sweet swiss energy research for the energy transition

PATHFNDR

On the Path to Net Zero

10 Statements on Sector Coupling and Flexibility for the Swiss Energy Transition

Synthesis Report

A report of the PATHFNDR Consortium

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On the Path to Net Zero: 10 Statements on Sector Coupling and Flexibility for the Swiss Energy Transition

Synthesis Report

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Disclaimer:
This report primarily presents research conducted within the PATHFNDR project, but includes selected external references where relevant to support, contextualize, or complement the findings. Detailed literature reviews can be found in the referenced papers and reports.

This report presents scenario-based results for Switzerland's energy system to 2050. These are projections, not forecasts or predictions. They arise from empirical data and system modelling using least-cost optimization under the stated assumptions. Results depend on input data, socio-economic and technological assumptions, and methodological choices. They should therefore be interpreted as indicative "best estimate" values rather than precise figures, given uncertainties in technology uptake, prices, and regulation. The authors are responsible for the analysis and its interpretation.

AI tools have been used to assist in correcting grammar and style, as well as to rephrase certain sections for improved clarity and readability. The authors take full responsibility for the content of the final publication.

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Acronyms

ADN Active Distribution Network. 28

ATES Aquifer Thermal Energy Storage. 18

BESS Battery Energy Storage System. 23

BTES Borehole Thermal Energy Storage. 18

CDR carbon dioxide removal. 13

CRM Critical Raw Material. 12

DACCS Direct Air Carbon Capture and Storage. 11, 17, 31

DSO Distribution System Operator. 32, 33

ElCom Swiss Federal Electricity Commission. 37

ENTSO-E European Network of Transmission System Operators for Electricity. 16

EPEX SPOT European Power Exchange. 27

EV electric vehicle. 6–13, 15, 17, 19–25, 30–33

FCfD Financial Contracts for Difference. 29, 30

FOEN Federal Office for the Environment. 35

HP heat pump. 6, 7, 9, 11–13, 15, 17–25, 30–33

LV Low-Voltage Grids. 23

MV Medium-Voltage Grids. 23

P2H2P Power-to-Hydrogen-to-Power. 18

PTES Pit Thermal Energy Storage. 18

PV solar photovoltaic. 6, 17, 19, 21–24, 33

SAF Sustainable Aviation Fuel. 13, 14

SFOE Swiss Federal Office of Energy. 7, 35

STES Seasonal Thermal Energy Storage. 13, 18

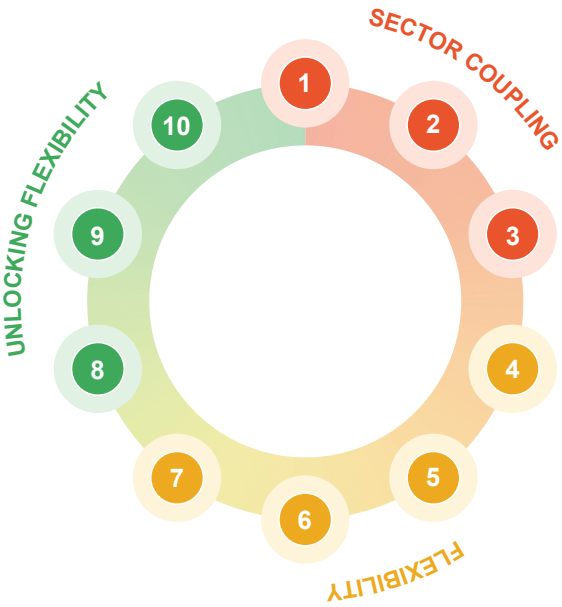
SWEET SWiss Energy research for the Energy Transition. 7

V1G Smart Charging. 21, 22

V2G Vehicle-to-Grid. 21, 22, 32

VOLL Value of Lost Load. 26, 27

The 10 Statements at a Glance



SECTOR COUPLING

1. **Direct electrification** of residential heating and road transport is the key lever for decarbonisation of the Swiss energy system.
2. **Decarbonisation** will strengthen Switzerland's ability to supply its own energy – and vice versa.
3. Switzerland's **demand for low-carbon hydrogen and synthetic fuels is low**, concentrated in industry and aviation, and most cost-effectively met through imports.

FLEXIBILITY

4. **Flexible hydropower infrastructure and electricity trading** are two central sources of flexibility for the Swiss energy system.
5. **Seasonal chemical storage via hydrogen or other synthetic fuels is unlikely** to become economically viable at scale for Switzerland.
6. **Electric vehicles and heat pumps can be major sources** of demand-side flexibility, benefiting the energy system.
7. Taking into account the **end-user demand and generation flexibilities in distribution grid planning** is necessary to reduce the need for distribution grid reinforcements.

UNLOCKING FLEXIBILITY

8. **Dynamic tariffs** are important to incentivise an optimal trade-off between grid-friendly and market-friendly dispatch and investment.
9. Properly designed **renewable support schemes** should provide revenue stability and reduce investment risks while retaining proper incentives.
10. Electric vehicle and heat pump flexibility only scales if **owners accept automated operation** that protects comfort and provides compensation.

Executive Summary

Switzerland's path to a net-zero energy system relies on two mutually reinforcing shifts: (1) the direct electrification of end-use sectors such as heating and transport, and (2) greater energy-system flexibility to balance the variable electricity generation from renewables. Over the past six years, the PATHFNDR consortium, part of the Swiss Federal Office of Energy's SWEET programme, tackled a key challenge of Switzerland's energy transition: figuring out how to increase the share of renewable electricity while transitioning away from fossil-based generation in a context where the future role of conventional baseload generation, particularly nuclear power, remains uncertain. This challenge required researchers to address two interconnected issues: 1) enhancing system flexibility and coordination across sectors, and 2) identifying the changes in infrastructure, markets, regulations, and society needed to enable and support this transition.

To bring together the required expertise, PATHFNDR united eight research institutions and more than 25 partners from the public and private sectors in an inter- and transdisciplinary effort spanning energy-system modelling, engineering, economics, and social science. The research findings were validated with stakeholders and tested through pilot and demonstration projects.

This report synthesises the findings from PATHFNDR into ten guiding statements across three areas: sector coupling (here: the direct electrification of heating and transport), flexibility, and the non-technical conditions needed to unlock flexibility. These ten statements are summarized below.

1. **Direct electrification of residential heating and road transport is the key lever for decarbonisation of the Swiss energy system.**

Replacing fossil-fuelled boilers and combustion engines with heat pumps and electric vehicles is the most cost-effective way to reduce emissions in buildings, low-temperature industrial heat, and road transport. Together, these sectors accounted for approximately half of Swiss greenhouse gas emissions in 2024. Electrification of these sectors also leads to efficiency gains: PATHFNDR models show that energy consumption will decrease by ∼40%, while electricity demand will increase by only 10-20%.

2. **Decarbonisation will strengthen Switzerland's ability to supply its own energy – and vice versa.**

Electrification, or sector coupling, will reduce Switzerland's dependence on foreign energy by at least half because domestic renewable electricity will replace imported fuels. The share of energy imports

– today mainly oil, petrol, and natural gas – will drop from today's 70-75% of total energy consumption to between 0 and 35% in the future.

3. **Switzerland's demand for low-carbon hydrogen and synthetic fuels is low, concentrated in industry and aviation, and most cost-effectively met through imports.**

Hard-to-abate sectors, such as industry and aviation, account for a significant share of greenhouse gas emissions (more than 25%). While direct electrification is also usually the preferred route to decarbonise, these sectors will still partly rely on synthetic and low-carbon fuels. However, the ideal conditions for building a supply chain for these fuels are not present in Switzerland: an abundant and scalable supply of inexpensive electricity, more land dedicated to biomass for fuel or more space dedicated to large synthetic fuel synthesis plants. Provided that Switzerland maintains unfettered access to international energy markets, imports of hydrogen and synthetic fuels will likely be less expensive than production within Switzerland.

4. **Flexible hydropower infrastructure and electricity trading are two central sources of flexibility for the Swiss energy system.**

Switzerland's current system already has domestic flexibility assets and infrastructure that can provide grid balancing. The established flexibility assets are pumped-storage and storage hydropower plants. Together, pumped-storage and storage hydropower offer roughly 10-12 GW of dispatchable generating capacity, exceeding Switzerland's current peak electricity demand of ~9 GW. Hydropower will also remain central to seasonal balancing as peak electricity demand increases toward 12-20 GW by 2050. In addition to its domestic flexibility, Switzerland also benefits from 41 cross-border electricity interconnections, making it a European electricity trading hub. With this infrastructure, Switzerland can use electricity trade as an additional source of flexibility.

5. **Seasonal chemical storage via hydrogen or other synthetic fuels is unlikely to become economically viable at scale for Switzerland.**

Switzerland will continue to face a winter electricity imbalance, but PATHFNDR modelling does not identify large-scale seasonal chemical storage as a cost-effective solution under the investigated assumptions. Existing hydropower assets substantially reduce the need for additional seasonal storage, while residual winter imbalances can be addressed through electricity trading, additional winter generation, industrial demand-side flexibility, bioenergy, and seasonal thermal storage. Bioenergy can support winter electricity supply, but its use must be balanced against competing needs in industry and fuel production. This conclusion is conditional on the availability of cross-border trade and the timely deployment of alternative flexibility resources. The conclusion does not exclude targeted hydrogen applications in strategic reserves or industrial applications, where hydrogen technologies may provide benefits.

6. **Electric vehicles and heat pumps can be major sources of demand-side flexibility, benefiting the energy system.**

Flexible operation of electric vehicles and heat pumps can provide more than 7.6 GW of adjustable load and 5.7 TWh of shiftable energy – comparable to ∼29 days of Swiss electricity use, or 8 GW of gas-fired power plants. This demand-side flexibility can reduce net electricity imports by ∼22%, lower total system costs by ∼4%, and reduce the required system-level battery capacity by 75-95%.

7. **Taking into account the end-user demand and generation flexibilities in distribution grid planning is necessary to reduce the need for distribution grid reinforcements.**

At the distribution level, grid planning that can rely on demand- and supply-side flexibility is crucial: curtailing less than 3% of annual solar photovoltaic energy can cut grid reinforcement investment by roughly 40-60%. Managing solar photovoltaic feed-in is more valuable in rural and semi-rural grids, where installed photovoltaic capacity is expected to be significantly higher than maximum demand (a ratio up to 4). Demand response from electric vehicles and heat pumps can be matched with solar photovoltaic feed-in in all regions but is relatively more valuable in urban grids, where photovoltaic capacity and demand are more balanced (a ratio close to 1).

8. **Dynamic tariffs are important to incentivise an optimal trade-off between grid-friendly and market-friendly dispatch and investment.**

Whether or not the technical potential of the existing flexibility options can be realised depends on market design, investment incentives, and user acceptance. Dynamic electricity prices can guide consumers to use electricity when it is cheap and when the grid has spare capacity by providing a price signal that reflects both the price of electricity production and the price of grid services. When consumers respond to high prices by reducing consumption and to low prices by increasing consumption, the consumer contributes to grid flexibility and balancing. To provide the best result, electricity prices should follow the dynamics of the wholesale market, whereas the grid usage fee should reflect the dynamics of the grid congestion probability. Since these dynamics can shift together or in opposite directions, the overall effect will provide a signal to the consumer. For price signals to be effective on a large scale, measures need to be taken to protect consumers from unpredictable bills and to reduce the burden of participating.

9. **Properly designed renewable support schemes should provide revenue stability and reduce investment risks while retaining proper incentives.**

Investment in renewables must become less risky. Renewable generation is capital-intensive, so financing conditions largely determine the cost of the electricity it delivers, and the risk premia investors require are ultimately borne by consumers. Support schemes are therefore beneficial, but today's schemes pay according to how much a plant produces. This reduces price risk while still exposing investors to volume risk from negative prices and weather, and it can distort behaviour in

short-term markets. Support schemes should instead be designed to provide stable revenues while preserving a clear incentive to produce electricity when it is most needed. Financial Contracts for Difference, which link payments to an established benchmark rather than to actual output, are one design pursuing this aim.

10. Electric vehicle and heat pump flexibility only scales if owners accept automated operation that protects comfort and provides compensation.

Above all, flexibility only becomes accessible if people accept it. Electric vehicles and heat pumps can provide flexibility only if owners do not perceive diminished comfort. Around 70% of consumers take part only if their comfort is unaffected. The design of flexibility contracts is also decisive for participation. When people are enrolled by default and can opt out, about 90% take part; when they must actively sign up, only 20-50% do. Uptake increases when offers are simple, transparent, and trustworthy, with clear consent, easy override, and predictable bills. Complexity for consumers is reduced with clear rules governing several parties with access to the same device.

The full report elaborates in greater detail on the research supporting these ten statements and concludes with recommendations specifically addressed to the federal government, the market and regulatory authority, cantons and municipalities, the transmission system operator, distribution system operators, aggregators and suppliers, technology providers, and consumers and prosumers, whose coordinated action is needed to help Switzerland achieve its emissions targets.

1 Introduction

Switzerland has formally pledged to reach net-zero greenhouse gas emissions by 2050 [86]. Currently, Swiss emissions are dominated by the transport sector (approx. 34%) and the building sector (approx. 22%), both of which rely heavily on imported fossil fuels [24]. A primary strategy for reducing greenhouse gas emissions is through electrification of the heating, transportation, and industrial sectors. This so-called '**sector-coupling**' – where the electricity sector connects to other sectors [71] – would shift primary energy supply from fossil fuels to renewable electricity. For example, heat pumps (HPs) can be used to produce heating and electric vehicles (EVs) can be used for the transportation sector. While direct electrification is an option for these sectors, hard-to-abate sectors such as heavy industry and aviation will have an indirect path to electrification. Hard-to-abate sectors will need to decarbonise using synthetic e-fuels [8]. Deploying synthetic fuels at scale is complex primarily because of the substantial conversion losses inherent in "Power-to-X" processes. To overcome these losses, it is necessary to have ample, inexpensive, clean electricity.

Historically, Switzerland has benefited from a domestic electricity mix that is already low-carbon. By domestic, we mean within Switzerland. The Swiss electricity mix is currently dominated by hydropower (approx. 60%) and nuclear power (approx. 28%) [89]. However, this stable baseline is expected to undergo a fundamental structural shift with the expected phase-out of the existing nuclear fleet and the current law that prohibits the construction of new nuclear plants [87]. To replace this capacity and to meet the growing electricity demand from sector-coupling, the Federal Act on a Secure Electricity Supply from Renewable Energy Sources mandates a massive upscaling of renewable generation, driven primarily by solar photovoltaics (PVs) [85]. These changes in generation supply will result in more variable electricity generation and require more **flexibility** to balance the energy system.

Flexibility refers to the ability of the energy system to manage the variability in the electricity supply and demand at different time scales, from short to long term, by adjusting energy supply, conversion, demand, storage, or trade with neighbouring countries [71]. Over the short term, flexibility can be implemented in the energy system to adapt to the hourly and daily variability of renewables using energy storage options such as batteries and demand-side management techniques such as flexible HP and EV operation. Balancing services from renewable electricity sources such as PV and wind can also provide valuable short-term flexibility. Over the long term, new sources of flexibility need to be implemented. Switzerland faces a growing seasonal imbalance where heating demand peaks during the winter while PV production is at its lowest. This imbalance has been historically mitigated through net electricity imports [57]. However, recent Swiss energy legislation places emphasis on domestic generation and instructs that net winter electricity imports should not exceed 5 TWh [85]. As a result, there is a growing policy push to incentivise more domestic electricity production, to lower demand in winter, and to expand seasonal balancing resources.

Switzerland's hydropower reservoirs can already provide seasonal energy shifting, depending on hydrological conditions. However, existing domestic flexibility resources alone may not be sufficient to meet the growing flexibility needs of the sector-coupled Swiss energy system. In other words,

there is a growing demand and market for alternative sources of flexibility. Therefore, identifying and integrating new sources of flexibility across all timescales is critical for a successful energy transition. From long-term options such as seasonal heat and alternative fuel storage to shorter term options like demand-side management, the technical potential of this flexibility is vast and the market value of it is high. In order to unlock consumer, prosumer, and producer flexibility, it is necessary to establish the corresponding regulatory and social frameworks and to create a coordinated market and contractual arrangements.

Establishing these frameworks is a multi-disciplinary challenge relying on national and international policymaking, long-term capital investments, innovative business models, and evolving societal acceptance and understanding. For instance, technical solutions such as flexible HP and EV operation only become viable when consumers are incentivised to participate through innovative business models, national policymaking, and economic incentives. Furthermore, the success of these frameworks depends on social acceptance and the active participation of technology owners, whose support is necessary to integrate decentralised assets into the daily operation of the Swiss energy system.

Sector coupling and flexibility were identified as central to a net-zero Swiss energy system by the Swiss Federal Office of Energy (SFOE) in the SWiss Energy research for the Energy Transition (SWEET) funding call. The PATHFNDR consortium set out to both evaluate the role of sector-coupling and flexibility for the Swiss energy transition and to establish the multi-disciplinary frameworks necessary for their national-scale deployment. Recognising that the Swiss energy transition is a vast systemic challenge, the project's ten work packages evaluated this role from many angles: from European and national energy system perspectives down to cantonal and technology-specific levels. The project's scope extended beyond technical modelling to assess the business models, policy interventions, and social dynamics – combining energy-system modelling, engineering, economics, and social science – required to progress Switzerland toward its emissions targets.

In this report, we synthesise the project's key takeaways into ten key statements, organised into three core areas: **sector-coupling**, **flexibility**, and **unlocking flexibility**. In Chapters 2, 3, and 4, we introduce the key statements for the three core areas, respectively. We conclude this report with targeted stakeholder recommendations in Chapter 5.

2 Sector-coupling

As introduced in Chapter 1, sector-coupling refers to the interconnection between energy sectors such as electricity, heat, transport, and industry so that the supply of energy can shift from fossil fuels to low-carbon electricity. Sector-coupling is therefore not just a technical interconnection between energy sectors; it is a fundamental shift in how energy is used. By linking the various energy sectors, Switzerland can replace fossil fuel combustion-based processes with highly efficient electrical alternatives. As the following statements demonstrate, this shift is not merely a necessity for reaching our climate targets. This shift is also a strategic opportunity to bolster national energy sovereignty and drastically reduce dependence on foreign fossil fuels.

Statement 1: Direct electrification of residential heating and road transport is the key lever for decarbonisation of the Swiss energy system.[1]

Together with low-carbon electricity, direct electrification is the most cost-effective way to decarbonise the residential heating sector, the low-temperature industrial heat sector, and significant shares of the road-based transport sector (international aviation is not included). Across scenarios for the 2050 Swiss energy system, the PATHFNDR models consistently electrify heating and transportation, as electrification is by far the most efficient option to reduce carbon emissions. The high efficiency of electrified technologies reduces overall energy consumption by roughly 40% while increasing Swiss electricity demand by only 10-20% [78], which, in turn, increases national energy sovereignty. Moreover, removing combustion from the Swiss energy system via electrification leads to substantial health co-benefits by reducing particulate matter exposure, creating synergies between decarbonisation and air pollution policies.

Key messages:

- **The Swiss road transportation sector is responsible for 38% of the total Swiss energy consumption and is the sector with the highest energy consumption in Switzerland**[*]. Today, more than 90% of road-based transportation uses fossil fuels [91]. Accordingly, transport accounts for about 34% of Swiss CO_2 emissions (excluding international aviation), of which about 96% come from road-based transportation [24]. Substituting fossil-based road transport with electric vehicles (EVs), rail transport, or human-powered transport hence provides a strong lever for reducing emissions of the Swiss energy system.
- **The provision of heat is another main source of carbon emissions in Switzerland**[*], with more than 50% of homes and 40% of hot water being heated with heating oil or gas as the

[1] This statement includes key messages that cover both background information from the literature and findings from the PATHFNDR consortium. Messages based on background information are identified with an [*].

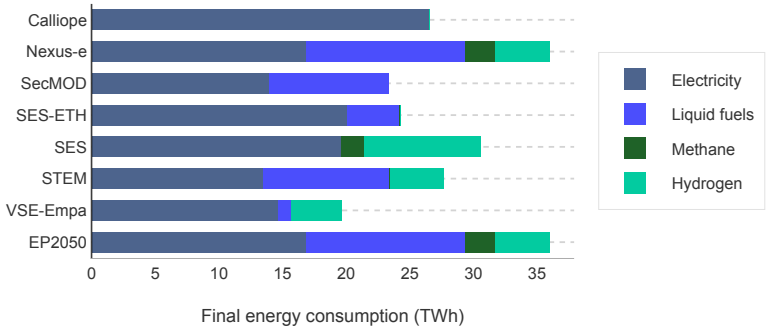
[*] Message covers background information.

main energy sources [90]. The building sector currently accounts for 22% of Swiss emissions. Industrial heat is also relevant for Switzerland, with a demand of 20 TWh per year across several temperature levels [54] and responsible for 23% of Swiss emissions. Industrial heat demand below 150 °C can be directly electrified via heat pumps, whereas higher temperatures require alternative solutions such as thermal power plants run on hydrogen, synthetic fuels, biomass or natural gas paired with carbon capture and storage. Each alternative has implications, whether high electricity demand to domestically produce synthetic fuels/hydrogen or competition for resources [31, 49].

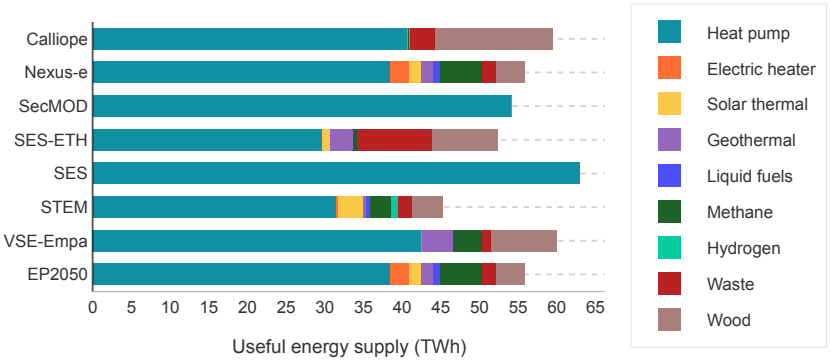
- **EVs and heat pumps (HPs) are the most cost-effective levers to reduce emissions from the transport and heating sectors.** In the cost-optimisation studies investigated in PATHFNDR, residential heat and private road-based transport are consistently electrified in the cost-efficient Swiss energy system configurations for 2050 [72, 77, 78]. For instance, model results show electrification rates between 81–86% for passenger mobility and almost 100% of domestic and low-temperature heat provision [78]. These rates should be interpreted as optimal shares within broader energy system models, not as adoption forecasts based on individual consumer choices or industry-specific transition dynamics. Nonetheless, the results are consistent with findings from the 2022 CROSS model comparison, where electrification rates lie within interquartile ranges of 60–75% for passenger vehicles and 55–95% for domestic space heating and hot water production [53] (Figure 2.1). Furthermore, we find that across energy sectors, EVs and HPs represent the most efficient use of renewable electricity, offering higher emissions reduction per unit of energy than the electrification of hard-to-abate sectors like high-temperature heat and the chemical industry [55]. Because these technologies maximize the decarbonisation impact of every additional kilowatt-hour, their rapid deployment is the critical step in the Swiss energy transition. By 2050, scenarios relying on electrification of energy demand cut the energy system's life-cycle greenhouse gas emissions by 82–92% compared to today, with EVs and HPs alone accounting for roughly a third to three quarters of this reduction [57, 61]. Importantly, the majority of residual emissions arises along supply chains of EVs, and is thus largely insensitive to Swiss policy [61].

- **To stay on track for the 2050 climate targets, all next-generation heating and transportation systems deployed today must already be climate neutral, avoiding long-term lock-in of carbon-intensive technologies*.** Since asset lifetimes in both road transport and heat provision technologies are significant, any vehicle or heating system sold today will emit CO_2 for decades to come. The average age of cars in Switzerland is more than 10 years [20], so once a new vehicle is purchased, it remains in the national fleet for over a decade. Similarly, household heating systems are replaced only every 15 to 20 years [39]. Thus, to reach the climate goals by 2050, the next generation of heating and transportation systems deployed today need to be climate neutral.

- **Electrification brings substantial health co-benefits in Switzerland, as combustion disappears from roads and buildings, creating synergies between air pollution and decarbonisation.** Today, internal combustion vehicles and fuel boilers together account for 64 % of Switzerland's domestic environmental externalities, with particulate matter released in areas of high exposure as the main driver [61]. The more a scenario electrifies, the larger the benefit: fully electrifying residential heating and road transport reduces monetised domestic externalities by up to 61 % compared to today [61]. Most of this benefit comes from HPs, which remove



(a) CROSS inter-model comparison modelling results for final energy consumption from private passenger road transportation (TWh) in 2050 [53]. The underlying results can be explored interactively at sweet-cross.



(b) CROSS inter-model comparison modelling results for useful energy supply for space heating (TWh) in 2050 [53]. The underlying results can be explored interactively at sweet-cross.

Figure 2.1: CROSS inter-model comparison modelling results for the energy supply of private passenger road transport and space heating in 2050 using the CROSS scenario 'Abroad-Together' [53].

combustion from buildings entirely, whereas EVs still emit particulate matter from tyre, brake and road wear. Biomass presents a paradox here: it is an attractive domestic resource that can directly replace fossil fuels in boilers, but combusting it in residential boilers keeps particulate matter emissions and their health impacts high.

Statement 2: Decarbonisation will strengthen Switzerland's ability to supply its own energy – and vice versa.[1]

Switzerland currently relies on imports for approximately 70–75 % of its final energy consumption driven primarily by the use of oil and natural gas in transport, heating, and cooking. As energy demand in these sectors becomes increasingly electrified, the need for fossil fuel imports will become marginal or even disappear, along with its associated greenhouse gas emissions. Furthermore, the phase-out of nuclear will halt uranium fuel imports. Overall, the share of energy imports in the Swiss final energy consumption is projected to decline to 0–35 %, depending on the extent to which

[1] This statement includes key messages that cover both background information, and findings from the PATHFNDR consortium. Messages covering background information are identified with an *.

domestic bioenergy is utilised in the energy sector. Switzerland will therefore significantly increase and diversify its domestic energy production as it decarbonises.

Key messages:

- **Switzerland currently imports 70–75 % of its final energy consumption. Most of Switzerland's current greenhouse gas emissions are directly related to these imports***. These imports are primarily driven by the transport and heating sectors, fuels for technologies like internal combustion engine vehicles, oil or natural gas boilers, and natural gas cooking stoves [88]. A small fraction of total energy imports also come from the import of uranium fuel for nuclear electricity production [88].

- **The energy transition will at least halve Switzerland's energy dependence.** Every EV or HP that replaces one of its fossil counterparts eliminates emissions and energy imports simultaneously, for the energy supplied will be provided by renewable electricity instead of fossil fuels. The high energy efficiency of these technologies combined with Switzerland's domestic electricity production imply that Switzerland can meet most of this demand with its own energy generation. Furthermore, the nuclear phase-out on the supply side of electricity means that uranium imports will also be cut [88]. Overall, the share of energy imports will drop below 35 % [57, 72, 77]. As a result, energy independence and decarbonisation go hand-in-hand for Switzerland.

- **The exact share of energy imports in Switzerland's net-zero energy system will primarily depend on the use of Swiss bioenergy.** While the share of energy imports is expected to drop below 35 % with the energy transition, the exact value within the 0–35 % range is contingent on choices made by energy providers, and particularly the use of Swiss bioenergy [1, 4, 28, 57, 73, 77, 97]. Beyond directly electrifiable sectors such as road transport and residential heating, hard-to-abate sectors such as heavy industry will likely require low-carbon fuels to produce high-temperature heat. Depending on whether these fuels are produced domestically, either via electricity or via biomass, or imported, some energy imports may remain (See Statement 3 and [1, 4, 57, 97]). Some scenarios suggest that using biofuels for electricity production or importing natural gas (paired with emissions compensation such as Direct Air Carbon Capture and Storage (DACCS)) could be an alternative way to produce electricity domestically [1, 4, 57, 77, 97].

- **Some transition pathways and technologies that appear promising at first may turn out to be 'dead-ends' because they cannot effectively address the net-zero challenge.** The effectiveness of different transition pathways and technology options can be assessed by three criteria: depth, breadth, and timeliness. **Depth** checks whether the option essentially eliminates emissions. For example, to use natural gas for trucking or shipping does not meet this criterion and is likely to be a dead-end. **Breadth** checks whether the option can be scaled sufficiently. Biofuels or biogas for heating do not meet this criterion because they compete directly for land with food production. **Timeliness** checks whether an option can be deployed in time to reach net-zero by 2050. Nuclear fusion, most likely, cannot meet this criterion due to the many legal and regulatory procedures that must be resolved [64]. With scarce (financial) resources, it is important to scrutinize competing pathways and concentrate on those that meet all three

*Message covers background information.

criteria, instead of spending resources on dead-ends [10, 75]. More details on other identified dead-end pathways can be found in the work by Rosenbloom et al. [75].

- **Integrating local renewables, electrifying heating, and integrating energy storage enables cost-effective decarbonisation and enhances energy security amid disruptions**. Cost-effective decarbonisation is achieved through efficiency gains by switching from fossil-based gas boilers to electric heat pumps and storing local renewables surplus as heat in low-cost thermal storage. In residential buildings, these integrated energy systems simultaneously reduce emissions by 64% and increase reliability by 80% during expected outages [83]. When designed for resilience against a 24-hour electricity outage, they save 20-30% in annual costs compared with deploying individual battery backups [82].

Research gaps:

- Future research should explore the near-optimal solution space of energy modelling research. Most PATHFNDR work (and, in general, most energy system scenarios in research projects) is derived using cost optimisation and provides a single cost-optimal configuration. Research has shown that solutions in the near-optimal solution space, for a minor difference in costs, can be vastly different [27, 50], with regard to system costs and energy dependence, among other dimensions.
- Future research should consider other types of energy-related dependence, including dependence on Critical Raw Materials (CRMs), technology supply chains (e.g., for solar panels), and intellectual property issues.
- Future research should incorporate more behavioural economics (e.g., individual consumer choices or industry-specific transition dynamics) to study adoption rates of EVs and HPs. Such adoption rates would be a helpful complement to energy system optimisation studies.

Statement 3: Switzerland's demand for low-carbon hydrogen and synthetic fuels is low, concentrated in industry and aviation, and most cost-effectively met through imports.

The majority of Switzerland's energy demand that currently uses fossil fuels can be directly electrified (Statement 1). In addition, seasonal chemical storage is unlikely to be cost-effective for Switzerland's energy system due to the availability of alternative seasonal flexibility options (Statement 5). As a result, Switzerland's demand for hydrogen or other low-carbon synthetic fuels is low. Residual energy demand not met by electricity will be heavily concentrated in hard-to-abate sectors, specifically in industrial applications, requiring high-temperature heat or fossil-based feedstocks, and in aviation, which requires liquid fuels. These sectors have a few competing options for decarbonisation: electricity-based fuels, bioenergy-based fuels, and emissions offsetting. To create a domestic supply of synthetic fuels or biofuels, Switzerland would need the following resources: an abundant and scalable supply of inexpensive electricity, more land dedicated to biomass for fuel, or more space dedicated to large synthetic fuel synthesis plants. Switzerland has few of these resources and therefore,

domestic production of synthetic fuels is unlikely to be cost-competitive or scalable. Consequently, any demand for synthetic fuels is most effectively served via imports, integration into the European Union infrastructure, and international agreements for offsetting, competing alongside biofuels.

Key messages:

- **Direct electrification is the primary decarbonisation strategy, minimizing the need for alternative fuels.** Key technologies like HPs and EVs allow cost-efficient decarbonisation for the majority of Swiss energy demand without relying on low-carbon fuels [57, 72]. See Statement 1 for additional details.
- **Chemical seasonal energy storage is not required for the Swiss power system.** Power-to-gas-to-power technologies are not cost-efficient at the system level in Switzerland under the modelled assumptions. To complement hydropower and electricity trading, other supply-side technologies, including utilising Switzerland's bioenergy potential, are more cost-effective than chemical seasonal storage [1, 28, 57, 73, 77, 97]. In addition, in the heating sector, Seasonal Thermal Energy Storage (STES) provides an additional seasonal flexibility source, shifting renewable heat and reducing winter electricity imports by 3.6 TWh [102].
- **Residual synthetic fuel demand will come from selected industrial sectors and aviation.** Supply of high-temperature heat and fossil-based feedstocks for industrial applications cannot be directly provided with current low-carbon technologies. In these areas, imported synthetic fuels will compete with bioenergy-based fuel alternatives, for which the Swiss domestic production potential could be sufficient to cover a large part of the demand [4, 57, 97]. Aviation also has limited decarbonisation pathways. Synthetic fuels in the form of Sustainable Aviation Fuel (SAF) are the only scalable decarbonisation solution alongside emissions offsetting with carbon dioxide removal (CDR). Bio-based SAF are technically possible; however, the potential in Switzerland–particularly if biofuel resources are divided between industrial applications and aviation–is too low to cover international aviation demand. The demand for imports of synthetic fuels will depend on biofuel availability in industry and demand for SAF [9, 15].
- **Importing hydrogen and other synthetic fuels is more economical than producing them domestically.** Because the cost of electricity is the primary driver of low-carbon hydrogen or synthetic fuels' costs, countries with plentiful renewable resources (e.g., Chile, Spain, the Netherlands, or Iceland) can produce these fuels at a fraction of the Swiss cost [2]. Even though Switzerland will curtail solar electricity surpluses in the summer, building capital-intensive electrolyzers solely to capture these surpluses would result in very low annual utilization rates, driving up the final cost of the fuel. Consequently, relying on imports of synthetic fuels remains more cost-efficient than domestic production [1, 2, 28–30, 57, 77]. To ensure access to hydrogen and synthetic fuels, Switzerland should thus maintain the connection to international markets.
- **Switzerland can leverage its geographic position to integrate with European synthetic fuel and hydrogen infrastructure.** Switzerland's geographic position in the middle of larger European countries presents an advantage: Active planning and participation in European infrastructure (e.g., hydrogen pipelines) and markets are thus crucial for efficiently meeting the Swiss demand for hydrogen and low-carbon fuels [4, 29, 30].

Research gaps:

- Future research should explore the roles of seasonal heat storage and geothermal energy production. These two technologies have mostly been studied in isolation, thereby missing links to other energy sectors and possible synergies with other storage or flexibility technologies.
- The decarbonisation of heavy-duty transport and international aviation requires further research. For heavy-duty transport, Switzerland needs to consider the impact of European policy strategies regarding its own decarbonisation pathways. For aviation, an important question is whether Switzerland should produce SAFs domestically at a premium, buy them abroad, or offset the emissions of conventional fuels [9], as it is a *hard-to-abate* sector [15]. Because synthetic SAF production requires hydrogen and low-carbon carbon inputs, this question should be assessed consistently with the broader finding that large-scale domestic hydrogen and synthetic fuel production is unlikely to be cost-competitive in Switzerland.

3 Flexibility

In Chapter 2, we establish that the electrification of heating and transport is the primary lever for decarbonisation. Simultaneously, sector coupling and the transition to an electricity system dominated by variable renewables equally introduce new pressures and opportunities on the energy system. Pressures include balancing variable renewable energy production over the day and the seasons. Opportunities include new sources of system flexibility[1] to help mitigate those imbalances. In particular, PATHFNDR researchers studied the potential of residential flexibility from heat pumps (HPs) and electric vehicles (EVs) (e.g., [60]) and industrial demand-side management (e.g., [54]). The project also showed the value of the already-existing flexibility assets for Switzerland.

In this chapter, we synthesise the findings regarding the interplay between Switzerland's established flexibility assets and Switzerland's emerging decentralised resources, identifying the most effective flexibility levers.

Statement 4: Flexible hydropower infrastructure and electricity trading are two central sources of flexibility for the Swiss energy system.[2]

Switzerland starts from a comparatively strong flexibility position because it has substantial reservoir and pumped-storage hydropower capacity as well as extensive cross-border interconnection. In 2024, reservoir and pumped-storage hydropower plants produced 24 TWh, equivalent to about 40% of the country's final electricity consumption of 57 TWh [88]. In addition, Switzerland is highly connected to the European electricity grid. The 41 grid interconnections with neighbouring countries allow Switzerland to exchange approximately 8 GW of electricity in each direction at any given time, making Switzerland a major European electricity trading hub. In combination, these flexibility sources exceed the Swiss peak electricity demand of about 9 GW [91]. In other words, Switzerland is already in a very good starting position today with regard to meeting its flexibility needs.

Key messages:

- **Flexible hydropower generation capacity exceeds peak electricity demand***. Swiss peak electricity demand is approximately 9 GW [91]. The two types of flexible hydropower – pumped and storage hydropower – together have a capacity exceeding peak demand. Pumped hydropower plants have a capacity of 3.5 GW and an expected average annual production of about 1.6 TWh, whereas storage hydropower plants have a capacity of 8.3 GW and an expected

[1] In this report, flexibility refers to the ability of the energy system to adjust supply, demand, storage, conversion, or electricity trade across different time scales in order to maintain balance between electricity production and consumption.

[2] This statement includes key messages that cover both background information, and findings from the PATHFNDR consortium. Messages covering background information are identified with an *.

*Message covers background information.

average annual production of 17.8 TWh [14]. Looking toward 2050, the electrification of buildings and transport is projected to increase the Swiss peak demand to approximately 12–20 GW [72, 74, 76]. Nonetheless, the combined domestic hydro capacity of nearly 12 GW, supplemented by interconnections with neighbouring countries, makes Switzerland well-positioned to cover these requirements (Figure 3.1).

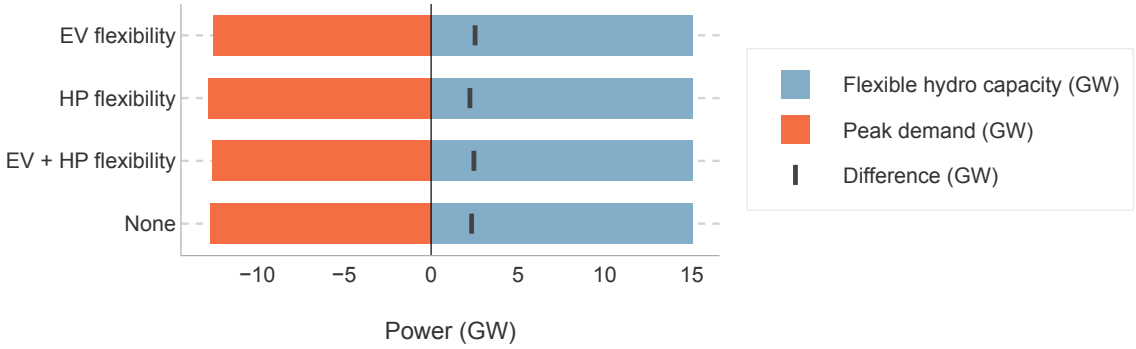


Figure 3.1: Flexible hydropower capacity (GW) compared to maximum peak demand in 2050 in the Nexus-e model. The underlying results can be explored interactively at .

- **A large share of the current electricity demand can be covered by flexible hydropower production.** In 2024, total Swiss electricity demand was approximately 57 TWh [91]. In the same year, flexible hydropower, that is, pumped and storage hydropower, produced about 24 TWh of electricity–roughly half of total demand [88]. Looking towards 2050, sector-coupling can drive the total Swiss electricity demand to approximately 80–90 TWh [72, 95]. Flexible hydropower is still expected to contribute a significant portion of this higher electricity demand. Furthermore, storage hydropower plants will play a critical role in the seasonal balancing necessary for the Swiss energy system [54].

- **Switzerland is a major hub of electricity trading, which provides ample access to flexible electricity trade*.** Approximately 10% of all electricity exchanged between countries in continental Europe that are part of the European Network of Transmission System Operators for Electricity (ENTSO-E) is transported over the Swiss electricity network. Of the ten percent of all European electricity that flows into Switzerland, roughly a quarter are transit flows [19]. In 2024, Switzerland imported 26 TWh and exported 40 TWh of electricity [88]. Actively participating in these markets provides Switzerland access to flexible electricity trade opportunities.

Research gaps:

- Future research should evaluate the long-term flexibility contributions of Swiss hydropower under different climate-driven hydrological shift scenarios. As global temperatures rise, Switzerland will experience altered precipitation patterns, shifting the timing and volume of water inflows into reservoirs. Because these changes directly impact the availability of stored energy during the winter electricity supply imbalance, future research and energy system modelling must integrate climate scenarios to accurately quantify the future flexibility potential of Swiss hydropower.

Statement 5: Seasonal chemical storage via hydrogen or other synthetic fuels is unlikely to become economically viable at scale for Switzerland.

While chemical seasonal storage is a suitable technological remedy for the seasonal imbalance Switzerland faces, PATHFNDR results do not identify large-scale power-to-gas storage as a cost-effective solution under the modelled assumptions. Switzerland has access to abundant sources of flexibility from its hydropower resources and demand-side flexibility (e.g., from industry, HPs, and EVs). Furthermore, Switzerland has potential for additional supply-side technologies (e.g., alpine photovoltaics, wind energy, gas-fired power plants) as well as bioenergy and seasonal heat storage. Switzerland may demand some synthetic fuels, but in order to competitively produce them for seasonal energy storage, Switzerland would need to have access to plentiful renewable electricity at a very low cost and space to build synthetic fuel plants at an economic scale. The PATHFNDR modelling results show that Switzerland cost-effectively deploys the many other options for seasonal storage it already has available – under favourable trade conditions – rather than developing a chemical storage supply chain.

Key messages:

- **Switzerland's abundant hydropower resources reduce, but do not eliminate, the need for other seasonal storage sources.** The Swiss winter imbalance will remain as a result of a seasonal mismatch between demand in winter due to heating and summer electricity surpluses with solar energy [57]. Across the investigated scenarios, existing reservoir hydropower provides a major share of seasonal balancing and consequently reduces the cost-optimal deployment of additional seasonal storage technologies [1, 28, 57, 73]. Switzerland is one of few countries in Europe with such high hydropower resources, which explains why it has less need for other seasonal flexibility sources than other countries [28, 92].

- **Remaining seasonal imbalances can be covered by electricity trading, other supply-side technologies, and industrial demand-side flexibility.** Switzerland has set itself a maximum winter net electricity import target of 5 TWh [85]. Nevertheless, assuming that the electricity agreement between Switzerland and the European Union is accepted and provides the necessary framework conditions for cross-border electricity trading, Europe's higher winter electricity generation potential from wind energy makes imports a cost-efficient solution at this time of year [57, 72, 77]. In addition, Switzerland has several supply-side options that are available to reinforce its winter electricity production, namely wind energy, alpine solar photovoltaic (PV) and gas-fired power plants [1, 57, 73, 77], although alpine PV and wind adoption can face societal challenges. Industrial demand-side flexibility has also been shown to have the potential to reduce Swiss seasonal flexibility needs thanks to certain industrial sectors which can operate flexibly [54]. However, chemical seasonal storage does not appear as a cost-efficient way of bridging the winter imbalance unless very restrictive trade conditions are applied [1, 57, 73], as a result of high power-to-gas production costs in Switzerland and gas-to-power inefficiencies. One alternative – but still hypothetical – approach for producing electricity in winter is generating electricity with fossil gas-fired power plants in winter and removing the residual emissions (besides those already captured with point-source capture) with Direct Air Carbon Capture and Storage (DACCS) in summer when electricity is inexpensive [54, 57].

- **Swiss bioenergy resources can help to bridge the gap, but then they may not be available for other important utilisation.** The potential for Swiss bioenergy resources to bridge the winter imbalance is high. A cost-efficient utilisation is to convert Swiss biomass to biogas to be used in gas-fired power plants [57], providing up to 12 TWh of electricity production in winter. This option in turn enables more electrification of heating with efficient HPs while meeting the 5 TWh net imports target. However, bioenergy can also play a major role in decarbonising chemical and industrial sectors through liquid fuels and high-temperature heat provision [4, 97]. Swiss biomass resources are not sufficient to cover all possible utilisations. It is therefore critical to design policies for the utilisation of biomass taking into account all related sectors and policy objectives at the national level [4, 97].

- **Seasonal heat storage can play a significant role in bridging the electricity winter imbalance through strengthened sector coupling.** Seasonal Thermal Energy Storage (STES) shifts renewable or low-carbon heat from summer to winter (e.g., solar thermal or waste heat), reducing fossil backup needs and improving overall system efficiency when combined with HPs and district heating networks. Large-scale STES options include Borehole Thermal Energy Storage (BTES), Aquifer Thermal Energy Storage (ATES), and Pit Thermal Energy Storage (PTES); feasibility and performance depend strongly on local conditions [26, 94]. In a cost-optimal decarbonised Swiss energy system, model results indicate installed thermal energy storage capacities of up to 10 TWh, leading to a significant annual reduction in winter electricity imports of up to 3.6 TWh. Additionally, imported fuels are reduced by up to 3.2 TWh/year through the deployment of thermal storage options [102].

- **Niche applications in local multi-energy systems can create economic value for hydrogen technologies without relying on seasonal storage.** While Power-to-Hydrogen-to-Power (P2H2P) is unlikely to provide a cost-efficient solution for Switzerland's seasonal electricity imbalance at the system level, hydrogen technologies can still provide value in specific local applications. In an autarkic P2H2P system, battery and thermal storage provide short-term flexibility while large hydrogen storage is needed to manage seasonal imbalances [43]. At the distribution-grid scale, combining short-term battery storage with longer-term hydrogen storage can also make active distribution networks more reliably dispatchable over multi-day horizons despite renewable uncertainty. Co-optimizing a week-ahead schedule and real-time control reduces uncertainty in power exchanges with the grid compared with battery-only solutions [35]. In building- and district-scale energy systems, this value can also arise from high-value flexibility services and sector-coupling synergies rather than only from bulk seasonal energy shifting. For example, fuel cells, particularly second-life units, can become cost-optimal as targeted peak-shaving assets for demand profiles characterised by high-amplitude, low-frequency peaks, with deployment occurring at peak power fees of around 18 CHF/kW-month [33, 34]. The corresponding consumer-side optimum remains relatively shallow, but peak reduction can also create value for distribution grids by reducing required peak capacity and potentially deferring reinforcement investments. Sector coupling through waste heat recovery provides an additional source of value: recovering heat from fuel cells allows their economic operation at hydrogen prices approximately 30% higher than without heat recovery [11], while waste heat recovery from hydrogen production can reduce hydrogen production costs by up to 5.3% when supplying a district heating network [93]. These results show that the limited role of hydrogen for seasonal

storage at the national system level does not preclude targeted local applications in which flexibility services, tariff structures, and heat recovery create additional economic value.

Research gaps:

- Future research should explore near-optimal solution spaces of energy system models to fully understand the trade-offs between solutions to meet the winter imbalance, particularly as regards the utilisation of bioenergy.
- Future research should include in a consistent modelling framework seasonal heat storage with the other energy sectors and supply-side options. Seasonal heat storage has mostly been studied in isolation, missing interdependencies and synergies with other sectors.
- Assess the value of a diversified seasonal-storage portfolio under conditions not fully represented in the current least-cost scenarios, including dry hydrological years, simultaneous electricity shortages in neighbouring countries, delayed deployment of domestic winter generation, and limited realisation of industrial demand-side flexibility. Such stress tests would help distinguish the least-cost value of chemical storage from its resilience and security-of-supply value.

Statement 6: Electric vehicles and heat pumps can be major sources of demand-side flexibility, benefiting the energy system.

Hydropower and trade will remain Switzerland's main sources of flexibility at the system level (Statement 4), and managed PV feed-in will support flexibility at the grid level (Statement 7). At the same time, EV smart charging and flexible HP operation are emerging as valuable additional sources of demand-side flexibility [42]. Together, flexible EV charging and HP operation can provide more than 7.6 GW of adjustable load and 5.7 TWh of shiftable energy [78]. Compared to today's dispatchable hydropower flexibility of around 12 GW [14], the flexibility of EVs and HPs represents almost a 75% increase in flexibility, comparable to about 29 days of Swiss electricity use or an 8 GW gas-fired power plant operating around the clock [78].

Key messages:

- **EVs and HPs complement each other and can become major flexibility pillars alongside hydropower and imports, especially when deployed together.** Modelled 2050 scenarios show that, when EV and HP flexibility are available, the system optimally shifts about 23% of HP demand (3.8 TWh / 16.4 TWh) and 20% of EV demand (1.9 TWh / 9.8 TWh), and around 5.7 TWh when combined [78] (Figure 3.2). Because EV and HP flexibility follow different daily and seasonal patterns, enabling both together delivers the strongest benefits. The shifted demand is large relative to batteries, which provide around 0.2 TWh, and complements other flexibility sources such as net imports (around 2.6 TWh) and pumped hydro (around 12.2 TWh) [72]. Combined EV and HP flexibility can also reduce supply-side investment needs, for instance by lowering required system-level battery capacity by 75% under full market integration and by as much as 95% when cross-border electricity trading is restricted [95].

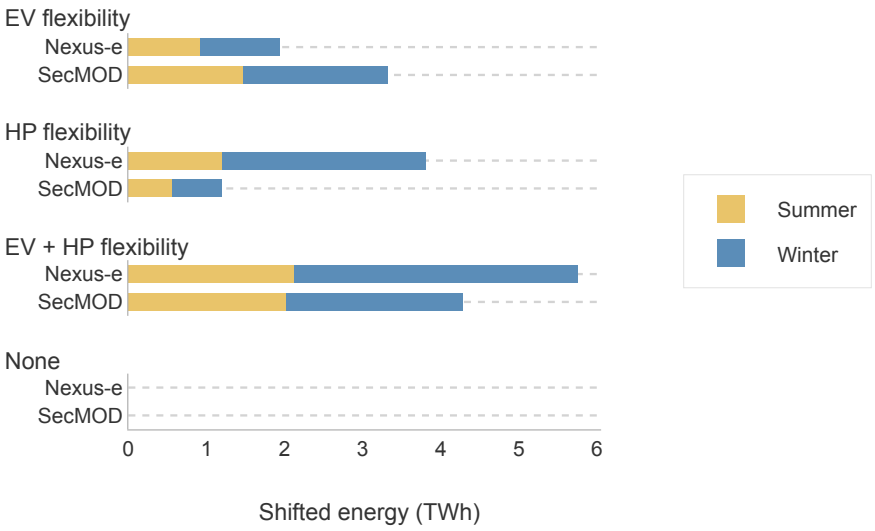


Figure 3.2: Modelling results from two PATHFNDR models showing optimal shifts in energy (TWh) in 2050 for electric vehicles and heat pumps. The underlying results can be explored interactively at sweet-cross.

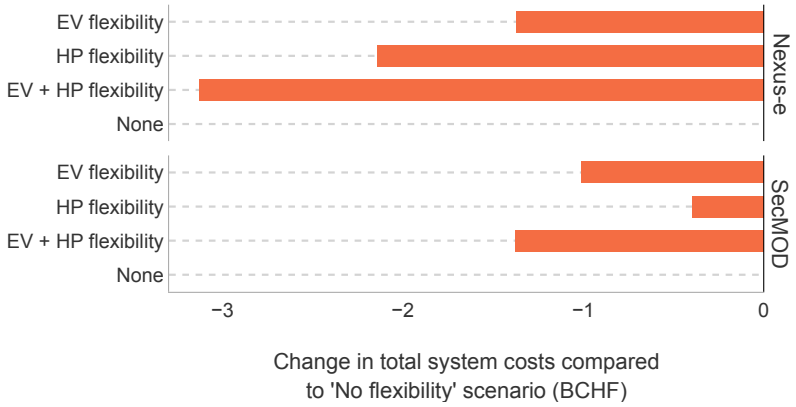


Figure 3.3: Modelling results from two PATHFNDR models showing changes in total system costs (Billion CHF) when 'flexibility' is used compared to 'No-flexibility' scenario in 2050. The underlying results can be explored interactively at sweet-cross.

- **EV and HP flexibility introduce numerous benefits to the energy system,** such as increasing renewables integration, reducing import dependencies, and reducing energy system costs. Renewables integration increases because we can shift EV and HP operation to times when renewables are available. Introducing these flexibility options increases renewables penetration by 3.8% and reduces energy system curtailments by 21% [72]. Furthermore, EV and HP flexibility reduce net imports by 11% and 12%, respectively [72]. HP flexibility leads to a larger import reduction due to its demand dominance during the winter months, when most imports occur. Both flexibility options together reduce net electricity imports by 22% [72]. Finally, deploying EV or HP flexibility reduces energy system costs by 2.1% or 1.7%, respectively or by 4.0% when both are deployed together [72] (absolute numbers in BCHF found in Figure 3.3 from [78]). These cost reductions are mainly attributed to decreased electricity imports, increased revenues from electricity exports, and decreased investment and operation of gas units, fuel

cells, and batteries. Overall, EV and HP flexibility displace other flexibility options in the energy system, thus leading to a decrease in the overall energy system costs.

- **Flexible charging of EVs is a demand-side resource with great potential to facilitate a higher PV penetration.** With a total electrification of the passenger vehicle fleet, smart EV charging could provide up to 2.4 GW of upward power-shifting capability and about half of downward power-shifting capability [69]. This flexibility is significant given the peak Swiss electricity demand of roughly 9 GW [91]. By 2050, with the right flexibility incentives, renewable energy curtailment could be reduced by over 10–30 %, depending on whether EVs perform Smart Charging (V1G) or Vehicle-to-Grid (V2G) [60] (Figure 3.4). These benefits occur thanks to EV charging demand being shifted to the daytime to better match solar PV generation [60, 95]. As a result, workplace charging is a key opportunity for shifting demand and increasing integration of PV [96], since about 40 % of vehicles are parked near work or education during peak solar hours on weekdays [68, 72]. At the household scale, smart EV charging can provide local flexibility averaging 1.27 kW [41]. This flexibility is comparable to the entire power draw of a modern dishwasher or the simultaneous operation of ten large LED televisions. While seemingly small, this flexibility represents 7.5% of a standard 17 kW Swiss household connection, providing a buffer that can be modulated for hours at a time. However, the realized flexibility potential remains contingent on charger capacity, tariff structures, and market signals, particularly if EVs perform V2G [6, 60].

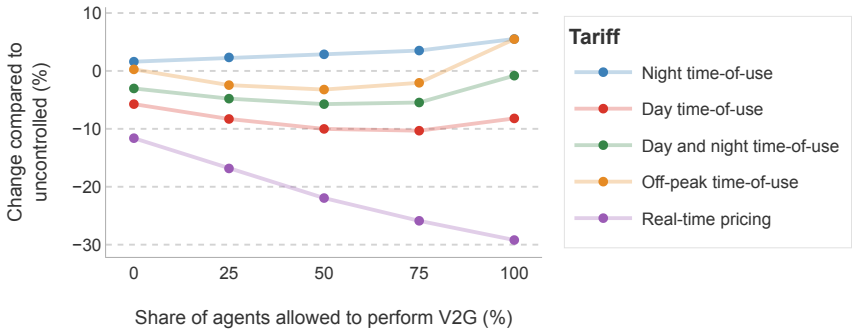


Figure 3.4: Modelling results showing the impact of the electricity rate design and charging infrastructure on curtailment, compared to uncontrolled charging [60]. The underlying results can be explored interactively at sweet-cross.

- **Flexible HP operation can also contribute to Swiss flexibility needs, particularly in winter.** Using thermal storage via buffer tanks or building inertia can shift a large share of heating load for limited durations. Recent bottom-up estimates for Swiss buildings, informed by monitored building data, show that HP load can be curtailed for 2–10 hours at 0 °C outdoor temperature while maintaining user comfort (Figure 3.5) [56, 72]. This flexibility potential depends strongly on building characteristics, heat demand, available thermal storage, and comfort constraints. Modelling of Swiss residential heating demand using public databases provides an important basis for aggregating this heterogeneous building-level potential to the national scale [81]. When considering the entirety of Swiss residential heat demand, flexible HP operation can yield 7.5 GW of upward power-shifting capability and 1.3 GW of downward power-shifting capability, summing to 3.6 TWh/y of energy flexibility nationwide [78]. Because the peak demand for HPs

occurs in winter, implementing HP flexibility is also a powerful strategy to help manage the winter electricity deficit and address higher electricity prices at that time of year [58]. To avoid or limit rebound peaks, this flexibility requires coordinated control, for instance by grid operators or local controllers [56].

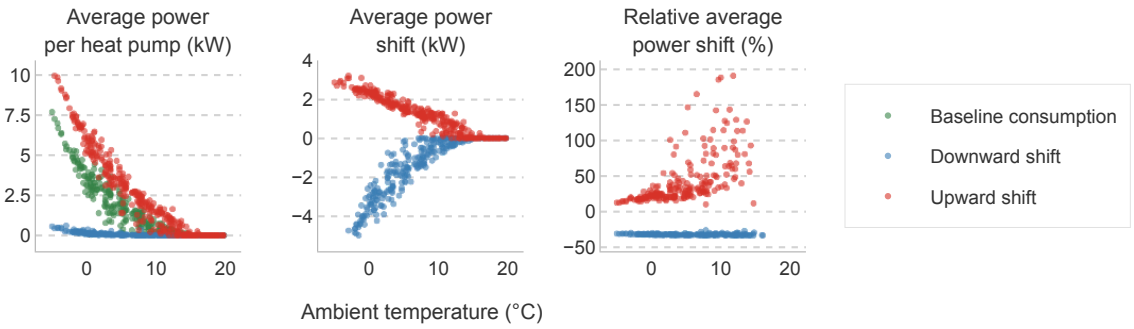


Figure 3.5: Modelling results showing the baseline consumption, downward shift, and upward shift of heat pump power consumption using 2 hour setpoint adjustments for the community of Liestal, starting at 6:00 AM [56]. The underlying results can be explored interactively at sweet-cross.

Research gaps:

- Future research should look into the relative advantages and disadvantages of V2G contributions vs. V1G. While most studies focused on V1G, V2G presents additional flexibility resources while also requiring tailored policies and more advanced tariff structures and/or market mechanisms [3, 60].
- Future research should quantify industrial flexibility options in Switzerland, including industrial heat pumps, cooling systems, thermal storage, flexible process operation, on-site energy conversion, and interactions with electricity, heat, hydrogen, and other energy carriers. Compared with residential HPs and EVs, industrial flexibility is likely to be more heterogeneous and site-specific, but it may provide valuable flexibility at larger unit sizes and across different temporal profiles.
- Future research should investigate how flexibility requirements can be translated into design criteria for future building energy systems. Further research is needed to define flexibility metrics, quantify trade-offs with efficiency, comfort, cost, and grid constraints, and assess how these criteria influence the design and operation of building energy systems.

Statement 7: Taking into account the end-user demand and generation flexibilities in distribution grid planning is necessary to reduce the need for distribution grid reinforcements.

Electricity distribution networks were not dimensioned to accommodate the power injection and withdrawal peaks that can result from the massive proliferation of rooftop PV, EVs, and HPs. Expanding the network to accommodate such large peaks with the traditional infrastructure paradigm will result

in high investment costs and a grid that is 'over-sized' for all but peak needs. Instead of building out the grid to such an extent, renewables can be managed with end-user flexibility (e.g., smart charging of EVs) or with curtailment at peak times. The utilities will need to devise schemes that promote these types of grid-friendly management. However, practical implementation will depend on the maturity of the responsible distribution system operator, as Switzerland's roughly 600 operators differ considerably in size, digital capabilities, planning resources, and experience with active grid management.

Key messages:

- **Flexibility-aware distribution grid planning frameworks allow utilities to make use of local sources of flexibility.** Traditional grid planning relies on physical hardware reinforcements, such as upgrading cables and transformers, to meet worst-case peak demand and generation scenarios. This traditional approach does not account for potential dynamic capabilities of distributed energy resources and other flexible technologies. Flexibility-aware planning frameworks, on the other hand, leverage various flexible resources and technologies to reduce or defer grid reinforcement costs while helping the utilities optimize network performance and investment efficiency [21, 79]. Flexibility-aware planning should become the new standard paired with mechanisms that enable utilities to trust and use end-user flexibility.

- **The primary factor driving a need for grid reinforcement is the rise in PV generation.** In rural regions, the ratio of the installed PV capacity in 2040 can be larger than 10 times today's maximum demand, while in urban regions it can be as high as 5 times. Although this ratio varies across different region types, a need for grid reinforcement investments is observed in all regions. The required investments tend to increase non-linearly within each region type as the installed PV capacity increases [22].

- **Effectively managing PV feed-in can significantly reduce the need for grid reinforcements, while minimally affecting the total PV energy production on an annual basis.** Distribution-grid studies across 50+ Low-Voltage Grids (LV) and Medium-Voltage Grids (MV) show that the median reduction in total grid investments by curtailing less than 3% of the available PV energy is $\sim 50\%$ in the studied rural regions in 2040, while it is $\sim 40\%$ in urban regions and $\sim 60\%$ in semi-rural regions (Figure 3.6) [22]. This management can be achieved through various (mutually enhancing) alternatives: (i) directly limiting peak power output, (ii) shifting flexible energy demand, such as EV charging and/or HP operation, to align with peak PV generation periods (Statement 6), or (iii) integrating local Battery Energy Storage System (BESS) that operate alongside PVs in a grid-friendly manner while maintaining self-consumption goals.

- **The benefits of managed PV feed-in and demand-side flexibility from EVs and HPs vary across regions.** Swiss electricity distribution networks are characterised by heterogeneity in demand and renewable generation profiles, making it impossible to generalize potential benefits across all grid types. In rural and semi-rural regions, where the ratio of installed PV capacity to local demand can be as high as four to one, managing PV feed-in is the most effective lever. In urban regions, characterised by installed PV capacity-to-demand ratios less than 1, demand-side flexibility offers greatest benefits, with cost reductions approaching and sometimes exceeding $\sim 50\%$ in the studied regions [22].

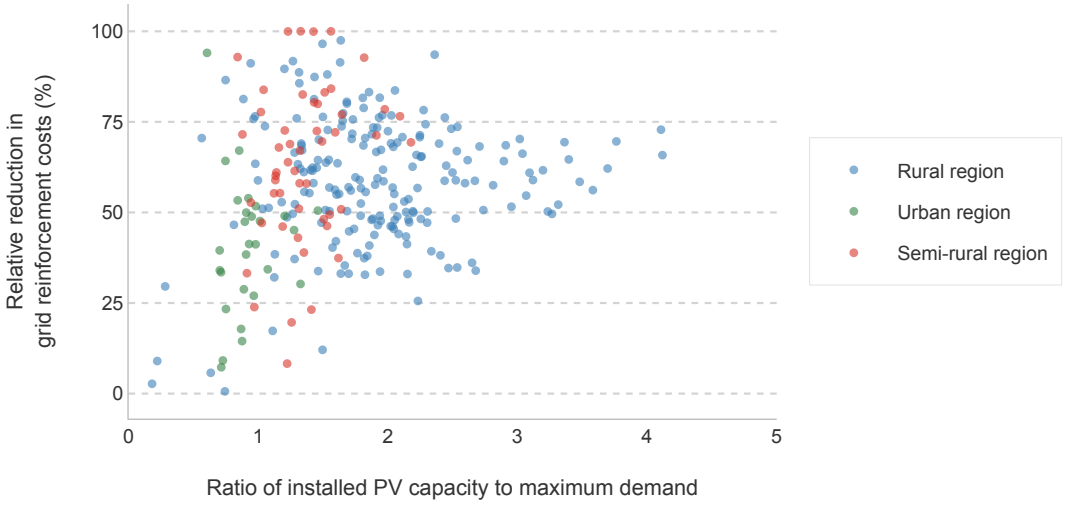


Figure 3.6: Relative reduction in total grid reinforcement costs [%] in the studied low- and medium-voltage grids in 2040 due to PV curtailment (resulting in less than 3% loss of annual expected PV generation) by region type and as a function of the ratio of installed PV capacity to maximum demand [22]. The underlying results can be explored interactively at sweet-cross.

- **Flexible voltage regulation will be of very high importance,** since in some regions, particularly in rural grids with high PV proliferation, nodal voltage violations are observed in addition to thermal overloading of cables and transformers. One way to achieve voltage regulation is by using the voltage support function of converters. PV converters are the natural candidates for this support, while the EV charging infrastructure and HPs can also be equipped with this functionality and can potentially provide this support [13].

Research gaps:

- Future research should focus on how flexibility-aware distribution grid planning can be applied in practice.
- One key challenge is that detailed grid models are often not available, especially for low-voltage networks.
- Another challenge is how to scale these planning methods so that they can be used efficiently across a large number of networks.
- A further challenge is translating national energy scenarios into realistic local assumptions. This includes estimating where and when technologies such as photovoltaics, charging infrastructure for electric vehicles and heat pumps will be deployed, down to the building level.
- It is also necessary to develop realistic future demand and generation profiles in sub-hourly time resolution for these technologies, especially for utilities to rely on them. Stochastic methods can help capture uncertainty, but they can require substantial computational effort, which may limit their use in large-scale industrial applications.

4 Unlocking Flexibility

The previous chapters established clear technical recommendations for the Swiss energy transition: Chapter 2 identified the electrification of heat and transport as the primary lever for decarbonization, and Chapter 3 detailed the technical potential of hydropower, grid infrastructure, and decentralised assets to manage flexibility. However, as noted in the report's overall introduction (Chapter 1), moving from technical potential to operational reality requires more than hardware.

In this chapter, we transition from the *what* to the *how*. For instance, while heat pumps (HPs) and electric vehicles (EVs) offer valuable flexibility potential, this flexibility only becomes functional if the market environment provides the right signals and, crucially, if technology owners choose to participate. Other sources of flexibility rely less on public participation; for example, electricity trading or battery storage. Nevertheless, making the large amount of flexibility available from private, distributed sources requires resolving the tension between market-friendly operation (reacting to price signals) and grid-friendly operation (protecting local infrastructure), while ensuring that the transition is financially de-risked and socially acceptable.

Statement 8: Dynamic tariffs are important to incentivise an optimal trade-off between grid-friendly and market-friendly dispatch and investment.

An end-consumer connected to the power network faces several cost components. Among those, electricity tariffs cover the cost of generating the actual energy used, while grid tariffs cover the infrastructure and delivery service required to transport that energy to consumers' door. Traditionally, these tariffs have been flat, or varying in pre-defined time windows over the day or year (time-of-use structure) [59]. With smart meters, these tariffs can become dynamic, changing every hour or even in 15-minute windows to incentivise self-dispatching prosumers to dispatch in a grid-friendly and market-friendly way [5, 12, 40, 51, 98, 103], resolving conflicting activation signals and directing flexibility to where it is most needed. For example, dynamic electricity tariffs can be based on wholesale electricity prices, as recently introduced in Swiss and European laws [59]. With the growing importance of flexibility, dynamic tariffs are essential to unlock the potential of prosumers, for example reducing Swiss system costs by 2–4.5 % when applied to EVs [60] or grid reinforcement costs by more than 50 % at the distribution level [103], when carefully designed. However, these tariffs and prices need to be appropriately designed to establish efficient dispatch and investment incentives and prevent the occurrence of rebound peaks [60, 103]. In particular, when passing wholesale prices through to prosumers, they must also be accompanied by risk-hedging measures to mitigate price risk and increase customer acceptance. Furthermore, digital technologies like automated pricing mechanisms only deliver system-level benefits when they are coherently integrated into business models and user-facing solutions, rather than implemented in isolation [66].

Key messages:

- **Dynamic tariffs should be accompanied by automatic load-control to maximise acceptance and impact.** Dynamic tariffs typically change every hour, or even every 15-minutes. This pace is far too frequent and responding manually to these changes at the same pace and frequency is too time-consuming for customers. Automatic load-control systems will therefore be needed to maximise the impact and have also been shown to increase acceptance of dynamic tariffs [23, 25].

- **To incentivise market-friendly dispatch, the energy component of dynamic tariffs should correspond to the wholesale price.** By contrast to today's regulatory framework, which requires dynamic prices to be calibrated to a fixed average value for a reference profile, the efficiency of dispatch and investment signals could be improved by passing the wholesale price through to the customers. Passing through the wholesale prices ensures that the incentive that flexible customers have to shift or reduce their loads corresponds to the cost savings in the electricity market. Flexibility will therefore only be used in ways that reduce system costs [100].

- **To incentivise grid-friendly dispatch, the grid component of dynamic tariffs for each grid level should be flat, unless the respective grid area is congested.** As long as the grid is not congested, dynamic grid-charges should be designed as flat charges which do not alter load-shifting incentives. This price stability ensures that load-shifting and load reduction incentives correspond to the undistorted wholesale price signals from the energy component [100].

- **To incentivise grid-friendly dispatch, the grid component of dynamic tariffs for each grid level should be regionally differentiated and provide symmetric incentives for injections and withdrawals.** Whenever a certain region of the grid is congested by too many loads, the dynamic grid charge for withdrawals should rise in proportion to the gridload. Likewise, when a region of the grid is congested by too many injections, by contrast to today's regulatory approach, injections should be exposed to a grid charge which is proportional to the gridload [100].

- **To ensure sufficient incentives when a grid reaches its capacity limits, dynamic grid tariffs should be set sufficiently high when the grid is overloaded by withdrawals, and sufficiently low – including negative prices – when the grid is overloaded by injections.** When the grid reaches its capacity limit in direction of withdrawals, an additional load increase may result in forced disconnections of the overloaded grid. To provide customers with sufficient incentives for preventing this situation, when loads reach capacity limits in the direction of withdrawal, dynamic grid tariffs should rise to the Value of Lost Load (VOLL). When the grid reaches capacity limits in the direction of injections, an additional load increase could also cause forced disconnection of grid-elements and customers with an associated cost equal to VOLL. However, if renewable generators are required to pay the increasing negative charges during this period, they will stop injecting, as soon as the sum of (negative) grid tariffs and (potentially still positive) energy charges equals zero, and therefore there is unlikely to be a need for dynamic grid tariffs to drop to minus VOLL when grids are overloaded by injections.

- **Dynamic grid tariffs, which rise to VOLL, and dynamic energy tariffs, which pass-through the wholesale price require appropriate risk-hedging**. During extreme events, such as grid bottlenecks or future energy crises, the true cost of electricity can be very high. Dynamic grid and energy tariffs which pass on these incentives by rising to VOLL during congestions and /or passing through the wholesale price provide the right incentives, but expose customers to excessive risks. Instead of today's approach of dampening the price signal by calibrating to a pre-specified average, or capping dynamic tariffs at levels below the VOLL – which would reduce the risk at expense of distorting incentives – a more efficient approach would be to equip customers with risk hedging contracts, that would reduce risks to similar levels while maintaining undistorted dispatch and investment incentives [101].
- **When the volume of flexible loads increases, dynamic grid tariffs may need to be fixed ex-post or combined with capacity charges to prevent rebound peaks.** In the beginning, dynamic tariffs are likely to be fixed ex-ante, typically at day-ahead stage, to enable load-management customers sufficient lead-time for planning their dispatch. However, as the volume of flexible loads that respond to ex-ante tariffs increases, load-shifting may cause new peaks during the hour with the lowest ex-ante price, whose magnitude exceeds the original peak and can adversely affect the power system [60]. When this starts to happen, dynamic per-kWh tariffs could either be set ex-post [12, 63] or accompanied by per-kWp capacity charges in order to incentivise customers to spread-out their consumption during the hours with low per-kWh prices.
- **If utilities offer dynamic tariffs, they must bid the aggregated flexibility in the day-ahead or intraday auctions to avoid a loss.** When a utility offers a dynamic tariff to end consumers, consumer demand will shift in response. To keep its balance group balanced, the utility must anticipate this shift and procure the shifted demand in the day-ahead or intraday auctions; otherwise, the balance group becomes unbalanced, and imbalance payments become necessary. To this end, the European Power Exchange (EPEX SPOT) operating the Swiss day-ahead and intraday markets, has introduced the "exclusive group of block bids" format, which allows utilities to procure electricity for a portfolio of aggregated flexible loads [18, 32]. This format lets the utility monetise the flexibility in its grid while ensuring that this aggregated flexibility is offered to the Swiss system, whether for day-ahead dispatch (via a day-ahead bid) or intraday dispatch (via an intraday bid) [18].
- **Dynamic tariffs necessitate the evolution of bid formats in the day-ahead and intraday auctions.** As end consumers respond to dynamic tariffs, utilities need to buy their end consumers' flexible load in the day-ahead and intraday auctions. The bid formats defined by EPEX SPOT for the Swiss market should be tailored to this purpose. The currently offered "exclusive group of block bids" largely suffices, but two improvements would allow flexibility to be traded more efficiently [18, 32]. First, it should be possible to submit a block bid with both positive and negative quantities, reflecting the nature of prosumers who can both buy and sell. Second, the number of bids per exclusive group should increase so that utilities can offer "more flexibility" [18, 32]. Finally, the power exchange should continuously advise utilities on the use of bid formats and evolve their design in response to the changing landscape of electricity producers and consumers.
- **Statistical optimisation methods can help make power grids more reliable under uncertainty through more robust planning.** Modern power distribution and transmission systems

must operate reliably despite uncertain renewable generation and changing electricity demand. Statistical methods capturing these uncertainties and ensuring that grid constraints are respected with high confidence can help utilities, transmission system operators and distribution system operators plan dispatch more efficiently and robustly [38].

- **Statistical methods can be used to aggregate distributed energy resources, unlocking otherwise untapped flexibility and enabling more effective grid support and system planning.** As renewable energy grows, numerous small, distributed resources – such as solar panels, batteries, and flexible loads – can help balance the power grid. A new and efficient statistical method has been developed to effectively and formally aggregate these resources and reliably estimate how much flexibility they can provide to support the system. By accounting for grid constraints, costs, and uncertainty, this approach ensures that flexibility can be safely and effectively offered to the transmission system, turning local energy resources into a valuable tool for maintaining grid power balance [36].

- **Statistical methods can be used to coordinate flexibility resources from different distribution networks to support the transmission grid.** Coordinating the dispatch of multiple Active Distribution Networks (ADNs) can unlock distributed flexibility and reduce the need for balancing services. This PATHFNDR research demonstrates a distributed optimisation method that enables multiple networks to work toward a common objective without disclosing sensitive information on distributed energy resources or grid models. Such methods will be very helpful in grid operations and planning. The method was successfully validated in experiments jointly conducted at the Distributed Electrical Systems Laboratory of EPFL and the NEST facility of Empa [37].

Research gaps:

- Future research on grid-aware aggregation of stochastic resources should focus on combining the aggregation and distributed optimisation frameworks, allowing to aggregate joint flexibility without sharing information of individual active distribution networks while considering multiple (superposed or disjoint) ancillary services.

- Extending aggregation framework to consider probabilistic service activations and refine cost-effectiveness constraint by considering dedicated risk metrics.

- While it has been shown that combinations of capacity prices can reduce rebound peaks while preserving load-shifting incentives, the optimal design of these tariff combinations is an area of active research.

- Likewise, while benefits of ex-post grid tariffs have been shown, the detailed design of these tariffs, and in particular, the feasibility and stability of optimal load control in response to uncertain price forecasts requires further research.

Statement 9: Properly designed renewable support schemes should provide revenue stability and reduce investment risks while retaining proper incentives.[1]

Renewable support schemes that link payments to realised electricity production – including Switzerland's two-sided sliding market premium ("gleitende Marktprämie") – can effectively reduce investor price risk and preserve most incentives to optimise production. Nevertheless, because settlements remain tied to production volumes, such schemes can still distort bidding behaviour and price formation in short-term markets (intraday and balancing) and do not hedge overall revenue variability. Production-independent support mechanisms can address these remaining limitations. Financial Contracts for Difference (FCfD) represent one such design, stabilising revenues while preserving operational price signals, and illustrate one possible direction for future policy development [65, 80]*.

Key messages:

- **Production-linked support schemes can affect short-term market functioning.** Support mechanisms that weight payments by actual generation (such as today's market premium scheme in Switzerland) influence opportunity costs perceived by generators in intraday and balancing markets. Even when reference prices are averaged over longer periods such as quarters of a year – restoring incentives to capture higher-value hours – settlement expectations may lead to bidding below variable costs in support periods or to curtailment incentives in clawback periods. These behavioural responses can affect price formation and dispatch efficiency in short-term markets, particularly as supported generation shares increase.
- **Production-linked schemes only hedge price risk, while leaving investors exposed to the risk of weather-driven output variability.** Existing designs reduce exposure to electricity price fluctuations but leave generators exposed to volume uncertainty arising from weather-driven output variability. In some cases, the linkage to production weakens natural market hedging between prices and availability, meaning revenue volatility remains significant despite price stabilisation.
- **Financial Contracts for Difference illustrate how production-independent designs can address these limitations** *. FCfD decouple settlements from actual generation by basing payments on benchmark output profiles rather than realised production. This benchmark approach removes incentives to adjust dispatch behaviour in response to support payments while stabilising revenues against both price and volume risks. By combining long-term hedging with preserved market exposure, FCfDs demonstrate one possible approach to addressing remaining shortcomings of production-linked support schemes without prescribing a single policy pathway. These designs also involve trade-offs. Settling against a benchmark leaves investors with basis risk wherever the benchmark deviates from a plant's realised output, and defining, verifying, and updating benchmarks adds administrative complexity.

Research gaps:

[1] This statement includes key messages that cover both background information, and findings from the PATHFNDR consortium. Messages covering background information are identified with an *.

*Message covers background information.

- Future research should quantify short-term market impacts of production-linked support schemes under Swiss system conditions.
- Future research should compare welfare, investment, and risk outcomes across alternative support designs.
- Future research should evaluate benchmark construction and basis-risk implications of production-independent mechanisms.
- Future research should analyse how renewable support-scheme reforms affect the incentives and business models of different market participants. This includes identifying potential sources of resistance to production-independent mechanisms such as FCfDs and assessing which regulatory changes could help align individual and business incentives with system-wide benefits.

Statement 10: Electric vehicle and heat pump flexibility only scales if owners accept automated operation that protects comfort and provides compensation.[1]

There is high technical potential for EV and HP flexibility (see Statement 6), but this potential can only be realised if customers (especially device owners) participate. This requires owners to allow automated, flexible operation of their devices through simple, user-friendly solutions that shift charging and heating while protecting end-user comfort and convenience. The key to scaling EV and HP flexibility are enabling mechanisms that support owners (e.g., policies, tariffs, and coordinated stakeholder actions), alongside aggregators who reduce complexity and help customers benefit from shifting demand.

It must be noted that the evidence base for acceptance is split across PATHFNDR/SWEET work and international studies. The latter is useful for identifying general mechanisms, but its transferability to Switzerland should be interpreted with caution. Throughout this statement, we will mark non-PATHFNDR findings with an*.

Key messages:

- **Flexibility from EVs and HPs delivers system benefits, but only if many EV and HP owners participate.** Evidence shows that EV charging can be shifted while maintaining current mobility patterns, as long as charging strategies respect drivers' mobility needs and availability windows [60, 68]. Likewise, HP operation can be shifted while preserving thermal comfort in buildings, when controls keep indoor temperatures within defined comfort bands and buildings' thermal inertia is used as short-term heat storage [56]. Participation is also not only a household issue: smart charging at workplaces can increase flexibility and EV alignment, making employers and site operators key actors [96]. Although surveys indicate relatively high stated willingness to accept values of between 48 and 542 CHF per year (for EVs) and between 1'150 and more than 4'000 CHF per year (for HPs), it remains uncertain whether recruitment programmes can offer

[1] This statement includes key messages that cover both findings from the PATHFNDR consortium and findings from outside the project. Findings from outside the project are identified with an *.

such compensations and still scale sufficiently. This highlights the importance of low-friction, comfort-safe programme design [48]*.

- **Participation increases when flexibility is automated and does not impact comfort.** Customers are willing to offer flexibility only if their comfort is protected, making automated scheduling crucial. Evidence on sector coupling innovation adoption shows that even environmentally superior technologies fail to scale unless they are perceived as attractive alternatives to conventional solutions, highlighting the central role of user evaluation alongside technical performance [67]. Surveys also show that around 70% of Swiss consumers offer flexibility only if comfort is not affected, while about 30% are willing to trade some comfort for cost savings [72, 99]. Automation works best when customers can set clear operating limits with easy overrides (e.g., a minimum EV state-of-charge by departure time or indoor temperature bands for heating) [70]*. Many customers also prefer direct load control of individual appliances over limits on total household electricity use. For HPs, direct load control contracts and operating settings (e.g., enabling preheating and longer shifting windows) strongly influence how much flexibility is actually delivered and help mitigate rebound effects [58]. Comfort-safe automation therefore needs clear operating rules and clear comfort limits.

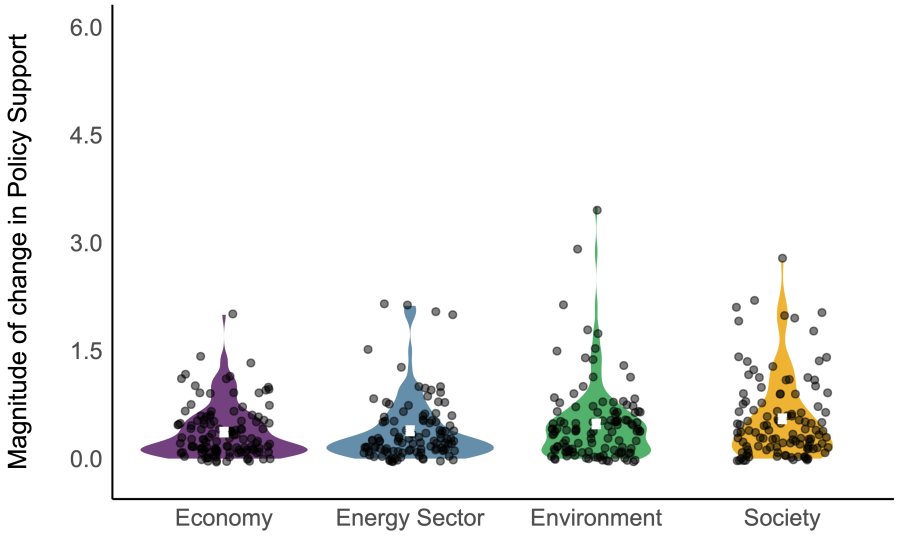


Figure 4.1: Change in policy support after participants received information on economic, energy sector, environmental or societal impacts. Information on societal and environmental impacts changed support the most [44].

- **Customers are more likely to enrol when programmes are transparent, trustworthy, and easy to understand.** Uptake increases when customers have clear information and control over automated operation, including informed consent and data protection [59]. This finding also links to broader Swiss public support: demand-side policies on flexible EV charging or the flexible operation of HPs tend to be more acceptable than supply-side policies on electricity trading or construction of Direct Air Carbon Capture and Storage (DACCS) facilities to allow the use of back-up fossil fuel power plants [45, 47]. Public support is also affected by how impacts

*Finding comes from outside PATHFNDR.

are communicated: support increases when societal and environmental impacts are perceived as beneficial (Figure 4.1) and decreases when impacts are perceived negatively [46, 47].

- **Even if flexibility is automated, customers prefer simple tariff structures with a predictable impact on their bill.** While automation can reduce aversion to price volatility [25]*, most customers prefer simple, fixed price contracts [16, 25, 84, 99]. One way to maximize participation could therefore be to offer customers a reduced fixed rate in exchange for allowing automated control by a utility that is exposed to dynamic prices [100]. Alternatively, participation could be increased by offering customers who want to control their loads themselves a profile contract, which hedges them against the risks from dynamic prices while keeping incentives to shift loads (Figure 4.2) [52, 101]. However, the most important step to maximise participation would be to use opt-out recruitment, which has been shown to achieve recruitment rates around 90%, much higher than the typical 20–50% achieved by opt-in recruitment strategies [70]*.

Contract	Price protection	Efficient dispatch	Efficient investment
Spot price	✗	✓	✓
Fixed price	✓	✗	✗
Fixed + dynamic load-control	✓	✓	✗
Spot + profile contract	✓	✓	✓

Figure 4.2: Incentives of different contract types. Comparison of contract designs in terms of consumer price protection, efficient dispatch incentives, and efficient investment incentives.

- **Scaling flexibility requires that devices are flexibility-ready by default.** EV chargers and HP systems need standardised, interoperable control and communication capabilities so automation works across vendors and settings [59]. As regulation shifts from supporting “simple” to “flexible” electrification, barriers in access, cost, and market participation must be reduced [59, 72]. For EVs, this means regulation and tariff design (e.g., time-of-use, dynamic, and hybrid tariffs) that support automation and viable business models [3, 60]. For HPs it means policy changes that help Distribution System Operators (DSOs) act as aggregators and providers of flexible multi-building heating solutions [62]. Switzerland is not yet fully flexibility-ready: the implementation of new "right to charge" regulations must be aligned with smart-charging standards, and new changes to avoid double charging Vehicle-to-Grid (V2G) for use of the network must be followed up with further changes to reduce the cost barriers that hinder participation [3, 59, 72]. Broader availability of suitable tariffs, clear market access for aggregators (a role not yet defined in Swiss electricity law), and wider coverage of direct load control can help scale EV and HP flexibility [3, 59, 72]. Local incentives can further support participation and enable prosumer solutions, such as the “nanoverbund” concept [7, 62].

- **Coordination of roles and product design make flexibility reliable.** Because DSOs, suppliers, aggregators, and prosumers may act on the same devices, coordination and clear priority rules are needed to avoid conflicting signals and local grid constraints. To avoid balancing problems, control of flexible loads should sit with the entity exposed to spot market prices and dynamic grid charges, otherwise independent aggregator control can create imbalances for the load-serving entity [100]. A key challenge for utilities remains uncertainty about how much EV and HP flexibility will actually be available. Reliable participation, together with good forecasting and verification, is therefore essential so flexibility can be planned and used as a dependable service and supported by viable business models [72]. Product design also matters: flexibility products should reward reducing demand to a predefined level, or use scarcity-linked remuneration (e.g., dynamic or nodal tariffs), rather than paying for a guaranteed "reduction by" a volume, so loads do not increase consumption ahead of scarcity periods [17]. Product design and anticipation of future policy can help firms meet customer needs and make flexibility-ready options the default [67].

Research gaps:

- Future research should determine the appropriate design of risk-hedging arrangements for end-customers in order to strike the right balance between maximising customer acceptance and ensuring undistorted dispatch and investment incentives.
- Future research should include further trials to understand how programmes should be designed to maximise enrolment and reliable flexibility delivery (e.g., opt-in vs. opt-out, communication, trust, price fairness).
- Future research should focus on how to measure and verify what flexibility was actually delivered to an end consumer so that operators can learn how to plan flexibility and offer it as a reliable service.
- Future research should build a stronger Swiss evidence base on acceptance of EV and HP demand response. Existing evidence combines PATHFNDR and related SWEET work with international studies. Further research should investigate how Swiss EV and HP owners respond to different tariff designs, automation schemes, compensation models, and communication strategies in real-world settings.
- Future research should explore the idea of capacity payments for solar photovoltaic (PV) production, where the utility pays a fixed price per kW of installed PV and in return may control the PV output.

5 Stakeholder recommendations

The findings presented in this report show that Switzerland's energy transition needs two inter-linked transitions: the direct electrification of end-use sectors, and the integration of flexibility to balance a power system dominated by variable renewables. As the energy system becomes more sector-coupled (i.e., linking electricity, heat, transport, and fuels), the need for flexibility grows, and unlocking it requires coordinated action across many actors. No single stakeholder can deliver it alone.

The recommendations presented in this report are grouped by stakeholder: the federal legislator and administration set the legal and strategic framework; the market and regulatory authority monitors the market rules; cantons and municipalities steer permitting and local planning; the transmission and distribution system operators adapt grid planning and operation; aggregators, suppliers, and technology providers turn the rules into products and devices; and consumers and prosumers put flexibility into practice. Each recommendation links to its supporting statements.

Federal government

The federal government sets the long-term direction of the energy transition. Its core task is to give investors and local authorities clear priorities, secure international integration, and adopt laws that make flexible, electrified operation the default. There are two roles: Parliament and the Federal Council decide on legislation and international agreements, while the involved federal agencies – the Swiss Federal Office of Energy (SFOE) and the Federal Office for the Environment (FOEN) – prepare and implement the corresponding legislation.

Parliament and Federal Council

- Realise net zero by the 2050 target set in the Climate and Innovation Act by making electrification of the heating and transport sectors the national priority. Prioritise the direct electrification of buildings (in coordination with the cantons[1]), road transport, and low-temperature industrial heat with policy support, as these are identified as the most cost-effective options to cut emissions and reduce the need for imported fuels. [Statements 1 & 2]

- Strengthen “right to charge” provisions and align them with smart-charging standards, and extend them beyond electric vehicles so tenants cannot be blocked from flexibility-ready installations. Remove residual cost barriers for vehicle-to-grid operation. [Statement 10]

- Align tenancy and self-consumption rules so that flexibility investments in rented and multi-party buildings pay off for both sides. Landlords should be able to recover the cost of flexibility-ready electric vehicle charging investments, heat pumps, and photovoltaic infrastructure, while tenants keep a share of the resulting energy cost savings and retain control and easy override. [Statements 6 & 10]

- Secure and deepen Switzerland’s integration in European electricity markets and infrastructure, including ratifying an electricity agreement with the European Union. Cross-border trading is, alongside flexible hydropower, one of the two central sources of flexibility for the Swiss system. [Statements 3 & 4]

- Secure international agreements with access to appropriate infrastructure for imported hydrogen and synthetic fuels and for CO_2 transport, storage, and removal. Synthetic fuels and hydrogen are necessary to decarbonise aviation and some industrial applications. Importing these fuels is expected to be more cost-effective than domestic production. [Statements 3 & 5]

- Set the national framework for dynamic tariffs in the Electricity Supply Act / Ordinance. The energy-related price component should follow wholesale prices, while the grid-related price component stays flat and varies only when the local grid area is congested. Where an area is congested, this grid charge should be regionally differentiated and provide symmetric incentives for withdrawals and injections. [Statement 8]

- Provide, in the Energy Act / Energy Ordinance, that photovoltaic feed-in remuneration follows wholesale prices. Payments then fall to low or negative levels during zero- or negative-price

[1] The federal level acts through the policy tools available to it (transport policy, national funding, and CO_2 pricing), while cantons act on building requirements.

periods. Revenue risk for investors should be reduced separately, through support schemes. [Statements 8 & 9]

- Set minimum consumer-protection rules for dynamic tariffs in the Electricity Supply Act / Ordinance to improve acceptance of automated flexibility. These rules should include bill transparency, price hedges, clear consent, easy override, and predictable bill outcomes. [Statements 8 & 10]

- Building on the flexibility rules in force since 2026 in the Electricity Supply Act / Ordinance, extend the rules on who controls a flexible device and in what order. A given unit of flexibility should be controlled by only one party at a time, so it cannot be sold or committed twice. In critical grid situations, the grid operator should keep priority access. [Statements 8 & 10]

- Define the role of aggregators in the Electricity Supply Act. Establish, in the Electricity Supply Act, fair and clearly defined market access for aggregators and other third parties, so that electric vehicle and heat pump flexibility can be monetised. [Statement 10]

- Provide, in the grid connection rules (Electricity Supply Ordinance and the applicable technical connection rules), that distribution system operators can require voltage support from photovoltaic inverters. Where feasible, require the same support service from electric vehicle charging and heat pump systems. Such voltage support contributes to voltage management in distribution grids. [Statement 7]

Federal administration (SFOE, FOEN)

- Systematically compare decarbonisation pathways and technologies before committing to them, so public support does not get locked into options that cannot reach net-zero. [Statement 2]

- Propose programmes and research funding calls to Parliament and the Federal Council that support the goal of cutting emissions at the scale and speed needed to meet the net-zero goals. [Statement 2]

- Support pilot projects and prepare the regulatory framework for renewable investment-support schemes, such as financial Contracts for Difference. The aim is to reduce investor risk while keeping short-term price signals undistorted. [Statement 9]

- Require electric vehicle charging and heat pump infrastructure to be smart-ready, interoperable, and override-capable by default, including through binding product and design standards, so automated flexibility can scale without costly retrofits. [Statement 10]

- Propose national incentives to accelerate the uptake of flexibility-ready electric vehicles and heat pumps. For example, make purchase or installation support conditional on devices that are interoperable and can be controlled automatically to respond to tariffs. Rewarding flexible operation itself is a task for market actors, so adapt the regulatory framework to let distribution system operators, suppliers, and aggregators compensate prosumers for it. [Statements 6 & 10]

Market and regulatory authority (ElCom)

Most tariff and market rules are set in federal legislation and ordinances – the Electricity Supply Act, the Electricity Supply Ordinance, and the Energy Act – by Parliament and the Federal Council. The Swiss Federal Electricity Commission (ElCom) does not set these rules and its role is monitoring, control, and verification. Its core task is to monitor the tariff and market rules so that flexibility is rewarded and neither automated response nor third-party access is blocked, and to flag to Parliament and the Federal Council where the legal framework needs to change to achieve this.

- Monitor and enforce compliance with the national rules for dynamic tariffs once in force. [Statement 8]
- Verify grid operators' tariff structures. [Statement 8]
- Once the legislator has set minimum consumer-protection rules for dynamic tariffs, monitor and enforce them to improve acceptance of automated flexibility. [Statements 8 & 10]
- Verify that the rules on the use of flexibility (Electricity Supply Act / Ordinance) are applied, including the grid operator's guaranteed use. Monitor any further priority rules once they are in force. [Statements 8 & 10]
- Once the role of aggregators is defined in law, enforce their fair market and grid access and decide related grid-access disputes, so that electric vehicle and heat pump flexibility can be reliably monetised. [Statement 10]

Cantons and municipalities

Cantons and municipalities are the level closest to buildings, mobility, and local grids. Their core task is to make flexibility-readiness the norm in what they permit, plan, and build, so that local infrastructure does not have to be reworked later.

- Integrate flexibility-readiness into permitting processes and building codes. New and renovated buildings should then be prepared for smart electric vehicle charging and flexible heat pump operation, without costly retrofits. Interoperability standards for the devices themselves are set at federal level. [Statements 6 & 10]
- Integrate flexibility-readiness for rented and multi-party buildings explicitly into permitting and building codes. Shared parking, heating, and metering should be prepared for smart electric vehicle charging and flexible heat pump operation, avoiding costly retrofits in occupied buildings later. [Statements 6 & 10]
- Design cantonal incentives for smart-ready and interoperable electric vehicle charging and heat pump systems, rather than for technology uptake alone. Installed devices can then actually take part in automated flexibility. [Statement 10]

- Promote workplace and other daytime charging through municipal and cantonal planning. For example, encourage deployment of public charging stations near photovoltaic producers where vehicles park during peak solar hours. This shifts electric vehicle demand into midday solar generation and increases local flexibility. These planning measures work best in combination with market and tariff designs, which lie outside cantonal and municipal competence. [Statement 6]
- Support local prosumer and multi-building flexibility solutions, such as coordinated neighbourhood or nanoverbund concepts. These lower participation barriers and enable coordinated local flexibility. [Statement 10]

Transmission system operator (Swissgrid)

At the national grid level, the transmission system operator, Swissgrid, ensures stable grid operation and needed expansion and coordinates system balancing. One core task is to make flexible resources usable for system-level services while keeping this coordinated with the distribution level.

- Establish operational coordination processes with distribution system operators, and with suppliers and aggregators where relevant. Flexible loads can then provide system-level services without creating local grid constraints, conflicting dispatch signals, or imbalances. [Statements 8 & 10]
- Publish transparent information on system flexibility needs, including location, timing, and required volumes. Communicate it to distribution system operators and market participants. This guides investment in and operation of flexible resources. [Statement 8]

Distribution system operators

Distribution system operators plan and operate the local grids where most photovoltaic systems, electric vehicles, and heat pumps connect. Their core task is to shift from reinforcing the grid by default to using flexibility from end-user demand and generation first within their regulated planning mandate.

- Apply flexibility-aware grid planning to manage grids with growing electricity demand and distributed renewable generation. Use local flexibility and managed feed-in before conventional reinforcement, where this is cost-efficient. [Statement 7]
- Differentiate flexibility strategies and incentives by region type. For grids serving rural and semi-rural regions, prioritise photovoltaic feed-in management. In urban grids, prioritise demand-side flexibility from electric vehicles and heat pumps. [Statement 7]
- Use local flexibility measures, such as electric vehicle smart charging and flexible heat pump operation. These align demand with peak photovoltaic generation periods and reduce local congestion. [Statements 6 & 7]

- Reward grid-friendly feed-in through cost-reflective connection and remuneration terms. For example, offer photovoltaic system owners better connection conditions in return for accepting temporary limits on peak feed-in during congested hours. This approach reduces grid reinforcement. [Statement 7]
- Use the voltage-support function of photovoltaic inverters by setting it in the technical connection requirements. This helps manage voltage in distribution grids with high photovoltaic penetration, at little additional cost. [Statement 7]

Aggregators and energy suppliers

Aggregators and energy suppliers turn market rules into products that customers actually use. Aggregators do not yet have a defined role in the Electricity Supply Act; today they operate on a contractual basis. Their core task is to package flexibility so that taking part is simple, low-risk, and rewarding for the customer, while still delivering value to the system.

- Build flexibility into the core product, so that market- and grid-friendly operation do not conflict. Keep control of a flexible device with the party exposed to both wholesale prices and dynamic grid charges, so its incentives point the same way. [Statements 8 & 10]
- Compensate customers and prosumers for the flexibility they provide, for example through reduced tariffs, bill-risk protection, or direct payments. This way, flexibility is rewarded by the market rather than by public subsidy. [Statements 8 & 10]
- Offer simple fixed-tariff contracts to customers who allow direct load-control of electric vehicle charging or heat pump operation. Flexibility can then be activated reliably, with minimal customer effort. [Statements 8 & 10]
- Offer automation-based flexibility products in which customers can set simple operating limits and easily override automated control. For example, let them set minimum electric vehicle state-of-charge targets or heating comfort bands. [Statement 10]
- Combine automated flexibility offers with bill-risk protection, such as a cap on the per-kWh price, a cap on the total bill, or a fixed-price hedge for part of a pre-specified share of consumption. Customers then get predictable prices, while flexibility incentives are preserved. [Statements 8 & 10]
- Offer available flexibility in the day-ahead and intraday auctions using tailored bid formats, such as the “exclusive group of block bids”. Work with the European Power Exchange to develop these formats further. This captures the full value of flexibility. [Statement 8]
- Design flexibility products that reward keeping demand below a set level or responding to scarcity-linked signals. Avoid paying for a guaranteed “reduction by” a volume, which can encourage higher consumption ahead of activation periods. [Statement 10]
- Scale smart electric vehicle charging now and offer bidirectional electric vehicle charging where technical, regulatory, and commercial conditions allow. This monetises electric vehicle storage

potential, reduces peak demand, and creates customer value from electric vehicle battery flexibility. [Statements 6 & 10]

- Communicate tariffs and flexibility in simple, benefit-oriented terms (comfort, low risk, long-term cost stability). Do not rely on technical detail alone. [Statement 10]
- Enable opt-out (as default-on) enrolment with easy withdrawal. Preserve informed consent and data protection. [Statement 10]

Technology providers and manufacturers

Technology providers and manufacturers decide what the installed devices are actually capable of. Their core task is to make flexibility a built-in, standard capability of electric vehicles, heat pumps, chargers, and inverters, so that flexibility does not depend on later upgrades.

- Offer flexibility-ready devices by default, including simple user settings, easy override, and interoperable control. Electric vehicles and heat pumps can then respond automatically to tariffs and control signals, without compromising comfort. [Statement 10]
- Design devices and controls so users can set clear comfort and operating limits (e.g., departure-time charging targets or heating comfort bands). Users should also be able to easily override automated operation. [Statement 10]
- Implement standardised interfaces that let devices and energy management systems automatically receive and apply dynamic tariff, spot price, and control signals. This allows flexible loads to respond reliably at scale. [Statement 10]
- Build devices to emerging flexibility standards ahead of any mandate, so products are already compliant when smart-ready, interoperable requirements become binding. [Statement 10]
- Where feasible, equip electric vehicle charging infrastructure and heat pump systems with a voltage-support function that photovoltaic inverters already have as standard. These resources then contribute to voltage management in distribution grids. [Statement 7]

Consumers and prosumers

Consumers and prosumers (including building owners, photovoltaic owners, and electric vehicle and heat pump users) are where flexibility is finally realised. Their core task is to choose flexibility-ready equipment and to allow automated, comfort-preserving operation, so that their assets can support the grid and lower their own long-term costs.

- When building, renovating, or replacing equipment, choose smart-ready, interoperable, and automation-capable electric vehicle chargers, heat pumps, and photovoltaic systems now. This avoids costly retrofits later. [Statements 6 & 10]

- Enrol in dynamic tariffs and automated flexibility programmes, and allow automated control within clear comfort limits. Flexibility can then be activated without day-to-day effort. [Statements 8 & 10]
- Use the override and comfort-setting options offered. Automated operation then stays aligned with personal needs, while still providing flexibility. [Statement 10]

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