Energy security in a net zero emissions future for Switzerland

Expert Group "Security of Supply" – White Paper

Report

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Energy Science Center (ESC)

Expert Group Security of Supply

White Paper

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Key findings

1. Consistent with climate science and the Paris Agreement, Switzerland must reach net zero greenhouse gas emissions by 2050. The centrepiece of this will be net zero emissions from energy use.
2. However, recent events, including the war in Ukraine, have raised concerns about energy security, particularly in winter months. This White Paper presents results from analyses undertaken primarily at ETH Zurich. They show that a complete decarbonization of the Swiss energy system can be harmonized with continuous energy security. But the challenges are significant.
3. Researchers across the ETH Domain have independently developed an ensemble of energy system models to explore four energy scenarios for Switzerland. The scenarios are determined by whether or not electricity trade with neighbouring countries will be constrained, and whether or not offsetting of Swiss residual CO_2 emissions can take place abroad. Across all four scenarios, electrification of transport and heating lead to both a greatly reduced overall energy demand and, at the same time, an increase in annual electricity demand from the current level of 60 TWh to at least 80 TWh, met mostly through a combination of domestic renewable energy sources and electricity trading. All scenarios did show that a net zero energy supply by 2050 is feasible and affordable.
4. Long-term efficient integration of Switzerland into the European electricity market and the rapid expansion of renewable electricity generation within and outside of Switzerland are fundamental conditions so that the transformation of the current energy system to reach net zero is technically possible while keeping high levels of security of supply.
5. Energy security can be further increased by expanding electricity generation, especially in winter. Alpine PV systems could be an important option, although investment costs and ecological impacts are still uncertain. Nuclear energy is another possibility. While current nuclear power plants can support a transition to net zero, new ones could probably first come into play after 2050 due to lacking political basis and uncertain construction times and costs.

Executive summary

Increasing concentrations of greenhouse gases (GHG) in the Earth's atmosphere causing climate change are a direct consequence of our reliance on fossil fuels for almost all aspects of the global economy. In order to mitigate the likely drastic impacts of rising temperatures, we must reduce emissions to (net) zero by 2050 (IPCC 2022). Phasing out the use of fossil fuels is one of the main steps towards reducing anthropogenic emissions. Like many other nations of the world, Switzerland has set the goal of reaching net zero emissions by 2050.

Changes in the energy system within the next years will be critical for setting the path towards net zero. At the same time, the energy crisis in Europe that was exacerbated by the war in Ukraine last year is still ongoing and the impacts on energy provision for the coming winter are uncertain. Since Switzerland mostly relies on electricity and gas imports in winter, the question of securing other energy supply sources is being debated.

The purpose of this White Paper is to shed light on the question if it is possible to reach net zero GHG emissions by 2050 whilst maintaining a high level of energy security for Switzerland. If yes, which conditions have to be met? To answer these questions, this assessment relies on energy system models developed at ETH Zurich that analyse scenarios of possible net zero energy futures. Similarities in the different model results can give a good indication about which conditions are essential for achieving such an energy system. Based on these results and other scientific work carried out within and outside of ETH Zurich, we then discuss if these conditions satisfy the criteria commonly used for evaluating energy security.

The results of several techno-economic energy system models that were developed independently across the ETH Domain, but simulating the same scenarios, were compared (Marcucci et al., 2023). Different scenarios were defined with varying assumptions, but all realizing a net zero energy system in 2050. All the results showed that the pathway to net zero includes the electrification of transport and heating supplied by hydropower, solar, wind, wood, waste and gas/biogas with carbon capture and storage. In all scenarios, the electricity demand could be satisfied by renewable supply sources with an annual net electricity demand between 80 – 100 TWh in 2050, compared to the current 60 TWh (SFOE 2022b). The energy demand of long-haul freight and aviation, which are more challenging to electrify, would be satisfied with bio or synthetic fuels.

These modelling results suggest that a net zero energy system is possible and would bring Switzerland on track to achieving climate neutrality, but would it in turn jeopardize energy security? The two commonly used criteria for energy security are continuous availability and affordability (IEA 2023; SFOE 2023d). Additionally, scientific studies suggest that more specific criteria such as diverse sources of energy supply (Grams et al., 2017; Pfenninger et al., 2014), import independence (Blumer et al., 2015) as well as reliability of supply infrastructure (Lilliestam & Ellenbeck, 2011) are also central.

Concerning continuous availability, an outcome of the models compared herein and also of other studies (SFOE 2022a), is that free access to the European electricity market has been and will remain essential for the Swiss energy system. This is because the energy systems of the countries in Europe and Switzerland have developed based on the resources available to them and this has led to synergies that are exploited through energy trade, especially trade in electricity. Like Switzerland, the EU member states plan to transition their energy system in order to reduce GHG emissions. Thus, the electricity system will become the foundation along with electricity trade for balancing supply and demand of the varying renewable sources that are available in different countries at different times and seasons. A Europe-wide energy system based primarily on renewable sources can provide uninterrupted availability if electricity trade is guaranteed.

As to affordability, the decarbonization of the energy system will come at a cost, yet benefits besides energy security will also arise. Under the premise of attaining high levels of energy security and energy trade with neighbouring countries, techno-economic models suggest that the costs of the energy transition in Switzerland could amount to an extra CHF 380 – 600 per capita per year (Guidati & Marcucci, 2023; Panos et al., 2021; SFOE 2021a) or even lead to cost savings (Balmer et al., 2022) depending on the specific assumptions. There are currently no simulations that take the benefits of reducing GHG and pollutant emissions into account. Improving the quality of air, water and soil as well as enhancing biodiversity – to only mention a few – will also have economic benefits for society. These potential savings could by far outweigh the costs of decarbonizing energy provision (Karlsson et al., 2020).

Relating to diversification, import independence and infrastructure reliability, Switzerland transitioning its energy system means a reduction in the use of fossil fuels and a higher diversification due to the use of different renewable resources. As the dependence on fossil fuel imports will decline, so will the risk of supply interruptions from single points of origin, as with natural gas from Russia. This along with decentralized electricity infrastructure being less at risk to damage compared to that of fossil fuels (Lilliestam & Ellenbeck, 2011), would lead to enhanced energy security. Net zero scenarios point out that Swiss reliance on oil products could drop from the current import levels of 120 – 130 TWh per year to 20 – 25 TWh per year, mostly for kerosene (Guidati & Marcucci, 2023). In the case of natural gas, imports could be completely eliminated if Switzerland has unrestricted access to the EU electricity market. Therefore, a successful energy transition requires Switzerland to be integrated into the European electricity market to ensure that the variability of renewable sources across the continent can be balanced, continuously and mutually beneficial as is currently already the case (SFOE 2022a). Such a long-term and binding agreement is however not a technical challenge, but a political responsibility.

Even if Switzerland is integrated into the European electricity system, it will probably still rely more heavily on electricity imports in winter. Energy security can therefore be further improved by expanding technologies that can provide or save electricity in winter, e.g. wind, alpine PV, seasonal heat storage or nuclear power.

Alpine PV, which is more efficient in the winter half year, could provide an estimated 45 – 300 TWh per year (Dujardin et al. 2022; Meyer et al. 2023). Given that alpine PV installations have uncertain ecological impacts, using only suitable locations for winter PV near already impacted areas (e.g. ski areas and hydropower dams) could be a compromise and could provide 5 TWh per year, of which 2 – 3 TWh are produced in winter (Meyer et al., 2023).

Nuclear energy is another such option, yet the construction time and costs for building new nuclear power plants in Switzerland are uncertain (IAEA 2023; Rothwell, 2022) and the political framework is currently not in place. Thus, it might be challenging to commission new nuclear power plants before 2050. However, keeping the current nuclear power stations in operation in Switzerland as long as they are deemed safe and can be run economically, can support Switzerland achieving decarbonization until 2050 and provide a large fraction of electricity supply even in winter (ca. 30 – 40%; SFOE 2022b).

In conclusion, this qualitative analysis based on quantitative model results suggests that the transformation of the current energy system to reach net zero is technically feasible while keeping high levels of security of supply. The main conditions for this are the long-term integration of Switzerland into the European electricity market and the rapid expansion of renewable electricity generation within and outside of Switzerland. This will ensure that discrepancies between supply and demand of electricity can be balanced across the continent to maintain a continuous supply. In addition, energy security for Switzerland can be further increased by expanding seasonal energy storage and technologies like alpine PV or wind to reduce the need for imports in the winter. This kind of transition will incur costs but also many benefits – both need to be considered when debating climate change mitigation. If we manage to reduce greenhouse gas emissions and stabilize average temperatures by mid-century, we will gain far more than energy security. We will gain enhanced air, water, soil and food security, among others, undoubtedly of high value for human life and all other forms of life that we share this planet with.

1. Introduction

The most recent assessment report of the Intergovernmental Panel on Climate Change (IPCC) makes it clear that to avoid consequences of climate change that are likely to be catastrophic for humanity and nature, greenhouse gas (GHG) emissions need to fall by half within the decade, and to net zero by 2050 (IPCC 2022). Net zero refers to the fact that some emissions from e.g. land use, agriculture and aviation will be hard to prevent, so that biological and technical measures need to be implemented in addition to compensate for these. Most anthropogenic GHG emissions derive from the combustion of fossil fuels. Simply put: the age of fossil fuels must end, completely and quickly (Hug et al., 2022).

Twenty years ago, this task did not seem possible, because the alternatives to fossil energy did not exist, or were prohibitively expensive. When Germany initiated its feed-in tariff for solar photovoltaic (PV) power in the year 2000, for example, it had to set that tariff to over €0.50 per kWh in order to incentivize investment. By now this has changed. The levelized costs of solar power have fallen by over 90% in the intervening years. At the same time, the electrification of the transport and heating sectors enables greater substitution of fossil fuels by renewable power. The total costs of ownership (purchase and operation) for battery electric vehicles (BEV) have decreased to below that of internal combustion engine vehicles (Guo et al., 2022; Noll et al., 2022) and heat pumps have gone mainstream. Furthermore, the production of liquid fuels for the aviation sector from water, carbon dioxide (CO_2) captured directly from the air and solar energy starts to take off (e.g. Schäppi et al., 2021).

Yet there are still major challenges to be addressed if the world, and Switzerland, want to transition to 100% non-fossil energy. First, it is vastly more challenging to store electricity than fossil fuels. Coupled with the intermittent nature of solar and wind power, the challenge of energy storage renders the matching of energy supply and demand at all times more intricate. Second, it can be challenging to transport electricity over long distances, compared to fossil energy carriers. Rather than simply loading coal or oil onto a barge, power lines have to be built. Third, and closely related to the second factor, an international and interconnected electricity system and the trade agreements needed for this are complex.

These challenges seem especially pronounced in Switzerland. Swiss geography is well suited for hydropower production and acceptably good for solar power, both of which are more productive in summer than in winter. Wind energy is more productive in winter, which naturally complements solar. However, wind turbine approval processes in Switzerland have been very lengthy and wind speeds are often less attractive than abroad (though good wind locations also exist in Switzerland), making domestic wind energy less economical when compared to wind developments elsewhere. While the European Union generates more than twice as much power from wind as it does from solar, in Switzerland the situation is reversed and far more extreme, with solar production surpassing wind energy by a factor of 20 (Eurostat, 2021; SFOE 2022c). Attractive wind energy sites in Europe are located more than 1 000 km away, necessitating long-distance transmission. Additionally, the EU has been moving forward with its regulation in order to promote greater electricity trade among member states, which will facilitate their own energy transitions, but Switzerland is not part of the EU. Without a bilateral treaty to place Switzerland on a similar status as the EU member countries, the ability of Switzerland to trade power with our EU neighbours will be further constrained in the future.

Concerns over energy security call into question previous decisions and highlight new conflicts. Popular initiatives and referenda in Switzerland are asking voters to reconsider nuclear power, or to overturn the net zero emissions targets for 2050 that have been approved by parliament (Swiss Federal Council, 2022a). Finally, there are arguments that in order to achieve the needed level of energy security, Switzerland must prioritize the construction of new energy supply sources, especially for the winter, above other societal goals including the protection of valued watersheds and wilderness landscapes.

The purpose of this White Paper is to summarize the scientific evidence, primarily obtained through studies conducted at ETH Zurich, that is relevant for current energy security debates. Most importantly, it strives to answer the question if current scientific knowledge suggests that it is possible to maintain high levels of energy security while also undertaking a fundamental restructuring of the energy system away from fossil fuels. What are the needed conditions and investments to achieve complete decarbonization while maintaining high energy security? And, what decisions made over the coming years will most heavily influence our ability to enable decarbonization with continued energy security?

2. Current status of energy security in Switzerland

In an energy future that does not rely on fossil fuels, but on renewable sources, the electricity system will be the backbone of the energy system. Currently the Swiss electricity supply system generates about 60% from hydropower (half from run-of-river power plants and half from hydropower plants with storage lakes), approximately 30 – 40% from nuclear power and the remaining part from thermal power plants (mostly waste incineration) and new renewable generation (SFOE 2022b). Hydropower not only covers a major portion of the electricity demand in Switzerland, but plants and pumps can be operated flexibly and provide storage. However, its availability is not uniform year-round, as water is bound in snow and ice in winter and the storage lakes are slowly emptied over winter and filled up in spring due to snowmelt. This along with an overall lower electricity demand in summer, makes Switzerland a net exporter of electric energy in summer (ca. 5 TWh per year averaged over the past ten years[1]; SFOE 2023a). In winter, the situation is reversed, i.e. increased consumption and reduced hydropower availability are compensated by net electricity imports (ca. 4 TWh per year averaged over the past ten years; SFOE 2023a). Neighbouring countries, especially Germany, France and Austria, have so far been able to supply the lacking electricity in winter (Figure 1).

[1] Values of net summer exports and net winter imports were derived by using monthly electricity import and export data from 2012 to 2022 (SFOE 2023a). For this, imports and exports for the summer half year (April-September) and the winter half year (October-March) were added. Subtracting total exports from imports in the summer or winter gives net import or export values for the corresponding half year. These were averaged over the past 10 years.

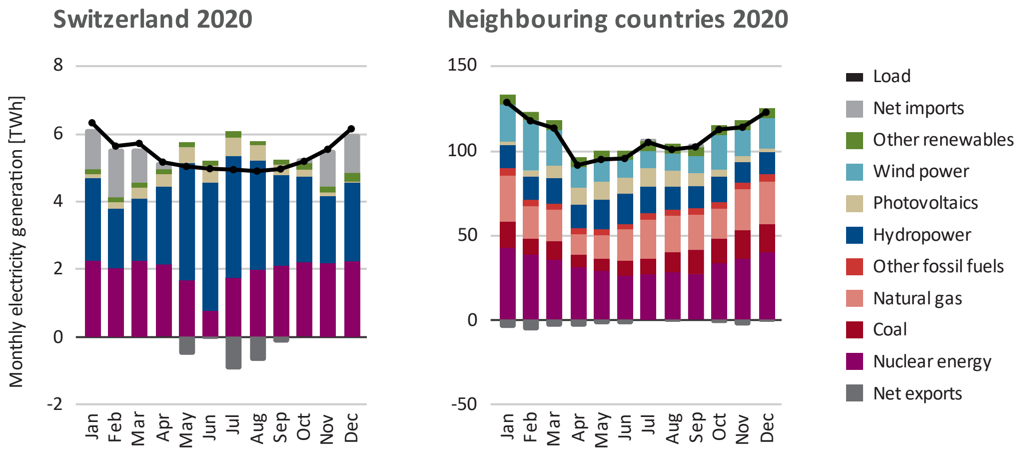

Figure 1. Monthly electricity generation and load in Switzerland (left) and in neighbouring countries (DE, IT, FR, AT, aggregated; right) in 2020. Data source: European Network of Transmission System Operators for Electricity (ENTSO-E) accessed through Energy Charts (Energy Charts, 2023b).

In 2022, three main factors led to a precarious situation in the energy supply system: (1) The winter 2021/2022 and summer 2022 were rather dry resulting in lower than usual inflows into the storage lakes. This was partly compensated by the additional melting of glaciers due to the high temperatures in summer. (2) A large part of the nuclear power plant fleet in France (up to 50% of the power plants) had to be taken out of operation because of corrosion issues even in some of the newer power plants (Figure 2). These unscheduled outages resulted in a significantly reduced generation in France and situations, where France had to import during times when they usually export (World Nuclear Association, 2023). (3) The war in Ukraine initiated by Russia resulted in a reduction in the gas deliveries to Europe. Even though Switzerland does not use gas for electric energy generation directly, this was of great concern because Germany, from where Switzerland imports electricity in winter, produces about 15% of its electric energy from gas-fired power plants (Statistisches Bundesamt, 2023). Furthermore, natural gas is used for domestic heating and for industrial applications (mainly high-temperature processes). As Switzerland does not have significant gas storage, it relies on imports from its neighbouring countries. In combination, these events also resulted in extremely high electricity prices (price increase of more than 500% from July 2021 to September 2022) on electricity wholesale markets across Europe during some months, signalling an existing scarcity.

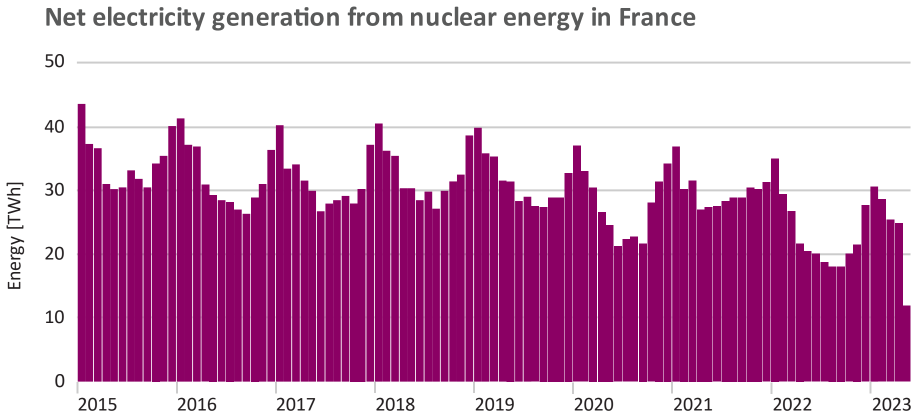

Figure 2. Net electricity generation from nuclear energy in France from 2015 to today. Data source: ENTSO-E accessed through Energy Charts (Energy Charts, 2023a).

Currently, in spring of 2023, the situation is less tense. Storage lakes are filled even more than in average years, in fact the levels are at a record high (Figure 3; SFOE 2023b). One of the main reasons is that energy demand in winter was lower than usual, largely due to the unusually warm winter in 2022/23, and the newly instated federal winter hydro reserve (Swiss Federal Council, 2022c) might have led to withholding some of the water. Likewise, the gas storages in Europe are at a record high fill level (ENTSOG 2023). This is mainly due to the EU diversifying its gas sources in 2022 and importing just over 130 bcm (billion cubic meters) as liquefied natural gas (LNG), a 60% increase from the 80 bcm imported in 2021 (IEA 2022). Furthermore, also in the case of gas, the mild winter helped alleviate the situation.

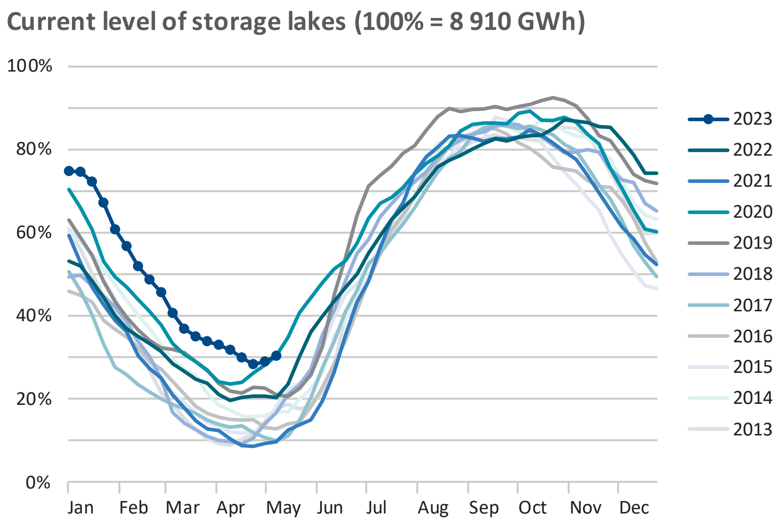

Figure 3. Current level of storage lakes in Switzerland compared to previous years. Figure adapted from Swiss Federal Office of Energy (SFOE 2023b).

While the danger of an electricity or gas shortage has likely been avoided for spring 2023, the situation in the coming winter 2023/24 is still unclear. In Switzerland, a variety of emergency actions have been put into place, which will also be active next winter, namely the implementation of a water reserve (400 GWh have been secured for winter 2022/23 which was released on 15 May 2023; Swiss Federal Council, 2022b), the purchase and installation of backup gas-fired power plants (new 250 MW plant in Birr) and the initiation of a pool of emergency standby units. These measures are only to be used in an emergency situation and the gas-fired power plant in Birr is temporary and is planned to be disassembled in 2026. At the European level, discharging the gas storages too much could be risky, since import sources (from Russia and via LNG) are still limited. Thus, it could be challenging to fully recharge the storages over the summer, which could in turn pose a risk for the next winter. Coordinated planning of gas usage could support countries to cope with future issues stemming from the gas supply shortage (Mannhardt et al., 2023). While these are effective and reasonable measures in an emergency situation, they are not thought and designed to be long-term solutions.

3. Options for a decarbonized energy system for Switzerland in 2050

A viable mid- to long-term solution is to rapidly expand renewable electricity generation in Switzerland as decided by the Swiss Federal Council (Swiss Federal Council, 2019). Transitioning to renewable energy sources and reaching net zero GHG emissions, while maintaining security of energy supply is a challenge. Yet a recent study comparing the results of multiple energy system models (Marcucci et al., 2023), offers useful insights into how a future energy system without GHG emissions could be realized.

Energy system models are computer-based models of energy systems that simulate scenarios, using a set of assumptions about certain parameters of an energy system, in order to assess technological or cost dynamics. Though models are useful for gauging future trends and developments, scenarios are not predictions, models have limitations and are not a 1:1 replica of reality. Therefore, actual number results need to be used with caution and can only offer a range of options for how such a future energy system could function and the order of magnitude of future energy supply and demand.

That being said, the study compared results for different net zero scenarios in Switzerland using five energy system models. The models are techno-economic in nature, meaning that current and possible future energy technologies are options to find the most economical solution for the set goal, i.e. an energy system with net zero GHG emissions. The four scenarios were defined along the dimensions climate policy and energy market integration (Marcucci et al., 2023). The climate policy dimension considers the Swiss climate goal to reach net zero by 2050 with or without compensation abroad. The energy market integration dimension assumes high and low integration of Swiss and international energy markets regarding electricity, biofuels, hydrogen and synthetic fuels. The study assumes a reduction in energy-related emissions to below zero to compensate for the hard-to-avoid emissions from agriculture and industry (Marcucci et al., 2022).

Results show that sectors like transport and heating can be largely electrified and that total electricity demand can be covered with renewable electricity generation (Figure 4). Applications that are harder to electrify like long-haul freight transport, aviation and high-temperature applications in industry can be supplied by bio- or synthetic fuels. Due to the electrification, the yearly net electricity demand ranges between 80 – 100 TWh in 2050, compared to today's 60 TWh (SFOE 2022b). Although the expected future electricity demand is significantly higher than today, this is more than compensated by a reduced use of fossil fuels. This is mainly because there are less conversion losses and although energy service demand increases, overall energy demand decreases (Figure 5). The main technologies that are used to supply electricity are hydropower, solar, wind, wood, waste and gas/biogas with carbon capture and storage (CCS). Considering the various assumptions (for the full set of assumptions refer to Marcucci et al., 2022) and limitations of the models (e.g. technological change and future cost reductions of low-carbon technologies are difficult to predict, see also Section 4.6), this gives an indication that it is possible to electrify most of our energy applications and that most of this electricity can be supplied by renewable sources. Depending on the level of integration within the European electricity market, Switzerland can satisfy part of its electricity demand through imports. In the scenarios with limited electricity imports, all models find that it is possible to supply the demand by replacing electricity imports with imports of natural gas (using CCS), biogas or hydrogen.

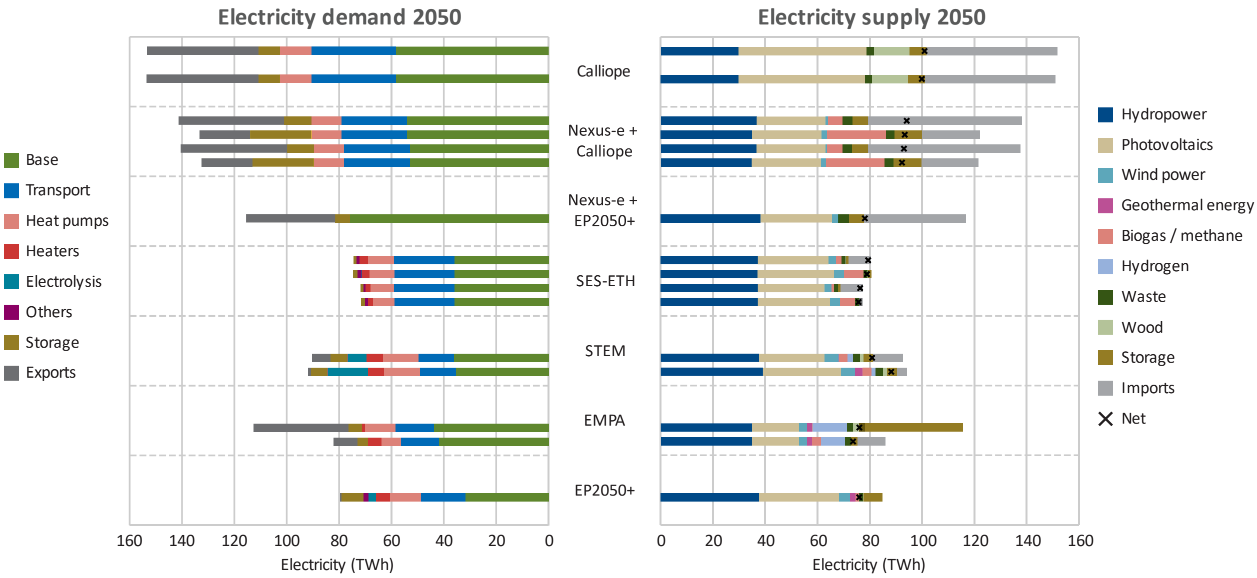

Figure 4. Model results of yearly electricity demand (left) and supply (right) in 2050 of the four scenarios. Scenarios were analysed with the SES-ETH (SWEET-CROSS, 2022), Calliope (Pfenninger & Pickering, 2018), Nexus-e (ESC 2023), STEM (PSI 2023) and the EMPA (Balmer et al., 2022) energy system models. EP2050+ refers to the ZERO Basis scenario of the Energy Perspectives 2050+ (SFOE 2021a). Nexus-e + Calliope and Nexus-e + EP2050+ refers to Nexus-e using assumptions from the Calliope model or the Energy Perspectives 2050+, respectively.

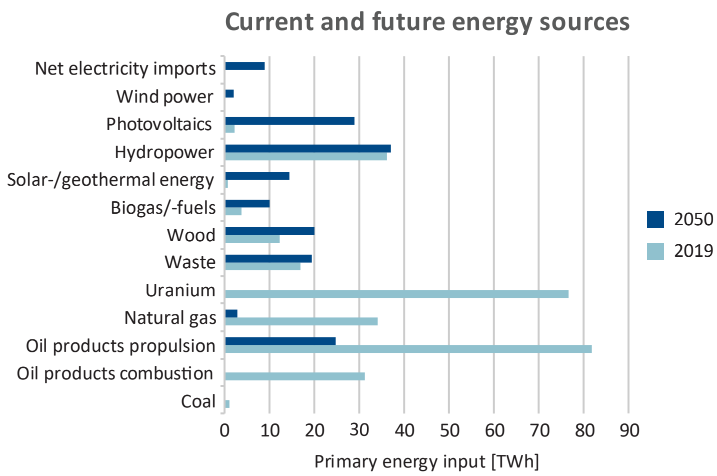

Figure 5. Energy sources in 2019 (SFOE 2020) and 2050 (Guidati & Marcucci, 2023) calculated with the SES-ETH (SWEET-CROSS, 2022) energy system model.

A similarity across all models and scenario results for the future Swiss energy system is that electricity trading with European neighbours remains important. As mentioned earlier, net imports are required mainly during the winter half year (October to March), whereas during the summer half year (April to September) there are net exports, as the Swiss electricity supply peaks in summer while electricity demand peaks in winter. By 2050, with increasing demand due to the electrification of heating and transport and a strong focus on scaling up investments in rooftop PV, net imports in winter might even increase. As it is unclear to which extent electricity imports remain possible in the future, it is important to consider further increasing inland generation. Here, alpine PV (see Section 5.1) and wind power could be part of the solution as they generate half respectively two thirds of their electricity in the winter months. Furthermore, seasonal storage such as heat storage could reduce demand for electrified heating (see Section 4.5) during the winter months. Yet, from a technical standpoint, Switzerland will most likely also be able to import electricity in winter because scenarios for the neighbouring countries based on their respective energy strategies illustrate a different path to net zero emissions than in Switzerland (Figure 6). While PV will also be an important building block in the neighbouring countries, wind and nuclear power constitute major shares of their production.

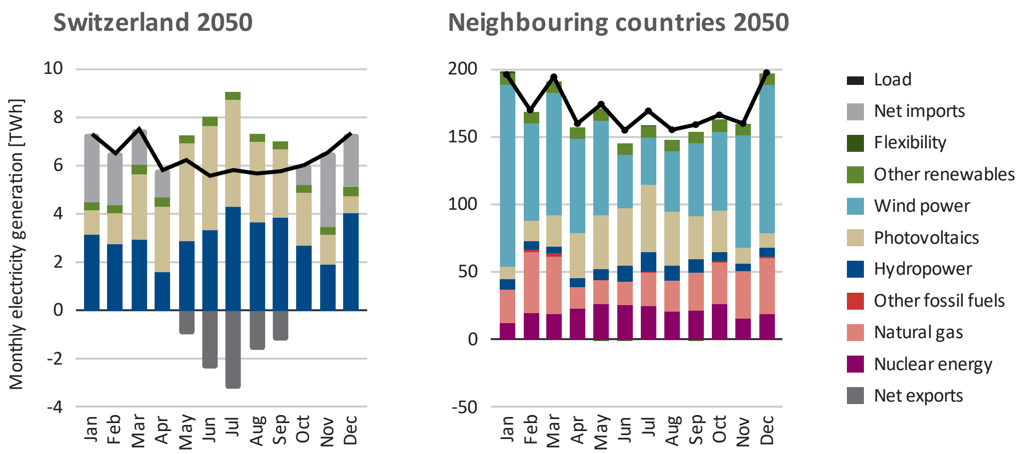

Figure 6. Scenario results of monthly electricity generation and load in Switzerland (left) and in neighbouring countries (DE, IT, FR, AT, aggregated; right) in 2050. Data source: Nexus-e scenarios (ESC 2023).

4. Energy security in a decarbonized system

From a technical perspective an energy system that does not emit GHGs and thus complies with set Swiss climate goals seems feasible. However, what does this mean in terms of energy security? In the following section, the term energy security is first defined and then the most important factors are discussed in the context of a net zero energy system.

4.1. What is, and isn't, security of supply

Most government agencies, including the International Energy Agency (IEA) and the Swiss Federal Office of Energy (SFOE), define energy security as the uninterrupted availability of desired forms of energy to consumers at an affordable price (IEA 2023; SFOE 2023d). Both elements – continuity and price – are important, as together they enable energy users to make long-term plans about their use of energy.

Most assessments suggest, as we do here, that a fully decarbonized energy system will be marked by a high share of electrification – such as heating and ground transportation – and a high share of intermittent renewable power generation, namely from wind and solar. In this type of system, unlike one dominated by easy-to-store fossil energy carriers, a major challenge to achieving high levels of energy security is to plan the type and location of energy supply infrastructure to match fluctuations in electricity production at the system level as closely as possible to fluctuations in demand levels. This reduces the need for excess generation capacity or energy storage – especially seasonal energy storage – as these decrease the efficiency of the system and impose high additional costs.

The primary approach lies in diversification. At a first order, this requires attention to the relative capacities of solar, wind, hydropower as well as other options such as biomass and waste combustion. Beyond this, however, geographic diversification can also play an important role. The balancing of intermittent supply sources (e.g. wind or solar power) over areas larger than synoptic weather regimes (roughly 500 km in diameter) can greatly reduce the variance of these sources (Grams et al., 2017; Pfenninger et al., 2014). For example, during days and weeks when wind speeds are strong over the North Sea, they are weak over the Balkans, and vice versa. By reducing supply variance, the need for energy storage can in turn be minimized, affecting affordability of energy security. For Switzerland, a country smaller than synoptic-scale weather events, this necessarily implies a certain level of international cooperation.

In the media, however, energy security is often equated with domestic production, and hence the absence of import dependence. Interviews have revealed that most Swiss energy consumers consider domestic production of electricity to be the factor most relevant for energy security (Blumer et al., 2015). Popular accounts from other countries suggest this to be a belief not limited to Switzerland. Two assumptions appear to underlie it. First, that energy coming from closer to home, such as from within Switzerland, in the case of Swiss energy consumers, is more likely to be there when needed. This assumption is in line with results from a recent survey, showing that the support for accelerating domestic solar and wind power deployment rose by almost 30% due to the Russia-Ukraine war and related uncertainty about oil and natural gas supply (Steffen & Patt, 2022). The common assumption is, that political decisions in other countries are likely to ignore the energy security needs of Swiss consumers, and may take actions that undermine those needs.

The disruption of natural gas deliveries following the war in Ukraine is an example of these latter concerns playing out. It is relevant to ask whether such events are frequent, and whether they are likely to be more or less frequent in the case of international trade of renewable electricity, compared to trade of fossil fuels such as oil and natural gas. A 2012 study completed by researchers later affiliated with ETH Zurich examined this, specifically the replacement of natural gas as an energy source by power production with renewable electricity sourced from the Middle East and North Africa (MENA) region (Lilliestam & Ellenbeck, 2011). Concerning the vulnerability of infrastructure to terrorist actions, the study concluded that the relative decentralization of renewable power generation infrastructure, compared to natural gas terminals, made it an unattractive target. Similarly, transmission lines can be repaired far more quickly than natural gas pipelines, typically within days to weeks rather than months. Concerning the likelihood of state-supported supply interruptions, the results suggest that such events would be rare, except in cases where importing countries are highly dependent on supply from a single exporting country, as in the recent disruption of gas exports from Russia to Germany. Moreover, the study found disruptions to be rarer still in the case of electricity trade. One reason is the relative ease with which power can be rerouted throughout the grid, compared to rerouting oil or gas flows. That means that an importing country can quickly compensate for a loss of supply from one of its power source countries. The other reason is the permanent loss of revenues when electricity derived from wind and solar is not exported. For oil and gas, by contrast, the resource stays in the ground, and can be exported later.

In short, availability, affordability, diversification, import independence and infrastructure reliability are important parameters for assessing energy security. The most important characteristics of a net zero energy system that influence these parameters are elaborated below in order to evaluate if decarbonization enhances the degree of energy security or at least sustains it at similar levels as today.

4.2. International energy exchange

Diversifying the energy supply sources and being integrated into a region that is larger than synoptic weather patterns can greatly enhance the continuous availability of energy. For a small country such as Switzerland, this means having access to international energy and electricity markets, which requires functioning political interactions and agreements.

In fact, the energy systems in the various countries in Europe have developed into their current form with intense international trade because different countries have different natural conditions and resources leading to synergetic availabilities of energy. Such a system coordinated across national borders reduces overall needed capacities, improves efficiency and reduces overall system costs (Tröndle et al., 2020).While many countries in Europe currently plan to transition their energy supply systems in order to become net zero by 2050, the developed strategies are highly dependent on the specific countries. Consequently, there are synergies between the resources in Switzerland and neighbouring countries that can be used to balance daily and seasonal supply discrepancies. But in order to take advantage of these mutual benefits, international coordination is needed; hence, it is much less of a technical issue than a political one.

Looking specifically at security of electricity supply, a recent study confirms that import capacity and overall European development play a major role (SFOE 2022a). Scenario simulations show that if hydropower and import capacity interact well, even major supply bottlenecks on the Swiss or European side remain uncritical for the local supply situation. This is due to the underlying hourly, daily and seasonal system dynamics, which allow Switzerland to maintain a secure supply in an interplay of imports and exports of hydropower generation (in the critical hours), while at the same time supporting the European supply situation. It is only when import capacities are severely restricted that the possibility of local supply problems arises. To maintain this mutually beneficial system in operation, Switzerland must be well integrated into the European electricity market.

Another political aspect that has a major impact on Switzerland’s current and future import and export situation is the so-called "70% rule" in the EU Clean Energy Package. The 70% rule requires EU member states to make at least 70% of the capacity of their network elements available for trade between EU member states, which can lead to increased trade within the EU. As

Switzerland is not an EU member state, the Swiss critical network elements are not included in the capacity calculation within the flow-based market coupling within the Central Western European (CWE) electricity market region. If Switzerland's neighbouring countries have problems complying with the 70% rule, there is a risk that they will unilaterally limit cross-border capacities in order to comply with the rule for intra-EU trade. They will then have to temporarily relieve their internal network at the expense of export capacities to Switzerland. This will potentially massively reduce Switzerland's import and export capacities without Switzerland being able to counteract. This could have a negative impact on Switzerland's security of supply, especially in the winter months, as Switzerland is and probably will remain dependent on electricity imports during the winter. An efficient integration of the Swiss energy system into the European energy trading system is thus one of the most effective measures for energy security.

4.3. Fossil fuel dependence

As expounded in Section 4.1, electricity grids are less vulnerable to international disruptions compared to fossil fuel infrastructure. This indicates that reducing the reliance on fossil fuels is a factor contributing to security of supply. When taking the whole energy system into account, results from analysing the same scenarios as introduced in Section 3 (Marcucci et al., 2023), show that imports of fossil gasoline and diesel can be reduced to zero mainly due to the electrification of the majority of the transport as well as heating sectors. The use of fossil fuels for heat provision could be almost completely avoided by switching to heat pumps, solar and geothermal energy for low temperature applications and by using high value energy carriers like wood or waste for high temperature process heat in industrial applications (Guidati & Marcucci, 2023). Some freight transport may be covered by hydrogen that is either imported or produced domestically by steam methane reforming with CCS or electrolysis with renewable electricity. Imports of fossil kerosene will likely still be needed and gradually replaced by synthetic sustainable aviation fuels (SAF). The production of all needed SAF in Switzerland is not a realistic option. It would require a four-fold higher PV generation or hydrogen/electricity imports at a scale similar to the current 60 TWh electricity demand (Guidati & Marcucci, 2022).

Imports of oil and natural gas for the purpose of heating and domestic hot water production could also decrease to zero due to the switch to heat pumps, the strong expansion of district heating networks fed by large heat pumps, waste to energy plants or wood combined heat and power (CHP) plants as well as the use of wood in buildings that are not suited for heat pumps. Some natural gas (or bio / synthetic natural gas) or hydrogen might still need to be imported for the purpose of CHP generation in the winter months. Alternatively, the extra electricity demand in this period could be satisfied by net electricity imports. Overall, model results indicate that imports of oil products decrease from today's 120 – 130 TWh per year to 20 – 25 TWh per year, mostly for kerosene (Guidati & Marcucci, 2023). Today natural gas imports amount to 30 – 35 TWh per year. This may remain unchanged in a scenario without net electricity imports, whereas natural gas imports also decrease significantly to 0 – 10 TWh per year with electricity trade.

In terms of energy security this means that transitioning to local renewable energy sources can decrease Switzerland's reliance on importing fossil fuels and associated international supply shortages as witnessed in 2022 with the ongoing conflict in Ukraine.

4.4. Electricity infrastructure

Expanding and integrating more renewable sources means that the electricity grid will be the critical element of the future energy system. From a technical perspective, a very important aspect of security of electricity supply is to ensure that the grid will be able to deliver the produced electricity particularly from remote areas, e.g. alpine regions, to end users. Therefore, it is crucial to plan grid expansion and the integration of increased renewable generation in a coordinated manner.

While energy security impacts the long temporal scales of seasons, months and weeks, the issue of electric power security concerns the safe and reliable delivery of electricity in the temporal scale of hours, minutes and seconds. From a technical perspective, security of electric power supply depends on the ability of the electricity system and infrastructure to deliver electricity to consumers continually. Data of blackout events across Europe from the past 30 years reveal that most of the large-scale blackouts result from cascading failures (Stankovski et al., 2022). Cascading failures are initiated by single or multiple failures of grid assets such as power lines and transformers. In fact, weather-induced damages to these components have the highest contribution to blackouts. Some of the most well-known events, i.e. the 2003 Italian blackout, 2006 European grid splitting, 2021 European grid splitting resulted from a single grid asset failure.

In a future power system with high shares of renewable electricity generation, it is likely that the risk of blackouts will increase. This can be attributed to the volatility of renewable energy sources, which demand for additional flexibility and affect the loading patterns of the grid assets. Current analyses of net zero scenarios with focus on Switzerland embedded in the European electricity system, support these concerns. Remarkably, with moderate investments in transmission capacity (power lines and transformers), the system maintains (technical) security to levels similar to past years (ESC 2023). To reduce the risk of blackouts, coordinated planning of grid infrastructure extension is indispensable.

4.5. Energy storage as part of a secure energy system

Switzerland's geographic suitability for PV power generation means that it will likely continue to rely on net electricity imports in winter months to balance daily and especially seasonal discrepancies between generation and use of electricity. Along with international electricity trade, various storage options of different energy forms can help counter these imbalances and thus enhance the security of the energy system. The analysed scenarios show that Switzerland will need various types of storage that complement each other (Guidati & Marcucci, 2023).

On a daily scale, the most important storage option is pumped hydropower plants. They charge electricity by pumping water from a lower to a higher storage lake, and can discharge by reversing the process and running water through a turbine. Moreover, stationary batteries are becoming increasingly viable: especially the cost of lithium-ion batteries has dropped immensely, so that they are now an economically attractive solution for short-term electricity storage (Beuse et al., 2020). Such storage options can absorb high PV power generation at noon and release it in the evening when the demand by the end user is high (for BEV charging, household appliances, etc.). Even batteries in BEVs can be used in the same manner, so called vehicle-to-grid (V2G), and reduce grid stress by shifting demand and thus lowering the need for overnight electricity imports (Di Natale et al., 2021; Liedekerke et al., 2023). Complementary to this, flexible hydropower plants with large reservoirs can balance PV production by operating exactly opposite (turning down during the day and up during the night).

Large hydropower reservoir lakes can also support seasonal balancing, meaning storing energy in summer (when PV production is high) and using it in winter. Other seasonal storage options include large thermal energy storage, gas storage (bio-methane, synthetic methane or hydrogen), synthetic liquid fuels and possibly waste. In Switzerland, hydropower reservoirs are and will remain the most important seasonal energy storage (see also Section 2). Other options such as seasonal thermal energy storage coupled to heat pumps are still limited, despite their technology readiness (Forum Energiespeicher Schweiz, 2022). Seasonal thermal storage can accumulate heat in summer, which can be released again in winter for heating purposes, thus effectively reducing electricity demand for heating. Biogas production and storage in gas caverns as well as waste storage at waste-to-energy plants can supply energy for the heating sector in winter as well.

However, the storage options described above will probably not be able to fully flatten Switzerland's net demand curve (Guidati & Marcucci, 2023). Therefore, an essential measure is efficient access to the international energy markets, especially electricity, natural gas and in the future possibly also hydrogen. Alternatively, surpluses in summer could be further exploited through other seasonal storage (e.g. power-to-X), but this would call for the installation of more renewable energy sources in Switzerland such as PV, conversion technologies such as electrolysis or methanation and long-term storage facilities for hydrogen and/or synthetic gas (Kober et al., 2019).

4.6. Cost and benefits of the energy transition

Under the assumption of reaching high levels of energy security, several techno-economic models of the Swiss energy system estimate the costs that will ensue from transitioning to a net zero energy system (Balmer et al., 2022; Guidati & Marcucci, 2023; SFOE 2021a). Model results indicate that the energy transition will increase system costs from anywhere between CHF 380 and CHF 600 per capita per year: CHF 380, average value of all four scenarios, discount rate 1.6% (SFOE 2021a); CHF 417, average value of all nine scenarios, discount rate 2.5% (Marcucci et al., 2023); CHF 400 – 600, discount rate 2.5% (Guidati & Marcucci, 2023). Only one recent study estimates overall cost savings (Balmer et al., 2022). All models show that the possibility of importing electricity from neighbouring countries, especially during high-demand hours in winter, is essential for minimizing costs. Substituting imports with Swiss generation to guarantee an even higher level of security is technically possible, e.g. by adding alpine solar PV (see Section 5.1) or wind, but will likely be costlier.

The resulting range in the estimates of future cost is due to the different assumptions of the models relating to e.g. availability and costs of future technologies, fuel inputs, import and export possibilities, and the flexibility of the demand side. This implies that a change in the assumptions will influence the values of the cost estimates. Therefore, these results can provide an idea of potential future developments but should be interpreted cautiously. Furthermore, all these studies are subject to three key limitations. First, technological change and future cost reductions of low-carbon technologies are hard to predict. Historically, most energy-economy models have overestimated the cost of renewable energy because learning effects have yet to be considered sufficiently. Consequently, decarbonization cost estimates are subject to considerable uncertainty, and experience suggests they might rather err on the high side (Way et al., 2022). Second, only partial equilibrium effects are considered. This means for example, that positive effects on employment and income determined by an increase of the activities related to the insulation of houses and the installation of heat pumps and solar panels, are ignored. At the same time, negative employment effects on workers in the fossil fuel industry are also often ignored. Third, co-benefits of replacing fossil fuels with renewable alternatives are completely ignored. For instance, such co-benefits include the reduction of air pollution, increased biodiversity, enhanced soil and water quality and improved energy security (Karlsson et al., 2020). Among these, negative health effects of air pollution is probably the costliest from a societal perspective (Vandyck et al., 2018). If monetized, the co-benefits from mitigating climate change might fully offset or even exceed the costs of decarbonization at a global level (Karlsson et al., 2020).

5. Options to expand electricity generation

From the analysis so far, it is clear that efficient electricity trade will be an important pillar in transitioning to an energy system based primarily on renewable sources. Especially in winter, Switzerland will probably remain a net importer of electricity to compensate for less hydropower availability and higher heating demand. Other technologies can be further expanded to assuage the need for winter imports like seasonal storage (see Section 4.5) or by increasing electricity generation capacities. Different PV systems and nuclear power are currently being discussed in Switzerland as a means to increase electricity security when it relies most heavily on imports (i.e. in winter). The potential for these is assessed in the following.

5.1. Rooftop and alpine PV

In the scenarios of the model comparison (see Section 3), there is common agreement that PV systems will be central for the future Swiss electricity supply. In these scenarios, PV accounts for 25 – 30 TWh of electricity generation per year (Marcucci et al., 2023). Results suggest that rooftop PV will take up the largest share. Already, the additional installation of PV in the past year is expected to be more than 1 GW of peak power (Swissolar, 2023), contributing approximately an additional provision of 1 TWh per year of electric energy. The advantage of rooftop PV is that it does not require additional land use and is close to existing electricity infrastructure and demand. Moreover, the potential of rooftop PV is large, with estimates between 15 – 53 TWh (Moro et al., 2021; Walch et al., 2020). The commonly quoted value of around 53 TWh is based on the national project known as “Sonnendach” (Figure 7). To achieve 53 TWh with rooftop PV, around 70% of all rooftops would have to be fully covered with PV panels.

Despite its potential, rooftop PV faces a few challenges. Only 20 – 30% of its electricity generation happens in the winter half of the year and its adoption has many barriers such as comparably high upfront costs for individuals and the landlord-tenant dilemma. Another challenge concerning household rooftop PV in Switzerland is the extreme policy fragmentation. This affects multiple facets of regulation and the electricity market, including varying building permitting rules (municipal level), tax rules (cantonal level), subsidies (cantonal and municipal level), electricity prices and tariffs for PV electricity fed into the grid (both at the level of the distribution utility). This patchwork results in a strong variance of the expected profitability of PV installations for households (Schmidt et al., 2023). On top, both the electricity prices and feed-in tariffs fluctuate annually, inducing a high risk for households/investors. The proposal to provide a Switzerland-wide minimum feed-in tariff can help address some of these issues, if it is fixed for a 15-20-year period and is high enough. Besides this, a harmonization between cantons and municipalities is strongly recommended (Schmidt et al., 2023).

Ground-mounted PV systems in alpine regions can address both challenges and could thus be an important complement. Up to 55% of alpine PV electricity generation occurs in winter (Anderegg et al., 2020) and sites are financed and installed by larger investors with lower adoption barriers. Current estimates show that the potential for alpine PV ranges between 45 – 300 TWh (Dujardin et al., 2022; Meyer et al., 2023). If only areas close to existing infrastructure such as ski areas and hydropower dams are considered, then the potential decreases substantially to 5 TWh per year, of which 2-3 TWh are produced in winter. This would require covering less than 30 km^2 (equivalent to 0.1% of the geographical area of the Swiss Alps) with winter-optimized PV panels (Figure 7).

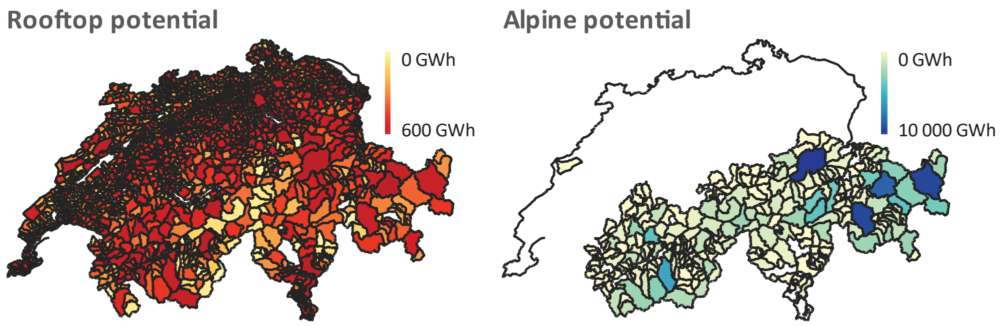

Figure 7. Distribution of rooftop (left; data source: SFOE, MeteoSwiss and Swisstopo 2023) and alpine PV (right; De Ferrars, 2023) potential in Switzerland.

Costs for rooftop PV comprise hardware (i.e. PV modules, inverters) and installation costs. Hardware costs are global commodities. Installation costs typically do not scale with PV size, making larger rooftop PV systems cheaper per kWp than smaller ones. Prices for rooftop vary mostly between CHF 800 per kWp and CHF 2800 per kWp (Bauer et al., 2019). For alpine PV, costs also comprise the construction costs for the supporting construction and grid extension. No ground-mounted alpine PV plants have been realized yet.

Given the significant investments needed for a rapid build-up of solar PV, it is important to understand which investors would need to commit capital. Until now, rooftop PV on residential houses and industrial facilities made up the lion share of newly installed capacity in Switzerland, with an average size of approximately 10 kWp (single house) to 130 kWp (industrial rooftops) (SFOE 2021b, 2022d). According to a recent study, for projects from 20 kW upwards, local utility companies are the primary investor, mainly financed directly via their balance sheets (Dukan & Steffen, 2023). Due to generally smaller project sizes, project financing is a less frequent form of finance for solar PV in Switzerland. At the same time, households provide a significant share of capital for smaller installations, frequently coupled with bank loans for household renovation. As introduced above, ground mounted alpine PV plants, e.g. in the range of 10 MW and larger, are a significant emerging market. Such larger project sizes attract balance sheet financing from utility companies, and project finance e.g. including pension funds. Therefore, many different investor types are expected to finance the Swiss energy transition. Larger utilities and financial investors have significant liquidity and actively seek domestic investments that fit their risk and return profile. The availability of capital is most likely not a barrier in Switzerland; rather, the large-scale deployment of solar PV is an opportunity for various domestic financial actors.

5.2. Nuclear power

At the moment nuclear power contributes approximately 30 – 40% to Swiss electricity generation (SFOE 2022b). Considering that nuclear power plants do not emit GHGs during operation, nuclear power can support reaching net zero climate goals. Yet there are other serious challenges associated with nuclear energy like risks of nuclear catastrophes, nuclear waste storage and dependence on uranium imports. In Switzerland, following the reactor disaster of Fukushima in 2011, the Swiss Federal Council and Parliament decided on a progressive withdrawal from nuclear energy production. This includes shutting down the existing five nuclear power stations at the end of their technically safe operating life and prohibiting the construction of new nuclear power plants (NPP). Following up on Parliament's decision, the Swiss population voted for the Energy Strategy 2050 in a 2017 referendum, which includes the gradual phase-out of nuclear power and instead a greater reliance on hydropower and other renewable sources. However, due to a 2016 referendum, there are no limits imposed on the operating lifetime of NPPs. The timing of the decommissioning of the Swiss nuclear power stations is therefore not defined.

Currently there are four nuclear power stations in operation in Switzerland: Beznau 1 and 2, Goesgen, and Leibstadt (Table 1). These reactors have a combined capacity of 3 095 MW. In 2022, they generated 23 TWh and were responsible for approximately 36% of total Swiss electricity generation (SFOE 2023c). The reactors will be allowed to remain in operation as long as the Swiss Federal Nuclear Safety Inspectorate (ENSI) considers them safe. Most scenarios (see Section 3) expect a runtime of 60 years for the reactors currently in operation. ENSI's periodic safety review (PSR) is conducted every 10 years to identify safety-relevant plant modifications. For example, based on the PSR in 2021, ENSI concluded that the safety requirements at both Beznau reactors are satisfied, so that they can remain in operation for the next 10 years. A 10-year license was also granted for the Mühleberg reactor in December 2009, but required substantial safety-related upgrades. BKW, the operator of the Mühleberg NPP, spent CHF 200 million on safety upgrades, yet finally decommissioned the reactor in 2019 (three years earlier than initially planned) based on their techno-economic assessment.

The extension of the runtime of an NPP has a substantial impact on the Swiss electricity system, as they have a very high utilization rate. In a system with high shares of solar PV, nuclear reactors provide electricity also in hours with low solar irradiation, making it especially useful for reducing required winter imports.

Table 1. Overview of Swiss nuclear power plants

Reactor unit	Status	Capacity [MW]	Commercial operation since	Expected operation until	
				50-year lifetime	60-year lifetime
Mühleberg	decommissioned	390	1972	2019	
Beznau-1	in operation	380	1969	2029*	2029
Beznau-2	in operation	380	1972	2032*	2032
Goesgen	in operation	1060	1979	2029	2039
Leibstadt	in operation	1275	1984	2034	2044

*already extended to 60 years lifetime

Analysing the possible impact of a 50-year vs. 60-year lifetime (considering the already planned lifetime extension of Beznau 1 and 2 in the 50-year scenario) on winter imports for the years 2030, 2040, and 2050, indicates that winter imports can be reduced from 4 TWh to 2 TWh in 2030 and from 9 TWh to 5 TWh in 2040 (Figure 8). Winter imports in 2050 would remain unchanged as even under an expected lifetime of 60 years, the last reactor would be decommissioned beforehand (i.e. Leibstadt in 2044). However, there are even discussions that the two newer units Goesgen and Leibstadt could even run up to 80 years. This would reduce the required imports up to 2064.

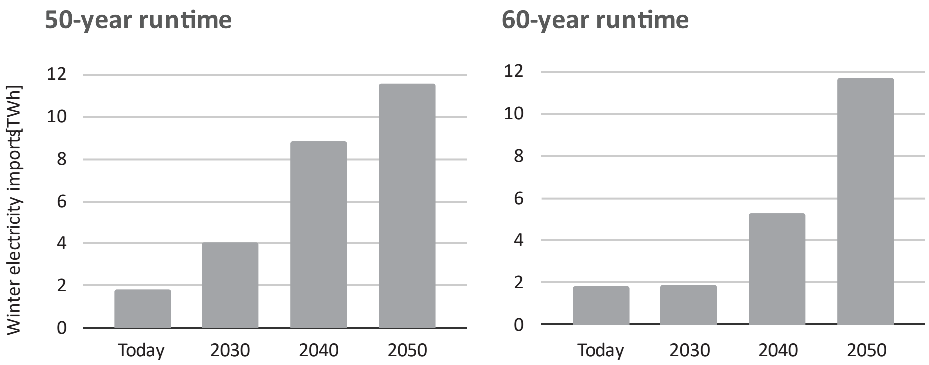

Figure 8. Impact of runtimes of nuclear power plants on winter imports in scenarios with a 50-year (left) and 60-year runtime (right). Data source: Nexus-e scenarios (ESC 2023).

However, modernization and safety upgrades to fulfil the requirements set by ENSI are costly. Since the start of operation of Beznau-1 and -2, more than CHF 2.5 billion had to be invested in the safety and reliability of the two plants (Nuklearforum Schweiz, 2022). To continuously modernize and increase plant safety, the operator Axpo will invest CHF 0.7 billion between 2019 and 2029. Similar, for the renewal and safety of the Leibstadt plant, Axpo has invested CHF 1 billion since 2010. It is important to note that whether such investments are made is a financial decision made by the plant owner. Simplified, if expected revenues over the next years are higher than the expected costs for required upgrades, then these upgrades are conducted and the lifetime extended. In 2019, similarly, it was decided to decommission the Mühleberg NPP because expected revenues (with low electricity prices at that time) were too low to cover investments costs. While required investments into modernization and safety upgrades are plant specific, the mentioned historical examples indicate that an extension of one reactor by 10 years costs around CHF 1 billion.

Currently, there are pushes to reverse the ban on new NPPs. Besides finding a suitable location and investors, the main challenges are uncertain construction costs and time. There are three new NPPs under construction in Central Europe with estimated costs ranging between $7 600 – 12 600 per kWp (Rothwell, 2022). All units are already exceeding the initial planned budget. Outside of Europe, construction costs are substantially lower such as $2 000 per kWp in Korea and $3 200 per kWp in China. Furthermore, when it comes to the construction time, projects in Europe take much longer compared to the global average of 7.5 years (IAEA 2023). In April 2023, Finland's Olkiluoto 3, the first new NPP in Europe in 16 years, began regular output after 18 years of construction (Lehto, 2023). Other European NPPs have been under construction for 16 years (France) and 5 years (UK) (Rothwell, 2022). For Switzerland, it can be expected that new NPPs would follow European examples in terms of construction costs and time. Therefore, they could only be realistic options for Switzerland past 2040, more likely even past 2050. It is thus important to note that new NPPs in Switzerland do not substitute the required rapid expansion of quickly available capacities such as solar PV in the near to mid-term. Furthermore, in a highly renewable dominated system, NPPs will likely not be able to continue baseload operation, but would have to be run much more flexibly, further increasing their cost per kWh.

In a nutshell, a longer runtime of existing NPPs can be a cost-effective option to lower required imports in winter and help reach climate goals by 2050. New NPPs come with techno-economic uncertainties but could be a feasible option for Switzerland most likely past 2050.

6. Conclusions

The next years will be crucial to set Switzerland on the path to transforming its energy system away from fossil fuels and towards renewable energy carriers by 2050. This is a great challenge, but urgent to make its contribution to mitigating climate change. At the same time, having a secure and continuous supply of energy for all activities of a modern life is indispensable. This White Paper has laid out the most critical factors for attaining climate neutrality and energy security of the Swiss energy system. This is based on a recent model comparison study, in which five independently developed models simulated four different net zero scenarios, along with other current scientific insights on the topic. The results of the models indicate that a net zero energy future for Switzerland is possible and, depending on the assumptions, this path can rely almost entirely on electrifying the energy system and/or also switching some applications to hydrogen and synthetic fuels.

However, reaching this objective requires certain conditions, namely efficient – on a technical and regulatory level – electricity trade with the EU, a fast roll-out of renewable energy infrastructure and generation capacity as well as similar developments beyond Swiss borders. This will help sustain synergies between the different European energy systems that have developed due to different national resource availabilities. Furthermore, it will lead to a significant reduction of the dependence on fossil fuel imports, which come from outside of Europe, and thus reduce the risk of supply disruptions as unfolding now with natural gas deliveries from Russia to the EU. Based on the commonly used parameters to assess energy security, these same conditions will also maintain energy security at similar levels as today.

This transformation is technically feasible, but will also come at a certain price. Based on the most recent studies, it is difficult to say how high these costs will be or if these changes will even result in cost savings. However, it is clear that decarbonizing the energy system will also provide society with many benefits like higher air, water and soil quality, increased biodiversity and food security. Monetizing these benefits would perhaps shift the way we perceive the economic feasibility of the energy transition.

Building on renewable sources for the future energy system and dramatically modifying how we provide and use energy services, will not happen overnight and time until 2050 is running out. The challenge of making the conditions that are suggested herein a reality is much less a technical matter than a political one. In particular, a long-term and binding agreement for Switzerland to be able to trade electricity with the EU is a political issue that should have top priority if we are serious about climate targets. Similarly, speeding up the expansion of renewable energy sources requires political boundary conditions that accelerate permit and approval processes as well as support investment and financing. At the same time research and development is also needed to improve efficiency and progress current and new technologies to harness renewable energy. And lastly, the public has to approve of and help promote this transformation. For this, access to reliable and comprehensible science-based information is essential as well as education and raising awareness.

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Expert Groups

The Expert Groups is an initiative by the Energy Science Center of ETH Zurich to address current hot topics in the energy sector and consolidate research insights for stakeholders outside academia. The goal is to offer practical, feasible and added-value recommendations for integrating knowledge and know-how into different sectors to promote the energy transition. Expert Groups do not conduct research, but rather gather established findings and synthesize conclusions. Topics are dealt with from a technical, policy, economic (markets and finance) and regulatory perspective. Expert Groups addressing specific issues are convened on demand depending on the developments in the energy sector and in politics.

Security of Supply

The Expert Group "Security of Supply" deals with topics that concern the entire energy system including the electricity grid, energy storage and sector coupling. It is made up of experts that represent the mechanical and electrical engineering sciences as well as climate finance and policy.

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