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Author(s):
Mellot, Adrien; Moretti, Christian; Tröndle, Tim; Patt, Anthony

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Research paper

Mitigating future winter electricity deficits: A case study from Switzerland

Adrien Mellot [a,*], Christian Moretti [a,b], Tim Tröndle [a], Anthony Patt [a]

[a] ETH Zürich, Department of Environmental Systems Sciences, 8092 Zürich, Switzerland
[b] Paul Scherrer Institut, Laboratory for Energy Systems Analysis, 5232 Villigen, Switzerland

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ABSTRACT

The transition to a net-zero economy with increased electrification of transport and heating poses electricity supply challenges during the winter months, particularly in PV-dominated systems. This study explores comprehensively various strategies and their combinations to address potential winter electricity deficits in Switzerland. Our innovative modelling integrates three sectors (electricity, heat, and transport), neighbouring countries, and environmental life cycle considerations.

Among potential strategies to mitigate Swiss winter electricity deficit, electricity imports from neighbouring countries are taken as the benchmark policy strategy. Our analysis reveals that only gas-fired power plants and alpine PV, if applied in isolation, are technology options that alleviate the Swiss winter deficit and reduce cost at the same time. Increasing other single power technologies individually, or importing hydrogen, alleviate the deficit, too, but they inflate energy system costs by 18%–34% compared to relying on electricity imports.

Despite the strategies for mitigating the winter deficit assessed being substantially different, our study found no significant environmental concerns regarding local land requirements or critical raw material needs. However, each strategy might imply the need for certain fuel imports and can have a profound impact on determining cost-optimal heating strategies for buildings. With an additional 1.4 GW of gas-fired power plant fuelled by domestic bio-methane, 4 GW of alpine PV, 2.2 GW of wind turbines, and no cost increase compared to its current roadmap, Switzerland could have a fully renewable energy system with a reduced winter deficit and no fuel imports.

1. Introduction

European countries signed the Paris Agreement in 2015, aiming to reach net zero greenhouse gas emissions by 2050. Achieving this target requires a drastic and transformative change in European energy systems, marked by the electrification of transport and heating, and coupled with an unprecedented surge in photovoltaic (PV) installations. An energy system with such features brings forth a pressing concern regarding potential winter electricity deficits, as PV panels produce mostly in summer [1] and demand is highest in winter, causing a seasonal supply and demand mismatch [2,3].

Wind energy, on the European scale, is one solution to avoid the undersupply of electricity thanks to abundant resources and geographical balancing [1,4,5]. However, this result may not hold at country level, as the achievable potential of wind energy may be limited in many countries, particularly those without access to offshore wind resources [5,6]. At country level, balancing effects are optimal in energy systems with roughly equal proportions of wind and solar capacity [1]. Conversely, PV-dominated electricity systems would exhibit electricity surpluses in the summer, but deficits in the winter [2], and as a result higher electricity prices at that time of the year [7]. In particular, countries facing cold winters while having a high share of electrified heating and limited wind potential will have the highest seasonal supply and demand mismatch [2,8].

Switzerland embodies these characteristics and, in this regard, serves as a case study as how a country with a future PV-dominated system could cover its winter electricity deficit. Having designed the Energy Perspective 2050+ (EP2050+) strategy [9] as a roadmap for its decarbonisation, the Swiss authorities envision the large-scale deployment of electric vehicles (EVs), heat pumps, and PV on roofs, combined with the phase out of Switzerland's nuclear reactor fleet. With almost 40 GW installed, PV panels are expected to generate around 34 TWh/a of electricity in the EP2050+ strategy, representing 44% of the annual Swiss production and consumption of electricity. On the other hand, wind energy is expected to generate around 4 TWh/a only [9].

Historically, Switzerland's energy system has already been subject to an electricity winter deficit, with electricity overproduction capacity in the summer but a limited production potential in the winter. The causes of this deficit are inherent to the large share of hydropower in

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* Corresponding author.
E-mail address: adrien.mellot@usys.ethz.ch (A. Mellot).

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the Swiss electricity mix, as the seasonal fluctuations of water inflows limit the contribution of hydropower in the winter months [9,10]. The nuclear phase-out and high PV deployment will only exacerbate this problem due to solar energy's seasonal imbalances [2,11,12]. As seasonal storage remains expensive and technically challenging [13], Swiss authorities plan to cover the deficit with electricity imports from neighbouring countries [9,10], as was the case historically [3]. Overall, the EP2050+ ZERO-Basis scenario projects about 9 TWh of net winter electricity imports in 2050 [9,10].

The estimate of the EP2050+ roadmap is consistent with recent studies, with net winter electricity imports estimated in a 7–12 TWh range [11,14–16]. However, Switzerland's electricity commission ElCom has warned that consistently relying on neighbouring countries for the winter electricity supply poses a risk to the security of supply in Switzerland [3]. In fact, there are technical considerations and uncertainties caused by the decarbonisation strategies of Switzerland's neighbours, which rely as well on increasing PV and electrifying heating and transport sectors [3]. Accordingly, the same commission concluded that strengthening the security of the electricity supply in winter is of paramount importance. Lienhard et al. [2] also conclude that Switzerland and its neighbours are likely to have concurrent electricity deficits in the winter and surpluses in summer peaks hours, limiting exchanges between countries. For Switzerland specifically, the exclusion from the European electricity markets might also limit the availability of electricity imports [3,17]. Furthermore, several studies indicate that a substantial portion of Switzerland's electricity imports in winter months may originate from conventional fossil-fuel power plants in the next two decades [2,18]. As a result of these issues, the Swiss Federal Council's proposed law on a secure electricity supply explicitly targets reducing Switzerland's winter import dependency [19].

From a social acceptance perspective, a recent survey of the Swiss population showed strong resistance against electricity imports, with only 5% of respondents wanting to see electricity imports as part of the energy mix in 2050 [20]. Therefore, increasing the winter deficit from 4 TWh (2005–2019 average [10]) to 9 TWh in 2050 may be a concern for the Swiss population. To compare, the Swiss population would prefer rooftop PV, biomass, wind turbines and open-field PV in their mix over importing electricity (with respective acceptances of 90%, 66%, 60% and 56%) [20]. The same survey also showed that even nuclear power and natural gas imports have higher shares of social acceptance than importing electricity [20]. Given the mixed opinions about different technologies by the Swiss population and different trade-offs that could arise for each solution, it is necessary to inform policy-making by assessing a range of winter deficit mitigation options beyond a single one.

Yet, there are only a few studies analysing possible solutions to reduce future winter electricity deficits in Switzerland, once substantial shares of photovoltaic and simultaneously of EVs and heat pumps are achieved. In such studies, wind energy, alpine solar, and gas-fired power plants with carbon capture and storage (CCS) are considered as potential mitigation solutions [2,14,21]. These studies looked at each solution in isolation, using models which included the electricity sector only. However, the complex nature of winter deficits requires the inclusion of other sectors, especially considering that residential heating has a substantial demand during the winter months.

In the present study, we therefore aim to analyse and compare a broad range of supply-side mitigation strategies for the Swiss electricity winter deficit, beyond those considered by the EP2050+ strategy and previous studies, and using a sector-coupled energy system. For example, wind energy has a high potential for winter electricity production and the limit to 4 TWh/a in the EP2050+ strategy could be doubled, as estimated by recent literature, reporting achievable installation potential up to 4 to 9 TWh/a [2], with the most optimistic estimates to up to even 30 TWh/a [22]. Alpine PV, a promising solution to the winter deficit [21,23,24], was not modelled in the EP2050+ strategy, as well as extra thermal power plants. Synthetic fuel production in summer using additional rooftop PV capacity, and imports of synthetic fuels or hydrogen could also reinforce the Swiss energy system in the winter by enhancing sector-coupling over the whole year.

Our study assesses comprehensively all these possible strategies for mitigating the electricity winter deficit in the 2050 net-zero Swiss (sector-coupled) energy system. For each solution, we discuss energy system costs, environmental implications, and political feasibility trade-offs. With respect to the environmental dimension, we assess local land use, given its significance in the acceptance rate of renewable energy technologies by the Swiss population [25–27]. We also assess critical and strategic raw materials needs to understand if a policy strategy may be infeasible due to materials demand, as environmental factors are crucial in determining the viability of energy policies [28]. The analysis of such environmental impacts is therefore performed by coupling environmental Life-Cycle Assessment (LCA) with the energy system model, as so far implemented in only a few recent studies [29–31].

2. Methodology

2.1. Power supply-side options to mitigate the winter deficit

In the Swiss context, the winter deficit refers specifically to the limited electricity generation potential in the winter months (October 1st to March 31st). Historically, France and Germany have been net exporters towards Switzerland in that period, while Italy has been a net importer of electricity from Switzerland [3]. Hence, in line with previous studies [2,10,14], we use the *net* electricity imports from October 1st to March 31st as the reference metric to quantify the winter deficit. This study analyses winter deficit mitigation strategies with respect to the planned EP2050+ roadmap. Therefore, we first model a *EP2050+* scenario, acting as a reference point of comparison for the mitigation strategies assessed. This scenario follows the features of the EP2050+ ZERO Basis scenario [9] as closely as possible. In particular, we constrain *net* Swiss winter electricity imports to 9 TWh, matching the planned value by the Swiss authorities [9].

To analyse mitigation strategies, the solution space of the model is then restricted by further constraining the net winter imports to 5 TWh. The choice of 5 TWh as an upper bound for the winter deficit is motivated by the Swiss political sphere, where this value was first discussed as a possible policy goal [32], and was then mentioned explicitly in Switzerland's proposed law on a secure electricity supply [19]. From the *EP2050+* scenario, we fix the neighbouring countries' energy systems (storage and renewable energy capacities), as we assume that Switzerland mitigating its own winter deficit will not affect neighbouring countries' energy systems, given Switzerland's relatively small size. Mitigation strategies are then implemented one at a time, respecting the 5 TWh winter deficit constraint. Compared to EP2050+, we analyse possible additional wind turbines, alpine PV, additional rooftop PV, hydrogen imports, additional combined heat and power (CHP) plants and gas-fired power plants. The latter can be Simple-Cycle Gas Turbines (SCGTs) or Combined-Cycle Gas Turbines (CCGTs), either running on renewable methane or on fossil methane. Local Direct Air Carbon Capture and Storage (DACCS) is used to compensate the gas-fired power plants' emissions that cannot be captured on-site. CHP plants can use waste, biomass and renewable methane (synthetic or bio-methane) as fuel. We further implement two *mix* scenarios which can use a combination of the mitigation strategies, one of which excludes any use of fossil fuels. All the corresponding scenarios are described in Table 1.

To assess the economic and environmental impacts of these strategies, we develop Swiss-Calliope, a capacity-expansion model of the Swiss energy system, and couple it with a life-cycle assessment module.

Table 1
Definition of the scenarios considered in this study. Apart from *EP2050+*, all scenarios have a constraint limiting net winter electricity imports to 5 TWh. As additional investments to reduce the winter deficit may reduce the need for variable renewable generation in Switzerland, we further allow the installation of up to 10% less rooftop PV and wind turbines in Switzerland compared to the *EP2050+* scenario. Similarly, the CHP production is capped to EP2050+ values, but we do not enforce any minimum amount.

Scenario name	Specific characteristics
EP2050+	Follows EP2050+ ZERO Basis assumptions as close as possible
EP2050+ (5 TWh constraint)	*EP2050+* scenario with the 5 TWh winter deficit constraint. Only additional fuels and/or storage technologies can be used compared to *EP2050+*
S/CCGT (Fossil) + DACCS	Allow SCGTs and CCGTs which run on imported natural gas up to the current import levels of 36 TWh/a in 2021 [33]. CCGTs have 90% Post-Combustion Capture (PCC) efficiency, SCGTs are assumed to be without PCC due to their already smaller fuel efficiency. We account for lifecycle emissions of the natural gas, from supply to combustion. DACCS compensates residual emissions, and must be done within Switzerland
S/CCGT (Ren. Methane) +H_2	Allow SCGTs and CCGTs running on renewable methane AND allow hydrogen imports in Switzerland, up to 11.1 TWh/a, which can be used for synthetic fuel production and/or in the transport sector directly
S/CCGT (Ren. Methane)	Allow SCGTs and CCGTs running on renewable methane. Compared to scenario above, hydrogen imports are not available
Alpine PV	Allow up to 13.0 GW and 22.0 TWh of Alpine PV close to existing grid infrastructure [34], based on the SUNWELL dataset [35]. Capacity factors and cost parameters account for snow cover and higher costs compared to low-altitude PV.
Wind	Allow 2x the wind capacity of EP2050+, i.e. up to 4.4 GW in total [22]
CHP	Allow 2x EP2050+'s electricity production from CHP plants
Roof PV++	Allow 20% more rooftop PV compared to *EP2050+*, i.e. an extra 7.5 GW
H_2 *Imports*	Allow hydrogen imports in Switzerland, up to 11.1 TWh/a, which can be used for synthetic fuel production and/or in the transport sector directly
MIX	Allow all of the above
RE MIX	Allow all of the above except fossil methane turbines (i.e. no fossil fuel imports are allowed)

2.2. Swiss-Calliope energy model

The *Swiss-Calliope* model was created for this study, relying on the *Calliope* framework [36]. Calliope is a cost-optimising linear modelling framework which allows the integration of multiple energy sectors at high spatial and temporal resolutions. The model adopts a central planner perspective and minimises the system cost, allowing for a comparison of mitigation strategies from an economic cost perspective. The Swiss-Calliope model integrates the electricity, heating and transport sectors of Switzerland at cantonal resolution, building upon the structure and data provided by both Euro-Calliope models, either the power sector one [37], or the sector-coupled one [38]. An entire year with a 4-hour time resolution is modelled, projecting data to 2050 when applicable. We use 2016 as the reference weather year, i.e. the year from which data is taken for energy demands, capacity factors, outside temperatures and water inflows, and analyse 2017 and 2018 as sensitivity analyses. Having consistent data per year allows to synchronise demand and supply profiles in both time and space.

Switzerland's neighbouring countries (France, Germany, Italy and Austria) are included and aggregated to one network node per country, using ENTSO-E's projected grid data to determine the Net Transfer Capacities (NTCs) across neighbours (computed in [37]). The cost optimisation minimises total system cost, including all sectors and countries. To reduce uncertainties and computational complexity, only the electricity sector is modelled in neighbouring countries, projecting an increase in their respective electricity demands to reflect the expected electrification of their heating and transport sectors, as computed in [14]. Unlike Switzerland's energy system which is constrained by EP2050+ assumptions, a full greenfield approach is used for neighbours, not making any assumptions about their electricity mix other than using Euro-Calliope model's data to cap their hydropower, solar and wind power capacities.

For Switzerland's electricity system, we align our assumptions with the EP2050+ roadmap capacities and corresponding energy production from solar, wind and CHP capacities. Namely, rooftop PV and wind turbine capacities are respectively 37.5 GW and 2.2 GW, each producing 33.6 TWh/a and 4.3 TWh/a maximum, while CHP plants may produce up to 5.1 TWh/a. Data from Euro-Calliope is used to retrieve capacity factors and water inflows for each canton. For hydropower, we freeze the installed capacities to today's levels, and rescale the capacity factor timeseries to match historical production values. Geothermal energy is neglected due to its small contribution in EP2050+ projections and uncertain deployment in Switzerland.

For Switzerland's heating and transport sectors, Swiss-Calliope relies on the Sector-Coupled Euro-Calliope model's structure, with more Swiss-specific data whenever possible. Transport demand is split into light and heavy transport, allowing battery EVs (BEVs), fuel-cell EVs (FCEVs) and internal combustion engine (ICE) vehicles (running on renewable diesel) as supply technologies. We do not use timeseries for the transport demand, but rather use annual amounts. For BEVs and FCEVs, we further require a minimum share of the annual demand to be met every week of the year to avoid unrealistic charging/refuelling behaviours. Heating demand is divided into buildings heat (space and water heating) and industrial process heat (divided into three temperature ranges: low-temperature: <200 °C, medium temperature: 200–800 °C, high temperature: >800 °C), with different supply technologies able to meet the different types of heat. While industrial process heat demand is assumed to be constant over the year, we derive demand profiles for buildings heat, using outside temperatures for space heating [39,40] and the When2Heat package [41] for water heating (section 5 in supplementary material).

Finally, the Sector-Coupled Euro-Calliope model also provides waste and biomass supplies for the whole model region (table 13S in supplementary). The import of synthetic fuels (diesel and methane) to Switzerland is capped at 17.8 TWh/a, in line with other modelling studies of Switzerland's energy system [42]. The three sectors are coupled thanks to a wide range of technologies, relying on the sector-coupling structure of the Sector-Coupled Euro-Calliope [38]. For example, it is possible to produce hydrogen and capture CO_2 using renewable electricity, and then combine the two products to make local production of synthetic fuels. The specific details about demand data, technology characteristics, costs, efficiencies and sector-coupling can be found in supplementary material.

2.3. Life-cycle assessment module

The environmental assessment focuses on the critical and strategic raw materials, as well as local land use of the strategies and the EP2050+ scenario. We first match technologies from the Swiss-Calliope model to technologies in the ecoinvent database version 3.9.1 [43] (table 24S). The Life Cycle Inventory (LCI) data of each technology is extracted using the Brightway software [44], and the results from Swiss-Calliope are used to compute the raw materials demand and local land use of each technology in a given scenario. We do not include the neighbouring countries' energy systems in the LCA and neglect land use abroad. With respect to biomass, only bio-based residues and wastes are considered in the model, disregarding their allocatable land use and materials demand. The list of raw materials assessed is based on the

Joint Research Centre (JRC) of the European Commission's assessment identifying critical and strategic raw materials for renewable energy, e-mobility and energy-intensive industry sectors [45].[1]

For transport technologies, the ecoinvent database version 3.9.1 does not include FCEVs or heavy EV trucks. These are taken from the Carculator package [46], which projects future LCI of transport vehicles to 2050 based on ecoinvent datasets. For consistency, all mobility-related technologies are taken from this package (table 23S). Direct Air Capture (DAC) plants, electrolysers, and bio-methane production are not present in the 3.9.1 ecoinvent database and are custom-made using prospective data from the literature (tables 20S–22S). The materials demand for synthetic fuels is accounted through their inputs (hydrogen, CO_2, electricity, heat). For synthetic fuel imports, we assume that the electricity for producing hydrogen and CO_2 comes from wind energy in regions with high capacity factors (taking the Netherlands as "proxy").

Compared to directly relying on emerging frameworks of environmental assessment of energy systems [29,47], we attempt to tailor the Swiss-Calliope – ecoinvent technology matching to the specific Swiss technology characteristics and energy system. In particular, we strive to use the installed capacities of technologies (in GW) as reference units for the processes selected in the ecoinvent database, instead of the produced energy (in GWh), which would rely on the capacity factors assumed by ecoinvent. This is particularly important for renewable energy technologies, for which the capacity factor is strongly dependent on the location of the PV panel or wind turbine, which is calculated with high spatial resolution by our model.

To avoid the double counting of environmental impacts, selected processes are removed from the supply chains of technologies in the ecoinvent database (table 19S). For example, to assess the operational impact of hydropower, the construction of the plants is removed, as the infrastructure is already built. In addition, for the operational impacts of certain technologies such as BEVs, we further remove the assumed electricity inputs from the databases used, as the electricity input comes from Swiss-Calliope directly in our modelling framework. Further details on the LCA module are provided in section 6 of the supplementary materials.

2.4. Sensitivity analyses

To determine which factors are the most influential in our study, we vary different weather, cost and infrastructure parameters from the model. For weather, we change the weather year from 2016 to 2017 and 2018. For costs, we double the CAPEX and OPEX of the DACCS technology, and reduce the alpine PV cost for the nine already planned projects [48]. For the infrastructure, we test for the import availability of fuels: we remove synthetic diesel and synthetic methane imports, divide by two the available imports of fossil methane, and allow hydrogen imports in scenarios in which they were not available. We further remove light FCEVs from the model, given that they may not be present in Europe by 2050. Finally, we modify the NTCs between Switzerland and its neighbours, by either reducing them by 70%, as an approximation for Switzerland's exclusion from European markets [17], or doubling them. When the changes are structural (weather year change, NTC change and light FCEV removal), we use the same process as for the weather year 2016: we first run the EP2050+ scenario, fix the production and storage capacities of the neighbouring countries, and then run the scenarios for each mitigation strategy.

3. Results

3.1. The winter deficit of EP2050+

In the *EP2050+* scenario, the technology mix leads to a significant deficit of electricity in winter. Solar energy represents a major share of Switzerland's mix but its electricity generation is drastically reduced in winter months compared to summer months (Fig. 1). Wind energy production, on the other hand, is higher in the winter months than in the summer but remains a small share of the total mix. Run-of-river hydropower is at its largest in the spring and early summer with snow melt, whereas hydropower with reservoirs is delayed until the winter thanks to its storage capacity. Yet, even delaying the reservoir hydropower use to the winter is not sufficient to meet the Swiss demand as lakes are emptied by April (figure 2S), in line with real historical behaviour [10]. As a result, Switzerland is a net importer of electricity in winter by the amount at which it is capped, 9 TWh. In this scenario, Switzerland fully electrifies its transport sector and reaches a 36.3% heat pump penetration for buildings heat. Complementary fuel-based heat is produced via the use of waste, biomass and the import of close to 10 TWh of synthetic methane (Figs. 3 and 4).

To address its winter deficit without relying on additional power supply-side technologies, Switzerland can either modify its transport and heating sectors, enhance electricity storage capacities, or import additional fuels. In our *EP2050+ (5 TWh constraint)* scenario, significant deployment of hydrogen electricity storage (power-to-hydrogen-to-power) and synthetic diesel imports for the transport sector allow this. However, this solution comes with a cost increase of 64.3% (Figs. 2–4). This scenario confirms that the winter deficit is not a simple dispatch problem which can be mitigated via seasonal electricity storage, but rather a structural issue of Switzerland's energy system. Therefore, our model captures the winter deficit well, as the Swiss electricity demand must be met by imports from neighbouring countries in the EP2050+ configuration, even with a limited electrification of its residential heating sector.

3.2. Mitigation strategies: resulting energy scenarios and economics

We rely on Swiss energy system costs calculations from Calliope, corresponding to capital and operational expenditures in Switzerland for all the sectors considered and technologies in the scope of our model. In this regard, the mitigation strategies based on gas-fired power plants and alpine PV can reduce system cost while mitigating the winter deficit (Fig. 2). These scenarios are those with the largest winter electricity production potential, whereas extra production capacities provided by CHP, wind and rooftop PV are not sufficient in isolation to mitigate the winter deficit in a cost-effective manner and require the imports of additional fuels (Fig. 3). Gas-fired power plants, when available, produce more than 12 TWh in the winter months, largely above the 4 TWh of net imports which had to be reduced (Table 2). This results in higher electrification rates of the buildings heat sector, entirely supplied via heat pumps (Fig. 4). The results further suggest that burning fossil methane in CCGTs with PCC and compensating residual emissions is more cost-efficient than producing and burning renewable methane. CCGTs are preferred over SCGTs, thanks to their higher fuel efficiency (when running on renewable methane) and PCC efficiency (when running on fossil methane), despite higher investment costs. Allowing hydrogen imports in the *S/CCGT (Ren. Methane)* scenario does not have any effect: the methane is cheaper to produce with domestic biomass supply than synthetically. Moreover, the transport and buildings heating sectors are fully electrified, implying that hydrogen imports are not necessary in this setting.

Allowing hydrogen imports without gas-fired power plants (*H_2 Imports* scenario) does result in FCEV penetration (Fig. 3) and in the production of large amounts of synthetic methane (used in heating, Fig. 4), but is not cost-efficient. Finally, with 10.3 GW of alpine PV

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[1] Baryte, erbium, germanium, holmium, iridium, lutetium, ruthenium, thulium, tungsten, ytterbium are removed as not present in the ecoinvent database version 3.9.1.

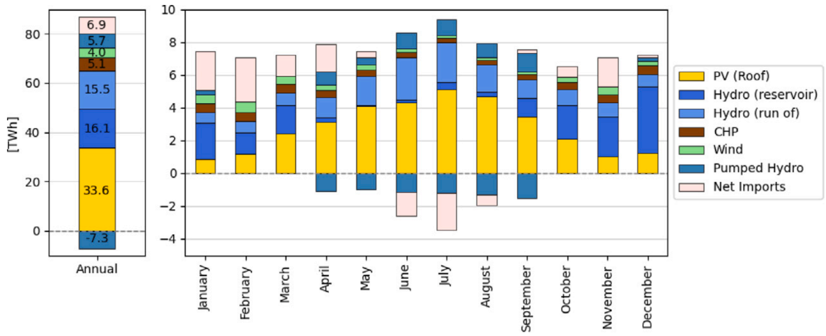


Fig. 1. Electricity generation in Switzerland in the EP2050+ scenario, aggregated annually (left) and monthly (right). Pumped hydro appears both as a consumer and a producer of electricity.

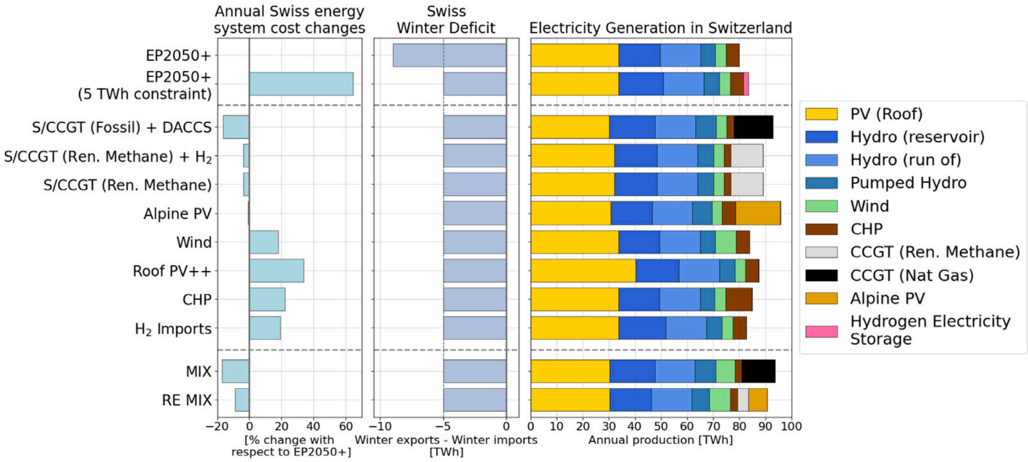


Fig. 2. Swiss energy system cost changes and corresponding winter deficit and electricity generation in all scenarios. Only the electricity generation from storage technologies is shown here, although they are net consumers of electricity overall.

Table 2
Electricity supply-side options exploited in each scenario, and corresponding installed capacities and production compared to the EP2050+ scenario. Monthly aggregated electricity production profiles are available in figure 3S.

Scenario	Technology	Capacity installed wrt. EP2050+ [GW]	Corresponding winter production [TWh]	Corresponding summer production [TWh]
S/CCGT (Fossil) + DACCS	CCGT (Fossil Gas)	+3.9	14.8	0.2
	Rooftop PV	−3.8	−0.9	−2.5
	CHP	−0.7	−1.8	−0.7
	Wind turbines	−0.1	−0.1	0.1
S/CCGT (Ren. Methane) +H_2	CCGT (Ren. Methane)	3.3	12.2	0
	Rooftop PV	−1.7	−0.4	−1.1
	CHP	−0.7	−1.8	−0.7
S/CCGT (Ren. Methane)	CCGT (Ren. Methane)	3.3	12.2	0
	Rooftop PV	−1.7	−0.4	−1.1
	CHP	−0.7	−1.8	−0.7
Alpine PV	Alpine PV	+10.3	7.1	10.0
	Rooftop PV	−3.1	−0.7	−2.1
Wind	Wind turbines	+2.2	2.7	1.3
Roof PV++	Rooftop PV	+7.5	1.8	4.9
CHP	CHP	+1.7	3.7	1.4
H_2 *Imports*	–	–	–	–
MIX	CCGT (Fossil Gas)	+3.4	12.5	0.1
	Wind turbines	+1.4	2.1	1.2
	CHP	−0.7	−1.8	−0.7
	Rooftop PV	−3.8	−0.9	−2.5
RE MIX	CCGT (Ren. Methane)	+1.4	4.3	0
	Alpine PV	+4.1	2.9	4.2
	Wind turbines	+2.2	2.7	1.3
	CHP	−0.7	−1.8	−0.7
	Rooftop PV	−3.8	−0.9	−2.5

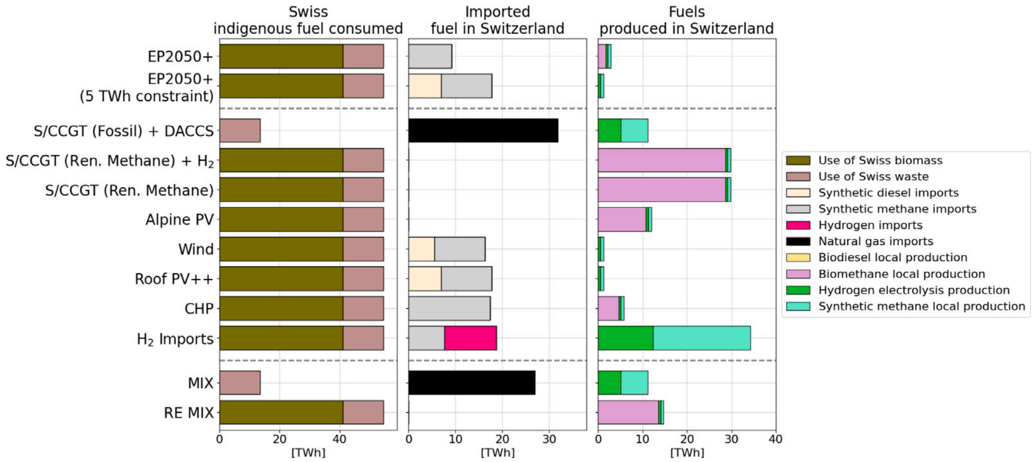


Fig. 3. Domestic fuel consumption, fuel import and fuel production in all scenarios. The fuels produced include all energy carriers, including intermediate carriers necessary to produce the end-product. Production profiles are shown in figure 6S.

installed, producing 7.1 TWh in the winter, the alpine PV scenario shows that it is possible to reduce the winter deficit cost-efficiently without relying on gas turbines and using a single additional technology (Table 2). In particular, a higher share of heat pumps is also feasible compared to the *EP2050+* simulation. Logically, alpine PV replaces rooftop PV investments in the *Alpine PV* scenario, thanks to a higher winter production. Indeed, in the *Roof PV++* scenario, the rooftop PV capacity barely contributes to the winter electricity production. Furthermore, it does not result in the summer production of synthetic fuels which could have been stored and used throughout the year, or in long-term hydrogen electricity storage (Power-to-Hydrogen-to-Power). In fact, investments in rooftop PV are reduced in all cost-efficient scenarios compared to the EP2050+ roadmap. The only scenario which exhibits some long-term electricity storage through hydrogen is *Alpine PV*, in which the model uses it to relieve the saturation of reservoir lakes thanks to its summer overcapacity (figures 2S and 3S). Still, amounts remain insignificant at the scale of the system, with only 240 GWh of electricity produced over the year.

The *MIX* scenario, which allows a combination of all mitigation strategies, essentially combines fossil CCGTs and wind turbines (Table 2). This shows that, although the *Wind* scenario was not cost-efficient with wind turbines in isolation, additional wind turbines are a good complement to the Swiss energy system. The result is similar in *RE MIX*, in which all the available wind turbine capacity is installed, along with alpine PV and gas turbines running on renewable methane. Unlike in the *S/CCGT (Ren. Methane)* scenarios, not all heat for buildings is supplied via heat pumps in *RE MIX*, and the biomass supply is not entirely redirected towards bio-methane. Thanks to the support from wind turbines and alpine PV, it is more cost-efficient to use a share of biomass in the heating sector directly, rather than converting it to bio-methane and producing electricity for heat pumps. Overall, these *mix* scenarios represent very different energy systems, with *MIX* allowing the full electrification of buildings heat, but relying on over 30 TWh of fossil gas imports, and *RE MIX* showing less electrification but requiring 0 TWh of any fuel imports and instead using all of the available domestic fuel supply (Fig. 3).

3.3. Sensitivity analyses

Results of the sensitivity analyses show that weather parameters are by far the most impactful factors on system costs (Fig. 5). Indeed, 2017 and 2018 were significantly warmer years, with buildings heat demand reductions of respectively 2.0 and 4.1 TWh (table 1S), leading to system cost decreases of over 20% for the *EP2050+* scenario compared to using the 2016 weather year. This cost decrease is attributable to a higher electrification of the heating overall (figures 10S and 13S), further removing the need for synthetic methane imports (figures 11S and 14S). In fact, no scenario is cheaper than *EP2050+* for these two weather years. This suggests that, if energy demand is lower overall, increasing the electrification of the heating system and covering the corresponding winter deficit with electricity imports is cost-efficient compared to producing the electricity domestically or having a fuel-based heating system. Overall, scenarios in which the share of electrified heat was smaller in the 2016 configuration benefit the most from warmer years, as they are able to increase their electrification shares too. As a result, cost differences between variable renewables-based mitigation strategies and gas-fired power plants decrease, with wind turbines becoming especially competitive.

Regarding fossil-based technology options, scenarios are robust to doubling the cost of DACCS. This is easily explainable by the PCC efficiency of 90% assumed, reducing the total amount of carbon capture necessary. On the other hand, allowing less imports of fossil methane impacts the *S/CCGT (Fossil) + DACCS* scenario by 17.1%, but only by 1.1% for the *MIX*, as other supply-side options may be used instead. The *MIX* scenario is not sensitive to the alpine PV subsidy, while it logically decreases system costs for the *Alpine PV* and *RE MIX* scenarios. The role of green fuel imports is negligible in cost-efficient scenarios, but removing or allowing them significantly impacts scenarios which needed them, including *EP2050+*. In particular, hydrogen imports allow to decrease system costs but do not lead to a reduced winter deficit, as all scenarios reached the net imports of 5 or 9 TWh (figure 8S). Removing light FCEVs from the model only affects H_2 *Imports* as the only scenario in which they make up a share of the mobility supply. Finally, a reduction in NTCs is causing a cost reduction in Switzerland but an increase in overall model region, and vice-versa (figure 7S). This is an artefact of our cost calculations, which do not integrate import costs and export benefits for each country. Limiting the NTCs significantly reduces cross-border trading, and as a result Swiss electricity production (figure 8S). This logically increases the cost for the whole region, but not Switzerland's one. If import costs and export benefits were accounted for, Switzerland's cost would likely increase when limiting NTCs and decrease when enhancing NTCs, reflecting the whole model region's cost changes.

3.4. Environmental assessment of mitigation strategies

We scale the demand for critical and strategic raw materials of the Swiss energy system in 2050 by the European Union's (EU) materials consumption over the 2016–2020 period in Fig. 6. Compared to current demand, possible decarbonised Swiss energy system configurations logically require larger amounts of materials because of BEV penetration, explaining surges in lithium, gallium, cobalt, neodymium, tantalum,

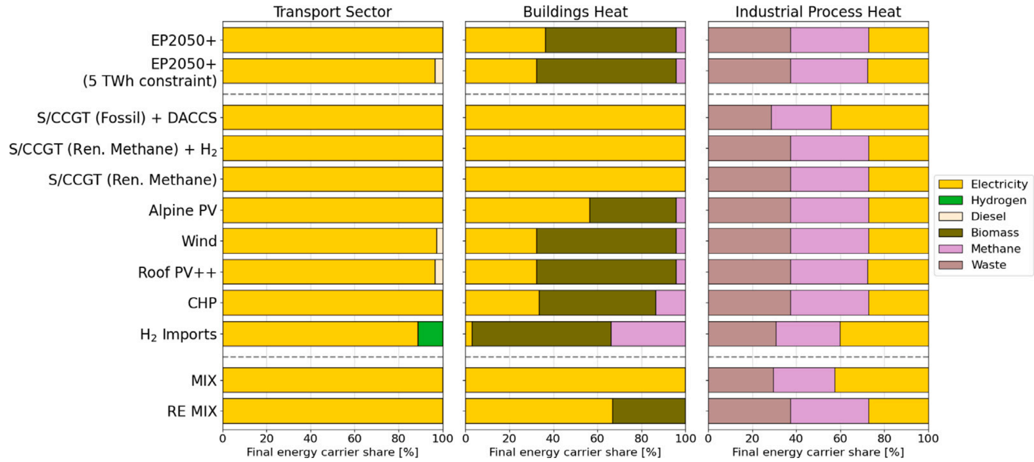
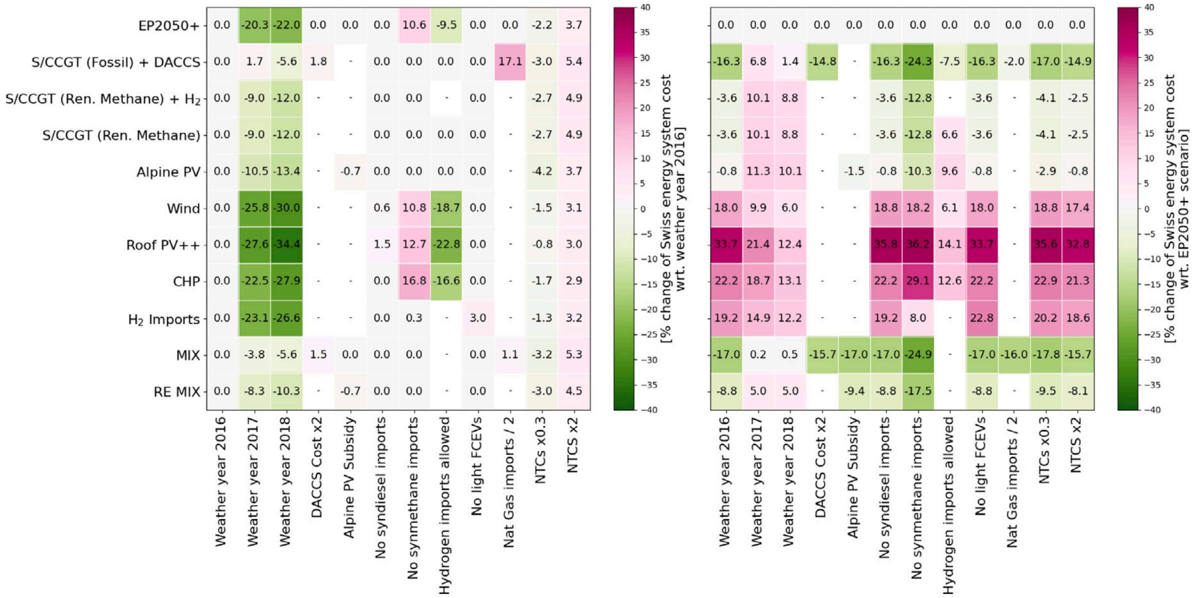


Fig. 4. Electrification shares in all scenarios for the transport and heating sectors for the weather year 2016. The three temperature ranges of industrial process heat are aggregated. The final energy carrier is represented, although some intermediate carriers may have been consumed along the supply chain. Refer to figures 33S–44S in supplementary materials for a full picture of all sector-coupled interactions and energy flows within each scenario.



	Weather year 2016	Weather year 2017	Weather year 2018	DACCS Cost x2	Alpine PV Subsidy	No syndiesel imports	No synmethane imports	Hydrogen imports allowed	No light FCEVs	Nat Gas imports / 2	NTCs x0.3	NTCS x2
EP2050+	0.0	-20.3	-22.0	0.0	0.0	0.0	10.6	-9.5	0.0	0.0	-2.2	3.7
S/CCGT (Fossil) + DACCS	0.0	1.7	-5.6	1.8	-	0.0	0.0	0.0	0.0	17.1	-3.0	5.4
S/CCGT (Ren. Methane) + H_2	0.0	-9.0	-12.0	-	-	0.0	0.0	-	0.0	-	-2.7	4.9
S/CCGT (Ren. Methane)	0.0	-9.0	-12.0	-	-	0.0	0.0	0.0	0.0	-	-2.7	4.9
Alpine PV	0.0	-10.5	-13.4	-	-0.7	0.0	0.0	0.0	0.0	-	-4.2	3.7
Wind	0.0	-25.8	-30.0	-	-	0.6	10.8	-18.7	0.0	-	-1.5	3.1
Roof PV++	0.0	-27.6	-34.4	-	-	1.5	12.7	-22.8	0.0	-	-0.8	3.0
CHP	0.0	-22.5	-27.9	-	-	0.0	16.8	-16.6	0.0	-	-1.7	2.9
H_2 Imports	0.0	-23.1	-26.6	-	-	0.0	0.3	-	3.0	-	-1.3	3.2
MIX	0.0	-3.8	-5.6	1.5	0.0	0.0	0.0	-	0.0	1.1	-3.2	5.3
RE MIX	0.0	-8.3	-10.3	-	-0.7	0.0	0.0	-	0.0	-	-3.0	4.5

	Weather year 2016	Weather year 2017	Weather year 2018	DACCS Cost x2	Alpine PV Subsidy	No syndiesel imports	No synmethane imports	Hydrogen imports allowed	No light FCEVs	Nat Gas imports / 2	NTCs x0.3	NTCS x2
EP2050+	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
S/CCGT (Fossil) + DACCS	-16.3	6.8	1.4	-14.8	-	-16.3	-24.3	-7.5	-16.3	-2.0	-17.0	-14.9
S/CCGT (Ren. Methane) + H_2	-3.6	10.1	8.8	-	-	-3.6	-12.8	-	-3.6	-	-4.1	-2.5
S/CCGT (Ren. Methane)	-3.6	10.1	8.8	-	-	-3.6	-12.8	6.6	-3.6	-	-4.1	-2.5
Alpine PV	-0.8	11.3	10.1	-	-1.5	-0.8	-10.3	9.6	-0.8	-	-2.9	-0.8
Wind	18.0	9.9	6.0	-	-	18.8	18.2	6.1	18.0	-	18.8	17.4
Roof PV++	33.7	21.4	12.4	-	-	35.8	36.2	14.1	33.7	-	35.6	32.8
CHP	22.2	18.7	13.1	-	-	22.2	29.1	12.6	22.2	-	22.9	21.3
H_2 Imports	19.2	14.9	12.2	-	-	19.2	8.0	-	22.8	-	20.2	18.6
MIX	-17.0	0.2	0.5	-15.7	-17.0	-17.0	-24.9	-	-17.0	-16.0	-17.8	-15.7
RE MIX	-8.8	5.0	5.0	-	-9.4	-8.8	-17.5	-	-8.8	-	-9.5	-8.1

Fig. 5. Change in Swiss energy system costs in the different scenarios for all sensitivity analyses, relatively to the baseline results whose weather assumptions are based on weather year 2016 (left), and relatively to the *EP2050+* scenario for each sensitivity (right). A dash implies that the sensitivity analysis did not apply to the given scenario.

nickel, praesodymium, europium, magnesium, silicon and samarium compared to today's demand (figures 15S through 25S). Other materials are less concerning, exhibiting demand levels of less than 10% of current EU consumption, despite an expected increase in consumption with decarbonisation [45]. Fig. 6 further shows that differences across scenarios are negligible, with fairly consistent materials demand despite representing significantly different energy systems. Potential energy transition challenges caused by materials demand would be faced equally across scenarios, independent of the winter deficit. The few outlying points are explainable by changes in demand for FCEVs, PV, fuel imports (natural gas, synthetic methane, hydrogen) and ICE trucks (figures 26S through 32S). In particular, platinum group metals (PGM) could be a concern if energy systems relied more on hydrogen-based technologies, such as FCEVs or synthetic fuels. Indeed, fuel cells and electrolysers can be major drivers of PGM [49]. In our scenarios, 7.5% of light FCEV cars on the road in 2050 consume as much of the platinum group metals than a fully electrified car fleet, suggesting that reduced lithium needs would traded for a higher PGM demand.

As we assume that all of the low-altitude PV deployed in Switzerland is installed on roofs, land use for the Swiss energy system is primarily driven by hydropower and alpine PV in all scenarios (figure 1S). Hydropower infrastructure being already built, only alpine PV deviations are large across scenarios. In particular, the *Alpine PV* scenario, with over 10 GW installed, sees a doubling of land use. Nevertheless, even in this case, the absolute values remain small, representing less than 4% of all Swiss 'settlement and urban areas' and roughly 0.3% of all Swiss territory, for its entire energy supply [50].

4. Discussion

4.1. Discussion of the results

Our modelling confirms that the Swiss winter deficit is inherent to the resources of hydropower and rooftop PV present in Switzerland, and must logically be covered via imports or additional domestic production. We show that, should Switzerland try to reduce its net winter imports within the boundaries of the EP2050+ roadmap, the energy system costs would be unreasonably high. From both economic and environmental perspectives, reducing Switzerland's winter deficit

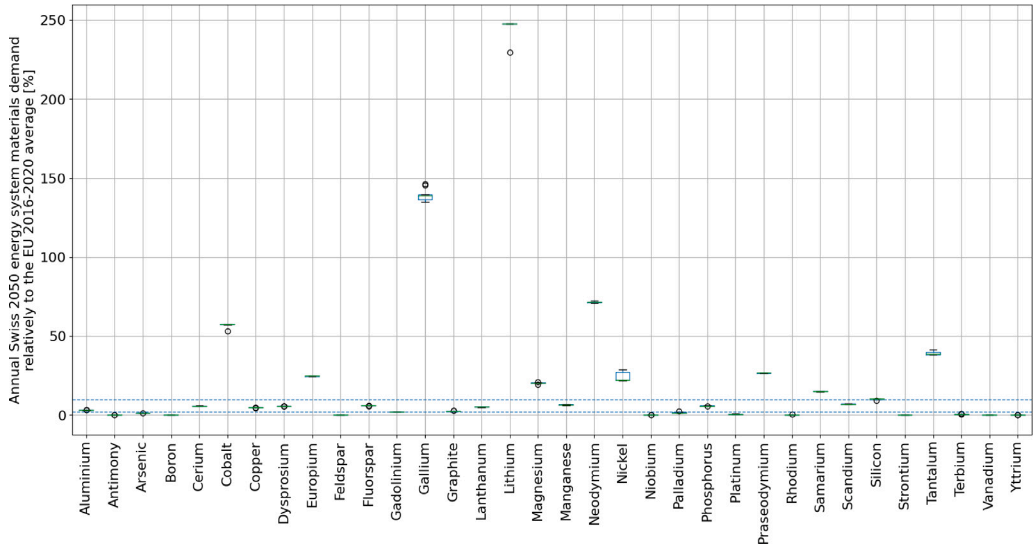


Fig. 6. Strategic and critical raw materials demand in the Swiss energy systems we model compared to the EU's 2016–2020 demand [51]. The dotted lines represent 2%, which is the Swiss final energy consumption compared to the EU's [52,53], and 10%.

is feasible with policies targeting the deployment of several power supply-side options, namely, gas-fired power plants, alpine PV and wind turbines. Moreover, in colder years with higher heating demand, the deployment of these technologies may even reduce costs compared to the EP2050+ roadmap, including by allowing a larger electrification of the Swiss buildings heat sector. In terms of critical and strategic raw materials demand, the variations across scenarios are minimal for materials which could show a supply risk compared to today's consumption. Instead, selected materials' supply concerns apply to all scenarios and the energy transition in general.

As they are fully dispatchable and have the highest winter production potential, our results show that gas-fired power plants are the most cost-efficient solution to the winter deficit, providing support to the system when intermittent renewables are not producing (figures 4S and 5S). In fact, gas-fired power plants in Switzerland also support the neighbouring countries. As a result, we may be underestimating the Swiss system cost reduction, as CCGTs in Switzerland may provide a competitive advantage when renewable electricity production is low in neighbouring countries as well, thereby increasing the value of electricity exports. However, the two configurations of gas-fired power plants in our model present different trade-offs. The fossil methane option relies on PCC and DACCS, two processes which have so far not been implemented at large scale. Furthermore, social acceptance issues may arise, related to keeping the reliance on fossil fuels [54] and the use of direct air capture [55]. The renewable methane scenarios instead rely on the reallocation of the entire Swiss biomass towards biomethane production, but do not require any fuel imports. Therefore, following such a strategy means Swiss policymakers should not target other uses of biomass.

On the renewable side, wind turbines and alpine PV are ideal complements to the rooftop PV and hydropower resources in EP2050+, thanks to high capacity factors in the winter months. The technical potential of both of these technologies is in fact much larger than assumed in our model [21,22,24], and could technically mitigate the winter deficit even further than 5 TWh of net winter imports. We show that the total land use necessary for these technologies is insignificant compared to the land available in Switzerland. However, this may not properly account for landscape disturbance and social acceptance issues which may limit their feasible potential [25–27]. In addition, the deployment of these technologies is, as of now, too slow to reasonably expect more alpine PV and wind turbines than projected in our study. Administrative procedures and social acceptance can be major hurdles here, as evidenced already in both wind and alpine PV projects [56,57].

The *RE MIX* scenario is a compromise in that regard, with reduced energy system costs by using an array of supply-side options and no full re-allocation of the Swiss biomass to bio-methane, implying limited reliance on a single technology. In particular, this scenario requires no fuel imports, unlike its *MIX* counterpart, and would require 1.4 GW of CCGT capacity only. On the other hand, the *MIX* scenario, with 3.4 GW of CCGT, requires replacing the 3.3 GW of Swiss nuclear power plants currently in operation entirely with CCGTs. These two scenarios therefore represent vastly different energy systems, in both electricity and heating sectors. Overall, the large variations observed in our results, and in particular in the buildings heat sector, reinforce the need to include multiple sectors and supply-side options in energy systems modelling.

In any case, reducing Switzerland's net electricity imports does not necessarily imply reducing exchanges with neighbouring countries, nor reducing gross winter imports as a whole (Table 3). On the contrary, Switzerland investing in additional winter production capacities can reduce the vulnerability of the Swiss electricity system in the winter months and at the same time that of the whole region, through more exchanges with neighbours overall. For example, the North of Italy could benefit from the higher availability of electricity to import in certain hours of winter days at a cheaper cost than e.g. by installing extra battery storage capacity. Such an enhanced electricity trade could reduce costs for all parties in the model region and ensure the security of supply at a low cost, including in hours when renewables barely produce in the winter. Electricity exchanges between Switzerland and its neighbours are necessary from economic and technical perspectives [3]. Our modelling shows that, even with increased winter electricity production, this is particularly true for weeks of unfavourable weather for PV production (figure 5S), in which Switzerland is a net importer of electricity at all hours of the day on average. Moreover, our sensitivity analyses showed that, in warmer years, electricity imports may be cost-efficient compared to domestic electricity production. Even though an energy system should be able to withstand colder years, this highlights the economic importance of electricity trade. Finally, all solutions to the winter deficit come with trade-offs which must be addressed by policymakers. We summarise all important results in Table 3.

4.2. *Limitations to the study*

This analysis provides insights into cost-minimised energy systems from a central planner perspective. However, we do not account for

Table 3
Summary of relevant quantities to assess winter deficit mitigation solutions. For the environmental concern, we assess scenarios with respect to the *EP2050+* benchmark, only including materials which go over the 2% threshold of Swiss demand relatively to EU. PGM = platinum-group metals; n.a.=not applicable (material demand and fuel needs of the neighbours were out of the scope of the analysis).
Source: Public acceptance data is taken from [20].

Scenario	Gross winter imports [TWh]	Buildings heat electrification [%]	Total fuel imports [TWh]	Swiss cost change [%]	Materials/land concern	Public acceptance
EP2050+	24.7	36.3	9.1	–	n.a.	5% for electricity imports
S/CCGT (Fossil) + DACCS	25.3	100	31.8	−16.3		25% for natural gas
S/CCGT (Ren. Methane) +H_2	24.4	100	0	−3.6		66% for biomass
S/CCGT (Ren. Methane)	24.4	100	0	−3.6		66% for biomass
Alpine PV	24	56.4	0	−0.8	Land use, Graphite	56% for open-field PV
Wind	22.7	32.4	16.3	+18.0	PGM	60%
Roof PV++	22.5	32.4	17.8	+33.7	Graphite, PGM	90%
CHP	23.2	33.5	17.4	+22.2	–	
H_2 *Imports*	22.3	3.0	18.7	+19.2	PGM	
MIX	25.2	100	26.9	−17.0		25% for natural gas
RE MIX	24.3	66.9	0	−8.8	Land use	66% for biomass, 60% for wind, 56% for open-field PV

agents' perspectives which follow profit maximisation. For example, owners of CCGTs may wish to not operate only half the year for their plant to be profitable. Policy intervention might be necessary to make investments into these CCGTs feasible. In addition, our modelling does not include electricity markets nor a proper dispatch model. As a result, import and export patterns and the dispatch of hydropower may be affected, although the results of our modelling shows patterns in line with historical data [58,59]. Another limitation is the model region itself, which entails only 5 countries. The inclusion of other European countries could affect the behaviour of Switzerland's neighbours and their trading patterns. However, given Switzerland's relatively small size compared to its neighbours, it is highly unlikely that the availability of imports would change with the inclusion of other European countries.

This study also only considers power supply-side options to the winter deficit, hence possible solutions in other sectors or on the demand side, such as thermal seasonal storage or stringent policies on buildings retrofitting, are not included. An important aspect that is not covered is also grid security assessment, which may vary across scenarios. In particular, we here optimise the cost for an entire year, assuming perfect foresight of demand and capacity factors. We also do not account for climate change effects on future weather in our scenarios in a detailed way. Heating demand may be reduced and water inflows may partly shift from spring to late winter [10], helping to reduce the winter deficit. We account for a possible change in heating demand following EP2050+ assumptions, but, given the results of our sensitivity analyses, temperature changes ought to be studied further in the case of Switzerland. The potential shift in water inflows was incorporated in EP2050+'s modelling [9], despite significant uncertainties [60]. This implies that the 9 TWh of net imports would in fact be higher without this projection. Incorporating it in our scenarios would likely improve the winter production, and corresponding system costs, across all scenarios consistently. In any case, the conclusions that Switzerland can manage its winter deficit with additional production would still hold, with Switzerland potentially reducing it further than 5 TWh. Finally, there are other environmental impacts besides materials depletion and land use that we do not assess, such as particulate and air pollution caused by biomass and (renewable) methane combustion.

5. Conclusion

In this study, we assess different power supply-side options to mitigate the Swiss winter electricity deficit and their combination. We use a sector-coupled model of Switzerland and its neighbours to analyse solutions from a cost minimisation perspective, and further couple the model with an LCA module to assess changes in critical and strategic raw materials requirements and local land use compared to the EP2050+ roadmap. We show that the electricity production deficit in Switzerland is structural and inherent to its large share of solar PV and hydropower. To reduce such a deficit, gas-fired power plants, alpine PV and their combination with wind turbines are the only options to form an energy system that is cheaper than relying on substantial net electricity imports in winter.

In particular, the combination of these technologies and utilisation of Swiss biomass in the energy sector allows Switzerland to have a fully renewable system, with no fuel dependency from abroad, limited electricity net winter imports, and reduced system costs compared to its current transition plan. Other fully renewable alternative options like substantially increasing the installed capacity of wind energy or roof PV in isolation or hydrogen imports would instead increase the energy system cost by 18%–34% compared to *EP2050+*. This cost increase is mainly caused by reduced electrification of buildings' heat provision and the consequential increase in required synthetic fuel imports. In any case, all these options do not show particularly higher environmental concerns compared to the EP2050+ roadmap in terms of critical raw materials needs and local land use.

On one hand, if none of these strategies is available and the availability of electricity imports in winter is limited, energy system costs can increase by around 65%. On the other hand, the winter deficit being a structural problem in the region, minimising Switzerland's electricity winter deficit by increasing winter power supply means fortifying the resilience of the entire region with mutual benefits during the entire year. Beyond costs, it is important to consider the social and political acceptance of these alternative technological strategies.

CRediT authorship contribution statement

Adrien Mellot: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christian Moretti:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Data curation, Conceptualization. **Tim Tröndle:** Writing – review & editing, Validation, Supervision, Software, Methodology, Data curation, Conceptualization. **Anthony Patt:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All model data and files are available on Zenodo: https://doi.org/10.5281/zenodo.10887523.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.enconman.2024.118426.

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