technologies at $390/kW and $45/kWh, respectively.

The first assumption reflects a conservative approach for small scale systems (e.g., user-sited) likely to be prevalent in the Swiss PV/storage build-up, while the second reflects utility-size systems that may also be [partially] considered. In both cases we use $4/kW/yr for PV OpEx, and 0.25%/yr for battery OpEx. Note that for scenario #6, we apply a smaller CapEx for the Swiss assumption – $786/kW – that is reflective of the larger

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[1] https://atb.nrel.gov/

proportion of agri-PV deployment assumed in this scenario.

All supply-side resources to the exception of new PV are considered as either dispatchable or must-run. Their financial impact is captured through their electrical generation costs identified in Table 2, i.e., we assume that these market-based prices embody both their CapEx and Opex.

Tab. 2: Assumed 2050 power generation cost of supply-side and storage resources on the Swiss grid

		Generation cost (¢/kWh)	**Notes**
Dispatchable Resources	Hydro storage	7/6.5	*7 ¢/kWh for Scenario #1 only*
	Pumped Hydro	6/5.8	*6 ¢/kWh for Scenarios #1-4 --discharge cost*
	Thernal Natural gas	11.1/14.1	*14.1 ¢/kWh for Sceario #3 (E-certification fee)*
	Thermal Bio gas	11.1	
	Thermal e-fuels	19.7/17.9	*17.9 ¢/kWh for Scenario #4 only*
	Imports	6	
	Exports	-5	
Must-run Resources	Run-of-River hydro	5	
	Existing Wind	15	
	New Wind	12/11	*12 ¢/kWh for Scenario #1 only*
	Existing PV	6.9	

We apply the Clean Power Transformation 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.

Figure 3 show the order of dispatch in the model not including import and export.

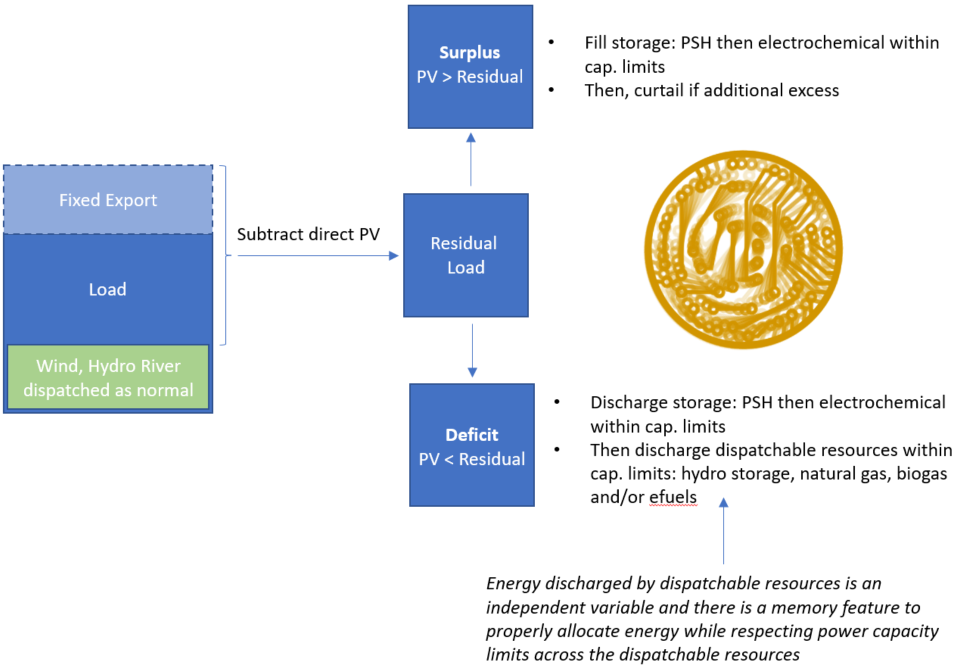

Fig. 3: Dispatch model applied in the Clean Power Transformation (CPT) model. PSH stands for pumped hydro storage.

We apply three years' worth (2018-2020) of experimental data consisting of hourly electrical demand, and measured hourly production of nuclear, PV, wind, and hydropower resources. Future new hourly PV generation is extrapolated from current measured production, prorating to new capacity.

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 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

In Figure 4, 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.

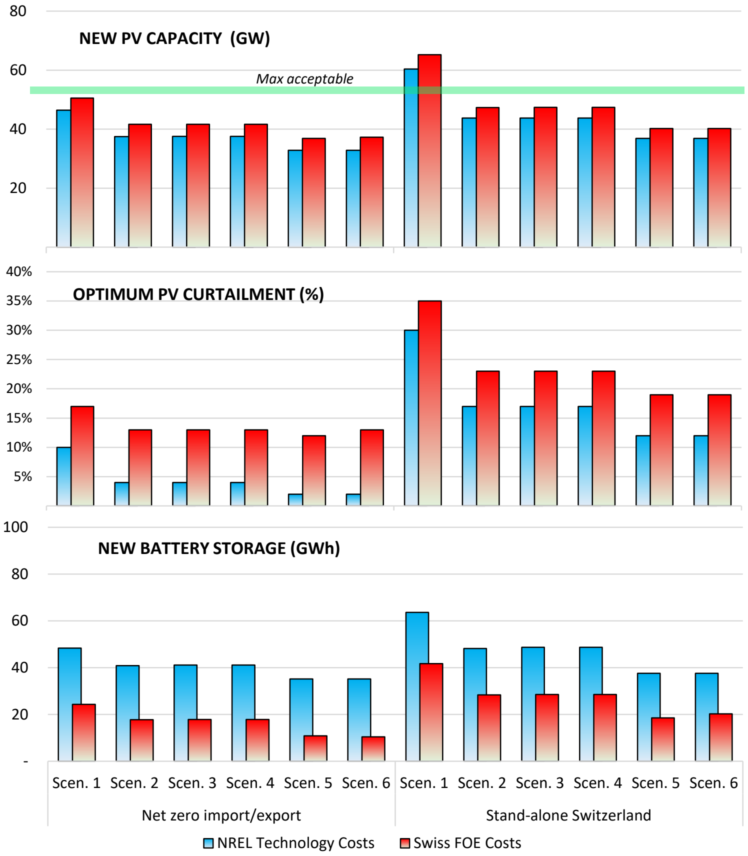

Fig. 4: New PV capacity, proactive curtailment, and battery storage required to meet the new Swiss demand 24x365 in each of the six scenarios, and each technology cost and grid interconnectivity assumption.

New PV capacities (Figure 4, top) range from 32.9 GW (scenario #5 & #6 with net-zero interconnectivity and optimistic technology costs) to 65.2 GW (scenario #1 stand-alone grid 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 Remund et al. (Remund et al., 2019) that considered all deployable in-country options (including roof space, exclusion zones, farmland, etc.) given current PV efficiencies. Importantly, all but one scenario (#1 autonomous grid) fall under this upper limit.

PV output curtailment (Figure 4, middle) ranges from 2 % (scenario #5 & #6 with net-zero interconnectivity and optimistic tech costs) to 35% (scenario #1 autonomous grid and conservative costs). Technology cost assumptions have a strong influence on required curtailment. Applying optimistic cost reduces the need for curtailment by an average of 41%. Stand-alone grid operation, without net-zero flexibility would increase operational curtailment by 130%.

New battery storage requirements (Figure 4, bottom) range from 10.5 GWh (scenario #6 conservative cost assumptions) to 64 GWh (scenario #1 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 beyond the small addition to the existing buffer hydro system (+10% for scenarios #2-6, +20% for scenario #1), as is often assumed when envisaging ultra-high PV or wind penetration. This observation corroborates results obtained in the USA (Perez, 2020).

Figure 5 reports the blended all-resources power generation LCOEs on the Swiss power grid.

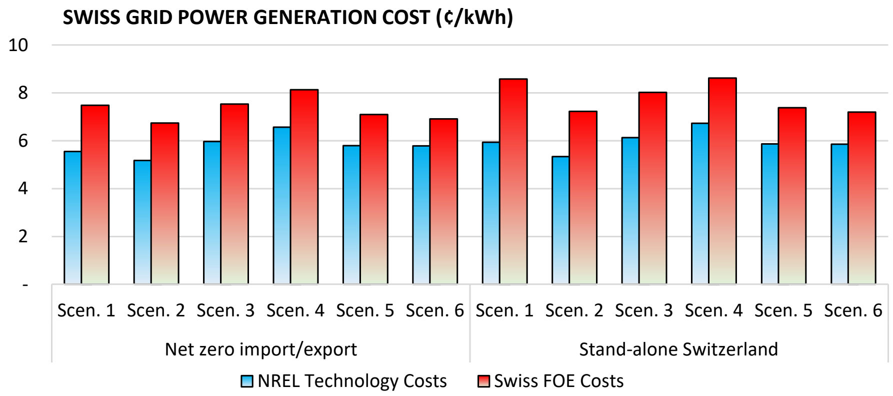

Fig. 5: Electric power generation cost on the Swiss grid in each of the six scenarios, and each technology cost and grid autonomy case.

Electricity production costs range from 5.2 ¢/kWh (scenario #2, net-zero interconnectivity, optimistic technology costs) to 8.9 ¢/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 5.5% i.e., not constituting a showstopper.

The new annual dispatch of all resources is illustrated in Figure 6 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.

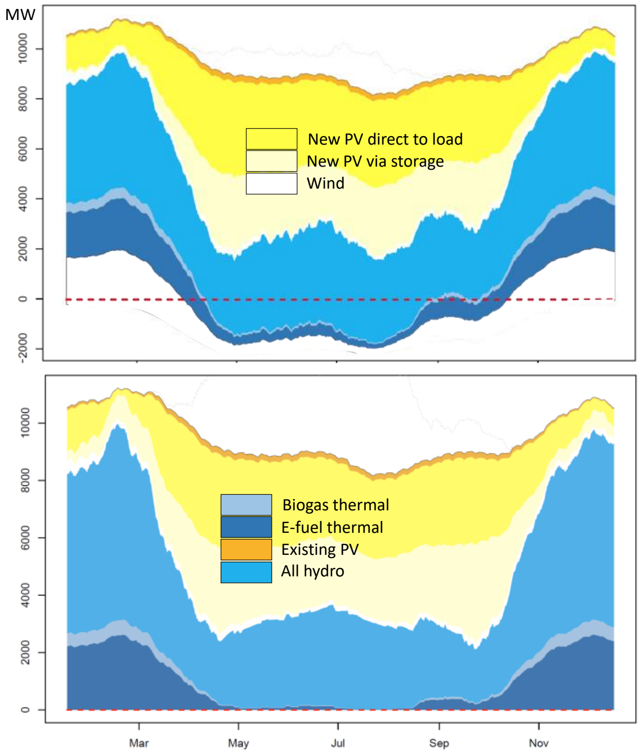

Fig.6: Annual dispatch of supply-side resources for the year 2020 illustrated for the 100% renewable scenario with e-fuels (#4). The top graph represents the net-zero interconnected configuration where winter imports are energetically matched to summer export amounting to net-zero. The bottom graph corresponds to the extreme stand-alone grid configuration.

Figure 7 shows the share of energy production in scenario #6.

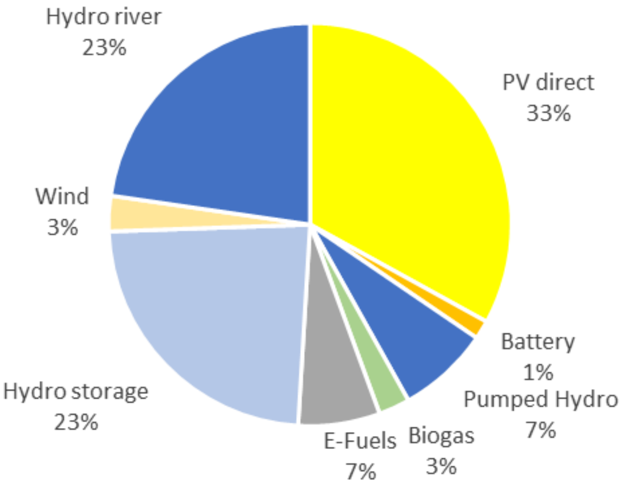

Fig. 7: Share of energy production types for scenario #6 for 2050.

<u>Implicit storage impact:</u> Figure 6 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.

Sensitivity analysis: The three years, analyzed independently, lead to very comparable firm power production cost results overall as seen in in Figure 8 for the 100% renewable scenario #4.

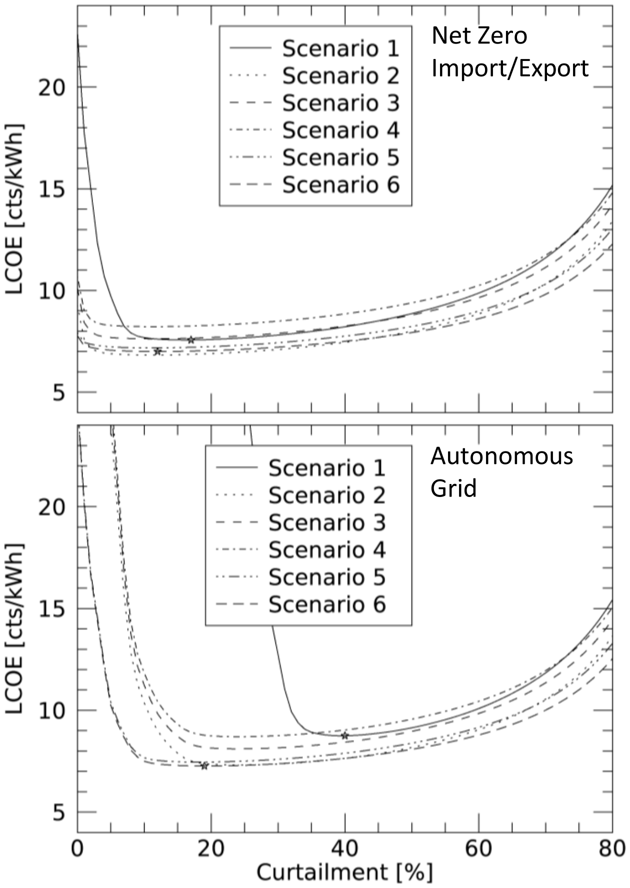

Figure 8: Electricity production cost on the Swiss power grid as a function of PV output curtailment for all scenarios. The top graph corresponds to the interconnected grid configuration with net-zero import/exports with the larger European grid. The bottom graph represents autonomous grid configuration.

5. Discussion

Our investigation shows that high-RE 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 ¢/kWh the last couple of months (Fraunhofer ISE and TNC, 2022). The present ultra-high RE costs are even reasonable when compared to earlier pre-crisis TSO wholesale prices (4-6 ¢/kWh) noting that these earlier TSO 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% RE scenario (#4). Not only are operational generation costs reasonable (6½/-8½ ¢/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 ¢/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.

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 the modelling shows, 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.

6. Acknowledgement

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