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Concurrent deficit and surplus situations in the future renewable Swiss and European electricity system

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ABSTRACT

European countries aim to achieve net zero CO_2 emissions by mid-century. Consequently, the European energy system and particularly the electricity system must undergo major changes. An increasing electrification of the mobility and heating sector is required for decarbonisation, which reserves electricity a central role on the path towards net zero CO_2 emissions. However, to meet emission targets, the electricity supply must originate from low emission generation sources. According to the TYNDP 2018 scenarios, the electricity supply in Europe is expected to predominantly originate from renewable energy converters, introducing new challenges to energy systems. Due to the seasonality of renewable energy sources, most European countries, including Switzerland, are expected to face seasonal imbalances of supply and demand in the electricity system. According to national energy strategies of countries with deficits in electricity, the resulting shortages in supply should be covered with imports from their neighbouring countries. This study assesses concurrent deficit and surplus situations among different balancing zones and highly renewable energy systems. Thereby, possible infeasible energy balances are identified by analysing the case of Switzerland and its neighbouring countries Austria, Germany, France and Italy based on published scenarios. The results show, that there are concurrent deficit situations in Switzerland and its neighbouring countries in particular during winter. Hence, the results of this analysis challenge the current energy strategies and the aim to reach net zero CO_2 emissions in Switzerland and Europe.

1. Introduction

Aiming to keep the global temperature increase well below 2 °C compared to pre-industrial levels [1], many countries, including the European Union (EU) and Switzerland, have signed the Paris Agreement [2]. In light of this commitment, countries must reduce their national CO_2 emissions by 50% compared to 1990 by 2030 [1]. To reach this target, the EU and Switzerland have drawn up national strategies to reduce CO_2 emissions within the next decade [3,4]. Additionally, the EU and Switzerland have agreed on reaching CO_2-neutrality by 2050 [5,6]. To achieve these goals, the governments have drawn up climate strategies [3,4], which foresee major changes in the energy sector.

According to those strategies, the mobility and building sectors will be largely electrified in Switzerland by replacing conventional technologies with battery-electric vehicles (BEV) and heat pumps (HP), respectively. The increase in electricity demand, accentuated during winter due to the added load from HP, will be compensated partly by improvements in energy efficiency in other sectors consuming electricity. Even so, a higher electricity demand is predicted [7,8]. Furthermore, the Swiss energy strategy states that this electricity demand will be covered with power generation from renewable energy sources (RES) only. In Switzerland, the technical potential for electricity for wind, biomass and geothermal energy is limited [9] and estimated to be 4.3 TWh/a, 2 TWh/a and 2 TWh/a [7], respectively. These potentials correspond to 7%, 3% and 3%, respectively, of the current (2019) electricity demand [10]. The potential for hydropower is mostly already exploited [11–13]. Hence, increasing the use of solar PV plays a key role in Switzerland's energy transition since an annual technical potential generation from PV of 24 TWh/a [14] up to above 45.6 TWh/a [15] is estimated. This increase in PV would correspond to approximately 40% to 75% of the current (2019) electricity demand [10]. The intermittent nature of PV and seasonal variations of hydropower in combination with an increased diurnally and seasonally changing demand will require great flexibility of the electricity system [16,17] to guarantee a stable and reliable electricity supply at all times. Additionally, due to the country's decision to phase out nuclear power generation within the

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next decades, a significant base load of electricity will be missing in the future [18]. So far, nuclear power plants accounted for roughly 35% [10] of the total Swiss electricity supply. During winter, when major contributions from hydropower is absent, nuclear power plants contributed approximatively 43% to the electrictricity supply today [10, 19]. In the future, this load will have to be compensated with new RES as much as possible and remaining mismatches in supply and demand require new dispatchable power generation, storage or imports from neighbouring countries [20]. According to Ref. [4], Switzerland plans to cover seasonal deficits with imports from neighbouring countries. Alternatively, to ensure security of supply especially during the transition phase of the electricity system, gas-steam combined-cycle power plants are considered in literature to be introduced as a back-up technology [21].

The EU has planned similar development paths as Switzerland by electrifying the mobility and heating sector and switching to power generation from RES to a large extent, mainly PV and wind power [3]. The uptake of the intermittent RES and their highly fluctuating nature will, as multiple studies mention [22–25], pose great challenges to keep the European electricity grid balanced and guarantee a security of supply when relying on almost exclusively RES.

Already today, Switzerland depends on imports from its neighbouring countries to cover shortages in electricity, mostly during winter when the hydropower generation is low and demands are higher [10]. In 2019, Switzerland imported 29.5 TWh of which 20.4 TWh were imported during winter alone [10]. The majority (77%) of the imports came from France and Germany [10]. However, also 35.8 TWh of electricity were exported from Switzerland in 2019. Hence, Switzerland was a net electricity exporter in 2019, while still relying on imports in winter. Some of the imports and exports are due to electricity transfer through Switzerland, for example from France to Italy. Additionally, within the balancing zones of Switzerland and its neighbouring countries Austria (AT), Germany (DE), France (FR) and Italy (IT), Switzerland plays a crucial role by linking the major Central European national electricity markets [26] and acting as a physical interconnecting hub of the national electricity grids [27]. Thus, due to its transit role, changes in the Swiss electricity system will influence its neighbouring countries and vice versa [26]. The interconnectivity becomes apparent in a Figure of the Global Energy Network Institute GENI showing the 380 kV and 220 kV electricity grid of Switzerland.[1] This highlights the importance of including Switzerland's neighbouring countries when trying to model its future electricity system.

For this purpose, we propose a methodology to model the future energy system of Switzerland, while taking the future energy systems of the neighbouring countries into account. Additionally, we consider seasonal fluctuations in electricity generation and demand. Therefore, we investigate generation and demand scenarios in a future renewable European energy system, focusing on seasonal imbalances of demand and supply.

1.1. Literature review

There are multiple studies focusing on the technical feasibility of reaching a 100% renewable Swiss electricity system [9,17,20,28,29] as well as of the European [22,30–36] electricity system. While Refs. [9,17, 20,28,29] look at Switzerland in an isolated manner with access to electricity imports given as a boundary condition, it plays a minor role in [22,30–36], prohibiting an accurate analysis of temporal imbalances of the Swiss system. Densing et al. present an overview of selected scenarios for the future Swiss electricity system [37]. While exact numbers on demand and supply differ, they agree on general strategic trends such as a large deployment of PV, the electrification of the mobility and heating sector and improvements on energy efficiencies. The same is true in national energy and climate plans (NECP) drawn up by the governments of the neighbouring countries establishing national strategies to reach the climate goals set by the EU [38–42] and different scientific studies [43–50], as well as [51], a model by the EU on all EU member states. Noteworthy, however, is the wide range of predictions on national electricity demands until 2050. They reach from a slight reduction of 7% [44] to significant increases of 50% [43] (compared to 2020) in Germany, while an increase of 15–20% [49] (compared to 2010) up to 66% [38] (compared to 2017) in Austria. At the same time, studies predict a national increase in electricity consumption in the range of 34% [47] to 55–79% [52] (compared to 2020) for France and Italy's demand is foreseen to increase by 29% (compared to 2020) until 2040 [42,46].

There are several studies of energy systems on municipal, national, continental and even global levels [34,35,53–55]. For the particular case of Switzerland, there are multiple studies utilizing optimisation models of the future Swiss electricity system on technical and economic levels [9,29,56,57]. However, to the best of our knowledge, only little research targets the interaction between the future electricity supply and demand between Switzerland and its neighbouring countries [27,58].

1.2. Research gap

The contributions of this study are the following:

- This studyfocuses on seasonal imbalances correleating the electricity supply and demand projections. .
- This study analyses potential national seasonal imbalances of supply and demand in future highly renewable energy systems and whether such imbalances are likely to occur simultaneously among several balancing zones within similar climate regions.
- The methodologies to address this research question are applied to the case of Switzerland, asking whether it will be able to cover national deficits with imports of renewable electricity from neighbouring countries in the long-term future.
- The insights and learnings are transferable to electricity systems with similar generation portfolios and demand patterns, causing seasonal mismatches.

1.3. Structure

The structure of this study is as follows: Section 2 presents the scenarios for 2040 and methodologies used to model the future electricity generation and demand. In Section 3, results of these models are presented, focusing on seasonal imbalances of supply and demand, followed by a discussion on possibilities to offset national deficits and on limitations of the study. Lastly, Section 4 concludes the study and finishes with an outlook on further research questions.

2. Methodology

2.1. Model

The investigation of this work focuses on the electricity system. Therefore, other energy carriers are only considered if they are directly dependent on electricity, such as the conversion of electricity to thermal energy via heat pumps.

For the case study presented here, the geographical system boundary includes Switzerland and its neighbouring countries Austria, Germany, France and Italy. Each country is aggregated to one node and the immediate electricity exchange is limited between each of those nodes. The energy supply, demand and import/export capacities are analysed with an hourly resolution for each country which is aggregated to one energy hub node. The data analysis is based on predictions of different pre-existing scenarios which are presented in Section 3.2. Assuming that

[1] http://www.geni.org/globalenergy/library/national_energy_grid/switzerland/swissnationalelectricitygrid.shtml.

hourly surpluses and deficits will be balanced in the future with increased demand side management (DSM) and small-scale, decentralised battery storage technologies (without modelling them explicitly), we focus on daily and seasonal mismatches of supply and demand. The generation technologies modelled include hydropower plants, solar PV, wind turbines, nuclear and coal thermal power plants. Biomass and geothermal power plants are taken together as other RES. For the balance of electricity deficits, gas power plants are additionally introduced as flexible backup technology. The only storage technology modelled is pumped hydro storage (PHS). The operation of flexible hydro and pumped-hydro power is modelled with a heuristic not optimal dispatch approach. This heuristic takes the residual load as a proxy for electricity market prices [59].

We choose the year 2040 as the model year, since well-documented scenarios with consistent data for all considered countries are available in the scenario datasets considered here. Also, 2040 is identified to be of special interest, since 2040 serves as a transition year and the fully renewable electricity system is not yet reached. However, the transformation has already started with several decommissionings of nuclear and coal power plants completed while RES are not fully expanded yet [60]. The underlying market model for the EU-wide energy transition is the one from TYNDP 2018.

2.2. Scenarios

2.2.1. Switzerland

The electricity generation and total annual demand in Switzerland in 2040 emulated in the scenario "ZERO Basis", is developed and published in the "Energieperspektiven 2050+" (EP2050+) [7]. The report, issued on behalf of the Swiss Federal Office of Energy (SFOE), constitutes different scenarios on the development of the Swiss energy system until 2050 under the constraint of reaching Switzerland's climate goal of net CO_2 neutrality by mid-century [4]. As it targets the whole energy sector, it includes sector coupling, allowing for the introduction of power-to-gas (PtG) technologies. DSM is implemented by means of flexible charging of BEV and shifting the operation of HP by including thermal storage. According to the authors of the EP2050+, the "ZERO Basis" scenario is advantageous in regard of cost efficiency, social acceptance, security of supply and the robustness of reaching the national climate goals. The "ZERO Basis" scenario is centred on a quick and comprehensive increase in efficiency, combined with a strong electrification of the energy sector, where conventional fossil-fuelled passenger cars and heating systems are replaced by BEV and HP, respectively. Despite higher efficiencies, these changes lead to an increase in electricity demand, reaching 71.5 TWh/a in 2040 (compared to 61.5 TWh/a in 2019). In accord with the national energy strategy [61], the power sector is dominated by the phasing out of nuclear power generation and a significant increase in the deployment of RES, predominantly decentralised PV plants. PV plants are estimated to reach an installed capacity of 24.1 GW by 2040 [7]. Meanwhile, a minor growth of wind power is foreseen, reaching an installed capacity of 1.2 GW in 2040 [7]. The potential for hydropower in Switzerland is already largely exploited [13,17] with an annual output of 40.6 TWh/a electricity in 2019, accounting for 56% of the electricity demand of that year [10]. By 2040, hydro reservoirs and run-of-river power plants are expected to reach annual outputs of 18.6 TWh/a and 17.5 TWh/a, respectively. According to the scenario "ZERO Basis", around 6 TWh/a from PHS will be available to balance the intermittent electricity generation. The resulting installed capacities as well as the annual demand load presented in the EP2050+ serve as inputs to our model of the future Swiss electricity system in 2040.

2.2.2. Neighbouring countries

We model the electricity generation and demand of the neighbouring countries based on the 2018 Ten-Year Network Development Plan (TYNDP), a report published by the European Network of Transmission System Operators for Electricity (ENTSO-E) [62]. The output of this report are different scenarios which describe three storylines of the gas and electricity system's transition from 2020 until 2040 for all ENTSO-E's member countries. The energy system is optimised under the constraint of reaching an 80–95% reduction in CO_2 emissions by 2050 compared to 1990 in Europe, in line with the goals set by the EU at the time of the TYNDP's development [3]. Our model follows the scenario "Distributed Generation" (DG) since it matches the "ZERO Basis" scenario used for Switzerland, as it also places prosumers with a widespread deployment of decentralised PV, BEV and HP at the centre. In the DG scenario, 27% of the total electricity generation comes from wind power plants and 25% from solar PV. Overall, around 74% of the total electricity demand is covered by RES. It is paired with a general decline in nuclear and coal power. The respective shares of the annual electricity generation per type and country are shown in Fig. 5. The TYNDP models each scenario for three different series of weather conditions, representing warmer or colder and drier or wetter years [62]. We choose to use the outputs from the "Normal (1984)" climate year, representing the intermediate climate between the "dry" and "wet" ones. In the framework of the TYNDP 2018, installed capacities and total annual generation for each country and technology are developed, which serve as inputs to our model.

2.3. Modelling of the demand

The TYNDP 2018 makes future demand time series in hourly resolution for each country available. Consequently, to model the future demand of Switzerland's neighbouring countries, we take the data directly from the TYNDP 2018 scenario. Compared to historical data from ENTSO-E [63] for 2019, the TYNDP 2018 predicts a quite substantial increase in annual electricity demand of +31% and +26% in Austria and Italy, respectively, while it is minor with only +5% in Germany and France.

The EP2050+ do not publish hourly demand time series but only predictions on the total annual demand. Out of this, we scale the time series from the TYNDP scenario with the predicted increase in total annual electricity consumption according to the EP2050+ scenario to model Switzerland's future demand. To note is that it is a simple linear increase of the demand which doesn't take into account possible differing assumptions on the annual evolution of the demand in the two models. However, predictions on the total annual consumption with 71.5 TWh/a in the EP2050+ and 63 TWh/a in the TYNDP 2018 are considered close enough to make our approach a valid simplified method.

2.4. Modelling of inflexible power generation

To model the electricity supply, we assume the weather-dependent electricity generation from PV, wind and hydro run-of-river [64] power plants to be inflexible. Other RES, such as biomass or geothermal, are assumed to deliver a constant base load throughout the year [65]. Similarly, we consider nuclear and coal power plants to be inflexible [66], since the ramp up and ramp down of their power is both more expensive and slower than others, such as gas power plants. Furthermore, nuclear and coal power plants have been predominantly used to deliver base load electricity in the past [65]. To be economically viable, it is important for them to run at as many full load hours as possible due to their high investment but relatively low marginal operating costs [67].

ENTSO-E provides in their mid-term adequacy forecasts (MAF) 2020 hourly profiles for PV, onshore and offshore wind generation for the year 2030 per country and the climate scenarios of the TYNDP. They take into account predicted technological improvements as well as climatic changes due to the continuing global warming until then and are based on a probabilistic analysis [68]. Assuming that these parameters will not change significantly between 2030 and 2040, we take the MAF time series for each country for the "Normal (1984)" climate scenario and scale them linearly with the corresponding annual generation of 2040 to obtain the output loads of PV and wind power plants in hourly resolution.

To model future production loads of the remaining inflexible power generation (coal, nuclear and other RES), we start with the historic hourly time series of each generation type of the years 2016–2019 from ENTSO-E [63]. We select these years since there are almost complete datasets available for them. Missing values are added with linear interpolations. For each country c, year y and generation type g, we calculate capacity factors by dividing the hourly loads by the total installed capacity (Equation (1)).

$$CF_{t,y,g,c}=\frac{load_{t,y,g,c}}{\max\limits_{\tau\in\{1,2,\ldots,8760\}}\left(load_{\tau,y,g,c}\right)},\forall t\in\{1,2,\ldots,8760\},y\in\left\{2016,2017,2018,2019\right\},g\in\{gas,nuclear,PV,wind,hydro\,RoR,other\,RES\},c\in\left\{AT,DE,FR,IT\right] \quad (1)$$

Next, we calculate averaged hourly capacity factors by taking the mean of the four years (Equation (2)).

$$CF_{t,REF,g,c}=\frac{1}{4}\cdot\sum_{y\in[2016,2019]}\left(CF_{t,y,g,c}\right),\forall t\in[0,8760],g\in[gas,nuclear,PV,wind,hydro\ RoR,other\ RES],c\in[AT,DE,FR,IT] \quad (2)$$

To obtain generation time series for 2040, we scale these capacity factors by multiplying them with the predicted installed capacities according to the respective scenarios presented previously in Section 3.2 (Equation (3)).

$$CF_{t,2040,g,c}=CF_{t,REF,g,c}\cdot Cap_{2040,g,c},\forall t\in[0,8760],g\in[gas,nuclear,PV,wind,hydro\ RoR,other\ RES],c\in[AT,DE,FR,IT] \quad (3)$$

Comparing the resulting total annual output of each technology with the predicted annual generation of the respective scenarios allows us to validate our approach.

2.5. Modelling of flexible hydro power generation

Contrary to the generation types discussed previously, times and amount of power generation of hydro reservoirs as well as PHS can be manipulated to some extent [64]. Hence, they can be used to balance temporary mismatches between supply and demand within the electricity grid and serve as storages [64,69]. To account for this flexibility, we use the following heuristic approaches to model their hourly generation in the future.

To model the contributions from flexible hydropower, we first calculate the scaled capacity factors for hydro reservoirs in the same manner as for inflexible generation, described in Section 2.4. Next, we aggregate the electricity generation of five days and then distribute it again to times of deficits. It is based on the assumption that hydro reservoirs can store and shift their dispatch within short terms such as five days. This is an approximation since how long energy can be stored varies with the size of the reservoir [70] and is often mainly driven by economic considerations. In other words, they produce at times of deficits when prices are high, and do not produce during surplus hours when prices are typically low [71] (at some times even negative [72]). Besides the flexible part, there is a minor inflexible part, which cannot be shifted. It corresponds to the minimal flow that is necessary in hydro reservoirs at all times to operate them properly [70]. This inflexible part of hydro storage is initially subtracted by the heuristic method presented by Beer [73]. For more details also on the mathematical derivation of the modelling of the dispatch of flexible hydro generation, refer to Refs. [74,75].

Lastly, contributions from PHS are added. We constrain them such that they use surplus electricity to pump up water and then generate electricity at times of deficits with a round-trip efficiency of 80% [76,77]. Additionally, they are limited by their maximum installed capacity and storage volume (taken from Ref. [78]).

We apply the methodologies presented above to all countries within the model's system boundaries separately to obtain time series in hourly resolution of the electricity demand and production loads for each of them.

2.6. Analysis of the CO_2 intensity

In order to reduce greenhouse gas emissions from the energy sector, emissions from the future electricity supply must be decreased. To

Table 1
Average life-cycle CO_2 intensities of electricity generation technologies.

Generation Type	CO_2 intensity (g_{CO2}/kWh)	Source
Hydro run-of-river	4	[8]
Hydro reservoir	7	8
PHS	5	[79]
PV	50	8]
Wind	20	[80]
Biomass	80	[79,80]
Nuclear	12	8]
Gas (CCGT new)	342	[81]
Coal	975	[79]

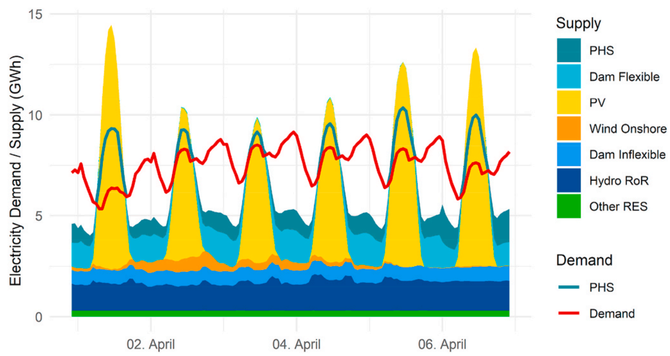

Fig. 1. Daily electricity generation and demand (with additional demand from PHS pumping superimposed in blue) in Switzerland of an exemplary week in spring in 2040.

investigate potential alteration of greenhouse gas emissions from the electricity sector, the CO_2 intensity of the future electricity mix is estimated with specific CO_2 emissions per kWh, as it is done in Ref. [8]. Here, as mentioned in Ref. [8], "CO_2" stands for "CO_2 equivalents", thus including global warming potentials of other greenhouse gases. For the analysis of the CO_2 footprint, we use average life-cycle analysis CO_2 intensities, listed in Table 1.

3. Results

3.1. Diurnal fluctuations

To analyse diurnal fluctuations, Fig. 1 displays the daily electricity generation and demand (in red) per technology in Switzerland in 2040 for an exemplary week in spring. It is visible that the partly flexible electricity coming from hydro reservoirs (Dam Flexible) and PHS are added at times of deficits occurring when the generation from the inflexible hydro reservoir (Dam Inflexible), PV, wind, hydro run-of-river (Hydro RoR) and other RES is not sufficient to meet the electricity demand, as described in Section 3.5. Other production types such as new gas power plants are not foreseen to be part of the future Swiss power plants portfolio according to the "EP2050+". The intermittent electricity generation from PV requires a highly flexible electricity system and causes daily fluctuations between times of substantial surplus and deficit. There is a clear surplus of electricity around midday, which is higher than the surplus electricity that can be stored by the PHS. However, there are significant deficits during night hours, which even the distributed outputs from flexible hydropower cannot cover, showing the need for additional storage or electricity sources. A corresponding plot of an exemplary week during winter in Switzerland can be found in the Supplementary Material.

3.2. Correlation between PV and wind power generation and demand

The electricity generation in Switzerland and its neighbouring countries is predicted to be dominated by PV and wind power in the future. By analysing the temporal correlation between their outputs and the demand, probable mismatches between supply and demand in the future electricity system are identified. Fig. 2 shows on the top left the average hourly PV, wind and demand profile for each month in 2040 in Switzerland. While the demand and wind generation remains rather constant during the day, there is a distinct supply peak of PV around midday. During spring and summer months, these peaks surpass the demand, signifying that PV and wind alone deliver more electricity than consumed at those hours of the day. Contrarily, at night, as well as during winter and autumn months, there is a clear deficit of electricity from these RES throughout the day.

Fig. 2 on the bottom left illustrates these diurnal distributions of the mismatch between demand and summed generation of PV and wind electricity in Switzerland for each month as boxplots. The distribution shows the variability of the hourly output to be expected during a month due to the technologies' dependence on weather. The hourly minimal and maximal output deviate up to 5 GWh from the average values, highlighting the flexibility a future electricity system must have to deal with hourly, daily and seasonal variabilities. Again, it is visible that PV and wind alone deliver not enough electricity both at night as well as during winter and autumn. Surplus generation from PV and wind, in turn, are likely to occur during spring and summer around midday.

In Switzerland's neighbouring countries the same tendencies can be observed, as climate conditions are similar leading to generally higher capacity factors of PV during summer and, contrarily, increased capacity factors of wind during winter [82,83]. With higher shares of domestic wind power, deficits at night are decreased, as wind generation is distributed more evenly throughout the day than PV. The influence of a higher share of wind power is depicted in Fig. 2 on the right with the example of Germany. Germany is predicted to depend to a large extent on wind power, accounting for around 43% of the total electricity generation according to the TYNDP in 2040. Due to this larger share of wind power, deficits during winter are also less pronounced than in Switzerland. This illustrates the opposing seasonal behaviour of the two generation types: While PV generation peaks during summer, wind power plants show increased outputs during winter. It allows the two electricity sources to partially balance each other out. This is in line with previous studies which investigated the correlation between PV and wind power capacity factors and how an optimal combination of the two can decrease the needs for seasonal storage or back-up technologies [20,84,85].

3.3. Electricity supply and demand in 2040

The total future Swiss electricity generation, stacked by technology, and total demand, including the additional demand from PHS, aggregated over five days is plotted on the left in Fig. 3. Clearly, the future electricity generation will be dominated by PV and hydropower. This leads to a notable peak in generation during summer, resulting in a surplus of electricity. Contrarily, there is a drastic drop in generation during winter, combined with an increase in demand, resulting in domestic electricity deficits. This result indicates that within the system modelled in this study, Switzerland will not be able to generate sufficient electricity during winter without additional seasonal storage or flexible power plants to meet its domestic demand at all times. The total annual surplus and deficit both amount up to around 7.5 TWh/a (corresponding to 11% of its total annual demand), meaning that the overall annual national supply and demand is balanced. It is to note that this was a boundary condition in the development of the scenario "ZERO Basis" and is part of the Swiss energy strategy for 2050 [19]. Despite an overall annual balance in supply and demand, the seasonal mismatches are substantial and show that hydro storage as the only implemented seasonal storage technology is not enough to overcome these seasonal imbalances [19]. Hence, while the Swiss future electricity system can generate enough electricity to meet the total annual demand, seasonal discrepancies are too large with not enough storage capacities to meet the demand during winter months.

A corresponding analysis is done for Switzerland's neighbouring countries. Fig. 3 shows on the right the resulting total generation of each country with the total summed demand superimposed in red. It shows that general tendencies among Switzerland's neighbouring countries are similar. Due to the higher demand and lower generation during winter months, they are characterised by deficits. During summer, renewable energy converters predominantly meet the demand in Germany, France, Austria and Italy although the surplus electricity is expected to be less significant in comparison to Switzerland.

The total annual deficit of all neighbouring countries summed up is 218 TWh/a (corresponding to 14% of the total annual demand) while

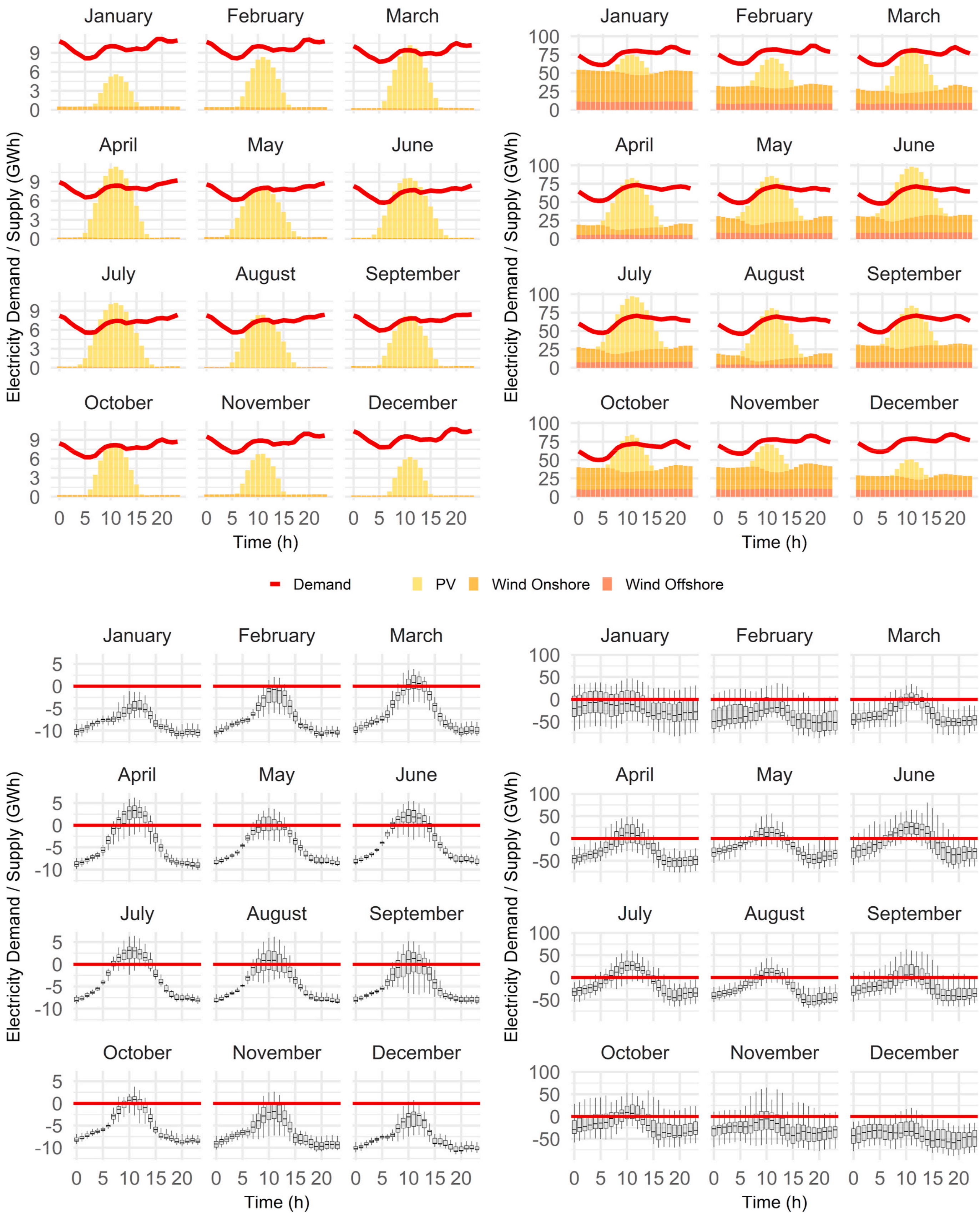

Fig. 2. Top: Average hourly generation from PV and wind (onshore and offshore) with averaged hourly electricity demand superimposed (in red) for Switzerland (left) and Germany (right). Bottom: Hourly distribution of deficits resulting from subtractig sum of PV and wind generation from electricity demand for Switzerland (left) and Germany (right).

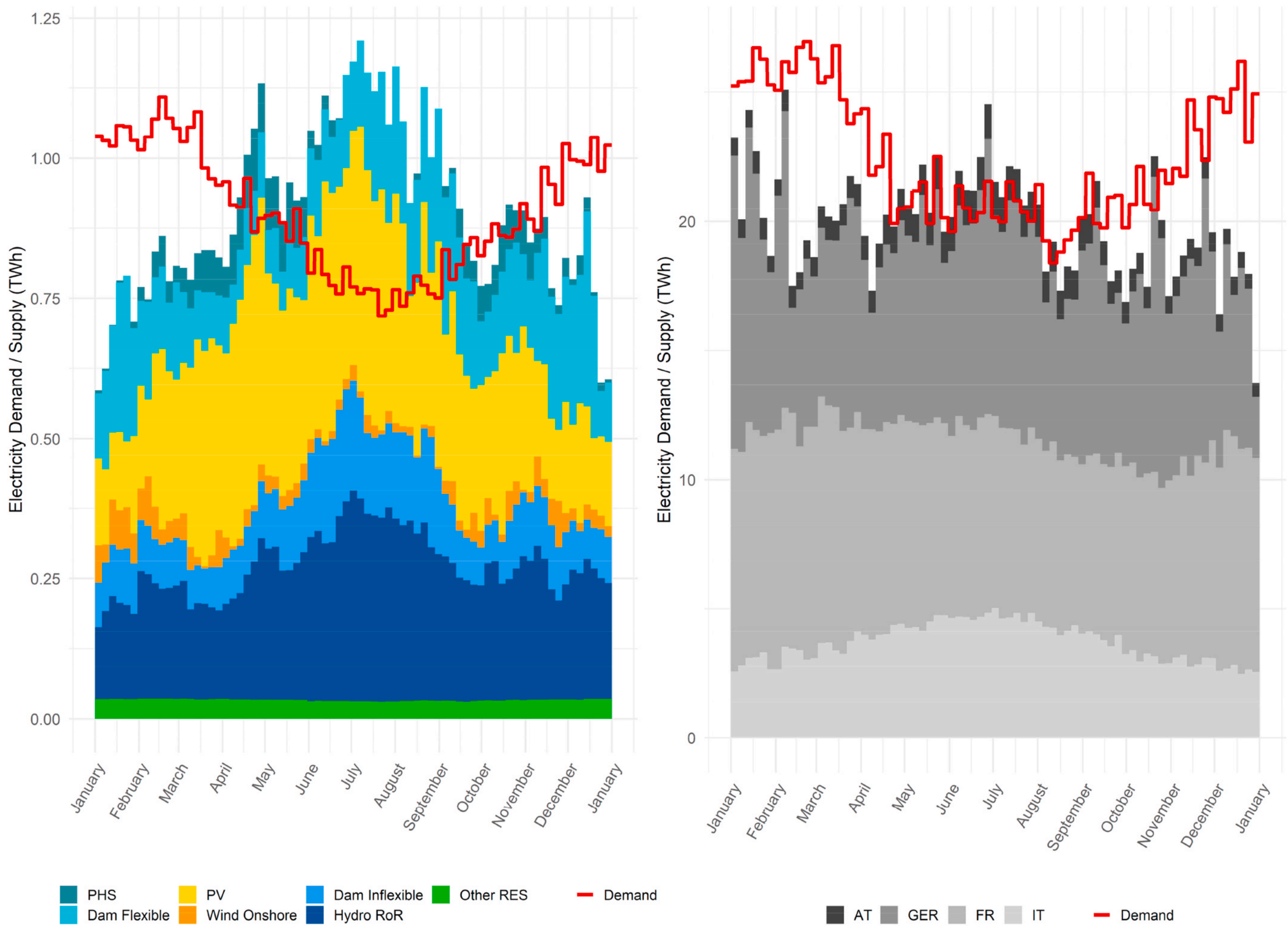

Fig. 3. Yearly electricity generation per technology in Switzerland with total demand (including demand of PHS), aggregated over five days (left). Total electricity generation and summed total demand of neighbouring countries, aggregated over five days (right).

Table 2
Net deficit and corresponding share of the deficit in the total annual demand.

	Net Deficit (TWh/a)	Share of Total Demand
All Neighbouring Countries	183	11%
Austria	23	25%
Germany	64	11%
France	−62	13%
Italy	158	40%

there is an annual surplus of only 35 TWh/a, resulting in a net deficit of 183 TWh/a (corresponding to 11% of the total demand). The net deficit results from subtracting surplus from deficit loads. The only country with a net annual surplus is France thanks to large contributions from nuclear power plants. The French government has agreed on reducing nuclear power, generating 50% of the total national electricity production in 2035 [41]. Even so, it will remain the dominant electricity source of France according to the TYNDP scenario. Italy displays the largest national shortage of electricity with a significant peak in generation during summer since PV is projected to be the country's main RES, delivering 60% of the total renewable electricity by 2040. Austria and Germany have a net deficit in 2040, as well. Austria shows a supply and demand profile comparable to Switzerland with the difference of having a larger share of wind power which delivers 11% (compared to 3% in Switzerland) of the total electricity generation. Germany is characterised by the large share of wind power, constituting 43% of the total national electricity generation in 2040, which results in a more evenly distributed power generation throughout the year. To note is that, with a contribution of 11%, coal is still part of the German electricity mix, contrary to official governmental plans [86]. Besides Germany, only Italy will, based on the TYNDP scenario, still have coal power plants. Yet, with an annual output of 3 TWh/a coal power generation plays a minor role. The resulting net deficits and their shares of the total demand are listed in Table 2.

3.4. *Concurrent deficits and surpluses*

As can be seen in Fig. 3, deficits of electricity must be expected in the Swiss electricity system during winter when modelling the scenarios presented in Section 2.2 for the year 2040. The EP2050+ state that these deficits will be covered with imports from Switzerland's neighbouring countries, mainly relying on wind power in northern Germany. Our modelling of the future electricity generations and demands of Switzerland's neighbouring countries, based on the TYNDP scenario, demonstrates that those countries show similar tendencies with a notable lack of electricity during winter and peak power generation during summer. It implies that relying on imports of renewable energy from its neighbouring countries to cover winter deficits will not be feasible for Switzerland based on the scenarios investigated in this study. This is emphasised in Fig. 4, where the daily deficits and surplus in Switzerland are shown. It is obvious that this concerns the great majority of days with domestic deficits in Switzerland (181 days out of 194), meaning that Switzerland misses around 7.1 TWh/a of renewable electricity

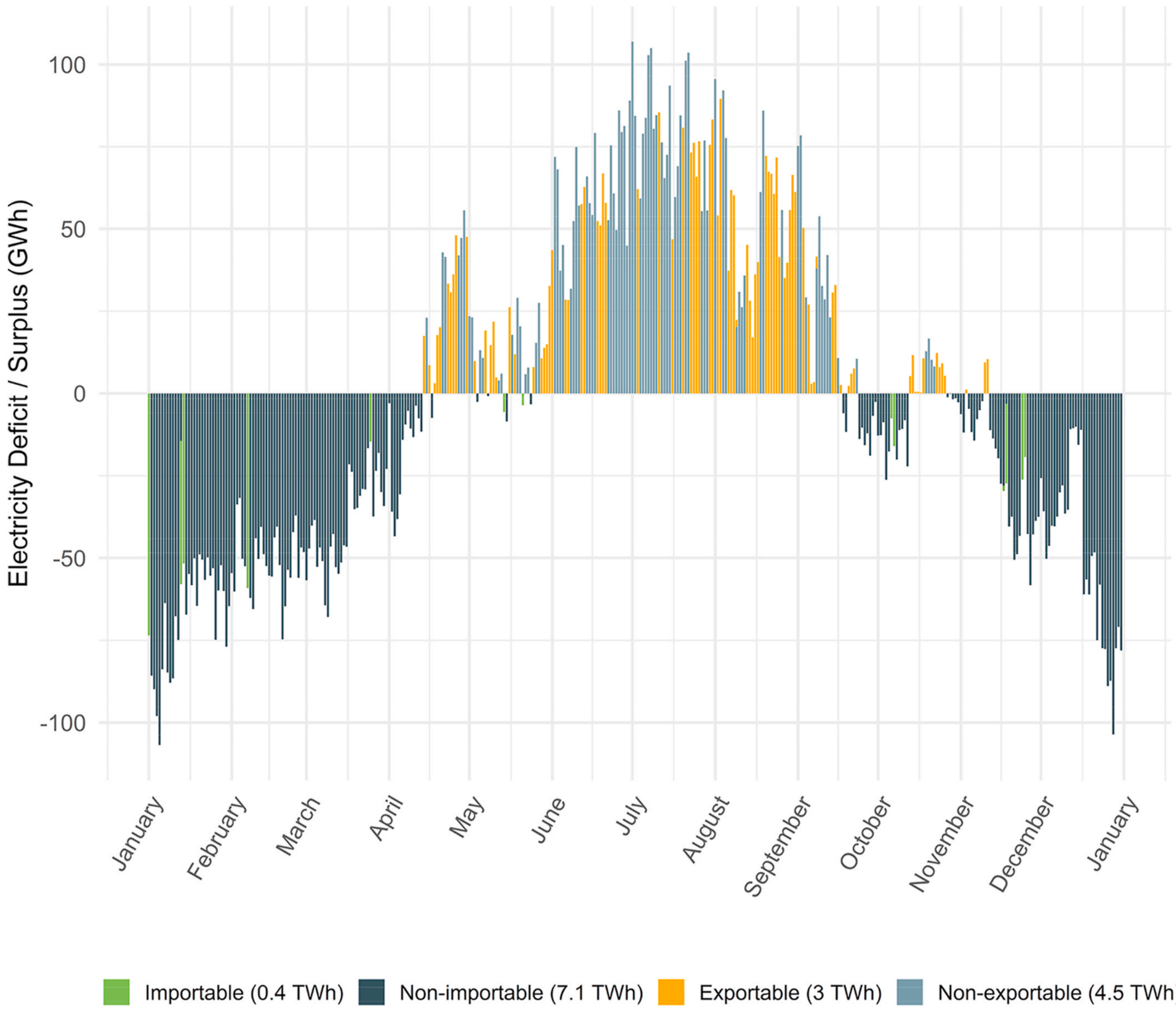

Fig. 4. Daily surplus and deficit of Switzerland in 2040. Only surpluses in orange and deficits in green do not coincide with corresponding surplus and deficit situations in neighbouring countries, respectively.

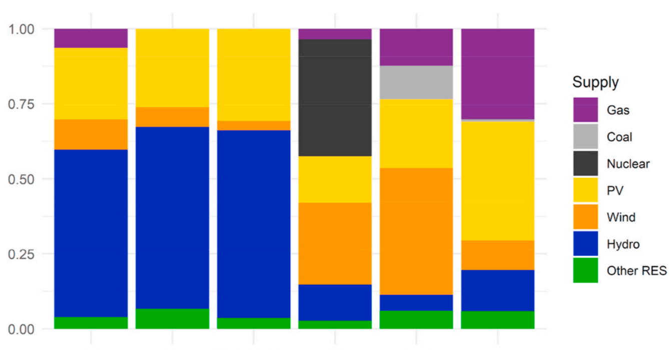

Fig. 5. Share of generation technologies according to TYNDP 2018 (DG Scenario) in AT, CH, GER, FR, and IT as well as the Swiss "EP2050+".

during winter that cannot be met with imports from neighbouring countries. Days, when exporting electricity will likely not be feasible for Switzerland as there is a surplus in the neighbouring countries simultaneously, occur at around half of all days with an surplus production in Switzerland, resulting in around 4.5 TWh/a (of totally 7.5 TWh/a) of electricity that is not viable to be exported.

3.5. Cover deficits with electricity imports – consequences on CO_2 intensity

According to the DG scenario in the TYNDP 2018, the national deficits in Switzerland's neighbouring countries (c.f. Section 3.2) are largely covered by electricity generated in flexible gas power plants. Especially Italy and Germany rely heavily on supply from conventional gas power plants which can produce power when needed [66] to balance the grid and meet the electricity demand. The respective shares of power generation per technology per country are shown in Fig. 5. To compare, the predicted shares for both scenarios, the TYNDP 2018 and EP2050+, are shown for the case of Switzerland. They differ mainly in more supply from wind power and biomass in the TYNDP 2018, which is compensated with more PV and hydro run-of-river generation in the EP2050+.

Gas generation is modelled such that at times of domestic daily deficits, gas power plants generate as much electricity as is needed to cover these deficits, limited by their installed capacity. With the additional gas generation, all neighbouring countries can supply enough electricity to meet their annual demand, except for Austria which still shows some deficits during winter which are covered with imports according to the TYNDP 2018. In Italy, the installed capacity of gas is designed such that it can cover its domestic demand at all times. Both, Germany and France, show available installed capacities during winter that are not needed to cover their national demands. Hence, spare capacities could be used to generate surplus electricity which is exported to Switzerland to cover its national deficits. Doing so, we see that on 148 out of 194 days (76%) with a deficit in Switzerland, enough electricity can be imported from Germany to cover the deficits. In the case of France, it is even higher with enough imports available on 174 days (90%). Taking the available capacities of both neighbouring countries together, the deficits of Switzerland of all but 9 days can be covered with imports from the two (corresponding to a coverage of 95% of all days with a deficit in Switzerland). The still missing electricity then amounts up to 0.4 TWh/a.

It must be kept in mind that this assumes that all additional electricity not used for their domestic demand is exported to Switzerland with an optimal 100% capacity utilisation. Note that possible bottlenecks in the transmission capacities are not taken into account here. Nevertheless, when including electricity generated in gas power plants in Switzerland's neighbouring countries, national shortages can likely be covered with imports from Germany and France to a large extent, in line with the results presented in the EP2050+.

3.5.1. Resulting CO_2 intensity of the electricity mix

Importing electricity from neighbouring countries, as discussed in Section 3.5, implies consequences for the CO_2 intensity of the Swiss electricity mix due to the higher CO_2 intensities of the imported electricity. To investigate the impact of electricity imports on the CO_2 intensity of the electricity mix, we apply the methodology described in Section 2.6. For the production mix of Switzerland and France, a comparable yearly average CO_2 intensity of 23 g_{CO2}/kWh and 24 g_{CO2}/kWh result, respectively, while Germany's CO_2 intensity is significantly higher with 154 g_{CO2}/kWh due to contributions from coal and gas power plants. Consequently, if Switzerland covers all its deficits with imports from France, its electricity will have a minor altered average CO_2 intensity of 24 g_{CO2}/kWh. Covering deficits alternatively with imports from Germany means a raise to a yearly average CO_2 intensity of 38 g_{CO2}/kWh for Switzerland's electricity mix. Considering only winter months (October until March), the difference is even more pronounced: during winter, Switzerland alone has a CO_2 intensity of 22 g_{CO2}/kWh while by including imports during that time from Germany leads to an intensity of 50 g_{CO2}/kWh. Alternatively, covering domestic deficits with imports from France leads to minor increases, only. As, most likely, Swiss deficits will be covered with a mixture of imports from France and Germany, the resulting CO_2 intensity would lie somewhere between the two extremes. Lastly, if Switzerland were to cover all its deficits with own gas power plants, its electricity mix had an annual average CO_2 intensity of 83 g_{CO2}/kWh and even 135 g_{CO2}/kWh during winter months. These correspond to the marginal CO_2 intensities [81] when all of the imports from Germany and France are from gas power plants. This shows that when covering deficits with imports, Switzerland has to account for increases in CO_2 intensity of its electricity mix. They are, however, lower when considering the CO_2 intensity of the whole electricity mix for the imports than alternatively covering deficits completely with power generated in conventional gas power plants.

4. Discussion

4.1. Discussion of results

The Swiss dependency on imports in a renewable electricity system, found in Section 3.3, agrees with results in Refs. [29,87]. Both studies are based on the Swiss energy strategy for 2050 published by SFOE [88]. The installed capacities of RES are chosen in their models such that they meet the total annual demand. Like in our study, they mention that imports are required to compensate for seasonal imbalances. To the author's knowledge, there are no comparable case studies or analyses on the energy system with the same system boundaries studied herein. However, the report "Klimaneutrales Deutschland" [43], presents a possible scenario for Germany to reach CO_2 neutrality by 2050 and makes comparable assumptions on boundary conditions as in the EP2050+. While explicit electricity generation and demand profiles showing variations throughout the year are not available, the report suggests that Germany will move from being a net exporting country (with a net export of 49 TWh/a in 2018) to a net importing country in 2040 (with a net annual import of 16 TWh/a). Similarly, Capros [51] predicts that Germany will import 15 TWh/a of electricity in 2050 (compared to exports of 15 TWh/a in 2010). This supports our conclusion that imports of renewable energy from Germany may not be guaranteed in the future. For Switzerland's second major electricity exporting neighbour France, Capros [51] predicts a minor decrease of exports from 30.7 TWh/a in 2010 to 28.8 TWh/a in 2050. The result hence suggests that access to imports in the range of today's 17.9 TWh/a [89] from France to Switzerland can be expected during the next decades until 2050. However, as Italy is one of France's major exporting countries [90], development in Italy's national demand and supply will influence the availability of imports from France. Similar to our results, Capros [51] predicts annual net deficits for Austria and Italy in 2050. These studies agree with our results on a high level but do not allow for in-depth comparisons on seasonal variations.

4.2. Recommendations for Switzerland to offset seasonal imbalances

4.2.1. Shift of the surplus load

As seen above, Switzerland will have a considerable amount of surplus electricity during summer based on the TYNDP 2018 and EP2050+ reports. Around half of this surplus cannot be exported based on the analysed scenarios due to surpluses occurring simultaneously in the neighbouring countries. Alternatively, this load can either be curtailed or offset by introducing conversion technologies which serve as seasonal storage. Today, power-to-gas (PtG) technologies are one promising option of seasonal storages which enable offsetting seasonal variations in other energy sectors by sector coupling. Converting the surplus electricity to hydrogen and using it directly or converting it in a subsequent methanation process to synthetic natural gas (SNG) allows for a coupling of the electricity and gas sector [91,92]. However efficiency losses during the conversion process have to be taken into account. The efficiency of the process is around 55% and 45% for the conversion of electricity to hydrogen and hydrogen to SNG, respectively [93]. Taking the surplus electricity that is not exportable from Switzerland (4.5 TWh/a), one can produce hydrogen with an energy content of maximal 2.5 TWh/a (ignoring additional storage and transport losses) or 2.0 TWh/a of SNG. Using the total electricity surplus of Switzerland (7.5 TWh/a) leads to 4.1 TWh/a hydrogen and 3.4 TWh/a SNG, respectively. The EP2050+ state that in 2040, Switzerland will still need 11 TWh/a of natural gas. This shows that using parts or all of the surplus electricity can substitute some of the conventional natural gas with CO_2 neutral SNG, but it is not enough to cover the full demand. Nevertheless, it helps stabilise the grid by offering a way to deal with fluctuations in the power generation which might be of benefit in future highly renewable energy systems. Converting gas back to electricity during winter is not considered here due to significant efficiency losses during the process which make the produced electricity very expensive with today up to 300 EUR/MWh_{el} [94]. The efficiency losses and high electricity prices lead to the assumption that converting the SNG back to electricity is technologically and economically unfavourable and will thus not be pursued largely in the near future.

4.2.2. Increasing domestic winter production with wind power

As covering winter deficits with imports of renewable electricity from neighbouring countries was shown to be infeasible for Switzerland, pursuing an increase in domestic wind power production can be an alternative to decrease domestic shortages, especially during winter. As seen in Section 3.2 and studied in Refs. [95,96], wind power plants generate power all year around with peak generation during winter, allowing for a reduction of Switzerland's dependence on imports. It tends to inversely correlate with PV, generating around two thirds of its annual generation during winter [96], which makes it a valid option to decrease winter deficits. While there is profound technological knowledge about wind parks in coastal areas, these insights cannot be transferred directly to wind parks in mountainous regions, such as Switzerland. The lack of technological research is complemented with only little experience with wind power projects in these areas [97]. Consequently, there are various differing estimations on the technical potential of wind power in Switzerland. According to Ref. [96], Switzerland has a maximum technical potential of generating up to 30 TWh/a per year. The authors consider wind parks generating 9 TWh/a annually with 6 TWh during winter months alone to be an attainable goal for Switzerland until mid-century. That is substantially more than the annual 4.3 TWh/a predicted in the EP2050+ to be reached by 2050 which base their model on the estimated maximum potential of 1.4–4.3 TWh/a wind power output annually published in Ref. [98]. However, the EP2050+ also take into account other aspects, such as cost efficiency and social acceptance. To compare, the TYNDP 2018 projects an annual generation of 4.7 TWh/a (2.6 GW) of wind power for Switzerland by 2040. There are multiple studies that assume a potential somewhere between the aforementioned extremes of 1.4 and 9 TWh/a annual wind power output [37]. Taking the most ambitious assumption of 9 TWh/a per year, up to 4.5 TWh of the total 7.5 TWh deficit can be covered with domestic wind power plants. However, besides uncertainties on the technical potential, there is the concern of social acceptance of wind power plants in Switzerland. There is a general opposition by the public but also by local environmental organisations which has hindered investments and the construction of various wind energy projects [97, 99–102].

4.3. Data limitations and further study

As described earlier, the modelling of future inflexible generation loads use historic data from ENTSO-E's Transparency Platform [63]. They were identified earlier as the most complete and consistent data available for all countries considered. However, they still contain missing values, do not include all installed power plants, are not fully congruent for all countries and it is not always fully transparent to what extent losses are included in the data. As noted in Ref. [103], the availability and accessibility of reliable and conclusive data on the European electricity system is limited, hindering accurate analyses and modelling. The same applies to production profiles of intermittent RES, such as PV and wind power, since the different yearly profiles available today are not in full agreement with each other [82,104].

Further studies should include a more detailed investigation of the immediate exchange of electricity supply among the neighbouring countries, as previous studies have shown that increased power transmission decreases the need for storage and back-up generation technologies [105,106]. Additionally, the option of importing renewable electricity from countries outside of this study's system boundaries (e.g. hydropower from Nordic countries, solar power from Mediterranean countries, etc.) should be considered.

A new study, conducted by the VSE in collaboration with Empa modelled the active electricity exchange between Switzerland and its neighbouring countries until 2050. The Energiezukunft 2050 study was conducted and published after submitting this work (https://www.strom.ch/de/energiezukunft-2050/startseite).

Furthermore, the Russian invasion of Ukraine will affect the future energy supply scenarios.

5. Conclusion

This study investigates concurrent deficits and surplus situations in renewable electricity systems among different balancing zones in similar climate regions. It shows that seasonal imbalances in supply and demand must be considered, as they tend to occur simultaneously among balancing zones in the future. In this study, the case of Switzerland and its neighbouring countries with a heuristic model based on existing reports (EP2050+ and TYNDP) was investigated and reviewed. Results show that the electricity system developed in the framework of the EP2050+ in accordance with the Swiss climate target of reaching net CO_2 neutrality by mid-century will not be able to generate enough electricity to meet the domestic demand at all times due to seasonal imbalances. Further, covering these deficits with renewable imports from neighbouring countries is not a feasible option based on the TYNDP 2018 DG scenario since they are expected to face shortages of renewable energy at the same time. Thus, if electricity is imported from Switzerland's neighbouring countries, it is likely to come from conventional fossil-fuelled power plants and prevent a completely renewable and CO_2 neutral power supply in Switzerland that must be compensated for. At the same time, Switzerland is expected to have a surplus of electricity during summer months which is partly not exportable to its neighbouring countries, as they do not have a shortage at those times. Alternatively, gas power plants can be installed to cover deficits completely but come at significant costs of a higher CO_2 intensity, requiring CO_2 negative technologies, such as CCS, to meet the emission targets. Thus, this study shows that scenarios for a CO_2 neutral national electricity system have to consider the scenarios of the surrounding countries in particular if an import dependency occurs. To address the topic, further investigations towards integrated energy systems with sector coupling are required.

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.

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